

# **MAGNETORHEOLOGICAL FINISHING OF POLYMERS FOR IMPROVING THE SURFACE FINISH**

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DOCTOR OF PHILOSOPHY  
IN  
MECHANICAL ENGINEERING

*Submitted by*

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## CERTIFICATE

I, Kunal Arora, Roll No. 901708012, hereby declared that the thesis entitled **“Magnetorheological Finishing of Polymers for Improving the Surface Finish”** submitted to the Department of Mechanical Engineering at Thapar Institute of Engineering and Technology, Patiala, Punjab (India) is an authenticated record of my own research work for the award of the degree “Doctor of Philosophy” under the supervision of **Dr. Anant Kumar Singh**. This report has not been submitted to any other institute for the award of any other degree.

Place: Patiala

  
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This is to certify that above declaration made by the student is correct to the best of my knowledge.

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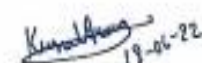
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## **Abstract**

In the present scenario, different shaped polymer components with improved functional performance are desired in the automobile, medical, and aerospace industries. Polymer gears, bearings, and bushings have replaced metal counterparts in various equipment such as micro, and macro devices, automotive equipment, farm and agricultural equipment, electrical toys, and marine transmission. Similarly, polymers play important role in the medical industry as they are notably used in hip joint implants, knee joint implants, dental X-ray systems, surgical robotic drives, etc. This is because the polymer-based components offer unique advantages over the metal components such as low weight, good corrosion-resistant, extremely good formability, compatibility, and ability to function without external lubrication with minimum noise and vibration. The uniform fine finishing of these polymer components is an important need of the various industrial machines for enhancing their efficacy. For the finishing of the polymer components, various traditional and advanced finishing processes are developed such as grinding, ball burnishing, chemo-mechanical process, etc. However, finishing the polymer workpieces with these processes can produce uncontrolled finishing forces. Owing to this, several surface defects such as micro-cracks, scars, etc. appear on the finished surface of the polymer workpieces.

To achieve efficient and defect-free finished surfaces of polymers, magnetorheological polishing (MRP) fluid-based finishing processes are utilized. The magnetorheological finishing (MRF) process provides a fine grade of surface finish with a minimal scar. The MRF process uses MRP fluid which includes the electrolytic iron particles, polishing grade abrasives, and the carrier fluid. The MR fluid-based finishing process does not leave pits or scratches. The process also has the potential to achieve nanoscale precision without causing harm to the workpiece's surface or sub-surface. Since the MR finishing has provided fine finishing over various optical applications and offers a clean and damage-free surface due to low normal forces on abrasives. Therefore, the MR finishing process can also be used for the polymer components which are used in various industries such as automobile, medical, marine, etc. Hence, in the present work, the advantage of the magnetorheological finishing process has been explored further for the fine finishing of various polymer industrial components with different shapes such as gears, bearings, valve seats, medical implants, and additive manufactured components, etc. Therefore, different magnetically controllable finishing tools, as well as workpiece fixtures, are designed and fabricated to fine finish these polymer workpieces.



For the design of the different magnetorheological finishing (MRF) tools, magnetostatic finite element analysis (MFEA) is performed. The MFEA is used to determine the required value of magnetic flux density (MFD) on the MR finishing tool's surface. The different MR finishing tools are designed as per the shape of the workpiece (flat, internal, hemispherical, gears). In all the cases, the MFEA result reveals the ability to retain the magnetorheological polishing (MRP) fluid over the tool surface for fine finishing the various shapes of polymer workpieces. The decreasing MFD value amid the working gap ensures that iron particles are retained on the tool surface and abrasive particles present in the MR polishing fluid perform proper relative motion over the polymer workpiece surface. Hence, the present developed finishing tools are feasible to provide fine finishing over the different types and shapes of polymer workpiece surfaces. Further, the magnetic flux density is also analyzed experimentally over the different fabricated MR finishing tools. It is found that the MR finishing tools provide uniform magnetic flux density over the tool surface which may lead to the fine finishing of the polymer workpieces. Further, the workpiece fixture and holders are designed and fabricated as per the shape of the workpiece to be finished. The fixtures are designed in such a way that a uniform working gap could be maintained between the tool surface and workpiece surface during the finishing process. Also, the fixtures are designed so that workpiece remains tight against different motions while finishing.

After the fabrication of tools and fixtures, to get insight into the process mechanism, the material removal by the different fabricated MR finishing tools over the polymer workpieces is analyzed. Because different shapes of polymer workpieces (flat, internal, hemispherical, gears, etc.) are finished in the current work, various types of motions are used for finishing, resulting in various forces acting. Further, theoretical analysis is performed to understand the process mechanism during the finishing of the flat, hemispherical, and gear surface using the newly developed magnetorheological finishing tools. The influence of the magnetic flux density, the path followed and the number of active abrasive particles have been explored in depth using theoretical analysis. Also, in the theoretical analysis, a surface roughness model is developed to predict the finishing of the different surfaces with the present magnetorheological finishing tools. From the theoretical model for the hemispherical cup, the percentage error amid the experimentally obtained values and the theoretically calculated value is in the range of 1.17 to 6.15 %. Similarly, for gear and flat surface, the percentage error amid the experimentally obtained values and the theoretically calculated value is in the range of 2.3 to 10 % and 0.55 to 9.09 %, respectively. Thus, from the results of the theoretical analysis, it is found that the MR finishing tools are capable for fine finishing the different shapes of polymer workpieces.

In the magnetorheological finishing (MRF) process, the MR polishing (MRP) fluid plays an important role, therefore, the effectiveness of the MRP fluid over the different polymer materials has been further analyzed. For this, the different MRP fluids are developed and experimentally tested over the polymer materials. The results reveal that water-based MRP fluid shows significantly effective finishing over polyamide surfaces as compared to the oil-based MRP fluid. Also, MRP fluid with  $\text{CeO}_2$  abrasives is found more effective for fine finishing the UHMWPE polymer as compared to the SiC and  $\text{Al}_2\text{O}_3$  abrasives. Additionally, the graphene-based MRP fluid is found effective for fine finishing of the polymers as compared to the non-graphene-based MRP fluid.

Further, to validate the efficacy of MR finishing tools for finishing the polyamide workpiece surface, preliminary experimentation is performed over the external flat cylindrical surface of the polyamide component. The process parameters magnetizing current, rotational tool speed, reciprocation tool speed, and rotational speed of workpiece are used for investigating the fine finish of the polyamide workpieces. The response surface method is further used to find the best process parameters for the fine finishing of the polyamide workpiece surfaces. In the 100 min of the finishing cycle, the surface roughness on a polyamide surface area of  $706.5 \text{ mm}^2$  is reduced to 100 nm from 560 nm. Furthermore, after the validation of the fine finishing of the polyamide workpiece surface, a detailed experimental study has been done for various polymer components such as acetabular cups, gears, bearings, valve seals and additive manufactured components.

UHMWPE is used for the manufacturing of acetabular cups in hip-joint implantation. For enhancing the life span and functionality of hip implants, the uniform fine surface finish of the acetabular cup is essential. For the fine finishing of the cups, the hemispherical tip-based magnetorheological finishing tool is used. After the experimentation on the  $1140 \text{ mm}^2$  surface area of the UHMWPE acetabular cup, the surface improvement obtained is 66.67 % in 100 min of the finishing cycle. Scanning electron microscopy, a coordinate measuring machine, and a microhardness tester machine are used to examine the surface morphology, circularity, and microhardness of the finished UHMWPE acetabular cup. Results show that the present process is suitable for the uniform fine finishing of the UHMWPE acetabular cup with improved surface characteristics.

Fine finishing of polymer bevel gears (BGs) plays a key role in defining the functionality of many industrial components. Polymer BGs are highly utilized due to their properties such as high damping resistance and low weight. A novel magnetorheological bevel gear finishing (MRBGF) process is utilized to finish the overall polyamide BG surface in minimum

time. After experimentations, the average surface roughness value of the overall polymer BG got reduced from 380 nm to 100 nm in 140 min finishing with predicted optimum parameters. Microhardness and surface morphology are also used to assess MRBGF process efficacy and BG tooth accuracy. The results reveal significant improvement in surface characteristics and an increase in average microhardness of the BG tooth surface. Also, gear run-out is reduced from DIN 8 to DIN 6 which demonstrates improvement in BG tooth accuracy.

Fine finishing of the internal polymer bearing is an important factor in deciding the surface quality of the manufactured products. Finely finished polymer bearing internal surface is highly utilized in several industries such as food, textile, etc. Fine finishing of the polytetrafluoroethylene (PTFE) internal surface has been done using the newly developed rotational magnetorheological (R-MR) honing process. After experimentation on the 4772.80 mm<sup>2</sup> surface area of bearing, the percentage of surface improvement obtained is 82.5% in 120 min of finishing. A study of surface morphology and dimensional accuracy over the PTFE bearing surface is also carried out to evaluate the efficacy of the current R-MR honing process. Results show that the current approach is capable of uniform fine finishing of the internal surface of PTFE bearings with enhancement in surface characteristics and functional efficacy. The polymer valve seat is an important part of the ball valves in the pipeline which are used for transporting the medium such as oil and gas from one place to another. However, during the practical application, inevitable events of the leakage of the pipeline valves during the gas or oil transportation process pose serious problems. Hence, the fine finishing of the polymer valve seat is of significant importance. For fine finishing of the polymer valve seat surface using magnetorheological (MR) finishing process with the hemispherical tip-based electromagnetic tool is used. After experimentation on the 4878 mm<sup>2</sup> surface area of the polymer valve seat, the %  $\Delta R_a$  obtained is 80.70 % in 140 min of finishing using the optimum process parameters. The dimensional accuracy of the valve seat surface is further analyzed in terms of circularity. Results show that the current method is capable of uniform fine finishing of the polymer valve seat surface with enhancement in surface characteristics.

Fused deposition modeling (FDM) is a common and cost-effective additive manufacturing technique for making cylindrical components such as printer rollers, turbine blades, and winding drums. The fine finishing tends to enhance dimensional accuracy and efficacy of FDM fabricated cylindrical components. The best process parameters are further utilized for the surface improvement of FDM workpieces. After experimentation on 18,840 mm<sup>2</sup> cylindrical surface area, %  $\Delta R_a$  obtained is 86.44 % in 140 min of finishing. To analyze present MRF process efficacy, a study of circularity, surface morphology, microhardness, waviness, and

wear test is done. After finishing, the dimensional accuracy and surface characteristics show a substantial improvement. All of these findings suggest that a novel hexagonal tool tip-based MRF process may be used to fine-finish the FDM-fabricated workpieces.

All these results signify that the presently developed magnetorheological finishing tools can be found to be effective for fine finishing of the various polymer workpieces with different shapes which can be beneficial for various industrial components such as gears, bearings, acetabular cups, and additive manufacturing components.

**Keywords:** Different shapes of polymers' surface, magnetorheological (MR) finishing, various shapes of magnetic tools' surface, magnetic field, MR polishing fluids, additive manufacturing components, surface roughness, surface characteristics.

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## **LIST OF ABBREVIATIONS**

|       |                                                  |
|-------|--------------------------------------------------|
| AAPs  | Active abrasive particles                        |
| AFM   | Abrasive flow machining                          |
| ANOVA | Analysis of variance                             |
| BEMRF | Ball end magnetorheological finishing            |
| CCD   | Central composite design                         |
| CIPs  | Carbonyl iron particles                          |
| CMM   | Coordinate measuring machine                     |
| CMP   | Chemo mechanical polishing                       |
| DOE   | Design of experiments                            |
| EEP   | Elastic emission process                         |
| EIPs  | Electrolytic iron particles                      |
| FMAB  | Flexible magnetic abrasive brush                 |
| MCF   | Magnetic compound fluid                          |
| MFEA  | Magnetostatic finite element analysis            |
| MR    | Magnetorheological                               |
| MRF   | Magnetorheological finishing                     |
| MRH   | Magnetorheological honing                        |
| MRP   | Magnetorheological polishing                     |
| MRR   | Material removal rate                            |
| OBC   | Oil-based carrier                                |
| PLC   | Programable logic controller                     |
| RSM   | Response surface methodology                     |
| R-MR  | Rotational magnetorheological                    |
| SEM   | Scanning electron microscopy                     |
| UMRCF | Ultrasonic magnetorheological compound finishing |
| WBC   | Water-based carrier                              |

## LIST OF NOMENCLATURES

$a_e$ : dept of cut in grinding (mm)

$A$ : The contact area during the burnishing process ( $\text{mm}^2$ )

$A_{bg}$ : The projected area of the bottom land of the bevel gear work part ( $\text{mm}^2$ )

$A_{gw}$ : The projected area of the straight bevel gear workpiece ( $\text{mm}^2$ )

$A_{fg}$ : The projected area of face-flank of the straight bevel gear work part ( $\text{mm}^2$ )

$A_{hex}$  : The projected hexagonal area of over the work part surface ( $\text{mm}^2$ )

$A_{wp}$ : The area of the hemispherical acetabular cup workpiece over which the shear force acts ( $\text{m}^2$ )

$A_t$ : The area of the hemispherical tool tip surface ( $\text{m}^2$ )

$A_{in}$ : The cross-sectional area generated by the AAPs chain over the surface of the acetabular cup ( $\text{m}^2$ )

$A_p$ : The indented AAP projected area over the polyamide surface ( $\text{mm}^2$ )

$B$ : The magnetic field (B) due to total length of the circular coil ( $2\pi$ ) (T)

$B'$ : The total magnetic field due to the total numbers turns of the electromagnetic field (T)

$B_c$ : The total magnetic field considering the influence of electromagnetic coil, core and magnetorheological polishing fluid (T).

$C_{bottom}$ : The circumference at the centre of the hemispherical cup (Point B) (m)

$C_{top}$ : The circumference at the outer radius of the hemispherical cup work part (Point A) (m)

$C$ : Percentage volume concentration of abrasive

$d$ : depth of cut with conventional MR polishing without graphene

$d_1$ : depth of cut with MR polishing with graphene

$\frac{dB_c(g)}{dg}$ : The positional gradient of the magnetic field along working gap

$\frac{d_s}{2}$ : Radius of raster path (mm)

$d_{aap}$ : Diameter of the single abrasive particle (m)

$D$ : Diameter of flat circular surface of the polyamide workpiece (mm)

$D_b$ : The bottom land length of the bevel gear (mm)

$D_d$ : The depth of the bevel gear (mm)

$D_t$ : The top land length of bevel gear (mm)

$d_{in}$ : The total depth of indentation by the AAP (m)

$D_{ind}$ : The indentation diameter as indented by the AAP over the hemispherical cup surface (m)

$\frac{du}{dy}$  : Velocity gradient with respect to displacement

$dB$ : Magnetic field induced at any random point P (x, y, z) [T]

$dl$ : Length of the coil at point P (m)

$E$ : Percentage volume concentration of electrolytic iron particles

$f_w$  : The face width of the bevel gear (mm)

$F$ : Reciprocatory motion of tool (cm/min)

$F_{ay}$ : Axial force along Y- axis (N)

$F_{az}$ : Axial force along Z- axis (N)

$F_{cb}$ : Compressive force (N)

$F_{ind}$ : The average value of the normal magnetic forces at different points in working space (N)

$F_{ng}$ : Normal force during grinding (N)

$F_{nrm}$ : Magnetic force due to single EIP (N)

$F_r$  : Normal reactive force (N)

$F_{rb}$  : Rubbing force (N)

$F_{res}$ : Net finishing force which is used for shearing the surface asperities (N)

$F_{tan}$ : Tangential force acting on the AAP (N)

$F_{tg}$ : Tangential force during grinding (N)

$F_{tt}$ : Tangential force due to tool rotation (N)

$F_{tw}$ : Tangential force due to workpiece rotation (N)

$F_w$ : Force acting during wear (N)

$g$ : Thickness of working space between the hemispherical tool tip surface and work part surface (m)

$H$ : Material hardness

$H'$ : Magnetic field strength due to n number electromagnetic coil (A/m)

$\nabla H$ : Derivative of intensity of magnetic field along working gap

$H_{BH}$ : Brinell hardness number (kgf/mm<sup>2</sup>)

$I$ : Magnetizing current (A)

$k$  : The number of factors studied

$k_a$  : Archard coefficient

$K$  : Consistency parameter

$l$  : length produced on a flat surface in one pass by profile grinding (mm)

$l_{fs}$  : The finishing spot over the workpiece surface (mm)

$L'$  : Sliding distance (mm)

$L$ : The length of the arc for the semi parabolic path (mm)  
 $L_{cw}$ : The chord length of the involute arc (mm)  
 $L_i$ : The involute profile length of the bevel gear (mm)  
 $L_g$ : The bottom gap between two teeth of the bevel gear (mm)  
 $L_p$ : The total length covered by the single active abrasive particle of the line chain in a single rotation of the hemispherical tool  
 $m$ : Module of gear  
 $m_a$ : Mass of single active abrasive particle (kg)  
 $m_e$ : Mass of single electrolytic iron particle (kg)  
 $M_{cr}$ : The magnetization of the tool core ( $\text{Am}^2/\text{kg}$ )  
 $M_{eip}$ : The magnetization of the EIP ( $\text{Am}^2/\text{kg}$ )  
 $n$ : Flow behavior index  
 $N_e$ : The total number of experiments  
 $N$ : Total number of tool core rotations (rpm)  
 $N_{ap}$ : The total number of abrasive particles  
 $N_{aap}$ : The total number of active abrasive particles  
 $N_s$ : The number of strings over the hemispherical cup consisting of overall AAPs  
 $n_c$ : The number of the AAPs in a single circumferential line chain structure  
 $P$ : Finishing pressure  
 $p$ : number of turns in the electromagnetic coil  
 $q$ : The number of replicates  
 $R_a^k$ : Average initial surface roughness value of  $(k)^{\text{th}}$  finishing cycle (nm)  
 $R_a^{k+1}$ : Average surface roughness value in  $(k+1)^{\text{th}}$  finishing cycle (nm)  
 $r'$ : Radius of coil  
 $r$ : Distance from point P to O (m)  
 $r_a$ : The distance from the axis of tool rotation to the location of the AAP lying on the work part surface (m)  
 $r_p$ : Position vector at point P  
 $r_t$ : The radius of the hemispherical tool tip surface (m)  
 $r_{aap}$ : The radius of the single  $\text{CeO}_2$  abrasive (m)  
 $r_{bw}$ : The base circle of the bevel gear work part (mm)  
 $r_{iw}$ : The involute arc radius of the bevel gear work part (mm)  
 $r_{wp}$ : The internal radius of hemispherical cup workpiece (mm)

$R_a$ : Average surface roughness (nm)  
 $R$ : Workpiece reciprocation motion (cm/min)  
 $R_q$ : Root mean square roughness value (nm)  
 $R_z$ : Average maximum peak to valley roughness value (nm)  
 $\% \Delta R_a$ : Percentage improvement in surface finish  
 $T$ : Rotary motion by the tool core (mm)  
 $t$ : Thickness of workpiece (mm)  
 $t'$ : The time taken for one finishing cycle (sec)  
 $\Delta t$ : The reduced MRP fluid thickness due to the squeezing during the reciprocation motion on the polyamide surface (mm)  
 $V_{ab}$ : The total volume of the abrasive particles (mm<sup>3</sup>)  
 $V_{aap}$ : Volume of the single abrasive particle (m<sup>3</sup>)  
 $V_{in}$ : Material cut-out from the finishing surface of the work part (m<sup>3</sup>)  
 $V_{MR}$ : Volume of the material removed by the total number of AAP (m<sup>3</sup>)  
 $V_{mrp}$ : Total volume of MR polishing fluid present in the working space (m<sup>3</sup>)  
 $V_g$ : Rotational speed of grinding wheel (rpm)  
 $V_{wc}$ : Longitudinal feed of workpiece during cylindrical grinding (mm/min)  
 $V_{ws}$ : Longitudinal feed of workpiece during surface grinding (mm/min)  
 $V_x$ : Velocity along X- direction (mm/min)  
 $V_z$ : Velocity along Z- direction (mm/min)  
 $w$ : The MRP fluid width placed on the tool tip surface (mm)  
 $W'$ : Volumetric wear rate  
 $W$ : Rotary motion by the workpiece (rpm)  
 $W_a$ : Average waviness (μm)  
 $W_q$ : Root mean square waviness value (μm)  
 $W_z$ : Average maximum peak to valley waviness value (μm)  
 $W_{sw}$ : Specific wear rates on the polymer gear  
 $\sigma$ : Yielding stress of the material (N/mm<sup>2</sup>)  
 $\alpha$ : The subtended involute angle at the center  
 $\mu_0$ : Magnetic permeability of air (N/A<sup>2</sup>)  
 $\mu_{cr}$ : Magnetic permeability of the tool core material  
 $\mu_{mr}$ : Magnetic permeability of MR polishing fluid  
 $\mu_{r\_cr}$ : The relative magnetic permeability of the tool core material (H/m)



$\mu_{r\_Mrp}$ : The relative magnetic permeability of the MR polishing fluid (H/m)  
 $\tau'_y$ : The viscous fluid shear stress  
 $\tau$ : Shear stress of the MRP fluid (Pa)  
 $\tau_0$ : Dynamic yield stress of MR polishing (MRP) fluid due to the magnetic field (Pa)  
 $\eta$ : The viscosity of MRP fluid (kg.m/s)  
 $\Phi$ : The angle subtended by two adjacent AAP with centre o (deg)  
 $\Phi'$ : The angle subtended by random AAP with centre o (deg)  
 $\delta$ : The pressure angle of bevel gear (deg)  
 $\chi_{eip}$ : Magnetic susceptibility of electrolytic iron particle (m<sup>3</sup>/kg)  
 $\gamma$ : Shear rate of MRP fluid (1/s)  
 $\omega$ : Angular speed of the hemispherical tip-based tool (rad/sec)  
 $\theta$ : Angle between electric current segment length and the resultant component of the magnetic field.

# CHAPTER 1

## INTRODUCTION

---

### 1.1 Introduction

The surface roughness plays a critical role in several fundamental issues, including friction, wear, and dimensional accuracy of workpieces (Gadelmawla *et al.*, 2002). The process of reducing the surface deviation is known as surface finishing. Surface finish is the nature of a surface which is defined by the lays, surface roughness, texture, and waviness. It comprises the small, local deviations of a surface from the perfectly flat ideal. In the industrial world, the surface finishing of components is necessary for their precise operational functionality with higher efficacy (Alsamaria *et al.*, 2012). The finely finished surface of the machining component tends to reduce power losses, and friction losses, and improves machine efficacy (Yamaguchi *et al.*, 2016; Krolczyk *et al.*, 2014). In addition, the finely finished surfaces lead to an upsurge in dimensional accuracy, closer fits, tolerances, and improves corrosion and wear resistance, etc. (Das *et al.*, 2012; Taufik and Jain, 2017).

Nowadays, the increase in the use of polymer components pushes the automobile and manufacturing industries towards a new energy-saving era. This is because the polymer-based components offer unique advantages over the metal components such as low weight, good corrosion-resistant, extremely good formability, high damping resistance, and ability to function without external lubrication (Golchin *et al.*, 2014). These properties of polymers play a key role in the rising demand in different industries (Golchin *et al.*, 2014). Automotive, medical, defense, aerospace, marine, etc. are the few industrial sectors where polymers play an important part. Polymer gears, bearings, and bushes have replaced metal counterparts in various places such as in the aviation industry, micro and macro devices, automotive equipment, farm and agricultural equipment, electrical toys, and marine transmission owing to its property of minimum noise and vibration (Bartosh 2015). This leads to minimum wear and increases the life span of the equipment. Similarly, polymers play important role in the medical industry as they are notably used in hip joint implants, knee joint implants, dental X-ray systems, surgical robotic drives, etc. (Horacek *et al.*, 2011). The uniform fine finishing of the polymer components is an important need of the various industrial machines for enhancing their efficacy. In addition to this, most of the polymer components are manufactured by additive manufacturing because it is easy to process and there is freedom in designing. As in the additive manufacturing processes, the polymer components are

manufactured layer-by-layer deposition (Guo *et al.*, 2018). Due to this nature, the surface quality of the additive manufactured components is found to be of lower grade (Guo *et al.*, 2018). The poor surface finish of polymers increases the volumetric wear rate and reduces dimensional accuracy while functioning. These drawbacks have led to delays in the implementation of additive manufacturing-based components in many industries. Also, polymers are not very hard materials and have poor wear resistance as compared to metals, so if they are not fine finished, they can easily get damaged because of higher wear rate and friction (Hoskins *et al.*, 2011). Therefore, selecting an appropriate finishing process to finish a specific polymer component to meet the functional application's requirements is critical. Hence, in the present chapter, various traditional and advanced finishing processes that can be used for finishing polymer workpieces are studied.

## **1.2 Traditional finishing processes**

In the traditional finishing processes, the abrasion of material from the work part finishing surface is owing to the direct contact of the multipoint sharp-edged cutting tools (Arif *et al.*, 2011). The firmly bonded abrasives are the multipoint cutting edges. Finishing complex-shaped components with exceptional material characteristics (low wear rate, high hardness, etc.) is time-consuming (Sankar *et al.*, 2009). The different shaped polymer workpieces that require a finely finished surface are utilized in a wide range of industries and individual machinery equipment. Various traditional finishing methods are used to finish the different polymer components. The following sections go through some of the most significant traditional finishing processes.

### **1.2.1 Grinding**

Grinding is one of the abrasive finishing processes which is widely used in various industries. The finishing process is required in industries to finish various components with different shapes (external cylindrical, flat, hemispherical, internal, etc.). This led to the development of the grinding process. In the grinding process, the grinding wheel is used as a tool with numerous cutting edges (Linke *et al.*, 2017). These numerous cutting edges are abrasive particles (Linke *et al.*, 2013). The abrasive particles bonded on the grinding wheel remove the material in the form of microchips. The non-uniformity of the abrasive particles in the grinding wheel affects the grinding characteristic of the workpiece surface. This leads to lower-dimensional accuracy of the workpiece and generation of the subsurface defects.

Based on the shape of the workpiece surface to be finished, different types of grinding processes are used such as surface grinding, cylindrical grinding, profile grinding, and internal grinding. For

flat workpieces, surface grinding is most commonly used. Surface grinding is a finishing process that uses a rotating abrasive wheel ( $V_g$ ) to smooth the flat surface of metallic or nonmetallic materials to give them a more refined look by removing the oxide layer and impurities from the workpiece surface. This can also attain a desired surface for a functional purpose. The schematic figure of surface grinding is depicted in Fig. 1.1.

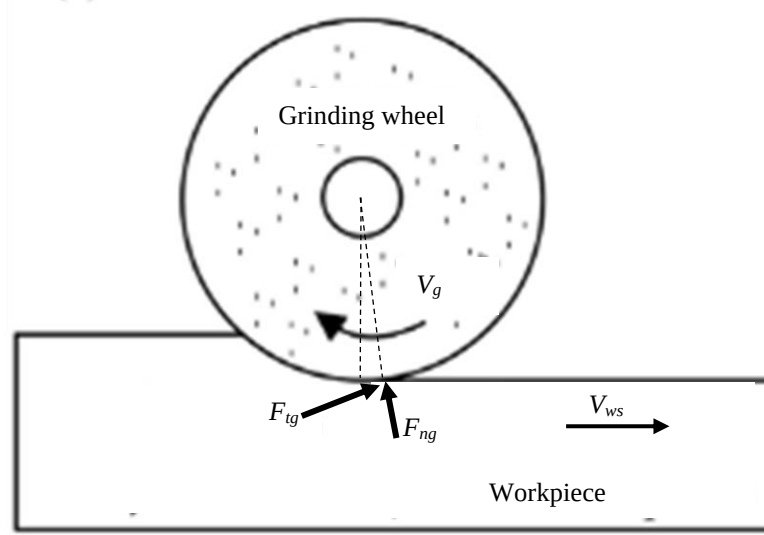


**Fig.1.1.** Schematic diagram of surface grinding (Yao *et al.*, 2014).

The longitudinal feed ( $V_{ws}$ ) to the grinding wheel is usually powered by hydraulics over the workpiece surface. Due to the rotating wheel, the normal force ( $F_{ng}$ ) acts over the workpiece and due to the reciprocation of the workpiece, tangential force ( $F_{tg}$ ) acts over the workpiece. The normal force ( $F_{ng}$ ) is the force applied perpendicular to the contact area between the wheel and workpiece, and tangential force ( $F_{tg}$ ) is the force applied parallel to the contact area between the wheel and the workpiece (Fig. 1.1). The removal of material from the workpiece surface occurs owing to the simultaneous effect of these two forces. The surface grinding is used to finish various flat surface workpieces such as molds, silicon wafers, BK7 glass, etc. Further, using the grinding process on the flat surface of polyamide material, the surface roughness value was reduced to 2.85  $\mu\text{m}$  from 15  $\mu\text{m}$  (Guo *et al.*, 2018). However, the demerits of surface grinding are that the grinding wheel is constantly degrading and requires much spindle power (Salmon, 1986).

For external cylindric surfaces, cylindrical grinding is the commonly used process. In cylindrical grinding, both the grinding wheel ( $V_g$ ) and the cylindrical workpiece ( $V_{wc}$ ) rotate in the opposite

direction of each other, and the grinding wheel also receives reciprocation motion (Grabowik *et al.*, 2019) as shown in Fig. 1.2. The feed rate mechanism is provided for giving the depth of cut to the cylindrical workpiece by the grinding wheel. The material removal from the workpiece surface is done by the relative motion of the cylindrical wheel having abrasives entrenched on it. Two forces are acting during the grinding operation namely normal force ( $F_{ng}$ ) and tangential force ( $F_{tg}$ ) as depicted in Fig. 1.3.

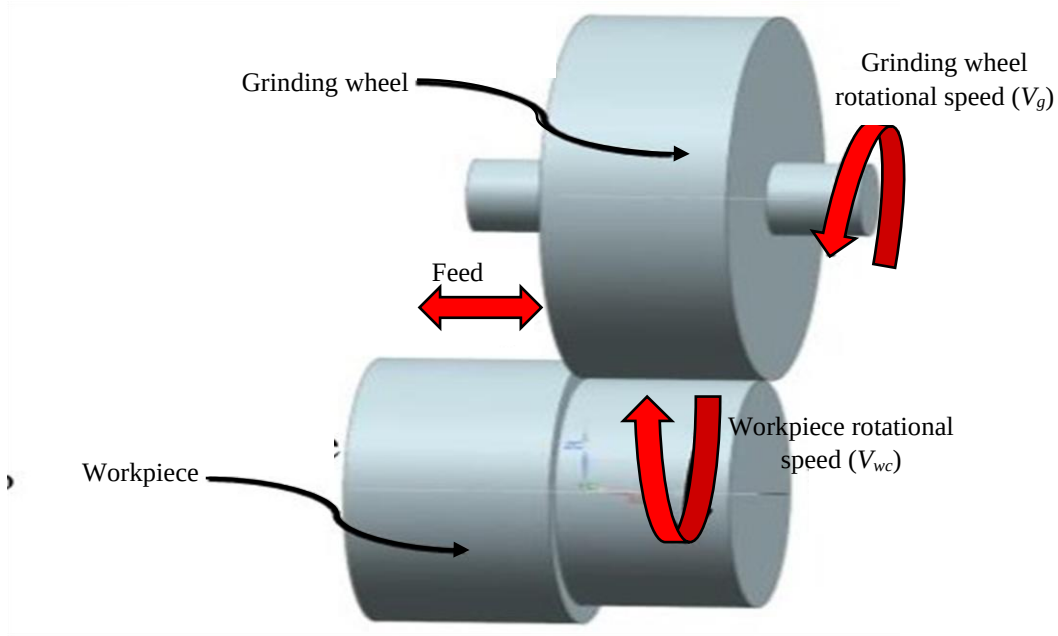


**Fig.1.2.** Schematic diagram of external grinding (Grabowik *et al.*, 2016).

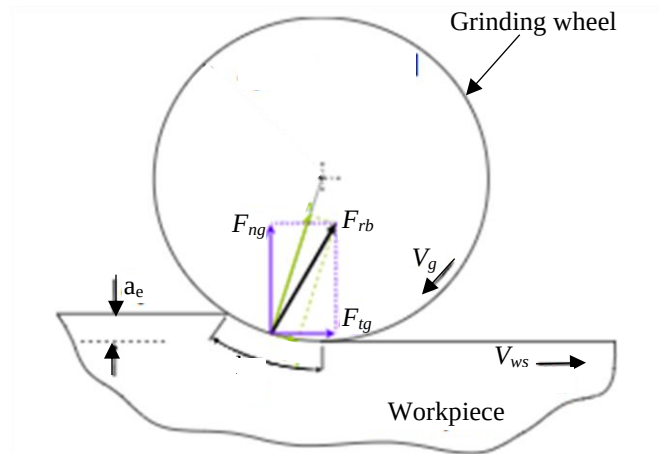


**Fig. 1.3.** Relationship between grinding force components (Mishra and Salonitis, 2013).

$F_{ng}$  acts normally on the external surface of the workpiece by rotating the grinding wheel. The normal force and tangential force both depend on each other for better finishing in lesser time. The

normal force depends on the depth of cut ( $a_e$ ) and the tangential force depends on the rotational speed of the grinding wheel. Further, the rubbing force ( $F_{rb}$ ) is the resultant of the normal force and tangential force (Fig. 1.3). The cylindrical grinding is used to finish various applications such as extrusion punches, winding groove drums, cold rollers, etc. The cylindrical grinding process is used to finish mechanical components in the automotive industry, and aerospace industries (Spina and Cavalcante, 2020). However, there are certain drawbacks to the external cylindrical grinding process. The grinding wheel creates a line contact over a significant length of the workpiece during the finishing. This significant contact length causes a substantial temperature rise. Due to heat generation during grinding, several adverse effects are produced on surfaces such as micro-cracks and thermal stresses (Salmon, 1992; Johnson *et al.*, 2011) which can produce adverse effects on the life span of components.

Further, for the finishing gear workpieces, the profile grinding process is used. In profile grinding, the grinding wheel is dressed with the profile to be produced. The aim here is to achieve the desired form and geometry tolerances of the workpieces. The profile of the grinding wheel can be produced using different dressing methods such as profile rolls, forming rolls, and profile diamonds (Ichida, 2001). The schematic diagram of profile grinding of a rectangular-shaped groove is depicted in Fig. 1.4.

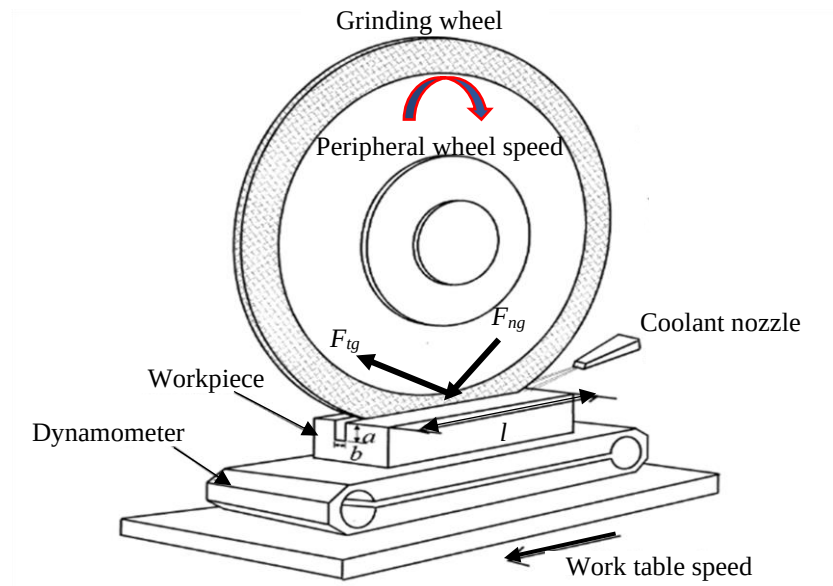


**Fig. 1.4.** Schematic diagram of profile grinding (Ichida, 2001).

Figure 1.4 shows a rectangular-shaped groove with a depth of  $a$  mm, width of  $b$  mm, and a length of  $l$  mm is produced on a flat surface in one pass by profile grinding. For all grinding wheels, metal

bond was selected because of its superior bonding strength (Ichida, 2001). Further, normal ( $F_{ng}$ ) and tangential ( $F_{tg}$ ) forces are acting on the workpiece which is used to shear off material as depicted in Fig. 1.4. The profile grinding process is mostly used for finishing the different types of gears such as bevel, spur, etc. used in industries. However, the demerits of the profile grinding are that the process is costly, and also due to heat generation, the surface of the workpiece tends to get adversely affected due to grinding marks and scratches (Tang *et al.*, 2013).

Further, for the internal workpiece surfaces, internal cylindrical grinding is a commonly used process (Daneshi *et al.*, 2014). Internal cylindrical grinding is a firmly hard bonded abrasive-based finishing technique for cylindrical components that grinds the inner surface. The diameter of the holes being ground is always less than the diameter of the cylindrical grinder. The cylindrical component is placed in the chuck and rotates in the opposite direction with the revolving and reciprocating cylindrical grinder for internal grinding of a cylindrical workpiece as shown in Fig. 1.5. The process is mainly used for the finishing cylindrical molds, bearings, dies, etc.

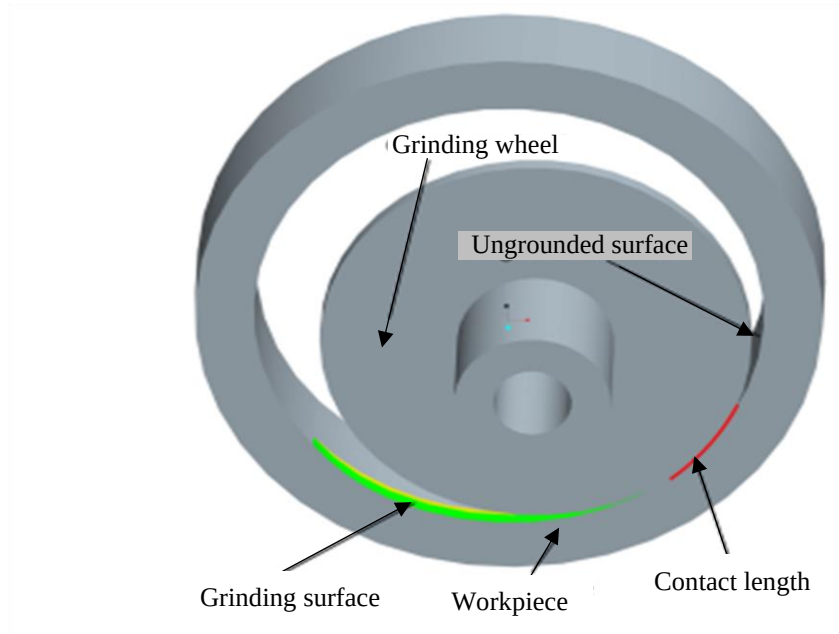


**Fig. 1.5.** Schematic diagram of internal grinding (Yan *et al.*, 2021).

The grinding characteristic of the workpiece surface is influenced by the non-uniformity of the abrasive particles in the grinding wheel. Also, the process has some limitations like no control over finishing forces. As a result, the workpiece experiences lower dimensional accuracy and subsurface defects (Jackson and Hitchiner, 2012).

### 1.2.2 Ball burnishing

Ball burnishing is a post-machining technique that is traditionally used on workpiece surfaces to impart certain physical, mechanical, and tribological characteristics. Since corrosion plays an important role in enhancing the wear rate of the components while functioning. Therefore, the ball burnishing process is developed to reduce corrosion and scratches from the workpiece surface. In the ball burnishing process, plastic deformation is obtained with the help of a highly polished ball which is exposed to the external force on the workpiece. The hardened steel rolls or balls are pressed and rolled on the workpiece surface which imparts the feed motion (Mahajan and Tajane, 2013). Figure 1.6 shows the ball burnishing mechanism on the flat surface. Residual compressive stress is induced in the workpiece which is due to the compressive force ( $F_{cb}$ ) of the ball-shaped tool on the workpiece.

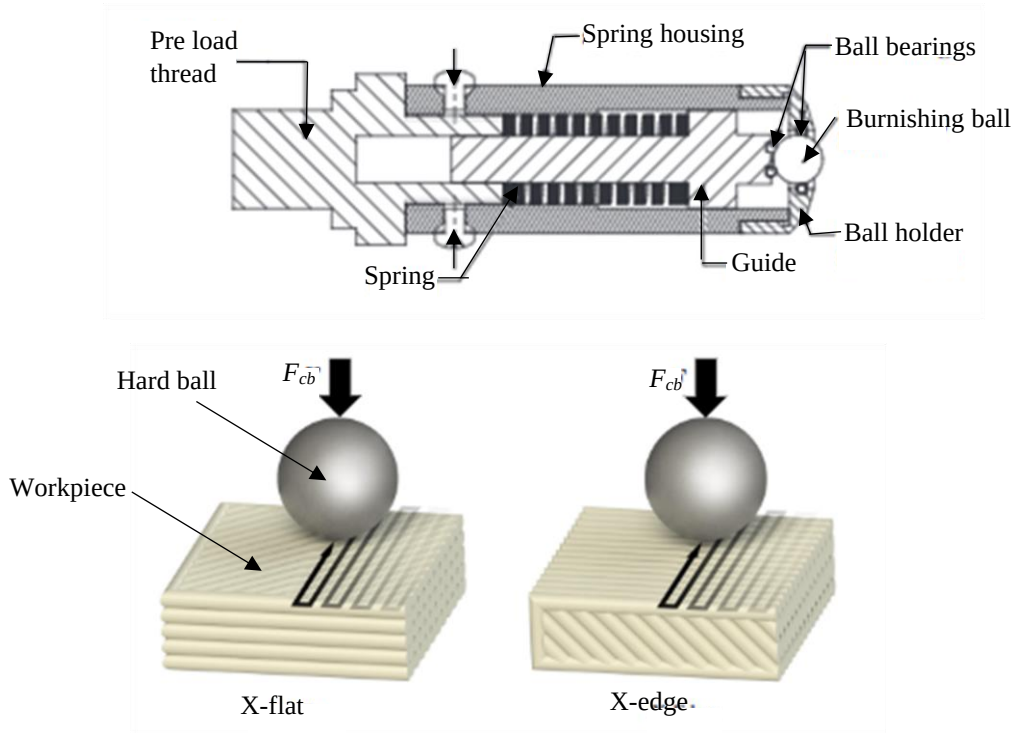


**Fig. 1.6.** Schematic diagram of ball burnishing process (De Bruijn et al., 2021).

This induced residual compressive stress is in a considerable amount during the ball burnishing process and this led to an increase in the fatigue strength and wear resistance on the surface (Shirsat and Ahuja, 2004). The compressive force ( $F_{cb}$ ) can be given by Eq. (1.1).

$$F_{cb} = \sigma A \quad (1.1)$$

where  $\sigma$  is the yielding stress of the material and  $A$  is the contact area during the burnishing process.



Burnishing works by eliminating the surface imperfections left behind from machining with a rotating spherical ball. The ball can freely revolve around its axis and is pushed against a workpiece surface. Plastic deformations of the surface imperfections accommodate the concentrated pressure generated by localized contact with the roller, resulting in a smoother surface. Furthermore, the localization of these plastic deformations in a thin surface layer causes compressive residual stresses, which improve the workpiece's fatigue resistance. Burnishing not only enhances the surface finish, but also improves the surface mechanical characteristics by inducing compressive residual stresses at the surface, which play a key role in enhancing surface hardness, and reducing corrosion which increases the life span of the workpiece. Owing to these characteristics, the external surface of polyoxymethylene (POM) material is finished using the ball burnishing process. The surface roughness value of the POM material is reduced to  $0.44\text{ }\mu\text{m}$  from  $0.80\text{ }\mu\text{m}$  (Low and Wong, 2011). However, the hardening process during the surface finishing affects the atomic structure of the workpiece which further affects its mechanical properties adversely. Also, the process is costly and can only be applied for miniature workpieces. The ball burnishing process is used to finish components such as polymer seals, molds, valves, and home appliances.

### **1.2.3 Lapping**

Lapping is an abrasive-based finishing method with low normal pressure and two movements (rotation and axial). To attain high accuracy of form and dimensions and good surface quality for softer materials, the lapping process is developed (Yuan *et al.*, 2003). Abrasive particles combined with fluid are used to remove material in this process. Between the lapping tool and the surface of the workpieces, the abrasive particles mixed with fluid are rubbed. In the lapping process, the loose abrasives are used for surface finishing. The principle used for the working of the lapping process is the three-body abrasive wear principle in which abrasion by hard particles is used for surface finishing. These hard-abrasive particles are stuck in between the work part and a relatively soft counter formal surface called lap (Lynah and Hoffman, 1989). After the abrasive slurry is placed between the work part and lap surface, the workpiece tends to be held against the lap due to force and is moved in different routes (Owat, 2002). The process mechanism of lapping is shown in Fig. 1.7.

The lapping process is done both manually and by using the machine. In manual lapping, the distribution of the pressure is not uniform which results in lesser uniform finishing over the surface of the workpiece. The machine lapping consists of the retaining rings and rotational lapping plate.

The retaining rings hold the workpiece. The holding workpieces are rotated and scrubbed on the lapping plate.

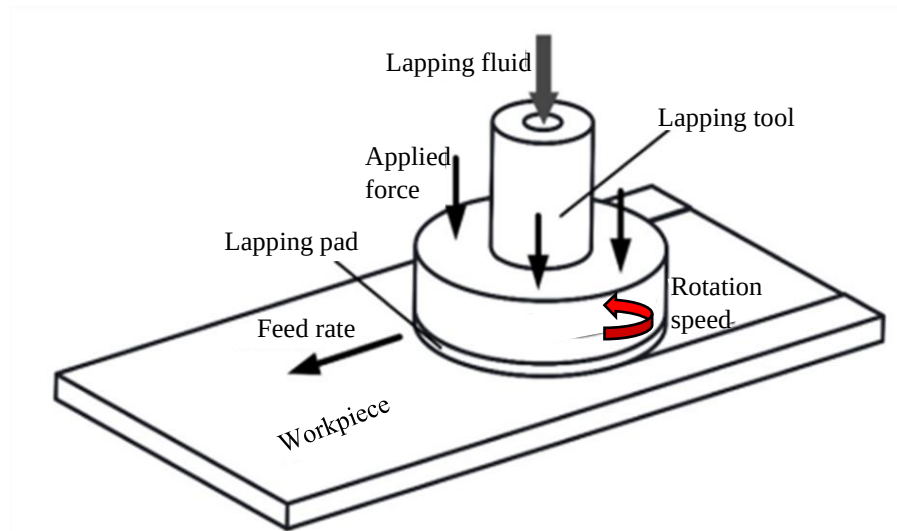


**Fig. 1.7.** Schematic diagram of the lapping process (Lin *et al.*, 2020).

The lapping process is used to reduce the out-of-roundness and surface roughness of components (Alavijeh and Amirabadi, 2019). The surface roughness is considerably impacted by using lapping, which enhances the component's service life and functioning. The lapping technique has several advantages, including good dimensional and geometric precision, reduced surface stress, and reduced surface roughness, among others. Owing to these advantages of lapping, the surface roughness value was reduced to 24.8 nm on the surface of the K9 glass with improved surface properties (Li *et al.*, 2010). However, the lapping process is unable to finish freeform surfaces. Also in this process, the direct contact of a hard abrasive with the surface is involved, resulting in a variety of surface flaws.

#### **1.2.4 Vapor polishing**

Vapor polishing is a surface treatment that reduces surface roughness while maintaining dimensional precision without degrading component shape appreciably (Neff *et al.*, 2018). The process is developed to enhance the surface characteristics of the polymer workpieces. The basic principle of the process is the application of solvent vapor that reacts to the workpiece surface, channels, and bores of a fluidic part. On a microscopic level, the vapor smooths the peaks of the surface of the plastic part and therefore enhances the optical appearance due to the refraction of light. It is also commonly utilized to enhance microfluidic passages for efficient and consistent flow. Vapor polishing involves introducing a solvent solution (acetone) with a high vapor pressure

into the workpiece surface and allowing it to penetrate. In a typical vapor polishing treatment, a work part is exposed to a solvent vapor (mostly acetone) that absorbs into the surface layer of the work part reducing the surface viscosity. In the vapor polishing process similar to viscous sintering, the high peaks of surface roughness “flow” into the valleys of the surface roughness driven by surface tension. Further, the surface temperature must be below the solvent's solution boiling point so that the solvent condenses on the surface and begins to dissolve quickly.

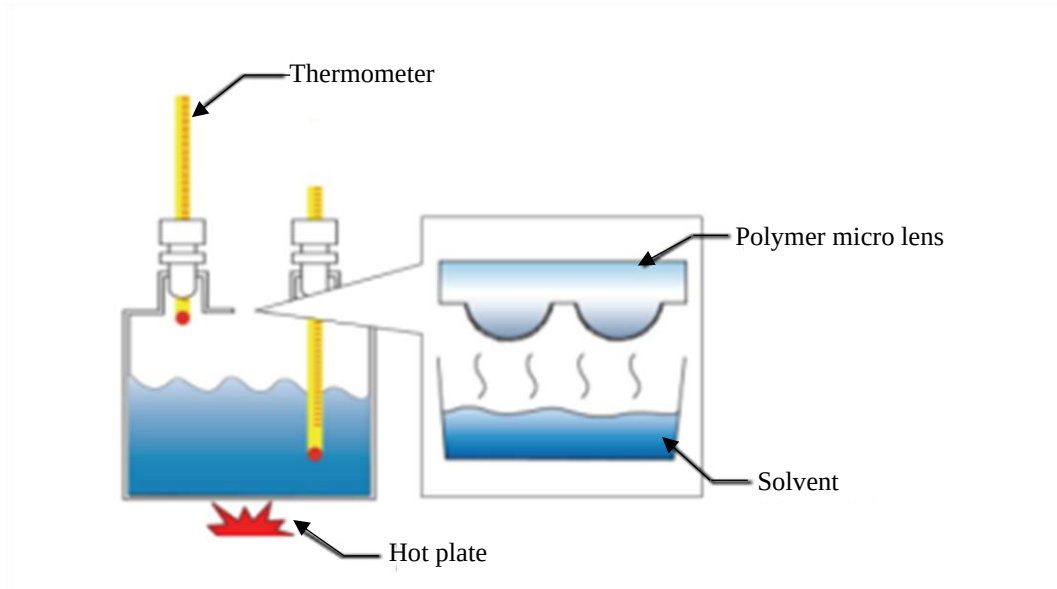


**Fig. 1.8.** Schematic diagram of vapor polishing process (Kim *et al.*, 2013).

The schematic diagram is depicted in Fig. 1.8. In this process, the solvent dissolves the polymer, and surface tension forces cause a decrease in surface roughness. This results in a surface finish that is more uniform, smooth, and of higher quality. As a result, vapor polishing is used to finish the ABS (Acrylonitrile butadiene styrene) components. The surface roughness value reduced from 37  $\mu\text{m}$  to 10  $\mu\text{m}$  on the surface of ABS components (Neff *et al.*, 2018). Further, various additive manufactured components used in automobile, medical and marine industries are finished using the vapor polishing process. However, the vapor polishing process is costly and labor-intensive. This is because the solvent is hazardous and solvent fumes are highly toxic owing to which it required highly skilled labor. In addition, because the vapor polishing process is carried out in a closed environment with minimal risk, the overall cost is higher. Further, Table 1.1 shows the comparative study of the various traditional finishing processes.

**Table 1.1.** Comparative study of different traditional processes for finishing of polymer workpieces.

| S. No. | Grinding                                                                                                                                                                                                                 | Ball burnishing                                                                                                                                              | Lapping                                                                                                                                                                                                | Vapor polishing                                                                                                                                                                                                                                                                                                                                             |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.     | Grinding is an abrasive machining process that uses a grinding wheel as the cutting tool and is capable of making precision cuts and producing finishing.                                                                | Ball burnishing is a post-machining technique that is used on workpiece surfaces to impart certain physical and mechanical characteristics.                  | Lapping is an abrasive-based finishing method that is developed to attain high accuracy of form and dimensions and good surface quality.                                                               | Vapor polishing is a surface treatment that reduces surface roughness while maintaining dimensional precision without degrading component shape appreciably.                                                                                                                                                                                                |
| 2.     | The grinding process is used in industries to finish various components with different shapes (external cylindrical, flat, hemispherical, internal, etc.) such as molds, silicon wafers, BK7 glass, etc.                 | The ball burnishing process is mostly used in industries to finish the external and flat surfaces such as polymer seals, molds, valves, and home appliances. | The lapping process is mostly used in industries to finish the internal, external, and flat surfaces such as K9 glass.                                                                                 | The vapor polishing process is mostly used in industries to finish flat surfaces such as ABS (Acrylonitrile butadiene styrene) components.                                                                                                                                                                                                                  |
| 3.     | The non-uniformity of the abrasive particles in the grinding wheel affects the grinding characteristic of the workpiece surface. This leads to lower-dimensional accuracy of the workpiece (Odior <i>et al.</i> , 2013). | The ball burnishing process is costly and can only be applied for miniature workpieces (Alghazoul <i>et al.</i> , 2019).                                     | The lapping process is unable to finish freeform surfaces and there is direct contact of a hard abrasive with the surface involved, resulting in a variety of surface flaws (Lynah and Hoffman, 1989). | The vapor polishing process is costly and labor-intensive. This is because the solvent is hazardous and solvent fumes are highly toxic owing to which it required highly skilled labor. In addition, because the vapor polishing process is carried out in a closed environment with minimal risk, the overall cost is higher. (Neff <i>et al.</i> , 2018). |

### **1.3 Advanced finishing processes**

The need for fine finishing with good surface properties has arisen as a result of the ongoing advancement of materials and their use in various sectors. To achieve these requirements using the traditional finishing processes is found a difficult task (Jain, 2008). Fine surface finishing of the various polymer materials with higher accuracy is a challenging task utilizing the traditional finishing processes (Khosravani and Reinicke, 2020). Many times, the traditional finishing processes are found less effective to finish products of various shapes and sizes. Also, finishing the workpiece surfaces with the traditional finishing processes can produce uncontrolled finishing forces. Owing to this, several surface defects such as micro-cracks, scratches, marks, etc., appear on the finished surface of the workpieces (Singh and Singh, 2019). As a result, different advanced finishing techniques have been developed to achieve high precision, high accuracy over position and size, to improve interchangeability of parts, to extend fatigue life, and to improve surface properties (Jha and Jain, 2006). For finishing the various polymer components, the advanced finishing processes are divided into two categories naming processes with no external control over finishing forces and processes with external control over finishing forces. The finishing processes without control over the finishing forces are chemo-mechanical polishing (CMP), and the elastic emission process (EEP). Further, the finishing processes with control over the finishing forces are magnetorheological finishing (MRF), ultrasonic magnetorheological fluid compound finishing, ball end magnetorheological finishing (BEMRF), and magnetic compound fluid (MCF) polishing process. In these MRF processes, an electromagnet or a permanent magnet is used to control a magnetic field over the tool's finishing surface.

#### **1.3.1 Chemo mechanical polishing**

Chemical mechanical polishing (CMP) is a planarization process in which chemical and mechanical actions are combined together. This process mainly has applications in the semiconductor manufacturing industries (Liang *et al.*, 1997). CMP includes the combined action of chemical and mechanical processes. Firstly, a chemical reaction occurs between fluid and the workpiece. After that, the abrasives remove the chemically reacted material by mechanical action (Nanz and Camilletti, 1995) as shown in Fig. 1.9. In the CMP, the proper eccentricity of the wafers and the pad is maintained as it affects the quality of the final surface finish. This is because, eccentricity tends to affect the tool trace of polishing which may lead to a poor finished surface (Xiao *et al.*, 2020). Further, many of the surface-related problems such as dislodgment of grains,

and scratches on surfaces can be overcome by the CMP. Further, with an increase in abrasive size, the material removal rate of silicon substrate reduces (Komanduri, 1996). This is because micro-cracks and scratches increase on the workpiece surface with the increase in abrasive size.

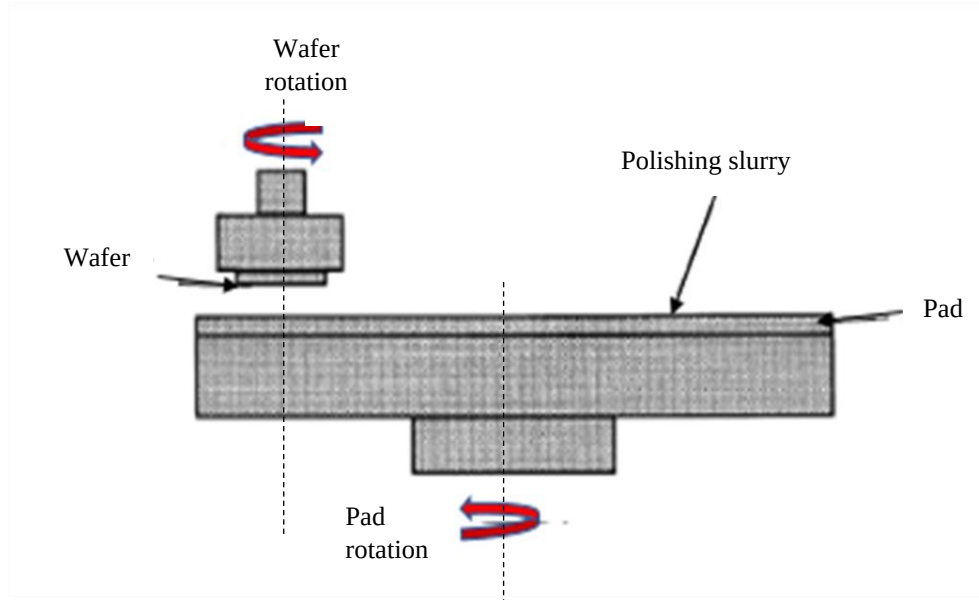


**Fig. 1.9.** Schematic figure of the chemo-mechanical process (Larsen-Basse and Liang 1999).

This leads to the surface finish. With the comparison of silica and alumina-based slurry, the colloidal-based silica gives fine finishing with minimum scratches as compared to alumina (Ahn *et al.*, 2004). Chemo mechanical polishing is mostly preferable in industries such as semiconductors for the surface finish of silicon wafers. CMP process is used for the surface finish of optical polymers (Zhao *al.*, 2004). However, the forces produced in these finishing processes are not controllable which sometimes leads to poor surface finish and damaged surfaces (Singh *et al.*, 2017).

### 1.3.2 Elastic emission process

The elastic emission process (EEP) was introduced due to its capability to eradicate the material at the atomic level. Mechanical methods are used to remove material and provide a mirror-like finished surface (Mori *et al.*, 1988). EEP was developed in late 1976. EEP can provide a surface finish up to 0.2 nm (Mori *et al.*, 1976). The schematic diagram of EEP is depicted in Fig. 1.10. This process is most effective for the smooth finishing of low thermal expansion components. In this process, the individual atom or group of atoms gets stricken by the ultrafine abrasive particles and separate from the workpiece. It can be seen in Fig. 1.10, that the motor is used to rotate the load acting on the workpiece so that slurry can remove the material. The slurry consists of fluid

mostly oil and abrasives. In EEP, it is possible to have atomic level finishing without any plastic deformation because during the material removal ultrafine abrasives collide with the workpiece surface causing an elastic fracture.

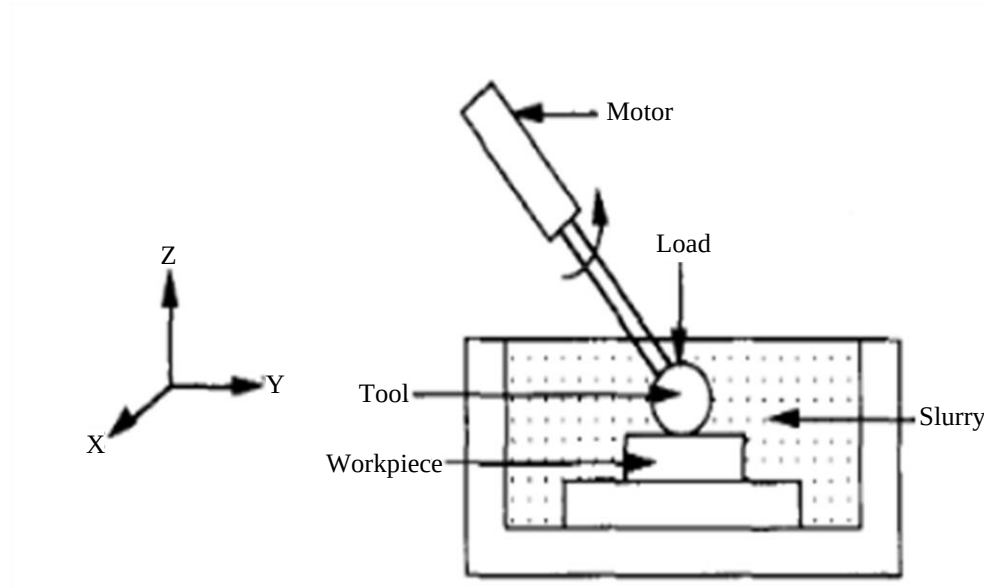


**Fig. 1.10.** Schematic figure of the elastic emission process (Mori *et al.* 1988).

Theoretically and experimentally, it has been demonstrated that atomic size fracture may be persuaded elastically, and the finished surface can be crystallographically and physically uninterrupted (Mori *et al.*, 2002). Also, the material removal process is a surface energy phenomenon that includes the removal of several atoms by each abrasive particle after coming in contact with the surface (Mori *et al.*, 1976). However, the main limitation of EEP is that it can only be used for optical components such as glasses or lens material. This is because, for harder materials, the load needs to be increased, however on increasing load, scratches and marks are produced on the surface leading to unevenness on the surface.

#### 1.4 Magnetorheological polishing fluid

Magnetorheological (MR) fluids are a type of smart controlled material that responds to a magnetic field by changing their rheological behavior (Kciuk and Turczyn, 2006). MR fluids are suspensions of a non-magnetic carrier continuous phase with a micron-sized dispersed magnetic phase and additives. The properties of the magnetorheological fluid are reported in Table 1.2. Further, the presence of non-magnetic abrasive particles in the magnetorheological fluid makes it a magnetorheological polishing (MRP) fluid. MRP fluid acts as a smart fluid under the influence of the magnetic field (Khatri *et al.*, 2018) as depicted in Fig. 1.11(a) and (b).

**Table 1.2.** Properties of the magnetorheological fluid (Olabi and Grunwald, 2007; Kciuk and Turczyn, 2006)

| Property                | Typical value          |
|-------------------------|------------------------|
| Initial viscosity       | 0.2-0.3 Pa.s (at 25°C) |
| Typical power supply    | 2-25 V, 1-2 A          |
| Yield point             | 50-100 kPa             |
| Magnetic field strength | 150-250 kA/m           |
| Energy density          | 0.1 J/cm <sup>3</sup>  |
| Response time           | Some milliseconds      |
| Density                 | 3-4 g/cm <sup>3</sup>  |

The MRP fluid is made by homogeneously mixing magnetic iron and abrasive particles in a base fluid containing a carrier medium such as vegetable oil, mineral oil, paraffin oil, water, as well as some surfactants or stabilizers such as grease, glycerol, or oleic acid (Jain, 2009; Jha and Jain, 2004; Genc and Phule, 2002). When the magnetic field is not present, the MRP behaves as the Newtonian fluid.

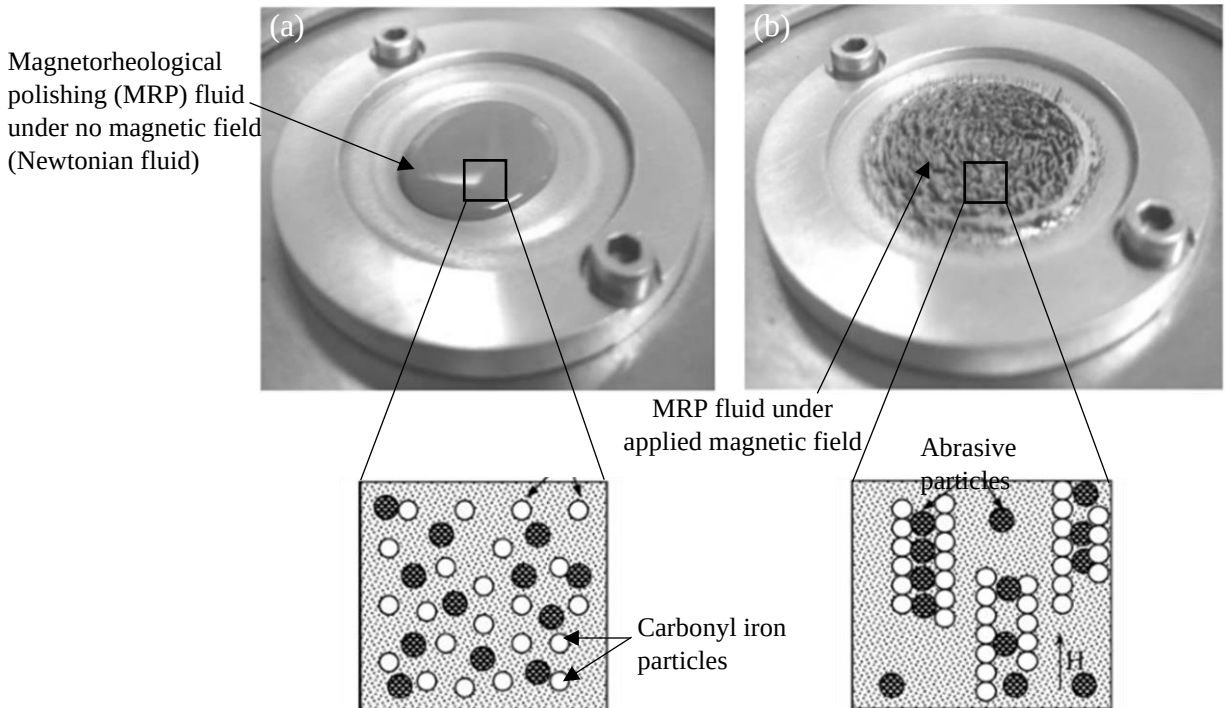


**Fig. 1.11.** Magnetorheological polishing fluid (a) in the absence of the magnetic field, and (b) under the action of applied magnetic field (Sidpara *et al.*, 2009).



However, under the influence of the magnetic field, the MRP fluid acts as the non-Newtonian fluid (Sidpara *et al.*, 2009). When a magnetic field is applied, the iron particles gain dipole moments and align in the direction of the magnetic field, forming a chain-like structure (Khatri *et al.*, 2018). The particles with dissimilar poles get attracted and make chain structures of the magnetic iron particles as shown in Fig. 1.11. The formation of these chains of particles shows MRP fluid flow, increasing the material's yield stress. With increasing applied magnetic field, the yield stress and shear viscosity of the fluid increase. To break this structure and ensure the flow of the fluid, shear stress is applied in the direction perpendicular to the chain formation. In the presence of a magnetic field, experimental data has revealed that MRP fluids display both a pre-yield phase characterized by an elastic response and a post-yield regime defined by a viscous response (Jolly *et al.*, 1996). Three constitutive models are commonly employed to characterize rheological properties (field-induced yield stress and viscosity), namely the Bingham Plastic model, Herschel-Bulkley model, and Casson Fluid model (Saraswathamma *et al.*, 2017).

The fluid material flow behaviour is supposed to be elastic solid up to critical shear stress (yield stress) in the Bingham Plastic model (Fig. 1.12), after which the material starts to flow and behaves like a Newtonian fluid. The Bingham Plastic model equation is as follows in Eqs. (1.2) and (1.3).

$$\tau = \tau_0 + \eta \dot{\gamma} \quad \text{for } \tau > \tau_0 \quad (1.2)$$

$$\tau = 0 \quad \text{for } \tau \leq \tau_0 \quad (1.3)$$

where  $\tau$  is the shear stress of the fluid,  $\tau_0$  is the field induced dynamic yield stress,  $\eta$  is the plastic viscosity of fluid, and  $\dot{\gamma}$  is shear rate (1/s). The dynamic yield stress is the intercept of extrapolation of the shear stress vs. shear rate curve to zero strain rate.

In the Herschel-Bulkley model (Fig. 1.12), the fluid behaviour of material flow is represented as non-Newtonian after the critical shear stress (yield stress), and the fluid acts as an elastic solid below this stage, which is the same as in the Bingham Model. This model is expressed as in Eqs. (1.4) and (1.5).

$$\tau = \tau_0 + K \dot{\gamma}^n \quad \text{for } \tau > \tau_0 \quad (1.4)$$

$$\tau = 0 \quad \text{for } \tau \leq \tau_0 \quad (1.5)$$

where  $n$  is flow behavior index and  $K$  is consistency parameter. The value of the flow index in this model indicates the fluid behavior. In the case of shear thinning, the flow index is less than 1 and for shear thickening, the value of the flow index is greater than 1. If the value of the flow index is equal to 1, then the behavior of the model is the same as the Bingham plastic model. Casson's

equation (Fig. 1.12), which links nonlinear shear rate and shear stress, is also a time-independent shear flow.

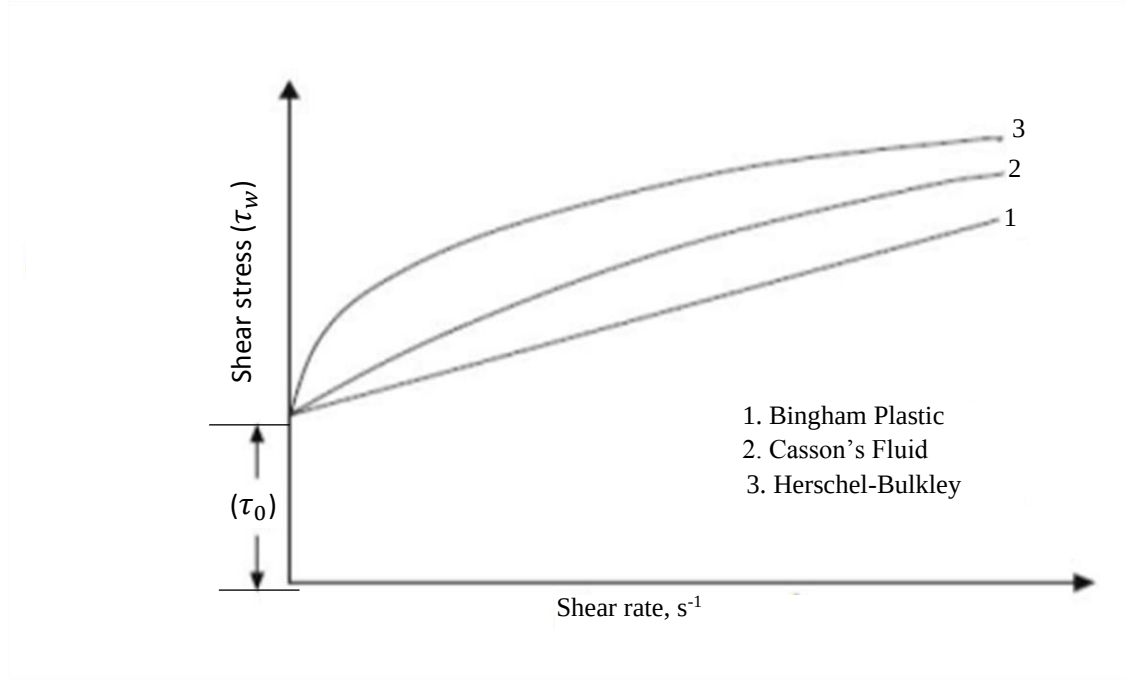


**Fig. 1.12.** Constitutive models for MRP fluid flow characterization (Saraswathamma *et al.*, 2017).

A Casson fluid is a shear-thinning fluid with an infinite viscosity at zero rate of shear, a yield stress below which no flow occurs, and a viscosity of zero at an infinite rate of shear. Casson's flow model is given as in Eq. (1.6).

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_1 \dot{\gamma}} \quad (1.6)$$

where  $\tau_0$  is yield stress,  $\eta_1$  is viscosity of the material at higher shear rates.

Out of all the above models discussed, the Bingham plastic model was a simplistic model and most of the researchers had used to represent the behavior of MRP fluid (without the addition of non-magnetic abrasives). This is because the Bingham plastic model is a two-parameter model (yield stress and viscosity) and the fluid behavior in pre yield is represented as rigid and post-yield as linear.

The MRP fluid has an extremely fast response time under the influence of the external magnetic field (Sidpara *et al.*, 2009). The characteristics of the MRP fluid are as follows.

- MRP fluid is very quickly responsive towards the magnetic field.

- The viscosity of the MRP fluid upsurges under the influence of the magnetic field.
- The base fluid used in MRP fluid is oil or water, which makes it corrosive-resistant and low viscosity.
- Because the MRP fluid is thoroughly mixed, the particles contained in it have fewer lumps.

#### ***1.4.1 Magnetorheological polishing fluid's constituents***

When a magnetic field is applied to the magnetorheological polishing (MRP) fluid, it plays an important part in the finishing process. The MRP fluid is a base fluid that contains magnetic iron particles and micron-sized abrasives suspended in it (carrier medium i.e., oil or water, and surfactants or additives) (Niranjan and Jha, 2014). To make the MRP fluid, the different sizes of iron particles and abrasives are suspended and blended homogeneously in the base fluid (Chen *et al.*, 2016). The temperature change and chemical composition of the MRP fluid influence its rheological character (Sidpara *et al.*, 2009; Sujith *et al.*, 2019). The rheological characteristics of the MRP fluid vary depending on the iron particle, abrasive particle, and base fluid compositions used, as well as the magnetic field's magnitude.

The magnetic particles play a significant role in the MRP fluid. These particles are solely responsible for the polishing fluid for forming chain structures and gripping abrasive particles, under the influence of a magnetic field. The tightly gripped abrasive particle performs the finishing process over the work part surface owing to the rheological behavior of the MRP fluid. The iron particles in the MRP fluid generate dipoles in the presence of the magnetic field. As a result, under the influence of an external magnetic field, each magnetic iron particle is attracted to the opposite pole of a neighboring magnetic iron particle. The intensity of the magnetic field determines the strength of the poles produced in magnetic iron particles. Therefore, as the distance between the MRP fluid and the magnetic field increases, the strength of the iron particle chain structures weakens (Jha and Jain, 2006), affecting finishing performance. The magnetic particles carbonyl iron particles (CIPs) and electrolytic iron particles (EIPs) are the most often utilized. The CIPs are made of pure iron pentacarbonyl and are highly pure iron. The CIPs are observed to be spherical. The EIPs are made by electrolytically depositing metal from an aqueous solution, which produces a suitable electrolytic iron. This metal can also be placed on a cathode and chipped away from the cathode before being crushed into a fine powder. The shape of the EIPs, unlike the CIPs, is observed to be irregular.

Further, in the MRP fluid, the abrasive particles are non-magnetic hard particles that are tightly gripped in the chain structure of the magnetic iron particles when the magnetic field is applied. These abrasives remove material during the finishing process due to their hardness and being firmly gripped into the stiffened chains of the magnetic particles. The abrasives that interact with the workpiece's surface during the finishing process are responsible for finishing. These abrasives are known as active abrasive particles (AAPs). Since the AAPs interact with the peaks of the surface roughness for abrading them while finishing action, so the properties of the abrasives play a vital role in finishing operation. Shape, size, and hardness are the characteristics of abrasive particle which influences the finishing performance (Torrance, 2002). Some of the commonly used abrasive particles are silicon carbide (SiC), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), silicon oxide ( $\text{SiO}_2$ ), cerium oxide ( $\text{CeO}_2$ ), and titanium oxide ( $\text{TiO}_2$ ).

The carrier fluid in the MRP fluid is used to suspend the magnetic and abrasive particles. For optimal performance in the MRP fluid, the carrier fluid must have the characteristics like high boiling point, corrosion resistance, low freezing point, and the ability to contribute rheological behavior to the MRP fluid. The most common carrier fluids are oil-based carrier (OBC) fluid and water-based carrier (WBC) fluid. The deionized water and glycerol were used as a carrier medium in WBC fluid while in OBC fluid paraffin oil and grease were used as the carrier medium. However, for fine finishing of the polymer surface, WBC fluid provides better results as compared to the OBC fluid. This is because the water molecules present in water-based MRP fluid chemically react with polyamides which may result in softening of the outer surface of the polymers as highlighted by Cook (1990). Further, the stabilizers are added to the carrier fluid to properly distribute the abrasive particles and magnetic iron particles for making the MRP fluid (Sidpara *et al.*, 2009). Glycerol is added to the MRP fluid as a stabilizer to help the magnetic and abrasive particles stay in suspension in the polishing fluid (Sidpara and Jain, 2012). It also provides the covering over the solid particles so that oxidation of iron particles can be reduced (Sidpara and Jain, 2014). The MRP fluid contains AP3 grease or thixotropic additives to improve particle stability. In order to prevent the oxidation of suspended magnetic iron particles in the MRP fluid, additional additives are also added immediately.

#### ***1.4.2 Magnetorheological polishing (MRP) fluid-based finishing processes***

The magnetically controlled advanced finishing techniques that employ the magnetorheological polishing (MRP) fluid as a finishing medium are known as magnetorheological polishing fluid-

based finishing processes. In these processes, by adjusting the external magnetic field, the rheological behavior of the MRP fluid may be changed as needed. Owing to these property, MRP fluid-based finishing process can finish a wide range of workpieces and from simple to complex intricate geometric shapes (Fan *et al.*, 2019). This happens owing to the fact that carrier fluid provides space for magnetic iron and abrasive particles to reform as per the component's shape. This benefits while finishing the surface of the complex workpieces. The magnetorheological polishing fluid-based finishing processes can finish ferromagnetic as well as non-ferromagnetic workpieces (Khan *et al.*, 2016; Singh *et al.*, 2019). Further, the advantages of using MRP fluid-based finishing processes are as follows.

- Ability to finish the workpiece surface upto the nano level scale with reference to the surface roughness profile's centerline.
- The stiffed flexible MRP fluid may finish the metal or polymer surfaces of the workpiece with complicated forms and geometry.
- The workpiece surface is subjected to low normal forces which minimizes surface and subsurface flaws (scratch, micro-cracks).
- Reduces wear and friction losses while enhancing the life of the work material.

#### 1.4.2.1. Magnetorheological finishing (MRF) process

Precision optical lenses are difficult to finish because they are composed of a fragile material. Grinding and lapping are commonly employed in the lens manufacturing industry. The profile required for the lens was obtained by grinding (Jain, 2008). The cracks and surface defects are generated after the grinding operation (Jain, 2009). The major limitation in lapping is the non-uniformity of pressure (Bedi and Singh, 2016). The magnetorheological finishing (MRF) process was developed in 1996 at Rochester's optics production center to accomplish fine surface finishing (Kordonski *et al.*, 1996). The magnetorheological polishing (MRP) fluid, also known as smart fluid, is used in this technique. Magnetic iron particles and abrasive particles are combined in a fluid-like silicone oil or paraffin oil to make MRP fluid (Kordonski *et al.*, 1996). When the magnitude of the magnetic flux density is varied, the rheological characteristics of the MRP fluid get change. The iron particles in MRP fluid are unevenly distributed when there is no magnetic field. Under the influence of the magnetic field, the iron particles align along the line of the magnetic field forming a columnar structure. MRP fluid is supplied via the nozzle over the rotating wheel rim in the MRF process as shown in Fig. 1.13.

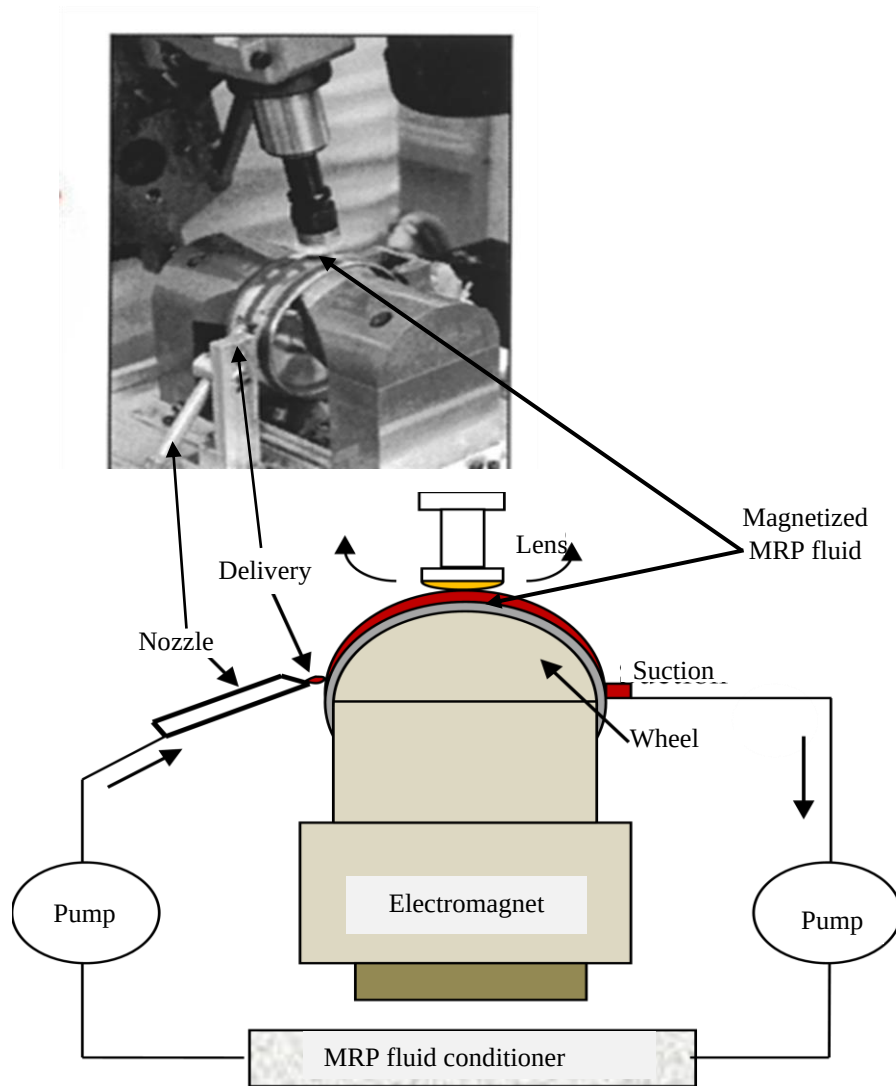


**Fig. 1.13.** Photograph and schematic diagram of the magnetorheological finishing process (Kordonski *et al.*,1996).

The abrasives particles are in touch with the workpiece's surface, while the MRP fluid is closer to the revolving wheel rim. The active abrasives transfer the indentation force to the work material, which penetrates the workpiece's surface as depicted Fig. 1.14. When the wheel rotates over the workpiece surface, the material is eroded out of the workpiece surface owing to relative motion between the gripping active abrasive and the workpiece surface, resulting in fine finishing. This process finishes the surface of the optical glass as well as crystals and produce surface accuracy in the order of 10 nm roughness value (Jain, 2008). The self-deformable magnetorheological polishing fluid transports heat and debris away from the finishing zone (Guo and Wu, 2016).

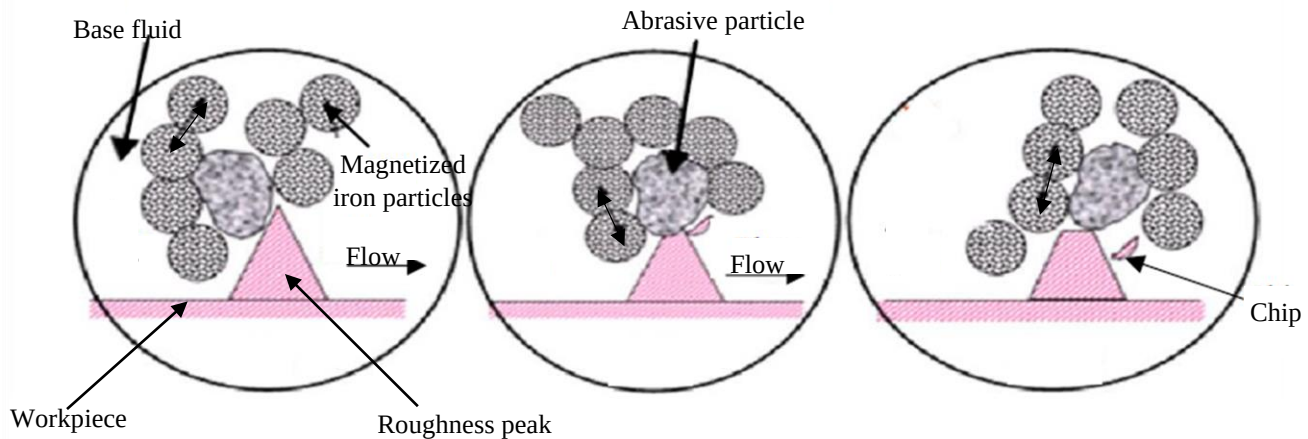


**Fig. 1.14.** Three stages of material elimination from the roughness peaks in MRF process (Jain, 2009).

#### 1.4.2.2. Ultrasonic magnetorheological fluid compound finishing

Ultrasonic magnetorheological compound finishing (UMRCF) is one of the new methods to manufacture the optical components. This process offers the advantage of both magnetorheological finishing (MRF) and ultrasonic polishing, simultaneously. This process is mainly utilized for the precise surface finish of concave surface and free form optical surface (Wang *et al.*, 2007). In this process, magnetorheological polishing (MRP) fluid forms a flexible magnetic abrasive brush (FMAB) on the application of magnetic field to the polishing head as shown in Fig. 1.15.

Owing to this the normal force ( $F_{nm}$ ) acts by the abrasives over the workpiece. The polishing efficiency gets improved after the application of the ultrasonic vibration to the polishing head. In this process, the polishing head rotates on the spindle axis and on its own at the same time with a definite speed. In between the polishing head and workpiece, a constant working gap is sustained. The workpiece and the polishing head, are rotated in opposite directions. Hence, the finishing zone encounters the tangential force ( $F_{tan}$ ) and the materials are removed accordingly (Fig. 1.15) (Kordonski and Shorey, 2007). The surface finishing of the whole workpiece is done by using the linear speed of the workpiece on the horizontal plane. Thus, the polishing efficiency is improved by the combined effect of the magnetic field and ultrasonic vibration. The application of the UMRCF can be found in the optical industries. They are used for the finishing of the concave lens and the glass.

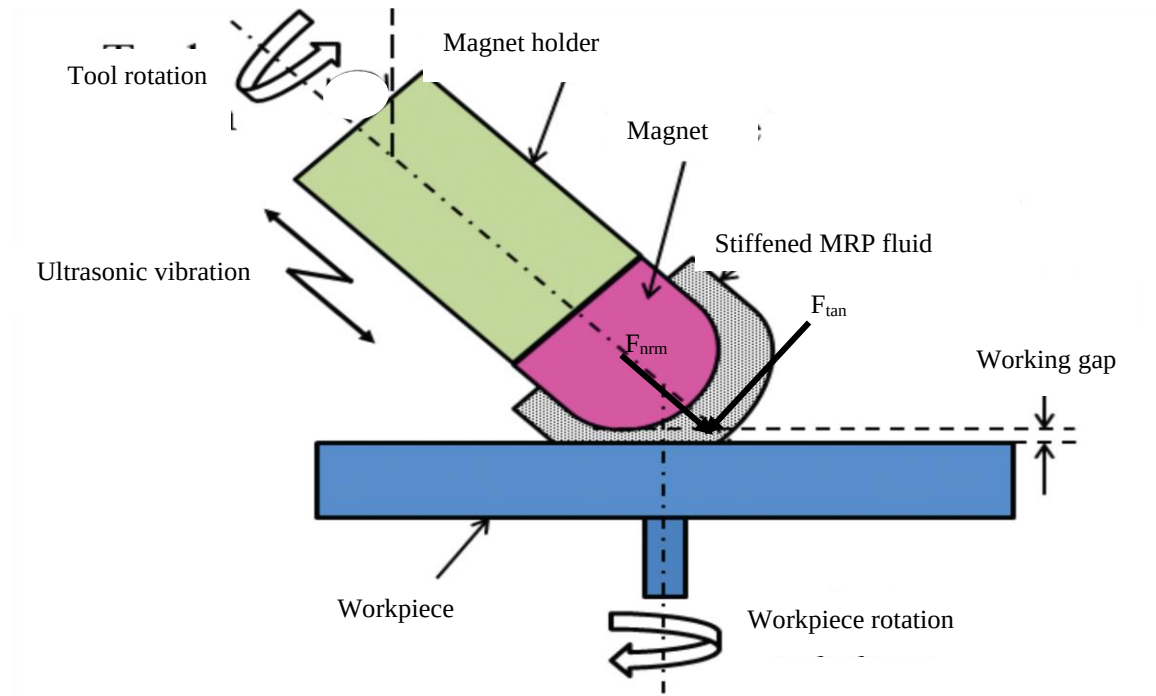


**Fig.1.15.** Schematic diagram of ultrasonic magnetorheological finishing process (Kordonski and Shorey, 2007).

#### 1.4.2.3. Magnetic compound fluid (MCF) based finishing process

In the MCF-based process, the magnetorheological polishing (MRP) fluid is used for finishing the optical workpieces. Under a static magnetic field, it has been demonstrated that MCF becomes more viscous and disperses particles more evenly than MRP fluid. The MCF polishing principle is shown in Fig. 1.16. With an eccentricity of  $r$ , a disc-shaped permanent magnet is connected to the bottom end face of the magnet holder. Between the magnet and the workpiece, at a distance from the magnet, is a non-magnetic slurry carrier. Both the magnet holder and the slurry carrier have their own axis that may be rotated. Chain-shaped magnetic clusters comprised of nanometer-sized magnetite particles and micron-sized carbonyl iron particles (CIPs) develop along the magnetic lines of force as a specific amount of MCF slurry is poured over the carrier. The magnet spins about its holder axis when the magnet holder is rotated at a speed of  $n_m$ , creating a rotating magnetic field subordately.

Although the magnetic flux density remains constant, the magnetic lines of force continue to spin around the magnet holder axis. Owing to this, the normal force ( $F_{nrm}$ ) is acted on the abrasive particles. As a consequence, the abrasive particles in the MCF slurry are dispersed more consistently, and the MCF slurry's capacity to restore shape during polishing is improved. Abrasive particles inside the MCF slurry are transported in clusters and a relative speed



is produced between the abrasive particles and the work surface because the slurry carrier rotates at a speed  $n_c$  and a working gap is provided between the slurry carrier and the work surface. This results in the tangential force ( $F_{tan}$ ) owing to which the abrasive particles eventually function as micro-cutters, removing undesired material.

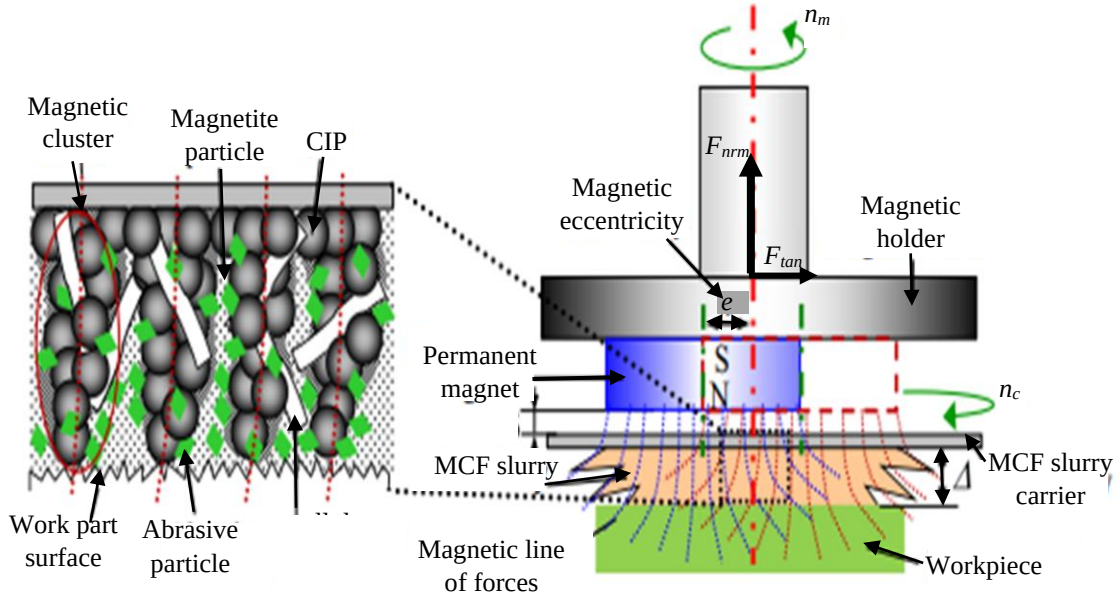


**Fig. 1.16.** Schematic diagram of Magnetic Compound Fluid (MCF) based finishing process (Guo and Wu, 2016).

#### 1.4.2.4. Ball end magnetorheological finishing (BEMRF) process

Using the wheel type magnetorheological finishing (MRF) process, only specific shape of surfaces, such as concave and convex are finely finished. Hence, the development of the BEMRF has addressed this restriction. In the BEMRF, the MRP fluid is magnetized over the tool surface in the form of the ball end, which was utilized to finish flat and 3D surfaces (Singh *et al.*, 2012). The tool tip is magnetized in the working gap owing to the electromagnetic coil. At the magnetic tool tip, the MRP fluid forms a ball shape spot.

The workpiece surface is finished by the relative motion between the ball end formed MRP fluid and the workpiece surface. In the MRP fluid, carbonyl iron particles (CIPs) form a chain-like structure and grab the abrasive particles on the workpiece surface when magnetic flux density is present. The magnetic normal force causes the abrasives to indent inside workpiece roughness peaks, as shown in Fig. 1.15. The indented abrasives shear the roughness peaks in the form of micro-chips as a result of the rotation of the rotating core and relative motion between the abrasives

and the workpiece surface, as shown in Fig. 1.17. All peaks on the workpiece's surface are eliminated due to the constant feed of the workpiece, and fine finishing is obtained. This process is used to finish flat and 3-D curved surfaces where fine finishing of the surface is of great concern (Singh *et al.*, 2012).

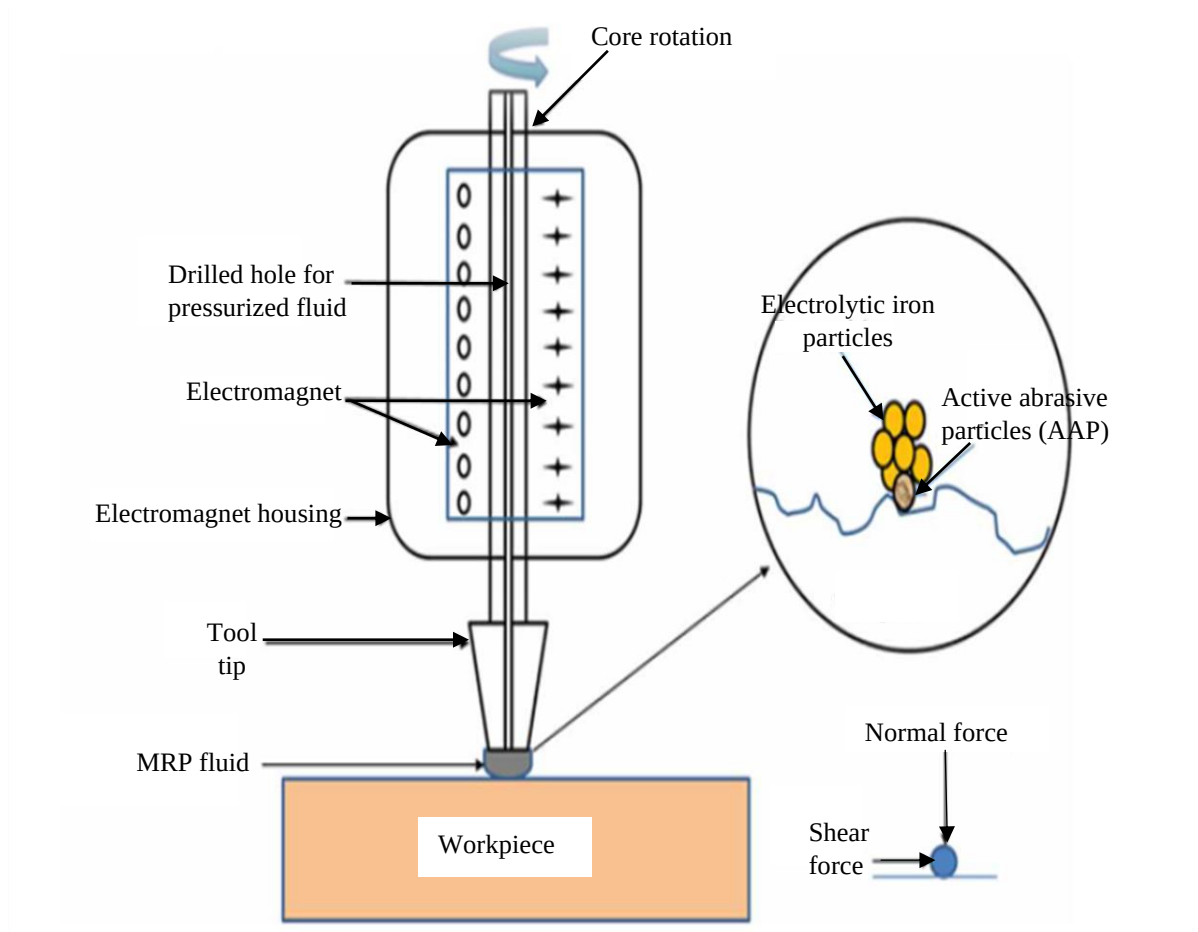


**Fig. 1.17.** Schematic diagram of Ball end magnetorheological based finishing (BEMRF) process (Kumar *et al.*, 2019).

### 1.5 Applications of various polymer workpieces in different industries

The use of fine finishing with a defect-free polymer workpiece surface with different shapes is critical for improving surface characteristics and operating performance. Polymer components with different shapes are utilized in a variety of industrial applications and equipment. The precise finishing of polymer components with less surface flaws might improve their functioning. As listed below, there are a variety of industrial uses.

- In the automobile industry various applications require a fine finishing to improve the efficiency of the engine by reducing the noise, friction, and wear and tear of the components. These components are polymer gears, and bushes.
- In the marine industries, the polymer bearings and valve seals require for reducing wear and malfunction cases during practical application. The polymer bearings are mostly used in pump shafts, water turbines, and marine propellers.
- In the medical industry, the acetabular lining for the hip joint, a spacer of the knee joint, and dentistry are components made up of polymers where fine finishing is required for improved service life.
- In the additive manufacturing industry, various components such as turbine blades, winding drums, medical implant prototypes, etc., are made up of polymers.

## CHAPTER 2

### LITERATURE REVIEW

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Polymer components in various shapes with a uniform fine polished surface play a significant role in enhancing their operational functionality in industries such as automotive, medical, marine, and optical, among others. Presently, there are many applications in an industry where nano-finishing of the polymer components is of great concern. Finely finished polymer components provide dimensional precision, close fit, tolerance, reduced wear and friction, and improve their service life (Jha and Jain, 2009, Singh and Singh, 2019). However, achieving higher accuracy and a finely finished surface is a time-consuming and labor-intensive task (Gorana *et al.*, 2004). The different shaped polymer components are often finished using traditional finishing processes such as grinding (Yan *et al.*, 2021), ball burnishing (De Bruijn *et al.*, 2021), and lapping (Li *et al.*, 2010), and vapor polishing (Kim *et al.*, 2013). Grinding wheels with strongly bonded abrasives are used in the grinding process. The grinding wheel has both rotating and reciprocation motions to finish the polymer workpiece's exterior flat or interior cylindrical surfaces (Tawakoli *et al.*, 2007). As a result of the rubbing action of the abrasive particles on the workpiece surface, the material is abraded and finished. In the ball burnishing process, the compressive force of the ball-shaped tool on the workpiece induces residual compressive stress in the workpiece (Mahajan and Tajane, 2013). This produces a significant amount of residual compressive stress which resulted in an increase in fatigue strength and wear resistance on the surface (Shirsat and Ahuja, 2004). Burnishing not only improves the surface quality but also improves the mechanical properties of the surface by producing compressive residual stresses. Further, in the lapping process, the rotational and reciprocation abrasive particles combined with fluid are used to remove material. After the abrasive slurry is placed between the work part surface and lap surface, the workpiece tends to be held against the lap due to pressure and is moved in different paths (Lynah and Hoffman, 1989). However, in traditional finishing processes, uncontrollable finishing forces act over the polymer workpiece surface. These uncontrolled finishing forces generate surface defects such as surface irregularity, scratches, and residual stress over the final surface (Gupte *et al.*, 2008; Jain, 2009). Therefore, to overcome the issues related to the traditional finishing processes, several advanced finishing processes have been developed. Some of these advanced finishing processes are without rheological behaviour in the finishing medium. While some advanced finishing

processes are with rheological behavior in the finishing medium. The present chapter contains a detailed literature survey on these traditional and advanced finishing processes. Further, it includes the problems related to the traditional finishing processes in attaining a fine-finished polymer component with different shapes. It also covers issues with standard finishing methods for achieving a fine-finished surface on the polymer components.

## **2.1 Literature related to the traditional finishing processes for various shapes of polymer workpiece surface**

The detailed literature review regarding traditional processes for finishing the different polymer workpiece surfaces are discussed as follows.

**Spina and Cavalcante (2020)** investigated the surface characteristics of the cylindrical polyamide workpieces (PA66 and PA66 GF30) with the  $\text{Al}_2\text{O}_3$  and SiC abrasive wheels. The surface roughness was used to assess the level of finishing of the final products. Both materials were ground by varying rotations, workpiece infeed speed, and depth of cuts for sequential roughing/finishing steps. The results show that as compared to the SiC wheel,  $\text{Al}_2\text{O}_3$  produced coarser surfaces in the rough pass and smoother surfaces in the finishing pass on both polyamide materials. The  $\text{Al}_2\text{O}_3$  wheel worked better than the SiC wheel because it produced lower forces, and contributed to a better surface finish. Also, an increased friability of the SiC abrasive resulted in a roughness fluctuation. The initial  $R_z$  value of PA66 and PA66 GD30 was measured as 4  $\mu\text{m}$ . The lowest  $R_z$  values with the  $\text{Al}_2\text{O}_3$  and SiC grinding wheels were obtained as 1.34  $\mu\text{m}$  and 3.01  $\mu\text{m}$  for PA66. The lowest  $R_z$  values with the  $\text{Al}_2\text{O}_3$  and SiC grinding wheels were obtained as 2.53  $\mu\text{m}$  and 3.99  $\mu\text{m}$  for PA66 GF30. These values were higher than those measured for the PA66. This is due to the presence of fibers in PA66 GF30 which leads to the deteriorated surface quality. Further, it was also found that low workpiece infeed and cutting rates, along with a low depth of cut, yielded good results for both the abrasives.

**Koysuren et al. (2010)** investigated the effect of the grinding process on the electrical conductivity and mechanical properties of polymer composites named polypropylene (PP), and polyethylene terephthalate (PET). The electrical resistivity of initial and ground PP and PET systems was measured by a two-point probe method with a constant current source. For better electrical contact in the two-point probe method, copper wires were placed into the compression molded composites during sample preparation. Conductivity measurement was performed by contacting probes with these copper wires. All measurements were done at room temperature. The tensile properties of

PP and PET composite systems were measured using a tensile testing instrument. The results reveal that the electrical resistivity of initial PP and PET composite systems which were in the insulating range was reduced to a semiconductive level with the grinding technique. The most distinctive difference in mechanical properties of conventional and ground systems was observed in the tensile strength. Ground PP and PET systems provided better tensile strength values as compared to the initial PP and PET systems. Electrical conductivity, tensile strength, and modulus values of ground composite systems molded at 280°C were lower than those of ground composite systems molded at 230°C. Based on the enhanced electrical conductivity and tensile strength values, the grinding technique can be applied to conductive polymer composites.

**Ferfecki and Hale (2011)** investigated the effect of the ground helical polymer gears in the NVH (Noise Vibration and Harshness) and operating efficiency over conventional high-quality iron gears. The polyether ether ketone (PEEK) polymer is used to manufacture gear and further grinding is done. The gear test run was done for 300 hours for both PEEK gears and conventional high-quality iron gears. The results reveal that PEEK gear provides up to a 3 dB improvement in NVH compared to the production gray iron gear set. Further, a single PEEK gear has a 69 % reduction in weight and a 78 % reduction in inertia compared to the gray iron gear. This results in about a 30 % reduction in system inertia and a savings of about 9 % in the torque required to operate the balance shaft module. This lower mechanical loss means higher operating efficiency.

**Wang et al. (2018)** investigated the effect of the rotary ultrasonic surface grinding carbon-fiber-reinforced plastic (CFRP). The study reports the effects of machining variables (ultrasonic power, tool rotation speed, feed rate, and depth of cut) on output variables (cutting force, torque, and surface roughness). The workpiece dimensions were 270 mm × 18.5 mm × 18 mm. The results reveal that cutting forces and torque decreased as ultrasonic power and tool rotation speed increased and as feed rate and depth of cut decreased. Also, lower surface roughness was generated at a lower level of ultrasonic power, higher level of tool rotation speed, lower level of feed rate, or lower level of depth of cut. The lower level of surface roughness was due to larger machining cutting contact time and smaller machining cutting contact area between the cutting tool and workpiece within unit cutting time, higher kinematic overlap time of abrasive trajectory, lower friction force, less fiber fracture and pull out from the machined workpiece surface, and a lower rate of tool wear.

**Low and Wong (2011)** investigated a new surface treatment process known as the ball burnishing process for the polymers. In this study, two polymers polyoxymethylene (POM) and polyurethane (PUR) were used for investigation. The surface quality and tribological study are done over the surface. Figure 2.1 (a-d) shows the effect of the burnishing force, speed, feed, and ball diameter on the specific wear rate for two different polymers. According to the findings of the surface quality and tribology investigations, the ball burnishing technique has a good prospect of becoming a novel surface treatment approach for polymers.

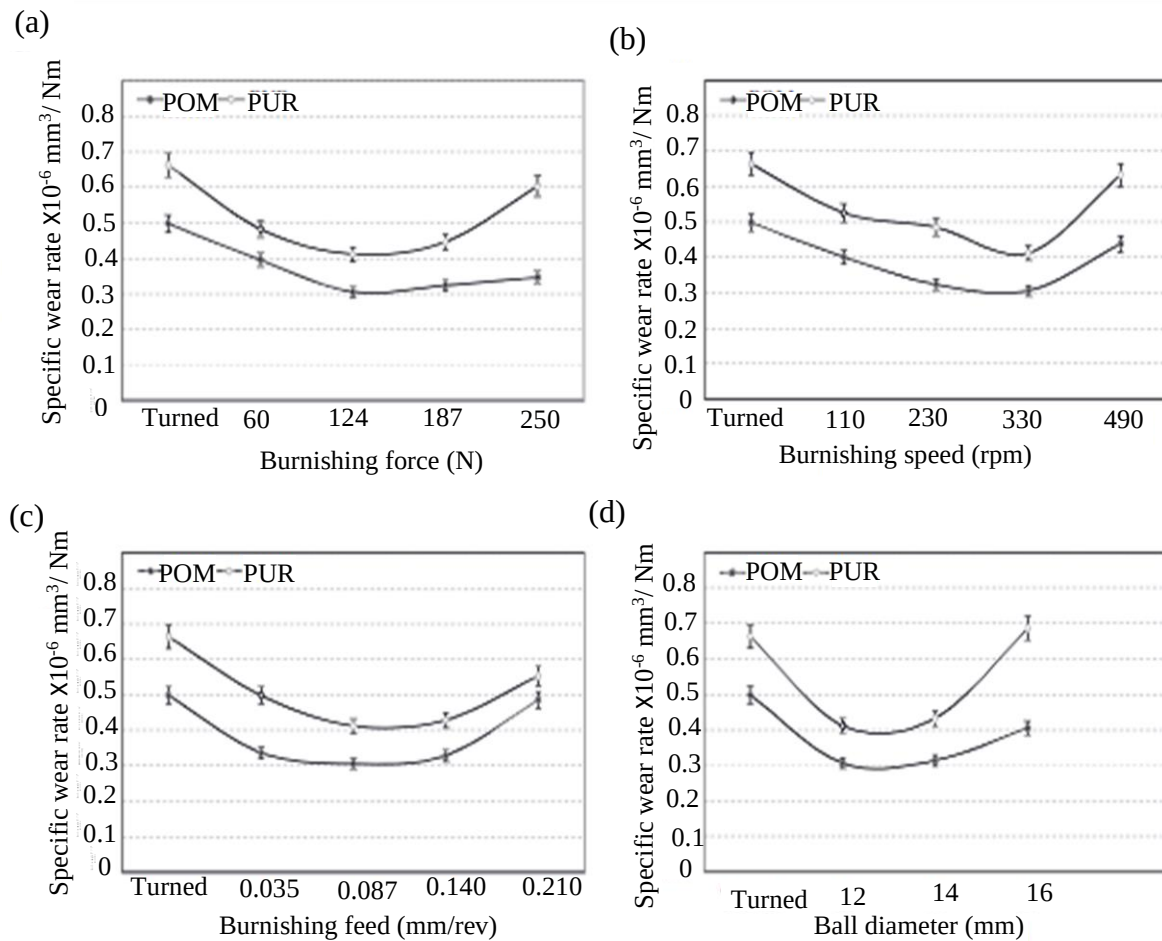


**Fig. 2.1.** The effect of ball burnishing on surface roughness as influenced by (a) burnishing force (b) burnishing speed, (c) burnishing feed, and (d) ball diameter.

During burnishing operations, a combination of moderate burnishing force and speed, low feed rate, and small ball size is suggested in situations where a good surface finish is desired. Furthermore, increasing burnishing speed up to a certain limit decreases the surface roughness, but any additional increase had a negative impact.

The lowest surface roughness value attained in this study was  $0.44\text{ }\mu\text{m}$  (45 % reduction) for POM and  $0.46\text{ }\mu\text{m}$  for PUR (42 % reduction). The amount of friction and wear reduction was mostly determined by the surface roughness imparted by the burnishing procedure. In this study, the lowest coefficient of friction values was obtained as 0.22 (32.9 % reduction) for POM and 0.24 (28.8 % reduction) for PUR. POM had the lowest specific wear rate of  $0.31 \times 10^{-6}\text{ mm}^3/\text{N m}$  (38.6 % reduction) while PUR had the lowest specific wear rate of  $0.41 \times 10^{-6}\text{ mm}^3/\text{N m}$  (37.9 % reduction). Hence, the reduction in surface roughness and specific wear rate reveals that the ball burnishing process may enhance the surface qualities of the POM and PUR in industries.

**Cagan et al. (2019)** experimentally investigated the effect of the ball burnishing process on the surface quality of the polymer rod workpiece. In this work, different medium conditions naming boron oil and mineral oil were used. Also, the effect of four different parameters (force, feed rate, number of passes, and medium) was studied on the polymer rod surface. Taguchi method was utilized in this process to optimize the process parameters. The optimum process parameter was obtained as 250 N force, 0.05 mm/rev feed rate, and 4 number of passes.

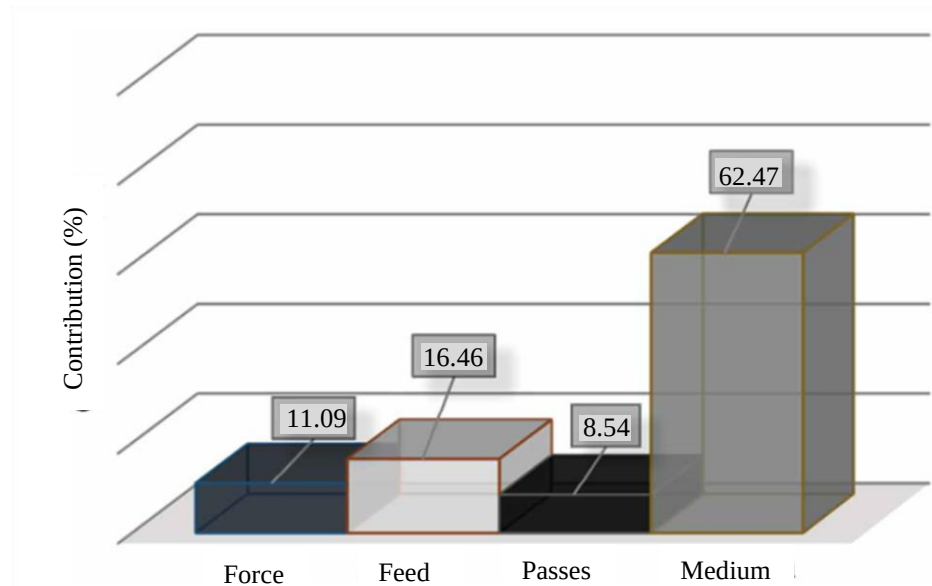


**Fig. 2.2.** Contribution percentage of the burnishing outputs.

Dry parameter is the best solution even if it has no lubrication medium. The reason for this is the effect of heat generated by friction on the surface caused better surface roughness values. In the burnishing process, the medium parameter (dry parameter) was found as the leading drastic factor affecting the surface quality of the carbon fiber reinforced polymer (CFRP) workpiece with a



percentage of 62.47 % (Fig. 2.2). It was observed that force (11.09 %), feed rate (16.46 %), and passes (8.54 %) have a role in minimizing the surface roughness.

**Janczewski *et al.* (2016)** investigated the end milled surface of the low density high molecular mass polyethylene using the ball burnishing process. In this process, the process parameters were taken as force and burnishing speed. After experimentation, an increase in temperature was found over the workpiece surface. The results show that at higher force, the surface roughness decreases significantly as depicted in Fig. 2.3(a). Also, hardness tends to increase, and wear rate tends to decrease when burnishing is performed after milling as depicted in Fig. 2.3 (b-c).

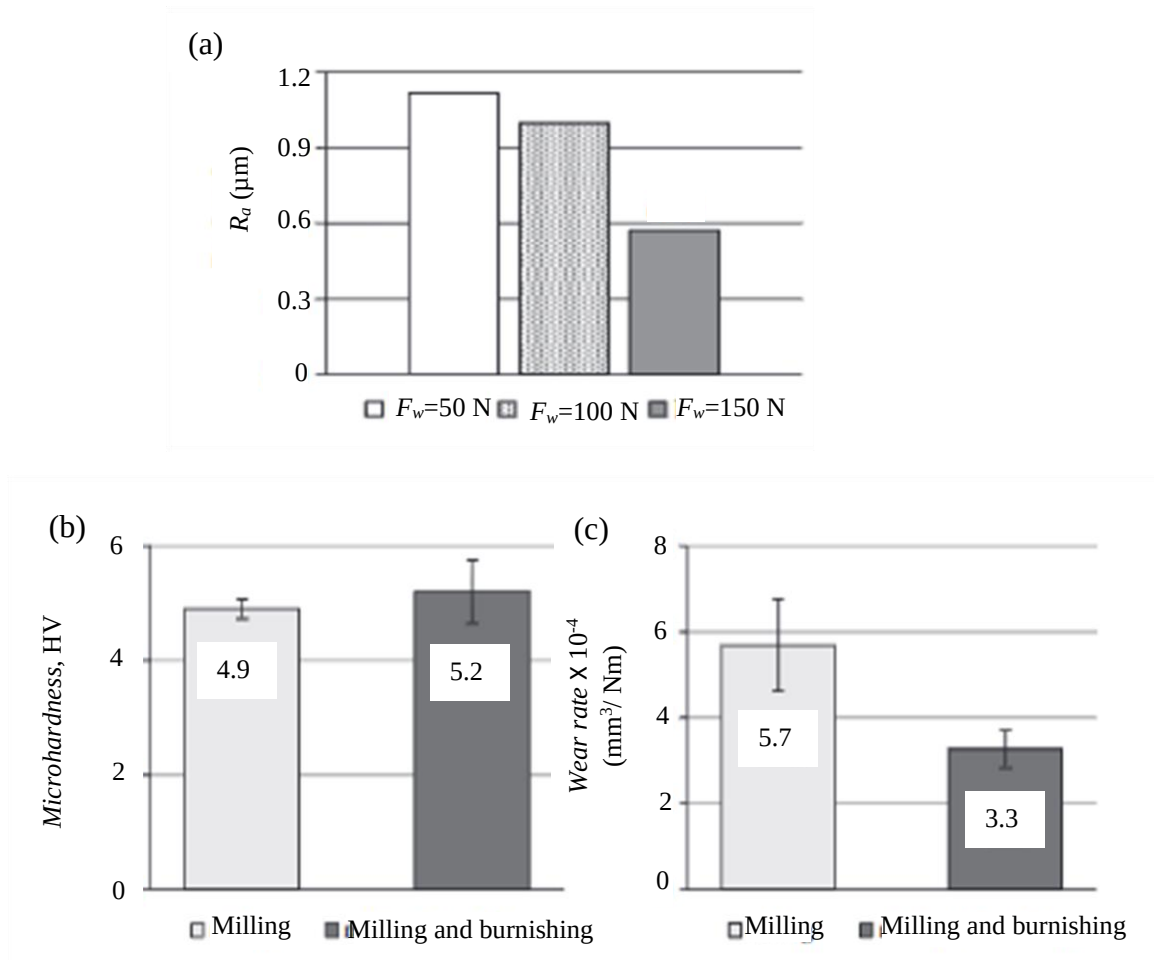


**Fig. 2.3.** Results of (a) surface roughness, (b) Vickers microhardness and (c) wear rate for force ( $F_w$ ) = 150 N, feed = 0.04 mm.

**Tayeb *et al.* (2008)** investigated the effect of roller ball burnishing to improve the hardness and surface roughness over the thermoplastics (acetal homopolymer, POM-H) and thermosets (polyurethane, PU). In this study, the process parameters were taken as burnishing force, speed, feed, and roller width contact. The workpiece used for experimentation is cylindrical. The results

reveal that this process is more suitable for thermoplastic as compared to thermosets. This is because thermoplastic polymers do not change their properties on being acted by external burnishing forces, However, thermosets do change their properties when external burnishing forces act on their surface. Depending on the burnishing conditions, the burnishing force can finish the POM-H and PU surfaces by 37 % and 28 %, respectively. Further, the effect of increasing the burnishing speed resulted in a decrease in surface roughness to a minimum value of 37 % for POM-H and 32 % for PU at a burnishing speed of 330 r/min for both polymers. Roller burnishing, however, worsened the surface finish above 460 r/min (for POM-H) and 430 r/min (for PU) burnishing rates. Aside from that, at the lower burnishing speed of 110 r/min, the improvement in surface hardness was more evident.

**Li et al. (2010)** investigated the novel fixed abrasive lapping and polishing (FALP) process for fine finishing of the K9 glass, mobile panel glass, and silicon wafer (Si). In the FALP process, a fixed-abrasive pad is used in which the diamond abrasives of size 5-10  $\mu\text{m}$  are fixed. In this study, the effect of the FALP process on the surface quality and material removal rate for different materials is studied naming K9 glass, mobile panel glass, or Si, onto the quartz. The FALP with 5-10  $\mu\text{m}$  diamond abrasives were selected in the experiments and were bonded on the platen. The polishing slurry was made with distilled water with abrasives, and the pH of the slurry was used about 9-11. Slurry flow rates of around 40-60 ml/min were utilized with an applied pressure of 75 kPa and a platen speed of 100-200 rpm. All of the tests were carried out at room temperature. The result shows that the maximum material removal was obtained for Si (4428 nm/min) followed by mobile panel glass (300 nm/min) and then K9 glass (241 nm/min). However, the minimum surface roughness ( $S_a$ ) was attained for mobile panel glass 2.10 nm followed by Si (13.9 nm) and K9 glass (24.8 nm).

**Tuazon et al. (2020)** investigated the effect of the vapor polishing process on the fracture behaviour of the fused deposition modeling (FDM) fabricated polymer at higher operating temperatures. The material used in this study is ABS. Further, the comparison was made between the vapor polished ABS workpiece with the unpolished workpiece. The experimentations were performed at three different temperatures (55<sup>0</sup> C, 80<sup>0</sup> C, and 105<sup>0</sup> C). The results were analyzed in the terms of the calculated impact resistance (IR) and impact energy (IE) absorbed by the polished and unpolished surfaces. The maximum IR and IE on the unpolished surface were found as 304.375 J/m and 2984.069 J/m<sup>2</sup> respectively. However, over the polished surface, IR and IE are

found as 309.375 J/m and 3033.088 J/m<sup>2</sup> respectively which were higher than the unpolished surface. According to the test results, vapor polishing had a substantial enhancement on the fracture behaviour of ABS material.

**Neff *et al.* (2018)** investigated the effect of vapor polishing on the surface quality and mechanical properties of additive manufacture polymer components. The results reveal that after vapor polishing, the average roughness value is reduced by 72.75 %, resulting in a noticeably smooth and glossy surface finish that is more aesthetically pleasing than the as-printed components. Vapor polishing also appears to overcome small surface process flaws. Further, it was found that vapor polishing has minimal effect on the mechanical properties except for the energy absorption. Hence, it can be concluded from the study that polishing significantly decreases surface roughness but has a modest impact on mechanical performance that decreases with increasing part thickness.

**Lavecchia *et al.* (2021)** proposed a quantitative analysis of the effects of a chemical treatment based on ethyl acetate vapors, to improve the surface finish of polylactic acid (PLA) polymer printed parts. The solvent was selected for its low toxicity, easy availability, and low cost. A full factorial plan is designed and a roughness analysis before and after the chemical treatment is done to highlight the influence of each parameter involved. The variable process parameters selected as input factors for the first (pre-treatment) experimental plan were: the layer height, the infill line distance (the same value for the internal, top, and bottom slices), and the deposition speed. The proposed treatment allowed to achieve almost a 90 % of roughness reduction, with several advantages in terms of toxicity, the quantity of solvent, and treatment time. By considering the solvent quantity and the treatment time, the best results (roughness reduction of about 90 %) were obtained by increasing simultaneously the duration of treatment and the solvent quantity. But when increasing the duration of treatment with a low quantity of solvent, leading to a lower surface finish improvement. Infill line distance had no significant effects on the roughness reduction, except for the cases with the minimum solvent quantity or the minimum treatment time, where the effect of the treatment is less pronounced. Further, the proposed ethyl acetate vapor treatment resulted to be effective and it was demonstrated that a proper choice of the treatment parameters can improve surface finish, regardless of the starting values of roughness.

The surface defects without fine finishing reduce the functional capability of the components for industrial applications. So, to attain the desired fine finishing and defect-free surface for the longer life span of functional applications of various industrial polymer components, the advanced

finishing processes without and with rheological behaviour in the finishing medium had been employed.

## 2.2 Literature related to advanced finishing processes for the polymer workpieces without rheological behavior in the finishing medium

**Zhong *et al.* (2006)** investigated the effect of the chemo-mechanical polishing (CMP) on the polycarbonate (PC) and poly-methyl methacrylate (PMMA) workpieces. In this work, four different slurries naming Marzin SRS1, Marzin SRS 3, ILD 1200, and Simlox are used for finishing the workpieces.

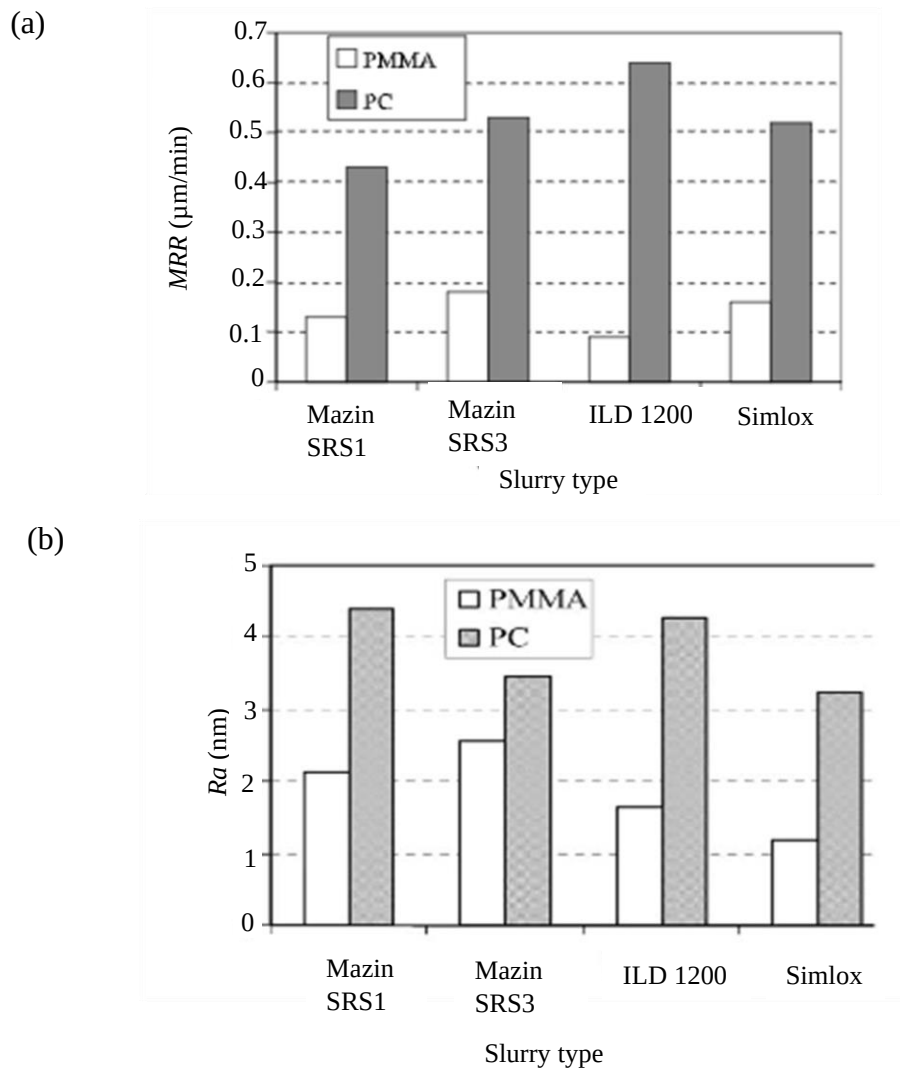


**Fig. 2.4.** (a) Material removal rate of the polymers polished using four types of slurry and (b) surface roughness of the polymers polished using four types of slurry

The material removal rate and surface roughness of two polymers using different slurries are depicted in Fig. 2.4 (a-b), respectively. The most suitable slurry for the polishing of the polymers was then selected based on the analysis of material removal rates (MRRs) and surface finish of polished samples. The process parameters used in this study are table speed and head load. Further, the spindle speed, processing time, and oscillation speed are kept constant at 40 rpm, 1 min, and 2 mm/sec, respectively. Further to optimize the process parameters, analysis of variance (ANOVA) was used. The results reveal that due to differences in material hardness, the material removal rate (MRR) and surface roughness of PC were found to be considerably greater than those of PMMA, and independent of the types of slurry employed. Simlox slurry was found to be suitable for the CMP of the two polymers. After ANOVA, the optimum parameters were found as table speed of 20 rpm and head load as 125 g/cm<sup>2</sup>.

**Tian *et al.* (2013)** investigated chemo-mechanical polishing (CMP) for the fine finishing of the optical workpieces. In this work, the fixed abrasive pad is used with different chemical slurries named de-ionized water, alkaline lubricant, colloidal silica, hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), and potassium hydroxide (KOH). The polishing performances of these slurries were evaluated and compared in terms of material removal rate (MRR), surface roughness, and flatness of the polished silicon substrates. The result reveals that the de-ionized water leads to the lowest MRR and the hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) leads to the maximum MRR. Further, surface roughness values of the silicon substrates polished with all slurries are below 53 nm while the MRRs of all slurries are more than 11.11 µm/min. It is confirmed that fixed abrasive CMP is a promising process for optical silicon substrates.

**Yamuchi *et al.* (2002)** developed the numerically controlled elastic emission machining (EEM) for ultraprecise finishing of the glass. In this work, novel nozzle-type EEM heads, by which a high shear-rate flow of ultrapure water can be generated on the work surface, have been proposed to transport the fine powder particles to the processing surface. The abrasive particle used in this work is the SiO<sub>2</sub>, with a fluid concentration of 10 % by volume and dwell time of minutes. The results reveal that the material removal is constant for over 100 hours and the relationship between the volumetric removal and dwell time was found to be linear.

**Hirata *et al.* (2014)** investigated the effect of the elastic emission machining (EEM) process over a steeply curved glass surface. In this work, the rotating sphere tool (diameter 60 mm) is used over the steeply curved workpiece surface and the rotational speed of the tool was kept at 750 rpm. The

results reveal that the surface roughness and error of glass are reduced effectively after rotary based EEM process. However, the effect of the axial directional ridges that appeared in EEM polished the surface on mirror performance is yet to be estimated.

### **2.3 Literature related to advanced finishing processes for the polymer workpieces with rheological behaviour in the finishing medium**

Several advanced finishing processes based on the rheological behavior in finishing medium have been developed to provide fine finishing with good surface qualities over the various shapes of the polymer industrial components. The literature review about the advanced finishing processes with magnetorheological behaviour of the finishing medium is discussed below.

**DeGroote et al. (2004)** utilized the magnetorheological (MR) finishing process for the fine finishing of the optical polymers. The workpiece used in this work is polymethylmethacrylate (PMMA), cyclic olefin polymer (COP), polycarbonate (PC), and polystyrene (PS). Further, the circular workpieces are used for experimentations with diameter ranges from 40-75 mm and thickness ranges from 2.5-25 mm. Polishing trials were conducted with standard CeO<sub>2</sub>-based and nano diamond-based MR fluids, or with MR fluids containing SnO<sub>2</sub>, ZrO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, or SiO<sub>2</sub>. The results reveal that the ZrO<sub>2</sub>-based MR fluid is best suitable for the PMMA surface as the RMS value obtained is 0.5 nm. Further, for COP, PS, and PC, Al<sub>2</sub>O<sub>3</sub> also provides good results over polymer surfaces.

**Khan et al. (2016)** utilized the computer numerically controlled ball end magneto-rheological finishing (BEMRF) process to polish the polycarbonate up to nanometer order level surface roughness. Further, in this study, cerium oxide, alumina, and diamond are used as the abrasives during finishing. The composition of the MRP fluid is taken as 15 % volume of carbonyl iron particles (CIPs), 15 % volume of abrasives, and 70 % volume of the base fluid (20 % acetone + 80 % deionized water). The finishing time of each experimentation is kept as 60 min. The results reveal that the optimum results are obtained with the diamond abrasives. The polishing results of alumina are almost the same as the results of diamond abrasives. So, on the basis of the cost of the polishing abrasives, alumina can be used for the polishing of polycarbonate. Further, the process parameters used in this study are working gap, magnetizing current, and tool rotation speed. To optimize the process parameters, response surface methodology was used. The optimized parameters were found as 0.53 mm working gap, 6 A current, and 300 rpm rotational speed. The percentage contributions of finishing parameters for alumina-based slurry are gap-64 %,

magnetizing current-14 %, and tool rotational speed-13 %, according to the regression analysis. Using optimum process parameters, the maximum percentage reduction of surface roughness value over the polycarbonate surface is found as 54 %.

**Kumar et al. (2019)** proposed a novel technique for fine finishing of the FDM fabricated polylactic acid (PLA) cuboid shape workpiece using the ball end magnetorheological finishing (BEMRF) process. The abrasives used in this process are  $\text{Al}_2\text{O}_3$  with mesh size 1000 and electrolytic iron particles (EIPs) with mesh size 300. The other parameters are current as 6 A, rotational speed 300 rpm, feed rate 40 mm/min, and finishing time 30 min. Further, to optimize the volume concentration of the magnetorheological polishing fluid (MRP) fluid, response surface methodology is utilized. The optimum MRP fluid composition was found as 16.17 vol % abrasives, 25 % of EIPs, and 58.83 % of distilled water as the carrier fluid. Using the optimized MRP fluid composition, the minimum roughness value is obtained as 81 nm from 511 nm in 75 min of finishing.

**Gupta et al. (2021)** analyzed the effect of the BEMRF process on the fused silica glass surface with optimized process parameters and fluid parameters. In this process, three parameters were used for finishing naming, working gap, current, and rotational speed. The cuboidal workpiece sample was used for experimentation. The MRP fluid composition was taken as 20 % vol of CIP, 10 % vol of  $\text{CeO}_2$  abrasive, and 70 % vol of deionized water as base fluid. After the experimentation, the optimized process parameters were found as 3 A current, 1.2 mm gap, and 300 rpm rotational speed. Using the optimized parameters, the average surface roughness is reduced from 0.594 nm to 0.154 nm.

**Guo et al. (2018)** presented the analytical and experimental analysis on the post-processing of the selective laser sintering (SLS) fabricated polyamide workpiece. The work focuses on improving the surface quality and clarifying interrelations between surface quality and process parameters. The impacts of post-processing on material removal, surface morphology, roughness, hardness, and tribology performance were quantified. Initially, precision grinding was used which reduced the surface roughness from 15  $\mu\text{m}$  to 2.85  $\mu\text{m}$ . Further reduction in the surface roughness is done using the magnetic field-assisted finishing (MFAF) process. Using the MFAF process, the surface roughness is reduced from 2.85  $\mu\text{m}$  to 0.89  $\mu\text{m}$ . When compared to the as-printed and precision ground surfaces, the MFAF treated surface had improved tribology performance, as evidenced by a lower coefficient of friction and higher wear resistance. After post-processing, Raman and XPS

measurements revealed that no apparent chemical changes were generated on the sub-surface level within 10  $\mu\text{m}$ .

**Wang et al. (2007)** investigated the novel ultrasonic-magnetorheological compound (UMRC) process for fine finishing of the optical polymers. The machining principle and the experimental procedure of UMRC finishing are introduced in this work. Experiments are carried out to study the material removal property in UMRC finishing of the workpiece. The polishing head in UMRC finishing is adjusted for different positions to form different angles between its own spindle axis and that of the workpiece during polishing. The profiles of material removal in UMRC finishing of optical glass are achieved by changing the location of the polishing head, according to the trials. It may be deduced that when there is an angle between the axis of the polishing tool and the axis of the workpiece in UMRC finishing, the form of the material removal profile changes. When the angle is  $0^\circ$ , the material removal profile has the shape of a letter W. When the angle of the material removal profile is 20 degrees, it resembles the letter V, avoiding the drawbacks of the W-shaped profile and making it more attractive in optical manufacturing.

**Alam and Jha (2017)** developed a model for the theoretical analysis of the surface roughness and mechanism associated with the flat workpiece using the ball end magnetorheological finishing tool. In this process, firstly the analysis of variation in magnetic flux density in the working gap is developed. Then, the theoretical models of the normal indentation and shear forces are developed to perceive the material removal mechanism. The Brinell hardness model was used to calculate the indenting force. From the model, finally, the surface roughness value is calculated. CIPs of 19  $\mu\text{m}$  and SiC of 18  $\mu\text{m}$  with average particle diameter form a BCC unit cell structure was proposed in this work. Considering the parameters like current, working gap, and tool rotation as 3 A, 1 mm, and 200 rpm, the surface roughness value is reduced to 78 nm in 10 min of finishing time. On comparing the theoretical and experimental data, the percentage errors were found to be in the range of 7.23 to 31.19 %.

**Paswan and Singh (2019)** proposed a model to enhance the finishing performance of the internal surfaces by adding rotational motion to the cylindrical workpiece. Owing to the addition of the cylindrical workpiece rotation, the relative motion of the active abrasive particle is increased. This increase in relative motion has reduced the gap between the pitch formed by the single active abrasive particle, thus the magnetorheological honing (MRH) tool is able to finish the internal cylindrical workpiece surface at a higher finishing rate. The path length of the rotational MRH tool



is calculated and compared with the existing MRH tool. Also, the theoretical model is developed to calculate the surface roughness value for the developed rotational MRH process. For the experimentation, the workpiece rotation, working gap, tool rotation, and reciprocation are taken as 40 rpm, 1.7 mm, 400 rpm, and 70 cm/min, respectively. After, the experimentation, the surface roughness value is reduced from 330 nm to 60 nm in 60 min of finishing time. The percentage error between the theoretically calculated and experimentally obtained surface roughness value is in the range of 3.33 to 5.92 %.

## **2.4 Research gaps**

After studying the wide literature review, it has been seen that many finishing processes are evolved as per the need to the finishing the different types of polymers with various shapes and sizes of the workpieces, level of finishing, etc. This led to the development of the traditional and advanced finishing processes. As the traditional finishing processes such as grinding and lapping utilize the direct contact of the bonded abrasive particles with the workpiece surface, the surface defects such as micro cracks, changes in microstructures, and residual stresses may occur (Gupte *et al.*, 2008). The traditional processes such as grinding, ball burnishing, and lapping do not have control over the finishing forces. Also, these processes do not provide precise and controlled finishing, which can lead to friction and wear in polymers during their functional life span. Sometimes, in severe cases, friction can cause overheating which is likely to have adverse effects leading to altering the shape of the objects. This results in lower efficiency of the polymer components (Shirsat and Ahuja, 2004). This led to the development of advanced finishing processes that can finish the polymer workpieces better than the traditional finishing processes. These processes are chemo-mechanical polishing (CMP) and elastic emission machining (EEM) processes. CMP and EEM provide fine finishing, however, the normal forces acting on abrasive lead to scratches and micro-cracks (Khan *et al.*, 2016). Further, magnetorheological polishing (MRP) fluid-based finishing processes were developed for the fine finishing of polymers with controlled forces. The magnetorheological finishing (MRF) has provided fine finishing over various optical applications as well as offers a clean and damage-free surface due to low normal forces on abrasives (Khan *et al.*, 2016; Kordonski *et al.*, 1996). Therefore, the process should be applied for the polymer components used in various industries such as automobile, medical, marine, etc. Hence, an advantage of the MRF process has been explored further for the fine finishing of polymers components with different shapes in the present work. Also, the effect of the

different types of magnetorheological polishing (MRP) fluid over the polymer surface has not been discussed limited in the literature. The MRP fluid plays an important role in the MRF process, therefore, its effect on the process mechanism needs has been discussed in the present work. Hence, from the above discussions, the important literature gaps are reported as follows.

- Traditional finishing processes do not offer accurate and controlled finishing (Shirsat and Ahuja, 2004). As a result, the efficiency of the traditionally finished polymer components may reduce while functioning.
- Polymers are playing a key role in the aerospace, automobile, and medical sectors (due to their light-weight and non-corrosive properties) where most of the parts of complex shapes are manufactured by additive manufacturing (AM) process. Since the AM process involves layer by layer deposition, the surface finish is not found as per the requirement of the industrial level (Guo *et al.*, 2018).
- Although processes like CMP and EEM give fine finishing, the normal forces acting on the abrasive cause scratches and tiny fractures which may affect the surface characteristics of polymer workpieces.
- The magnetorheological finishing (MRF) process is used for polymers having optical applications to date. As the MRF process offers a clean and damage-free surface due to low normal forces on abrasives, therefore, the MRF process can be used for the polymer components which are required in various industrial applications.
- The effect of water-based and oil-based magnetorheological polishing fluid on the finishing performance of polymers has not been discussed in the literature. Therefore, it is important to consider in the study.
- The mechanism of material removal for different types of polymers and their validation via experiments can give insight into the process mechanism, hence, it has to be discussed.

In considering the above-mentioned literature gaps, there is a requirement for utilizing the magnetorheological fluid-based finishing process for improving the surface characteristics of the polymer components with various shapes such as flat, internal, external cylindrical, hemispherical, etc. used in industries such as medical, automobile, marine, etc. So, in the present work, to fine finish the polymer industrial workpieces with different shapes and sizes, the magnetorheological polishing fluid-based tools are designed and fabricated. Depending on the shape of the polymer workpieces, the tool should provide fine finishing over the entire

surface with minimal surface irregularities. Based on the research gaps as identified through the literature, the research objectives are mentioned below.

## **2.5 Research objectives**

- To develop and fabricate the improved tools and fixtures for magnetorheological finishing of the different polymer workpieces.
- To develop different magnetorheological polishing fluids and test their effectiveness for finishing the different polymer materials.
- To study the effect of process parameters with plan of experiments on the process response such as surface finish improvement using response surface methodology in order to optimize the parameters for the better process performance in finishing the different polymer materials.
- To analyze the surface characteristics, material removal mechanism, and mechanical properties before and after the magnetorheological finishing on polymers.

## **2.6 Organization of the thesis chapters**

The thesis is organized into the following chapters including the references.

**Chapter 1** gives the introduction of the various traditional and advanced finishing processes with their applications for the various polymer workpiece surfaces. This chapter states the benefits of using advanced finishing processes with the control of finishing forces by controlling the magnetic field as compared to the traditional finishing processes.

**Chapter 2** contains a discussion about the existing literature review on the traditional and advanced finishing processes utilized for the finishing of the polymer workpieces. From this literature work, the requirement of present work for the effective, uniform, and fine finishing of polymer workpieces are reported. The research objectives of the present work are reported at the end of this chapter.

**Chapter 3** describes the design and fabrication of the different magnetorheological tools and fixtures to fine finish the different polymer workpieces.

**Chapter 4** reports the theoretical analysis and material removal mechanism for developed MRP fluid-based tools for fine finishing the different polymer workpieces with various shapes.

**Chapter 5** discusses the development of magnetorheological polishing fluid and preliminary experiments to evaluate their effectiveness for finishing the different polymer materials.

**Chapter 6** reports the effects of various process parameters on the percentage improvement in the surface finish ( $\% \Delta Ra$ ) utilizing response surface methodology to predict the optimum parameters for better finishing of different polymer workpieces such as gears, bearing, and valve seal, acetabular cup and additive manufactured components. Further, the improvement in the surface is investigated using a roughness profile. Also, surface quality enhancement is investigated using the surface characteristics such as scanning electron microscopy and circularity.

**Chapter 7** provides the conclusions and significant outcomes from the present research work and also defines the scope for future work.

## **CHAPTER 3**

### **DESIGN AND FABRICATION OF THE MAGNETORHEOLOGICAL FINISHING TOOLS FOR THE FINISHING OF THE SURFACE OF DIFFERENT SHAPES OF POLYMER WORKPIECES**

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As stated in the research gaps (chapter 2), the magnetorheological finishing (MRF) process has the potential to nano-finish the polymer surfaces. However, only limited work has been reported over the polymer workpiece using the MRF process. The increased utilization of polymer material in today's world is propelling industries towards a new energy-saving era. For a wide range of industrial applications, polymer-based components provide distinct benefits such as low weight, cheap cost, excellent damping resistance, and the ability to work with or without external lubrication. Various industrial components such as gear, bearing, valve seals, medical implants, etc., are being made of polymer nowadays. The various shapes of polymer components are manufactured in industries as per the requirement. Therefore, for attaining uniform and fine finishing over the different shapes of polymer components, MR finishing tools and fixtures are required to be designed accordingly. In the MR finishing process, the magnetic flux density (MFD) plays an important role, therefore tools are to be designed in such a way that a higher and uniform magnetic field can be achieved on the tool surface during the finishing of the workpiece. Similarly, the workpiece fixtures need to be designed in such a way that the uniformity in the working gap amid the tool and workpiece surface can be achieved during finishing. Hence in the present work, depending on the shape of the polymer workpiece components, the tools and fixtures are designed as well as fabricated.

#### **3.1 Design and fabrication of the magnetorheological finishing tools for the different shapes of the polymer workpieces**

To fulfill the need for fine finishing the different shapes of the polymer components, the magnetorheological finishing tools, as well as workpiece fixtures are designed and fabricated accordingly. Fig. 3.1 depicts the schematic figure where different magnetic tools can be used as per the shape of the polymer workpiece surface that needs to be fine finished. So, in the present study, the different magnetic tools are designed as per the shape of the polymer workpieces.

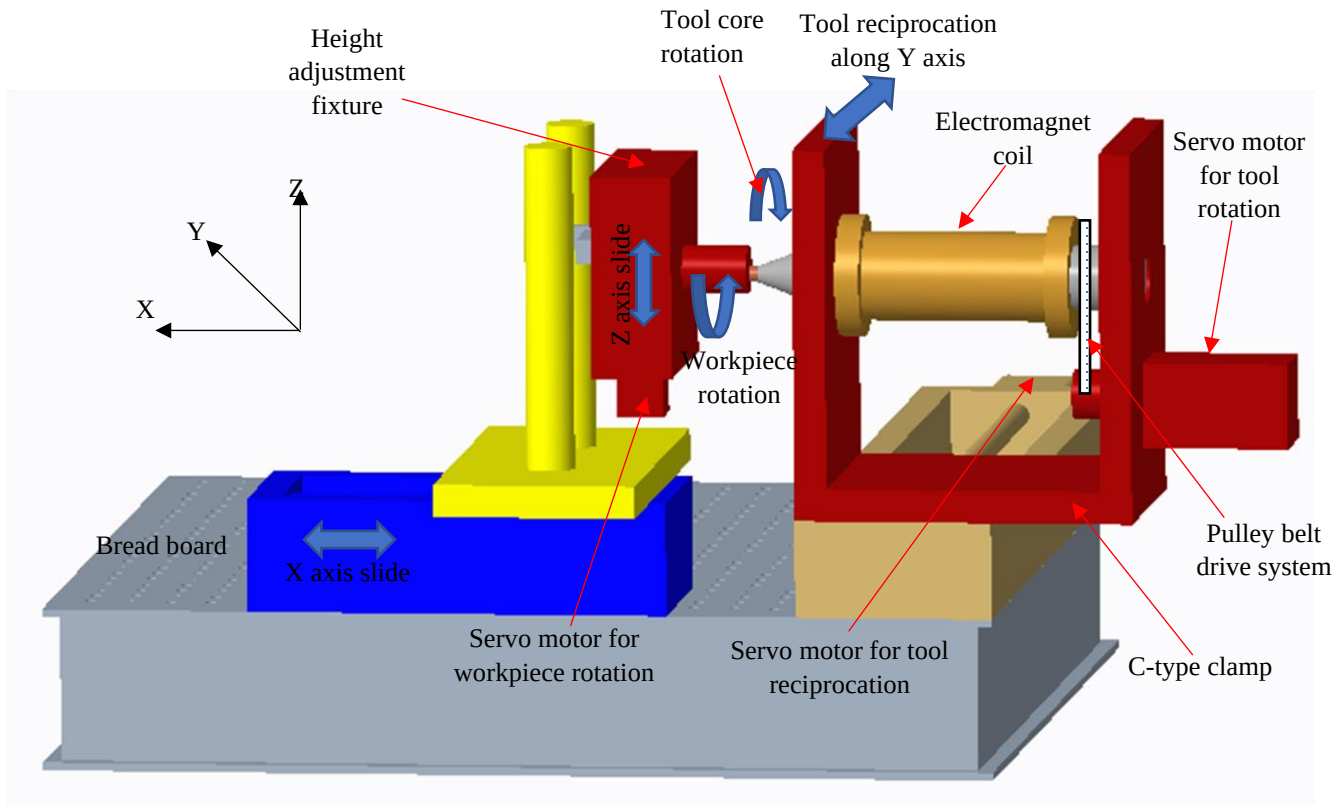


**Fig. 3.1.** 3-D CAD model of the magnetorheological finishing experimental setup where different magnetic tools can be used for fine finishing of the different shapes of the polymer workpieces.

The present setup comprises a stationary electromagnetic coil, a programmable logic controller (PLC), and a height adjustment mechanism for holding and maintaining the constant working gap during the finishing of the different polymer components. The PLC controls the different motions of the MR finishing tool and polymer workpiece during the finishing process. In the present setup, there are four servo motors and drivers have been used. These drives are controlled through a PLC which plays an important part in providing precise motion to the workpiece and tool core. The motion to the Y-axis slide is provided using a servo motor, which is used for the MR finishing tool's reciprocation motion along the longitudinal direction. Further, the height adjustment fixture is fixed over the Z-axis using the bolts. The workpiece structure is bolted over the Z-axis slide which is driven by a servo motor. The reciprocation of the workpiece to maintain the constant working gap is provided by the servo motor. Next, a C-type clamp holds the ball bearing, MR finishing tool core, bobbin, timing pulley belt drive, and servo motor to the tool structure. The timing pulley belt drive system ensures that rotational motion from the servo motor is smoothly transmitted to the MR finishing tool core. Further, the structure of the workpiece holder has been designed in such a way that the polymer workpieces can be kept in a horizontal position as per the workpiece shapes as shown in Fig. 3.1. The workpiece holder is designed according to the shape of the polymer workpiece to be finished while maintaining the uniform working gap between the

different shaped polymer workpieces and the MR finishing tool. Further, the MR finishing tool core rotates in the opposite direction to that of the workpieces. The relative motion between the MR finishing tool and the polymer work part surface is enhanced as a result of this opposite motion of the tool core (Paswan and Singh, 2019b). As a result, the shearing off surface asperities from the work part surface increases. The tool core is magnetized with the assistance of an electromagnetic coil wound around a stationary aluminum bobbin to finish the polymer workpiece. During the finishing, when the current is allowed to pass through the stationary electromagnetic coil, the temperature tends to rise. Therefore, to avoid overheating the coil and also to avoid the change in viscosity of MR polishing (MRP) fluid due to the temperature rise, the coolant is passed through the bobbin over the electromagnetic coil.

In the present work, different shaped polymer components (bearings, gears, valve seals, medical implants, and additive manufactured parts) are finely finished using the magnetorheological (MR) finishing process. The MR finishing tools are designed and fabricated for finishing as per the shape of the components such as flat, hemispherical, internal, and gears. Further, the presently proposed magnetorheological finishing tools must ensure a higher and uniform concentration of magnetic flux density (MFD) which is to be acquired on the tool surface amid the working gap while finishing. This results in strongly retaining the magnetorheological polishing (MRP) fluid on the finishing surface of the tool. In the present study, four different tools were designed as per the shape of the polymer workpiece components to be finished. Similarly, the different fixtures were designed and fabricated to provide a uniform working gap as per the shape of the polymer to be finished. Further, magnetostatic finite element analysis (MFEA) is performed to design the MR finishing tools to get the uniform and maximum feasible value of magnetic flux density (MFD) on the tool's finishing surface. MFD is defined as the number of magnetic field lines passing through a given closed surface. It provides the measurement of the total magnetic field that passes through a given surface area. The removal of material from the workpiece surface during finishing is mainly dependent on the strength of the magnetorheological polishing (MRP) fluid which further depends on the magnitude of the magnetic field applied to it. The MRP fluid consists of magnetic electrolytic iron particles (EIPs), non-magnetic polishing abrasives, and carrier fluid (Singh and Singh, 2019). The higher MFD on the tool's finishing surface amid the working gap leads to a more finishing rate with uniform removal of asperities from the polymer work part surface.

### **3.1.1 Design and fabrication of the hemispherical tip-based electromagnet tool**

For fine finishing the various hemispherical shape-based polymer components (acetabular cup and valve seat), a hemispherical tip-based tool is designed and fabricated. The dimensions of the finishing surfaces of the hemispherical tip-based tool are selected based on different trials performed in the magnetostatic finite element analysis (MFEA) for obtaining the maximum value of magnetic flux density (MFD). The Ansoft Maxwell V13 is used for the MFEA. The computer-aided design (CAD) model of the proposed hemispherical tip-based tool is depicted in Fig. 3.2. Since the inner surface of the workpiece surface in a hemispherical shape, the tip surface of the tool core is also made as an exact replica of the shape of the workpiece. The modeling of the hemispherical shaped tool core with the electromagnetic coil, MRP fluid, and the hemispherical shaped workpiece is done using the PTC Creo software as shown in Fig. 3.2(a). The taper length was made to the tool core just before the hemispherical tool tip surface so that higher MFD can be concentrated on the tool finishing surface. Further, the IGES files of the modeled design are imported to the Ansoft Maxwell V13 student version software. This software is used to analyze the concentration of MFD on the hemispherical tool tip surface. In the model, the thickness of 0.6 mm is assigned to the MRP fluid which acts as the working space amid the hemispherical tool core tip surface and ultra-high molecular weight polyethylene (UHMWPE) work part surface. The relative permeability of the different components used for the analysis is reported in Table 3.1. In electromagnetism, permeability is the measure of magnetization that a material obtains in response to an applied magnetic field. Further, relative permeability is defined as the ratio of permeability of the medium to that of the free space. The boundaries, materials, and source conditions are allotted over a finite space using Ansoft Maxwell V13. With these parameters, the MFEA using Ansoft Maxwell V13 software is performed for the concentration of MFD on the hemispherical tool core tip surface. The result obtained from MFEA is depicted in Fig. 3.2(b). The tapered length of the hemispherical tip-based tool is determined to be 35 mm after MFEA with multiple trials for attaining maximum flux density, as shown in Fig. 3.2(a). From the MFEA, it can be seen that the concentration of MFD is higher on the hemispherical tool core tip surface (0.358 T) and lower on the work part surface (0.314 T) as depicted in Fig. 3.2(b). From the literature, the MFD value over the tool surface for fine finishing of glass workpiece was reported as 0.315 T (Shorey *et al.*, 2001). This reveals that the MFD results obtained are in the same range as those obtained previously.



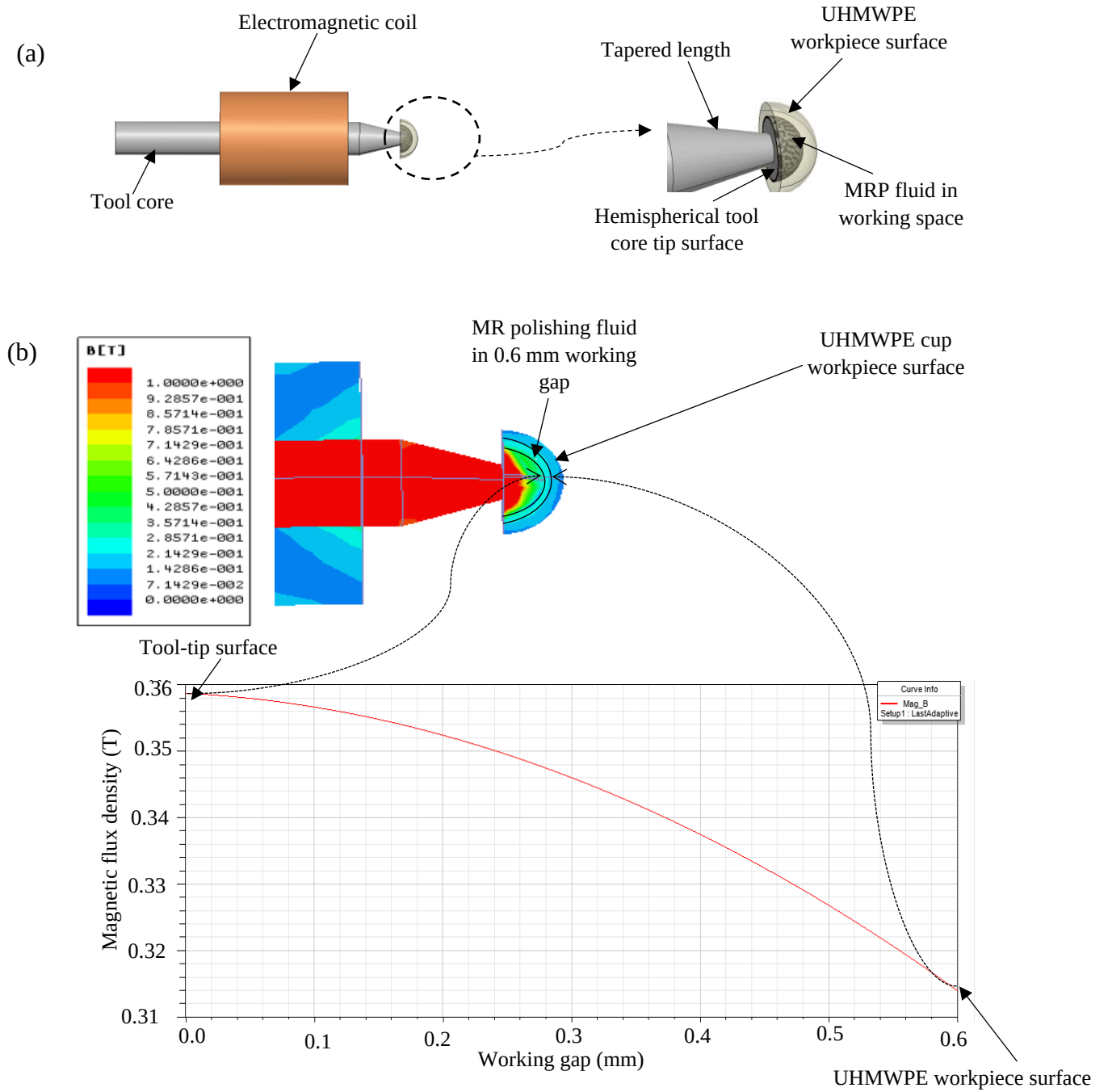


**Fig. 3.2.** (a) CAD model design of the hemispherical core tip-based tool along with the MRP fluid and UHMWPE cup workpiece, and (b) MFEA 2-D plot of the concentration of magnetic flux in the working gap between the hemispherical tool core tip surface and inner surface of the UHMWPE cup workpiece.

This ensures that the electrolytic iron particles (EIPs) of the MRP fluid are attracted and retained on the tool finishing surface and nonmagnetic active abrasives due to the levitation forces move towards the lower concentration of MFD i.e., polymer work part surface. Owing to this, when active abrasives of the MRP fluid with the required shear strength get rotated over the surface asperities of the polymer workpiece surface, it shears the asperities with higher efficacy which further leads to the fine finishing. From the result of the MFEA, it is determined that the present proposed hemispherical tip-based tool can be utilized to finish hemispherical-shaped polymer surfaces. Fig. 3.3 (a) and (b) show the final dimensions of the hemispherical tip-based tool core after several FE analysis attempts for attaining maximum magnetic flux density on its finishing surface (Fig. 3.2 b).

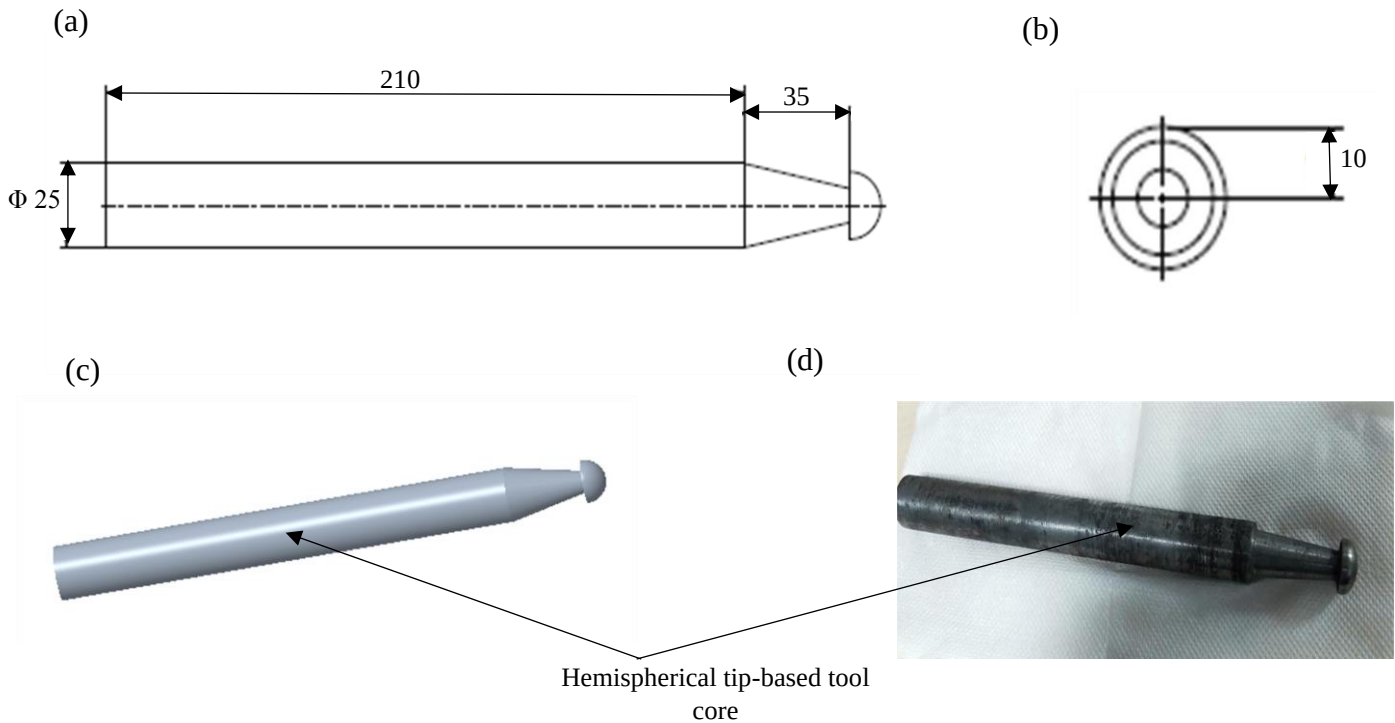


**Fig. 3.3.** 2D drawing of the (a) projected front view, (b) projected side view, (c) 3D CAD model, and (d) fabricated hemispherical tip-based tool core (all dimensions in mm).

Further, the hemispherical tip-based tool is fabricated (Fig.3.3c and d) and the magnetic flux density is measured over the tool surface using the gauss meter as depicted in Fig 3.4 (a) and (b). The results of the experimentally measured flux density are depicted in Fig. 3.4 (c). The results show that the uniform magnetic flux density over the tool surface which reveals the uniform finishing over the workpiece surface.

**Table 3.1** Parameters with their value in MFEA.

| S. No. | Parameters                                     | Value |
|--------|------------------------------------------------|-------|
| 1.     | Relative permeability of the tool core         | 600   |
| 2.     | Relative permeability of the MRP fluid         | 5     |
| 3.     | Relative permeability of the copper coil       | 0.9   |
| 4.     | Relative permeability of the polymer workpiece | 1     |
| 5.     | Current                                        | 2 A   |
| 6.     | Number of turns                                | 2600  |

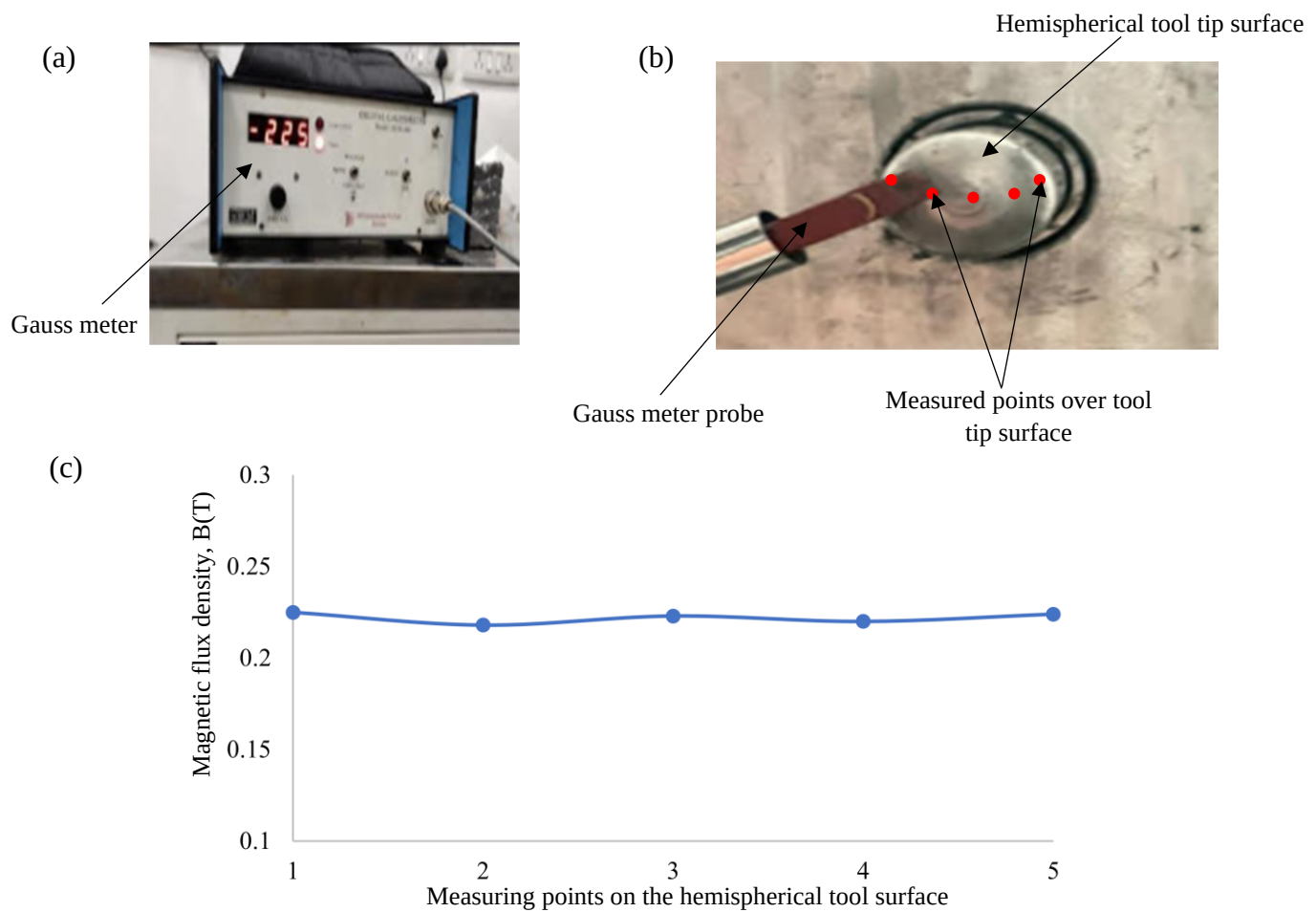


**Fig. 3.4.** Experimentally measured magnetic flux density (MFD) values (a) using a gauss meter, (b) different points over hemispherical tool tip surface where MFD is measured, and (c) value of MFD at different points over hemispherical tool tip surface.

Fig. 3.3 shows a two-dimensional drawing of the projected front view, projected side view, 3D CAD view, and manufactured hemispherical tip-based tool core. After different trials of the FE

analysis for inducing maximum magnetic flux density on the finishing surface of the hemispherical tip-based tool (Fig. 3.2b), the number of turns of copper wire (diameter 0.8 mm) on the electromagnetic coil is obtained as 2600 with the dimensions as shown in Fig. 3.5.

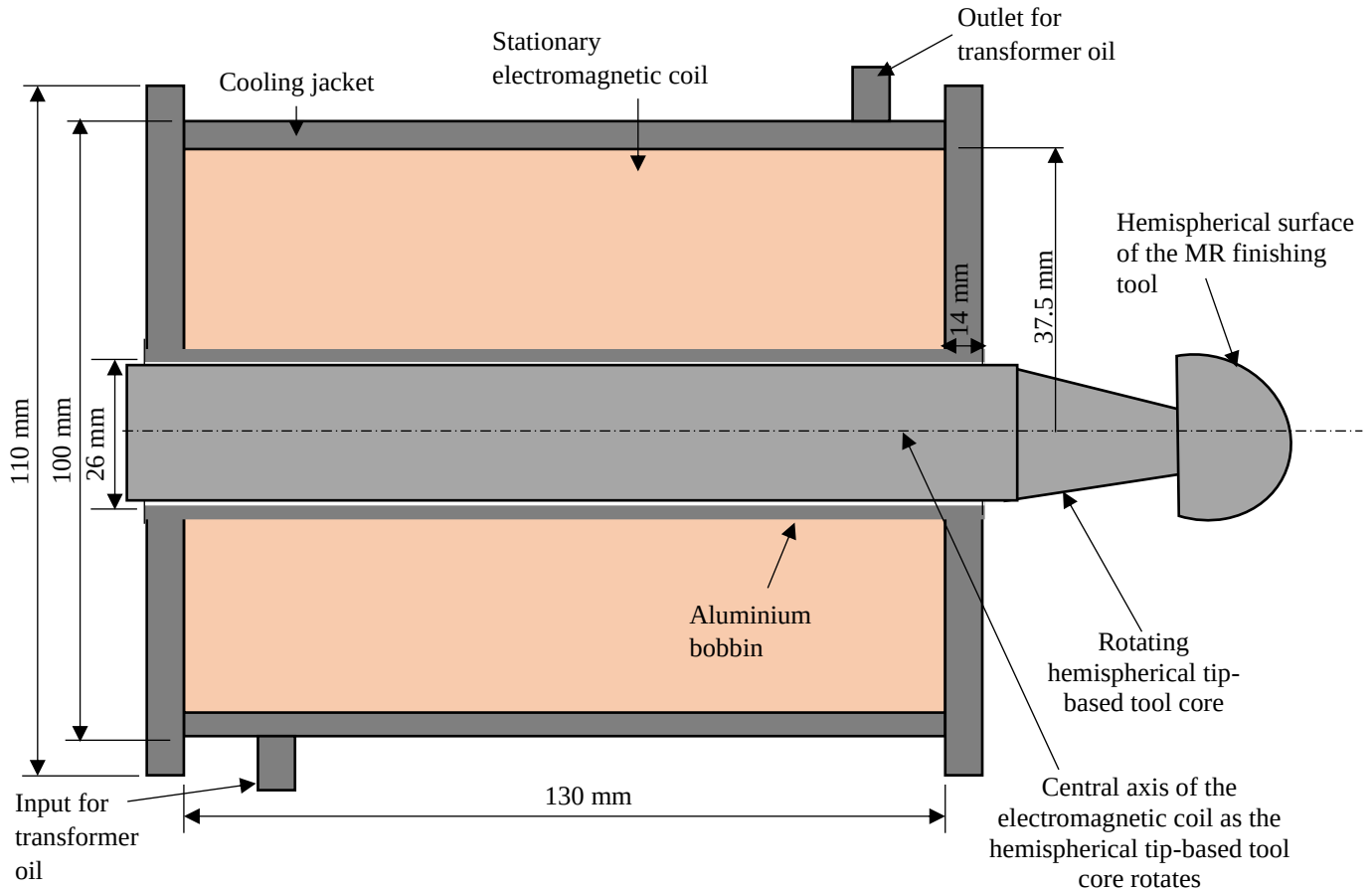


**Fig. 3.5.** Dimensions of the electromagnetic tool coil along with the hemispherical tip-based tool core finishing surface.

The copper coil is used to magnetize the electromagnetic tool which produces a magnetic field due to a direct current supply. The controlling DC power supply provides the DC current. Magnetic flux density at the tool core tip surface is affected by the copper wire size, supply current, radius of the wounded electromagnet coiling, and a number of turns of the copper coiling.

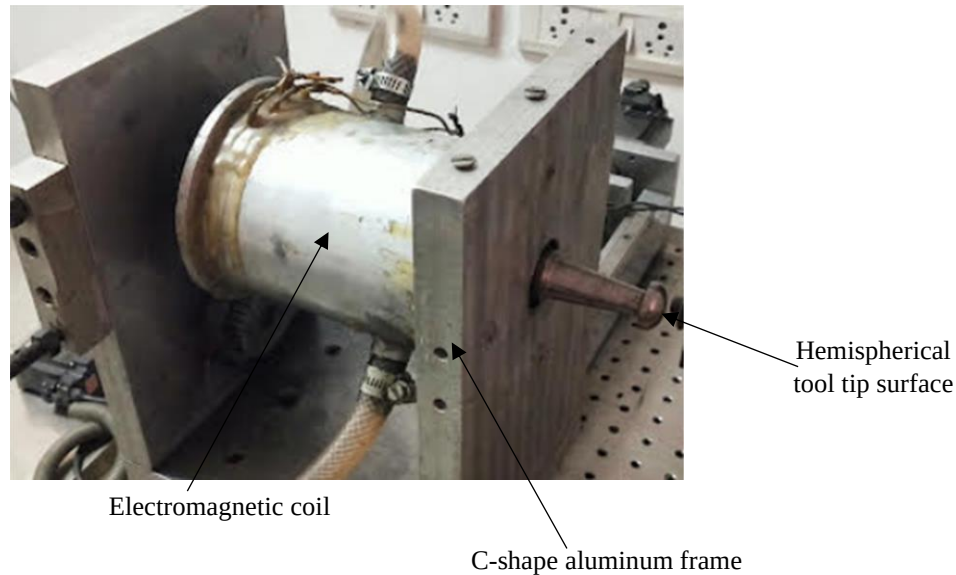


**Fig. 3.6.** Fabricated photograph of the electromagnetic coil with the final design hemispherical tool core tip surface.

Before selecting the electromagnet coil's final parameters, a magnetostatic finite element analysis was used to compare the dependent parameters. The maximum magnetic flux density (MFD) was achieved at the hemispherical tip-based tool core surface using a 20-gauge copper wire (0.8 mm diameter) with 2600 turns at a 2 A current. The electromagnetic tool's bobbin is an internal component. The dimensions of the aluminum bobbin were defined by the tool core and copper coil measurements because the tool core is to be rotated within the bobbin and the copper wire is wrapped over the bobbin. The bobbin's internal diameter is determined by the least gap through which the tool core may rotate, as well as minimal magnetic flux losses. An aluminum cover protects the magnetic coil and acts as a cooling jacket. The aluminum cover's exact dimensions are given in Fig. 3.5. This cover provides cooling jackets for the copper coil winding. The coil warms up due to the constant DC delivery to the magnetic coil during MR finishing. A cooling jacket is installed on the electromagnetic coil to prevent magnetic field loss due to temperature rises. Coolant is provided in the cooling jacket during MR finishing to reduce the temperature of the electromagnetic coil. The copper coil is kept stationary by a C-shaped frame that holds the electromagnetic coil with the cooling jacket. As shown in Fig. 3.6, the final designed electromagnetic coil along with the hemispherical tip-based magnetorheological finishing tool is fabricated. The finishing of the hemispherical-shaped polymer workpieces is done using this hemispherical tip-based magnetorheological finishing tool.

### 3.1.2 Design and fabrication of the electromagnet bevel gear finishing tool

For finishing the polymer bevel gears (BGs), a novel bevel gear finishing tool is designed and fabricated. The tool is designed such that with every tool core rotation, each polymer BG's tooth gets meshed properly with the magnetorheological polishing (MRP) fluid. Due to this, with every tool rotation, the asperities present over each polymer BG tooth surface get clipped off till a fine finish is attained. The material of the polymer BG surface gets abraded owing to the magnetization force of the MRP fluid. The uniform and higher magnetic flux density (MFD) on the finishing tool surface in the working gap contributes to the fine finishing of the polymer BG surface.

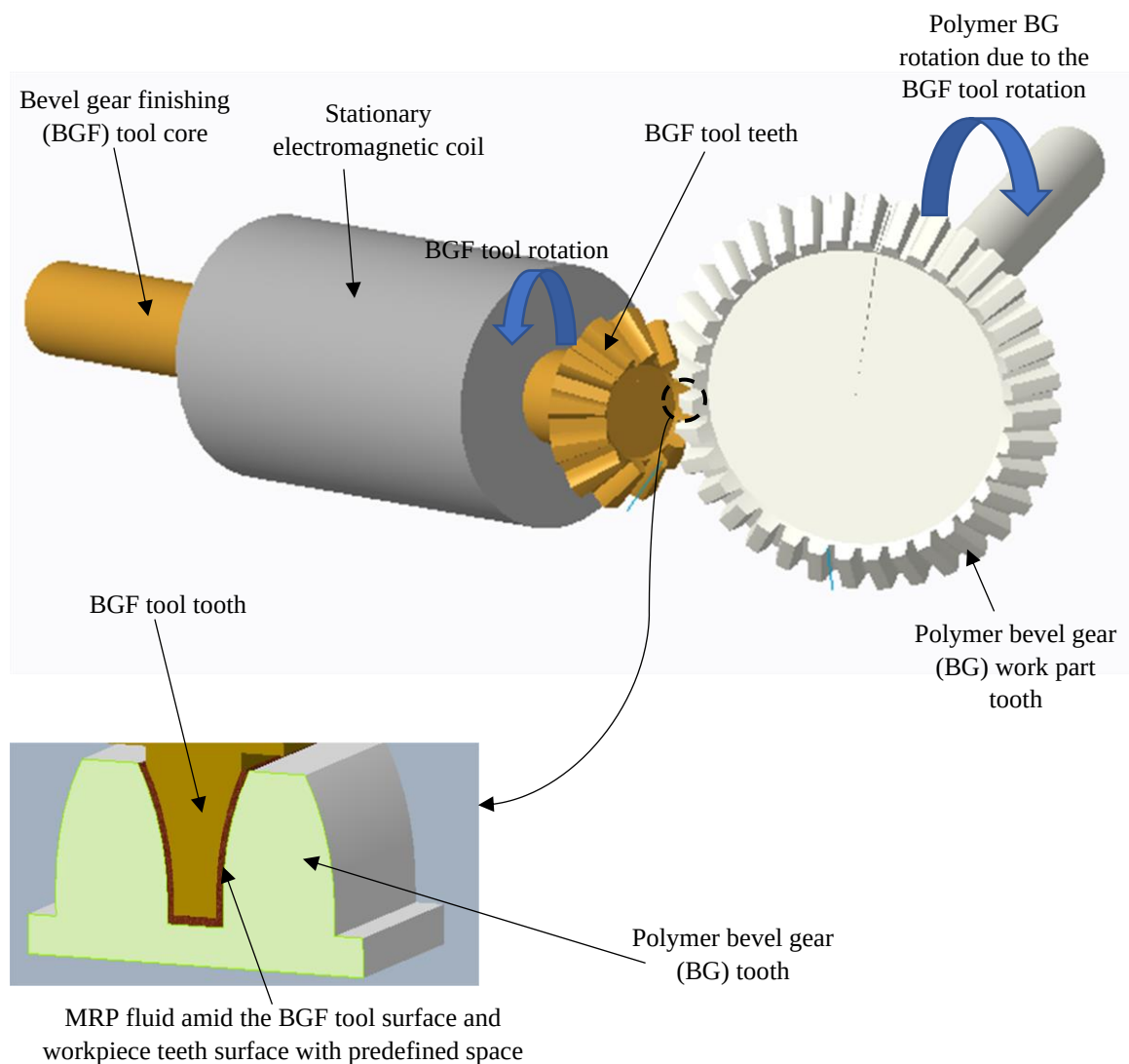


**Fig. 3.7.** CAD model design of the bevel gear finishing tool along with the MRP fluid and polymer bevel gear.

Magnetostatic finite element analysis (MFEA) is used to analyze the efficacy of the presently used magnetic bevel gear finishing (BGF) tool. Further, for studying the MFD of the BGF tool with the electromagnetic coil, the polymer bevel gear (BG), and MRP fluid, initially, 3D modeling is done in PTC Creo 5. The main aim is to provide overall fine finishing of the polymer BG in minimum time, therefore modeling of the present setup is done such that the proper meshing could take place amid the surface of polymer BG tooth and BGF tool tooth with a predefined working gap for the MRP fluid as displayed in Fig. 3.7. Owing to this, with every BGF tool core rotation, the polymer BG rotates. As a result, the asperities get clipped off from each tooth of the gear surface. Hence, the overall finishing time reduces for the polymer BG.

In addition, the IGES 3D model design files are imported into the student version of the Ansoft Maxwell V13 software. Using this software, the analysis of MFD over the novel BGF tool is performed. The MRP fluid present in the 3D model amid the BGF tool teeth surface and polymer BG teeth surface acts as a working gap and its thickness is assigned as 0.6 mm. All the other parameters used are reported in Table 3.1. Next, all the boundaries and materials are assigned within the Ansoft software over a finite space. Further, finite element analysis over the BGF tool is carried out for analyzing the MFD and the result are depicted in Fig. 3.8. From the MFEA, it can be seen that the concentration of MFD is higher on the bevel gear finishing (BGF) tool surface (0.497 T) and lower on the work part surface (0.448 T) as depicted in Fig. 3.8. The magnetic flux is higher on the BGF tool's finishing surfaces and decreases as it approaches the surface of the gear workpiece surface, as seen in the 2D plot of the magnetic flux gradient in Figs. 3.8. The MFD gradient in the working gap (Fig. 3.8) ensures that the electrolytic iron particles (EIPs) of the MRP fluid are attracted and retained on the tip of the novel BGF tool surface and nonmagnetic active abrasives due to the levitation forces move towards the lower concentration of MFD i.e., polymer BG work part surface. Owing to this, when the active abrasives of the MRP fluid with required shear strength get rotated over the surface asperities of the polymer work part, it shears the asperities of the work part surface which further leads to the fine finishing.

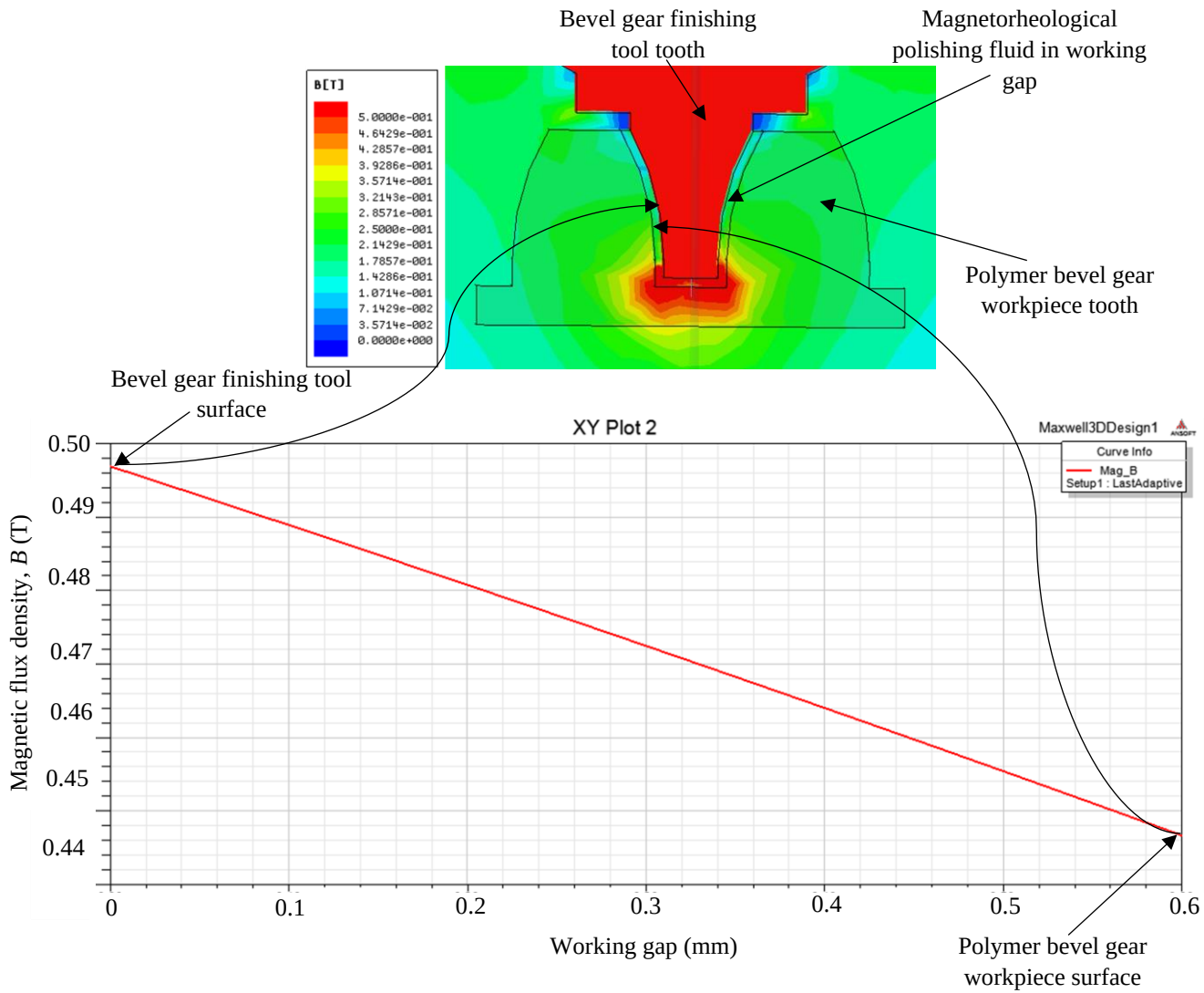


**Fig. 3.8.** Result MFEA and its 2-D plot of the magnetic flux density in the working gap between the bevel gear finishing (BGF) tool teeth surface and polymer bevel gear workpiece teeth surface.

From the result of the MFEA, it is determined that the present BGF tool proposed may be utilized to finish over the polymer BG surface in a minimum time. Further, the bevel gear finishing tool is fabricated and the magnetic flux density (MFD) is measured over the flank surface of the BGF tool using the gauss meter as depicted in Figs. 3.9(a) and (b). The results of the experimentally measured flux density are depicted in Fig. 3.9(c). The results show that the uniform magnetic flux density over the flank surface of the BGF tool reveals the uniform finishing on the overall polymer bevel gear workpiece surface for improved performance.



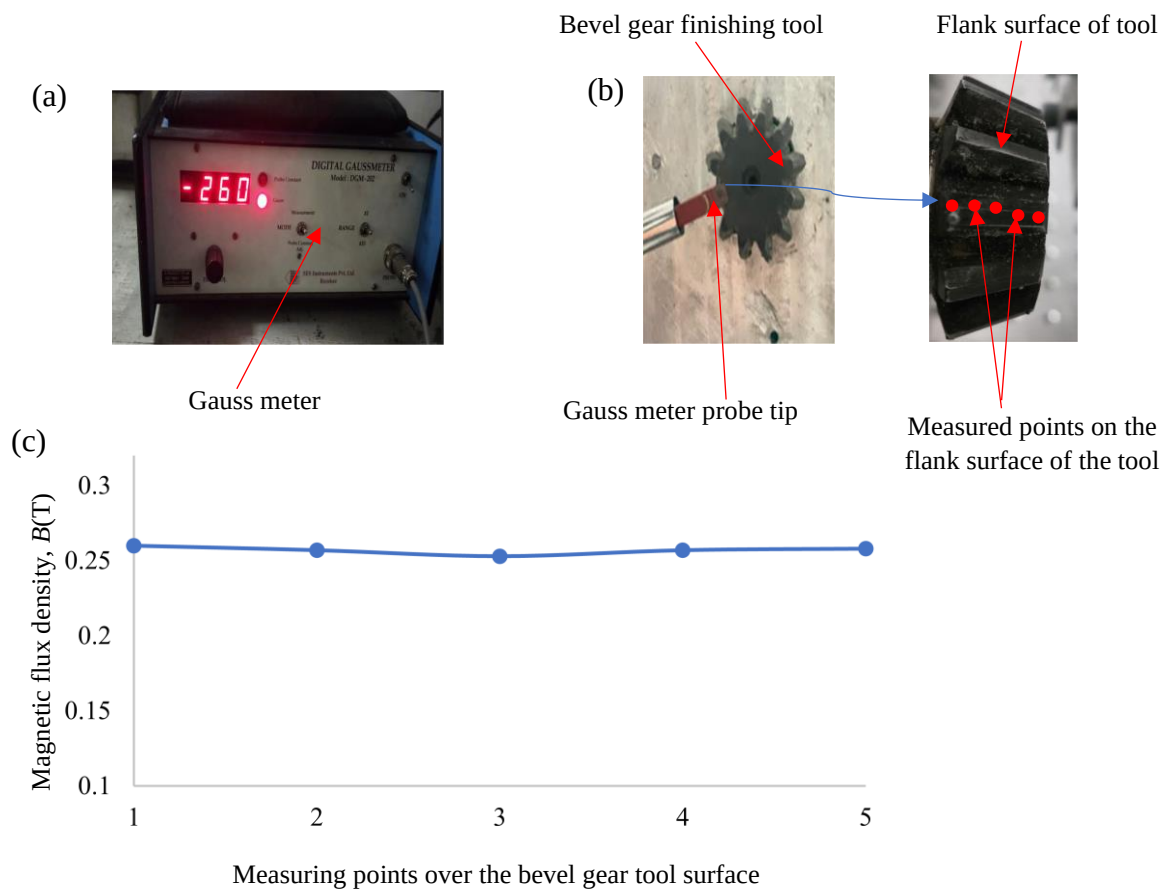


**Fig. 3.9.** Experimentally measured magnetic flux density (MFD) values (a) using a gauss meter, (b) different points over bevel gear finishing tool surface where MFD is measured, and (c) value of MFD at different points over bevel gear finishing tool surface.

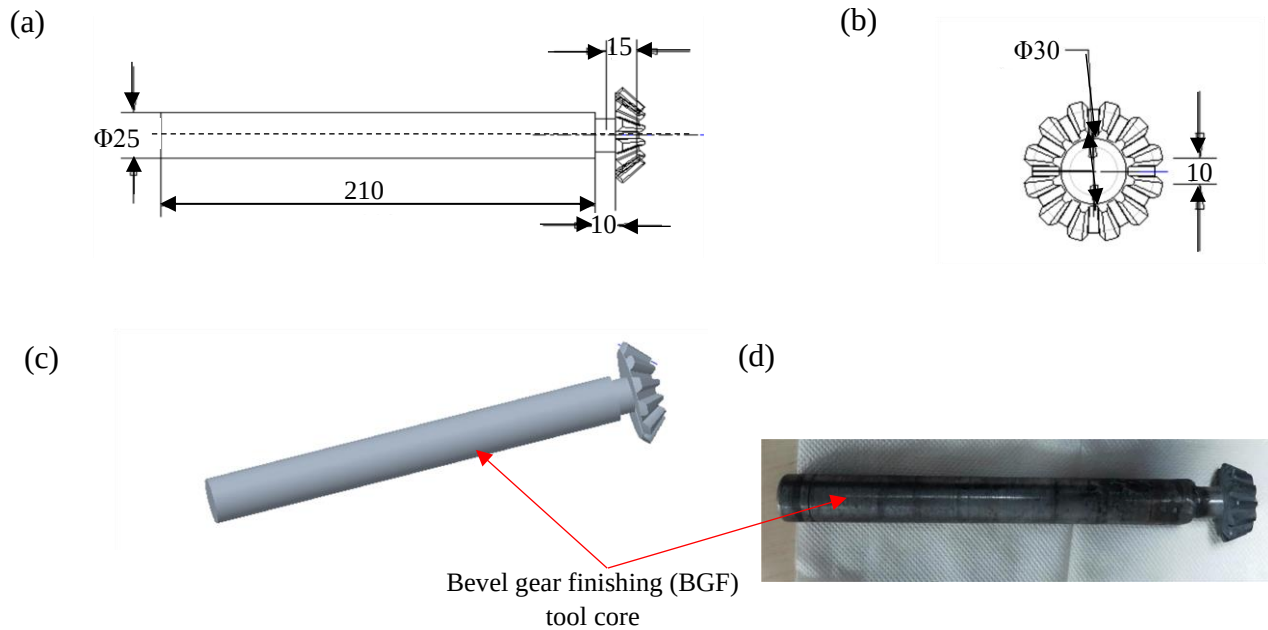


**Fig. 3.10.** 2D drawing of the (a) projected front view, (b) projected side view, (c) 3D CAD model, and (d) fabricated bevel gear tool core (all dimensions in mm).

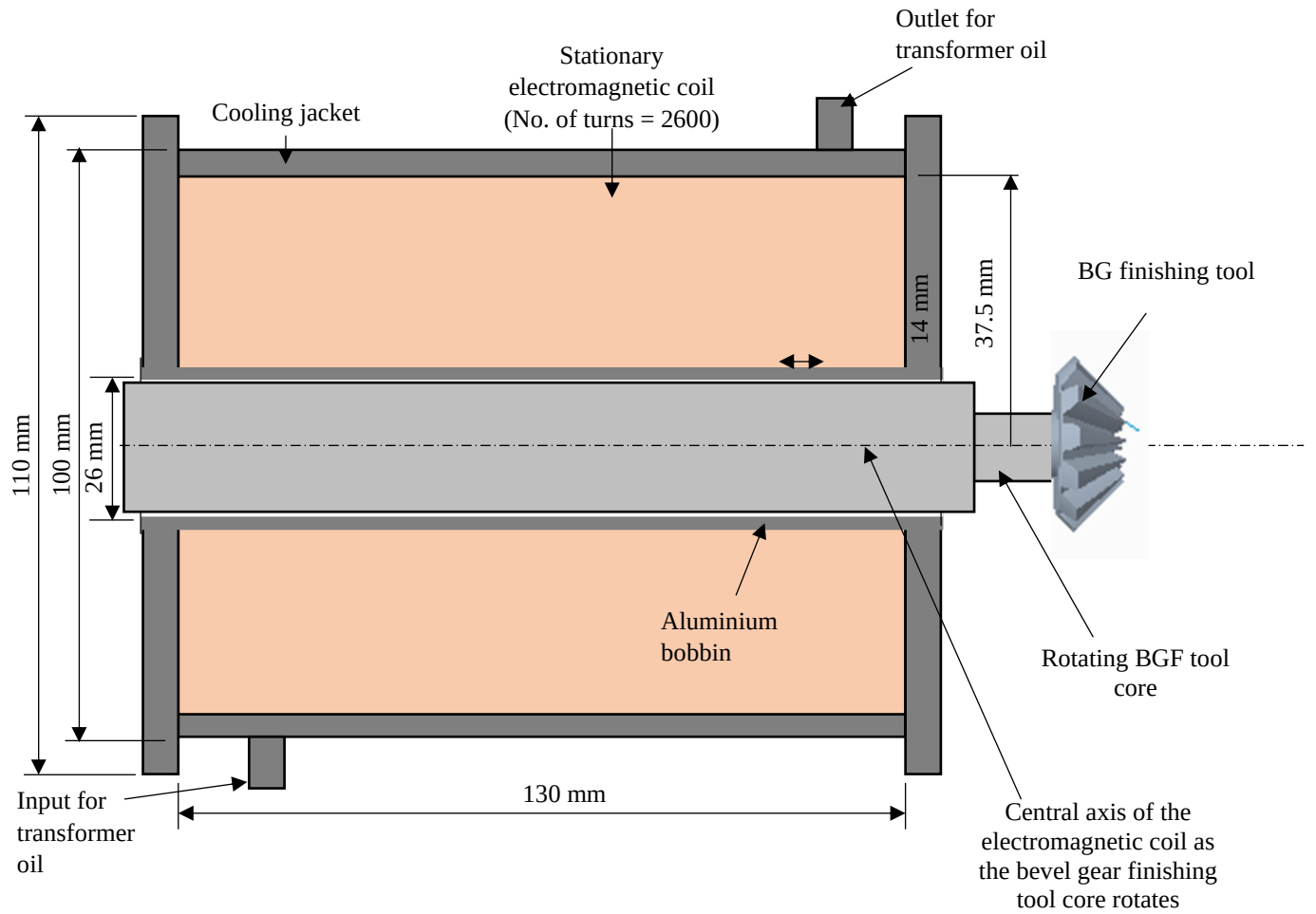


**Fig. 3.11.** Dimensions of the complete assembled electromagnetic bevel gear-designed finishing tool.

Fig. 3.10 depicts the final dimensions of the bevel gear finishing (BGF) tool core attaining maximum magnetic flux density on its finishing surface. Fig. 3.10 shows a two-dimensional drawing of the projected front view, projected side view, 3D CAD view, and manufactured BGF finishing tool core. The dimensions of the complete assembled electromagnetic bevel gear finishing tool are depicted in Fig. 3.11.

### ***3.1.3 Design and fabrication of the electromagnetic hexagonal tip-based finishing tool***

Next, for finishing the various external cylindric and flat surfaces, a novel hexagonal tip-based finishing tool is designed and fabricated. As already discussed, in the MR finishing process, the magnetic normal force over the work part surface controls due to the MRP fluid's magnetization. To achieve a fine finish over the external surface of the cylindrical workpiece, uniform and higher magnetic flux density (MFD) on the tool surface is important. To study the effectiveness of the higher MFD, the same Ansoft Maxwell software is utilized to perform the magnetostatic finite element analysis (MFEA).

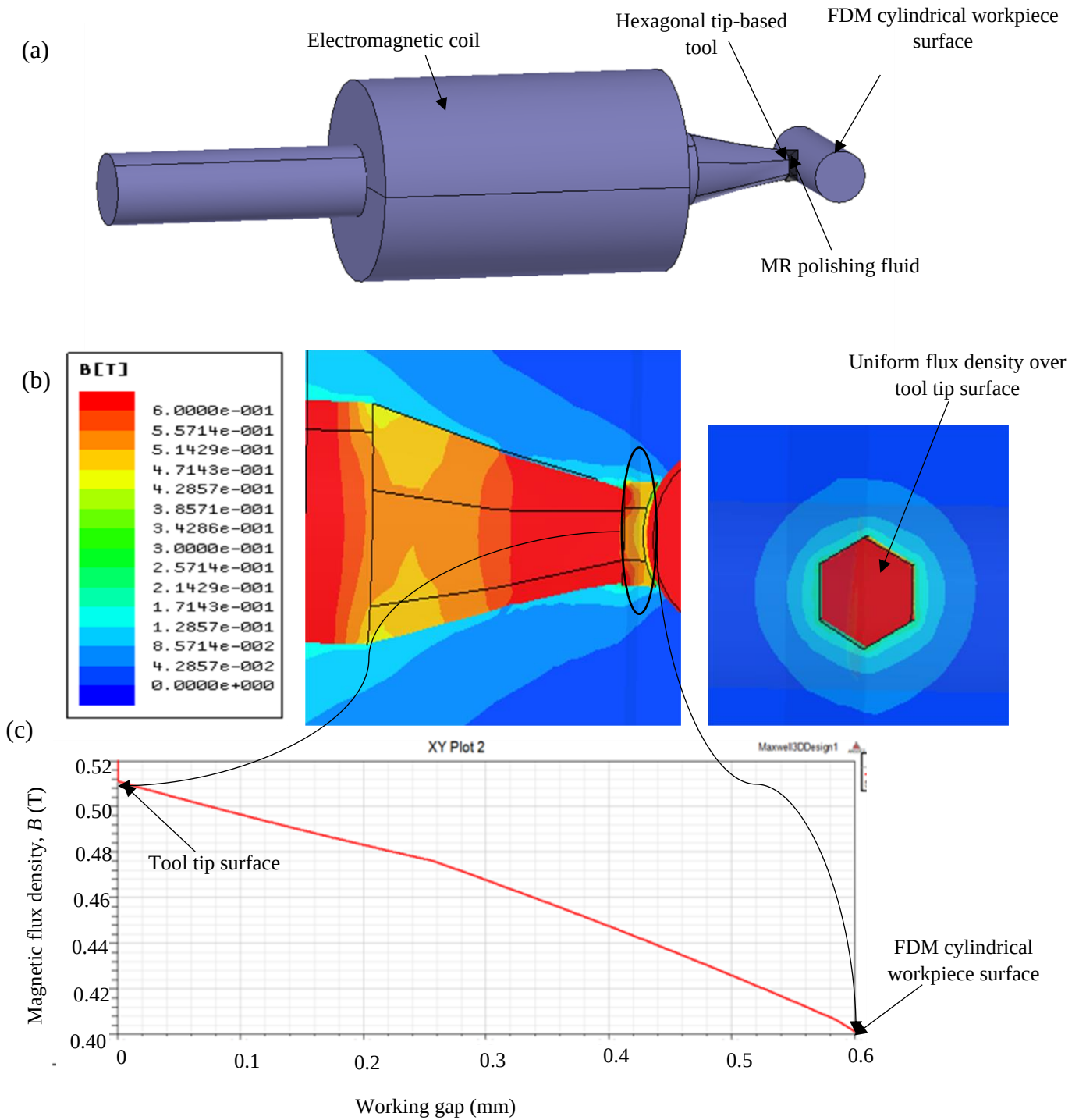


**Fig. 3.12.** (a) CAD model of the hexagonal tip-based tool along with the MRP fluid and cylindrical workpiece, (b) result of MFEA and 2D plot of the concentration of magnetic flux in the working gap between the hexagonal tip-based tool surface and external surface of FDM workpiece, and (c) result of MFEA for magnetic flux density distribution over the hexagonal tip surface.

MFEA is a tool that is used for analyzing MFD in the working region between the tool and the workpiece. Singh and Singh (2019) studied the effect of the MFD on different tool core tip shapes

while finishing the external cylindrical surface. The results show that the edges of the tool-tip tend to produce the edge effect which plays an important role in attaining the uniform MFD over the tool surface. This further helps in the fine finishing over the workpiece surface. The edge effect tends to increase the magnetization which influences the localization of magnetic field lines. This edge effect depends on the geometry of the tool core tip surface (Singh and Singh, 2019). Therefore, to design the tool for attaining the finishing with a more edge effect over the external cylindric workpiece surfaces, trials with several tool-tip shapes were performed using the MFEA, and the hexagonal tool tip surface was found more effective. For the analysis, initially, the electromagnetic finishing tool's CAD model is designed using Creo Parametric 5.0 as depicted in Fig. 3.12(a). The thickness of the MRP fluid between the workpiece and the tool surface in the CAD model is assigned as 0.6 mm. The assigned parameters with their relative permeability are reported in Table 3.1. The MFEA results of the distribution of the MFD is shown in Fig. 3.12 (b). The MFEA results after simulation reveal that the MFD amid the working space varies between 0.515 T - 0.402 T (Fig. 3.12c). From the literature, the MFD value over the tool surface for the finishing of the gallium arsenide (GaAs) wafers was reported as 0.45 T (Nie *et al.*, 2019). This reveals that the MFD results obtained are in the same range as obtained previously. The result reveals higher MFD over tool surface and the lower workpiece surface. In hexagonal-shaped tool core tip surface, the six corner edges increase the localization of the magnetic field lines. As the workpiece's external surface is cylindric, the working space between the hexagonal tool tip surface and the workpiece changes. The strength of the magnetic field decreases with the rise in the working gap and vice versa. Due to the fluctuation in the magnetic field strength, the AAPs cutting edges change their orientation which increases the cross-cutting effect of abrasives and enhances the polishing efficiency of the external cylindrical workpiece. Further, the hexagonal tip-based finishing tool is fabricated and the magnetic flux density is measured over the tool surface using the gauss meter. The results of the experimentally measured flux density are depicted in Fig. 3.13. The results show that the almost uniform magnetic flux density over the tool surface which reveals the uniform finishing over the workpiece surface. Figure 3.14 shows a two-dimensional drawing of the projected front view, projected side view, 3D CAD view, and fabricated hexagonal tip-based tool core. Further, the fabricated hexagonal-based tool core is assembled along with the same electromagnet as shown in Fig. 3.5 and Fig. 3.11.

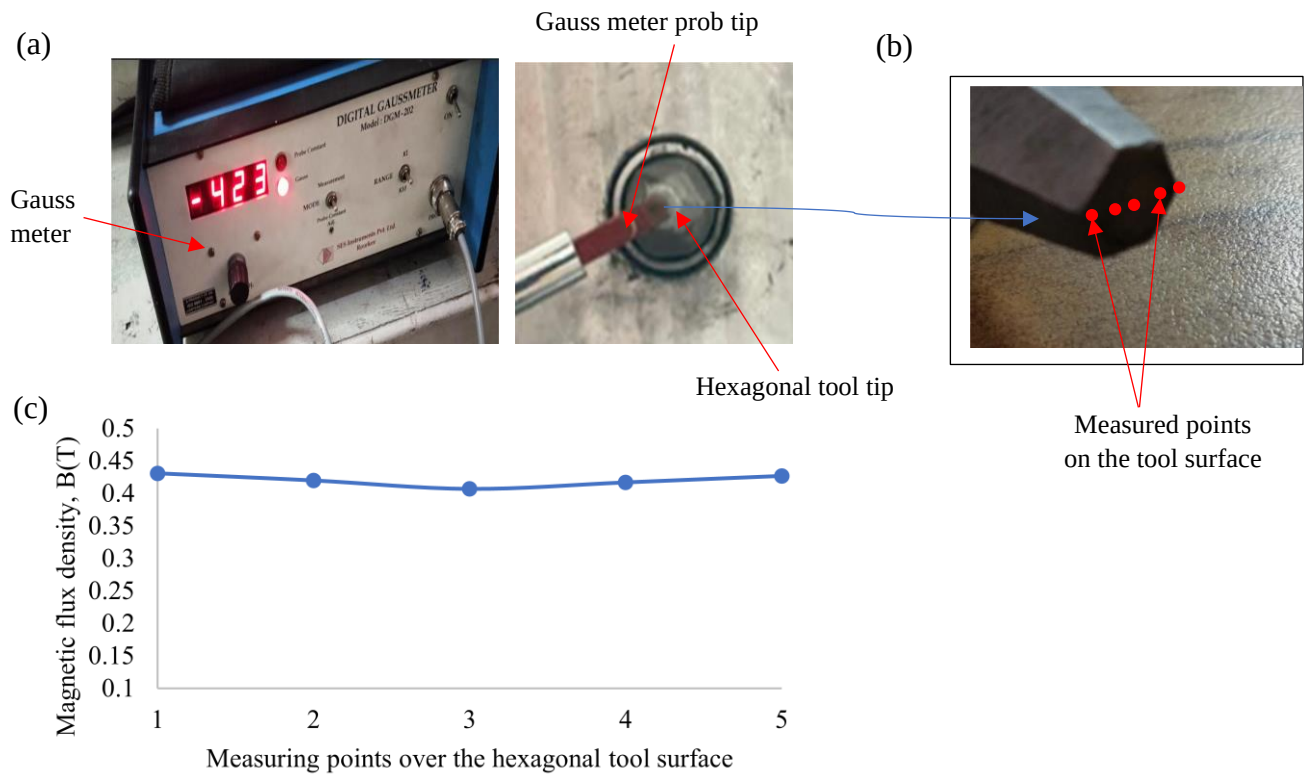


**Fig. 3.13.** Experimentally measured magnetic flux density (MFD) values (a) using a gauss meter, (b) different points over hexagonal tool surface where MFD is measured, and (c) value of MFD at different points over hexagonal tool surface.

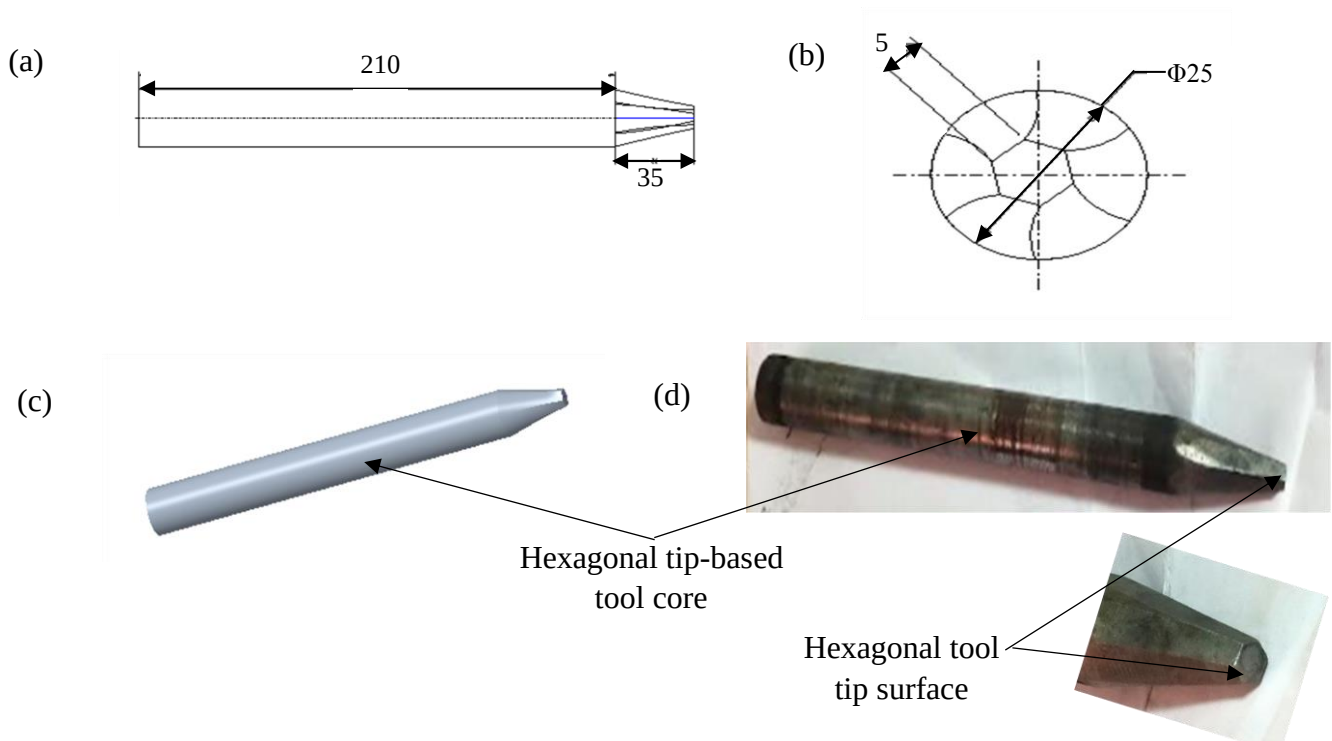


**Fig. 3.14.** 2D drawing of the (a) projected front view, (b) projected side view, (c) 3D CAD model, and (d) fabricated hexagonal tip-based MR finishing tool (all dimensions in mm).

### 3.1.4 Design and fabrication of the permanent magnet based magnetorheological honing tool

The material removal from the internal surface of polymer bearing workpiece is dependent on the magnetic field. In the MR finishing (MRF) process, the higher strength of the magnetic field is the foremost requirement. The higher and uniform magnetic field contributes to the stiffer magnetorheological polishing (MRP) fluid that binds the abrasive particles tightly over the bearing surface. Therefore, for the fine finishing of the polymer bearings (PBs) internal surface, a suitable finishing tool using a permanent magnet has been used in the present work. Initially, magnetostatics finite element analysis (MFEA) is conducted to understand the effectiveness of the present permanent magnet-based magnetorheological honing (MRH) finishing tool. The Ansoft Maxwell software is utilized to analyze the magnetic flux density (MFD) over the MRH tool. The FEA is performed along the magnet tool surface and amid the working space. The present MRH tool is made up of three curved NdFeB magnets which are the source of the magnetic field and each magnet is located at  $120^\circ$  to each other.

**Table 3.2.** Parameters selection for FEA.

| S. No. | Component           | Material        | Relative permeability |
|--------|---------------------|-----------------|-----------------------|
| 1.     | Permanent magnet    | NdFeB           | 1.10                  |
| 2.     | Polishing fluid     | MRP fluid       | 5                     |
| 3.     | Bearing workpiece   | PTFE            | 1                     |
| 4.     | Rotating tool shaft | Stainless steel | 1                     |

The 3D modeling of a permanent magnet tool, MRP fluid, and PTFE bearing using PTC Creo 5.0 is initially performed for the MFEA as shown in Fig. 3.15. Further, the IGES files of modeled design are imported to the Ansoft software. The thickness of the MRP fluid amid the tool and internal bearing surface is assigned as 0.8 mm. The other parameters used during the simulation are reported in Table 3.2. The materials, boundaries, and source conditions are allocated over a finite space. The results of the FEA amid the working space and along the magnet tool surface are depicted in Figs. 3.16. It can be seen from Fig. 3.16 that amid the working space, the MFD higher on the tool surface and lower on the internal PBs surface. This confirms that the iron particles present in the MRP fluid can be retained on the finishing surface of the MRH tool and nonmagnetic abrasives can move towards the work part surface. As a result, the PTFE bearing surface constantly remains rich with abrasives during finishing.

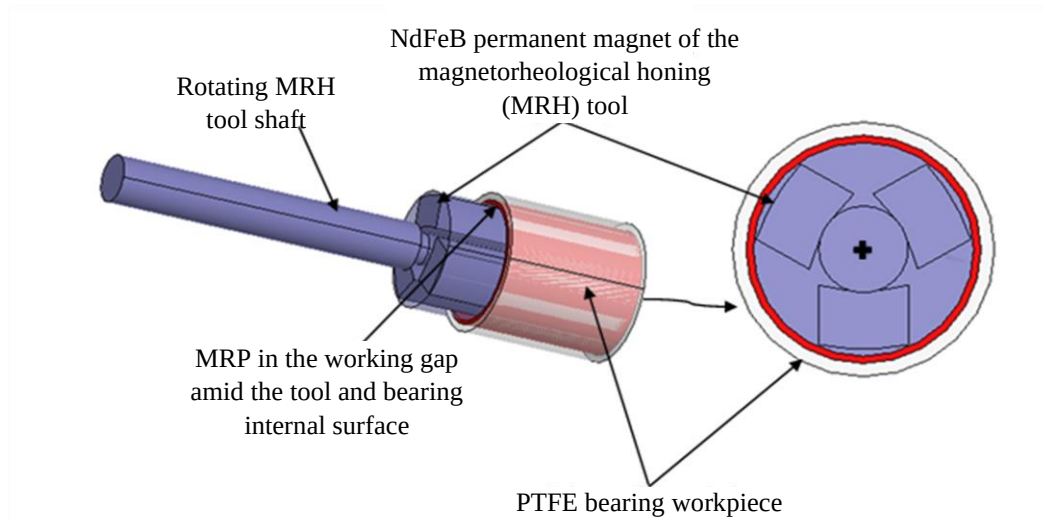


**Fig. 3.15.** 3-D CAD model of the magnetorheological honing tool along with PTFE bearing and MR polishing fluid.

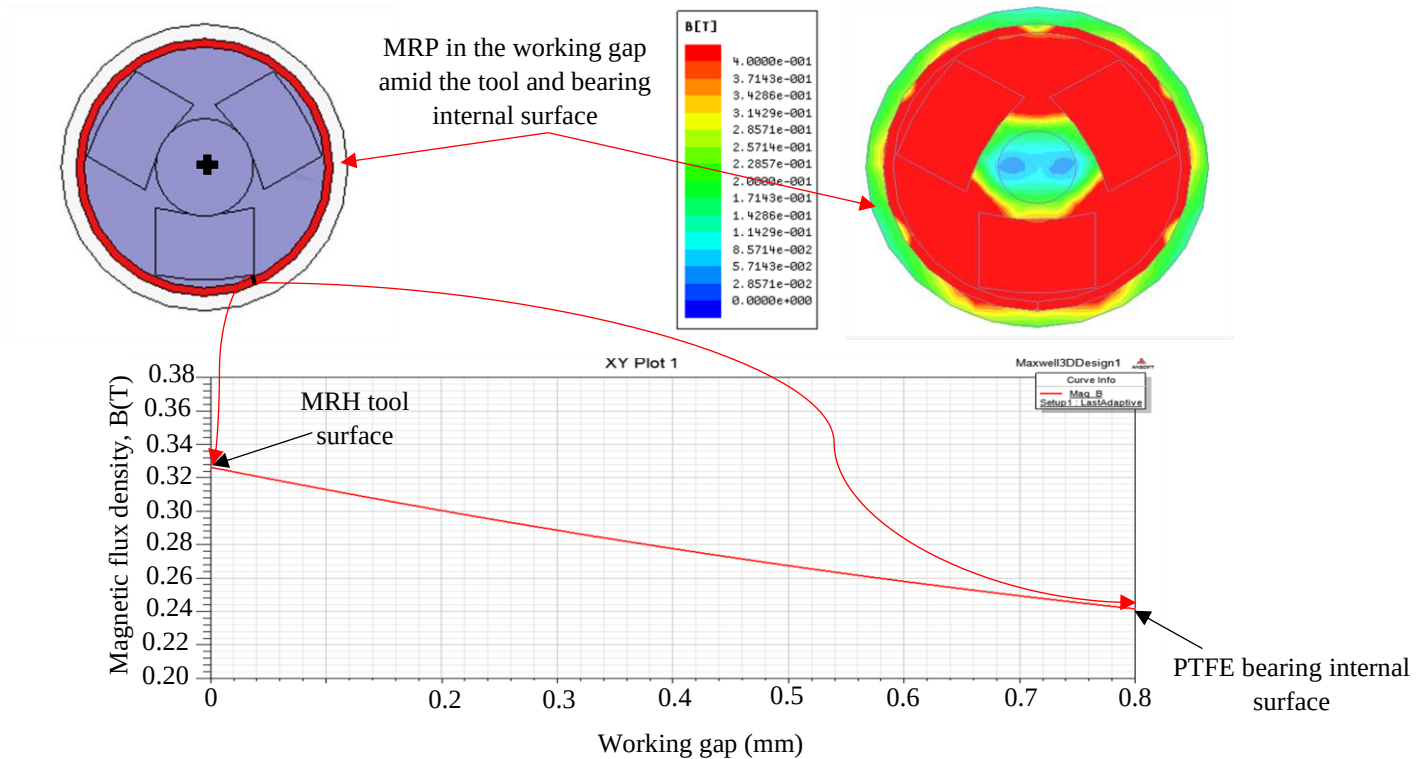


**Fig. 3.16.** Result of the MFEA of the magnetic flux density distribution in the working gap between MRH tool and workpiece surface.

Further, the magnetorheological honing tool is fabricated and the magnetic flux density is measured over the tool surface using the gauss meter. The results of the experimental measured flux density are depicted in Fig. 3.17. The results show that the uniform magnetic flux density over the tool surface which reveals the uniform finishing over the workpiece surface.



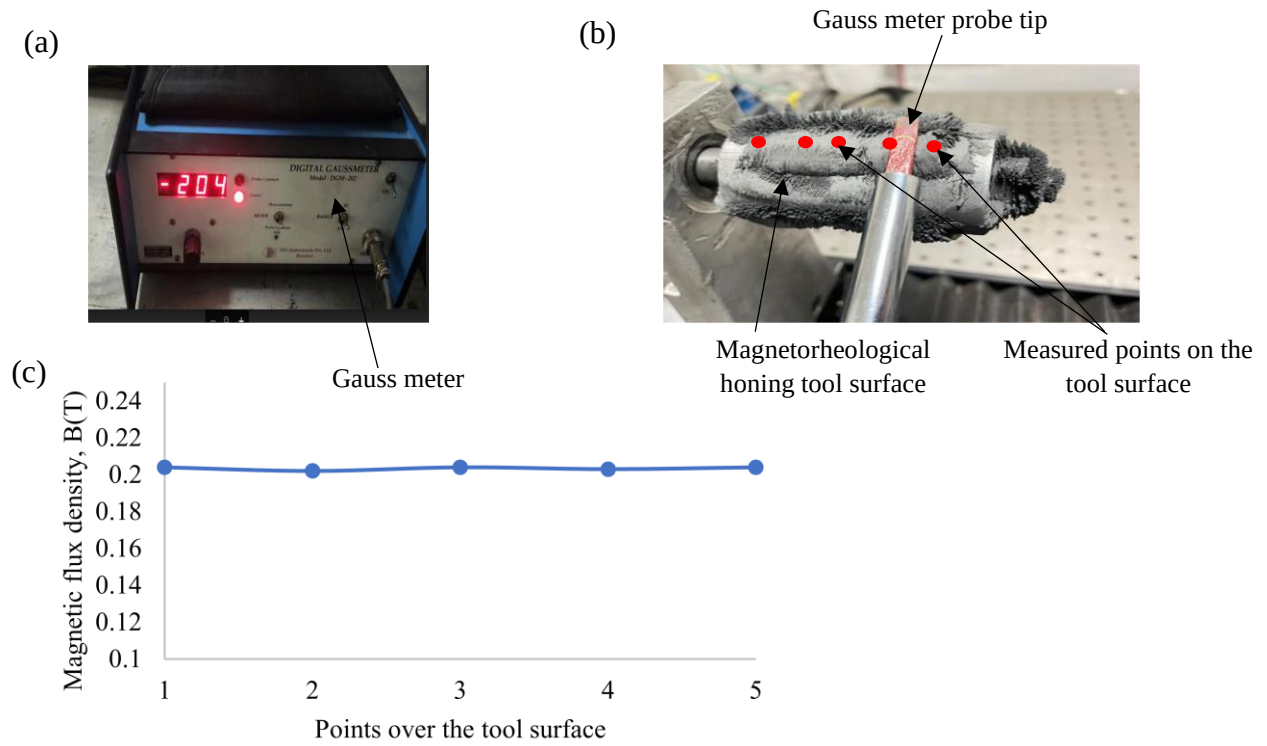


**Fig. 3.17.** Experimentally measured magnetic flux density (MFD) values (a) using a gauss meter, (b) different points over magnetorheological honing (MRH) tool surface where MFD is measured, and (c) value of MFD at different points over MRH tool surface.

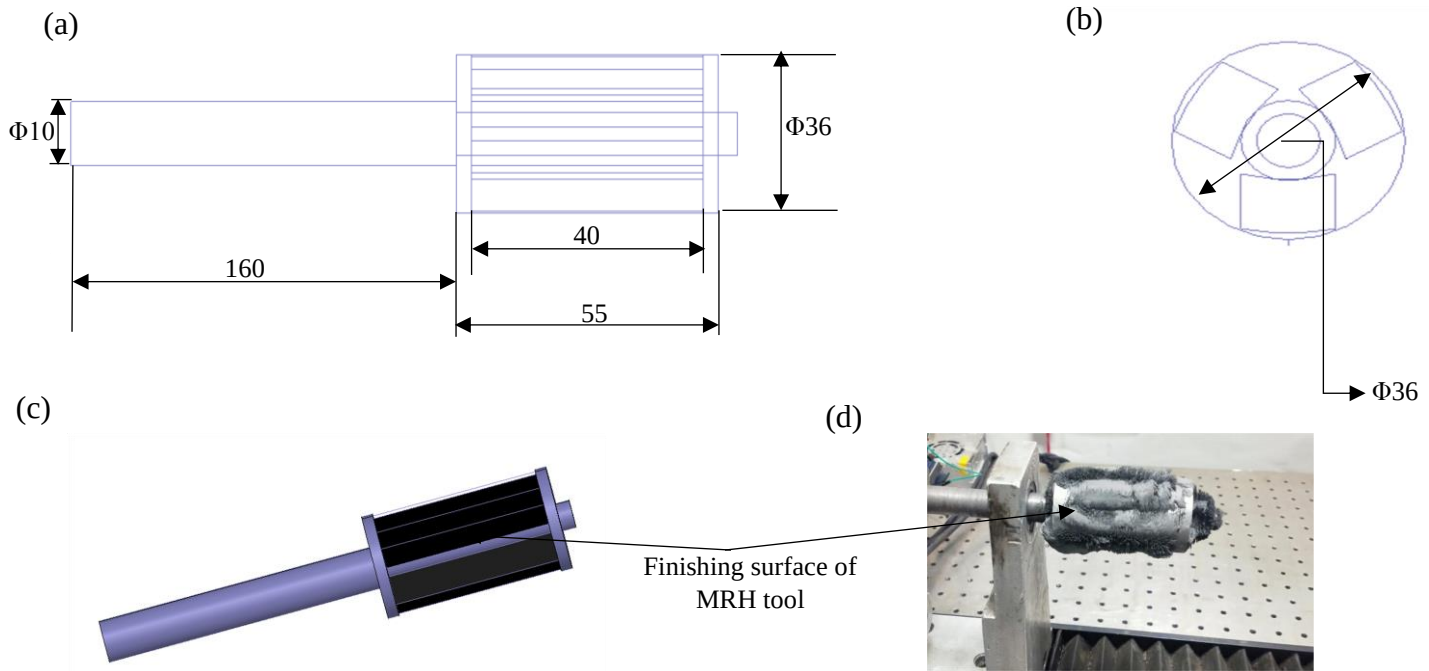


**Fig. 3.18.** 2D drawing of the (a) projected front view, (b) projected side view, (c) 3D CAD model, and (d) fabricated MRH tool (all dimensions in mm).

Figure 3.18 shows a two-dimensional drawing of the projected front view, projected side view, 3D CAD view, and manufactured magnetorheological honing tool.



### 3.2 Design and fabrication of height adjustment fixture for holding the workpiece holder as well as helps in maintaining a uniform working gap

In the present work, a structure is required to maintain a uniform gap between the different polymer workpiece surfaces and the surface of the magnetorheological finishing tool. This is because if the working gap is not uniformly maintained throughout the finishing process, it might lead to the non-uniform finishing over the workpiece surface. So as per the shape of the polymer workpiece to be finished, height adjustment fixtures are designed and fabricated.

#### 3.2.1 L- shape height adjustment fixture

Figure 3.19 depicts the L-shape height adjustment fixture. This fixture comprises of the base plate, end plate, slider, guide rail, and top plate. The L-shape height adjustment fixture is used to adjust the workpiece sample's height up and down as per the requirement with the help of the slider over the guide rail. The parts of the fixture are made of aluminium which makes it light in weight. The workpiece sample is attached to the holes present on the top-plate along with the plummer block using nut and bolt. The plummer blocks are attached vertically over the top plate. Further, the L-shape fixture is fixed on the breadboard by screwing a nut on the base plate. The fixture is made L-shaped so that the proper gap could be maintained amid the tool surface and the workpiece surface while finishing. The uniform gap is necessary for attaining the fine finishing over the different polymer workpieces.

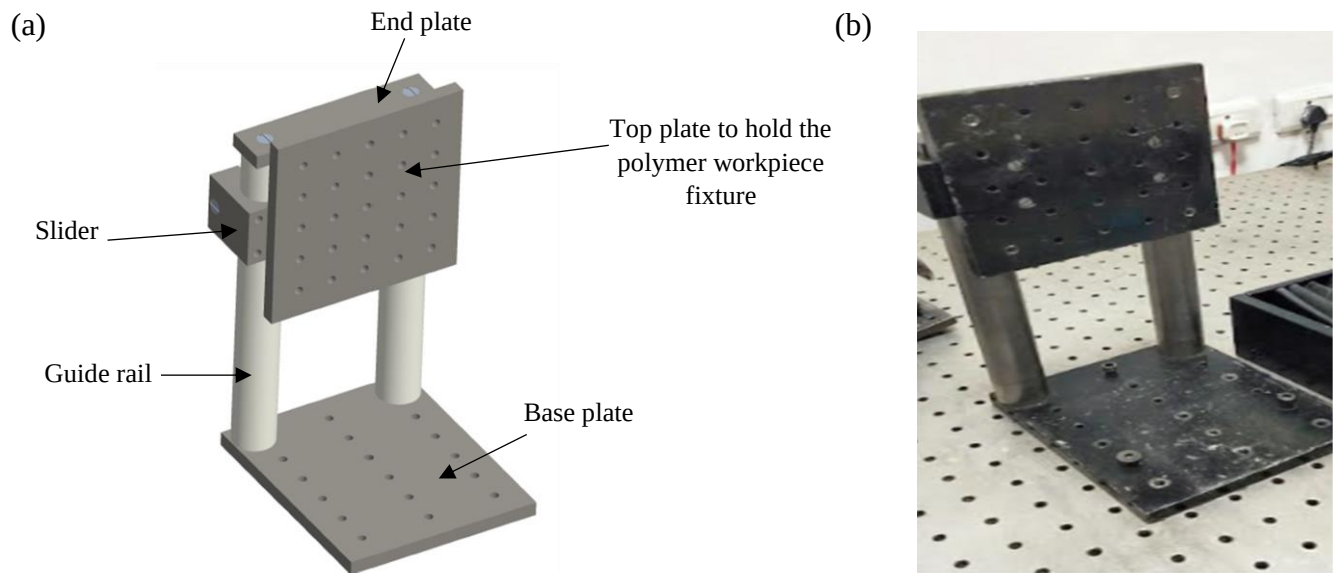


**Fig. 3.19.** (a) 3-D CAD model and (b) fabricated L-shape height adjustment fixture.

### 3.2.1.1 Base plate of the height adjustment fixture

The base plate is used for fixing the height adjustment system to the bread board. The base plate is made of aluminium which makes the height adjustment system lighter. The dimensions of the base plate can be observed from the front view, side view, and top view in Fig. 3.20(a-c). Figure 3.20(d) shows the base plate in a 3-D CAD model. The base plate's thickness is set at 10 mm. The thickness is taken as 10 mm so that nut is properly screwed with the bread board. The height adjustment fixture is fixed over the bread board of experimental setup using an array of M6 holes.

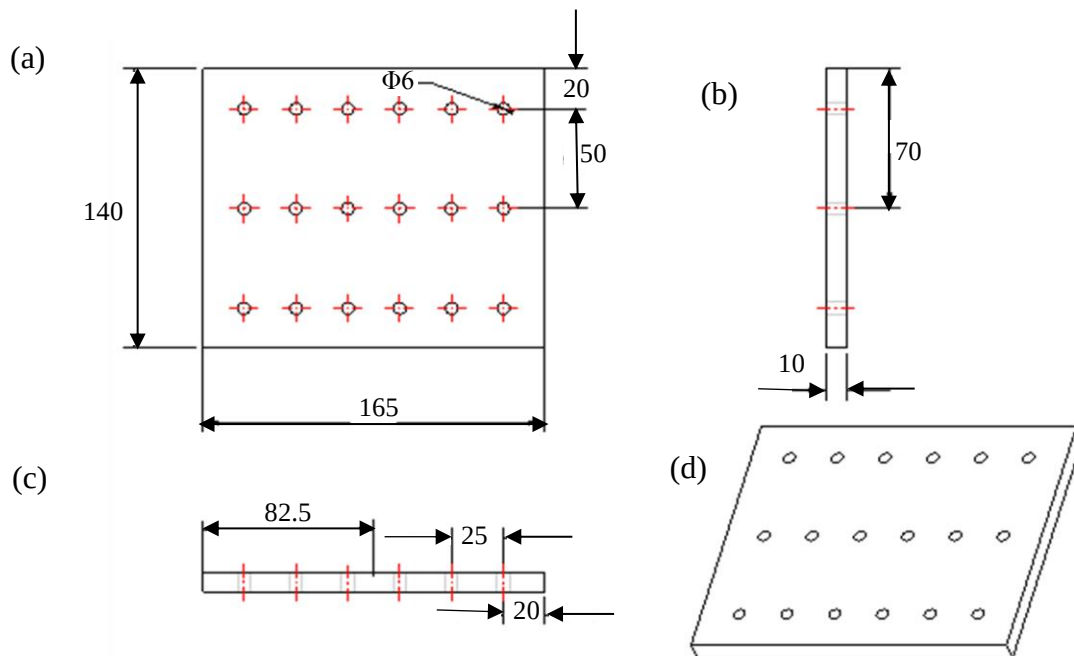


**Fig. 3.20.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the base plate to mount the height adjustment system (all dimensions in mm).

### 3.2.1.2 Slider of the height adjustment fixture

The height adjustment system's slider aids in adjusting the height of the workpiece to the tool as per the shape. The nut and bolt, as well as the washer purchased from the market, are utilized to secure the slider in a specific height of the workpiece. To minimize the weight of the height adjustment mechanism, the slider is manufactured of aluminum. The dimensions of the slider can be seen in Fig. 3.21(a-c) from the front, side, and top views. Figure 3.21(d) shows the slider in a 3-D CAD model. Each guiding rail is controlled by a slider.

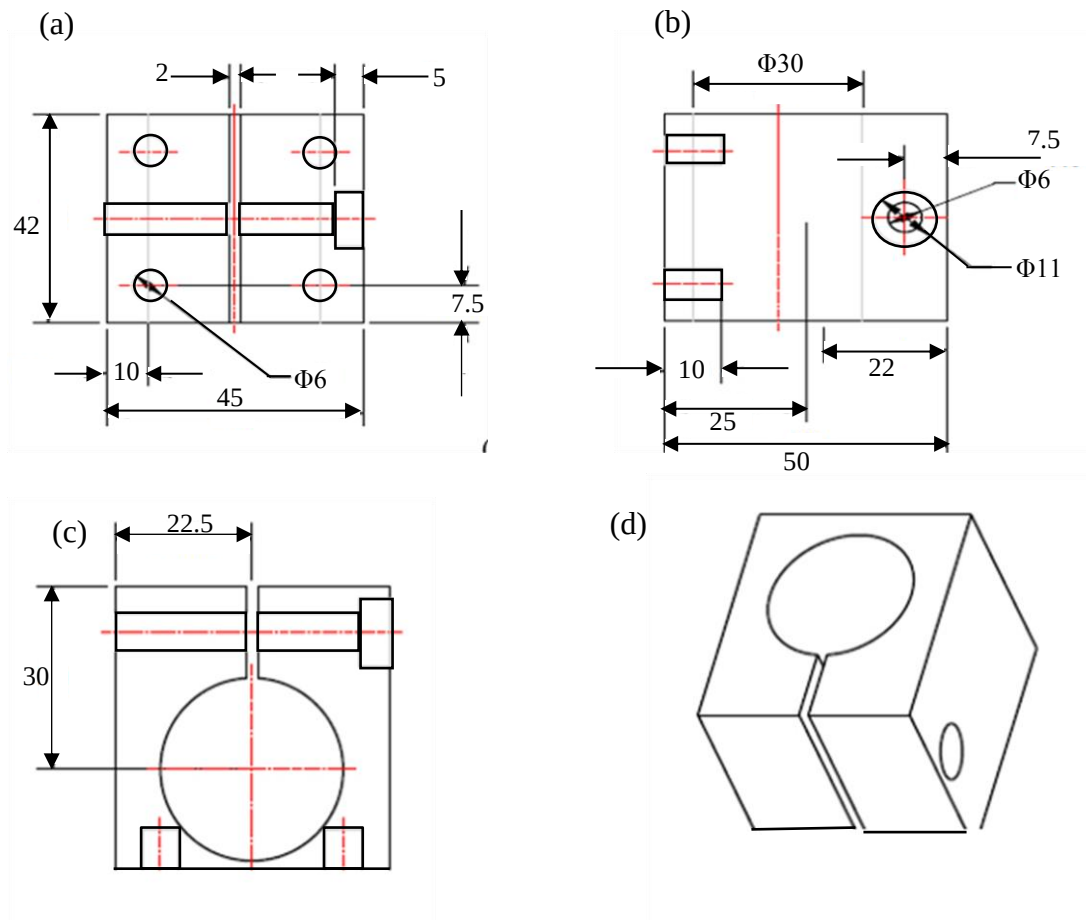


**Fig. 3.21.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the slider for the height adjustment system (all dimensions in mm).

### 3.2.1.3 Guide rail of the height adjustment fixture

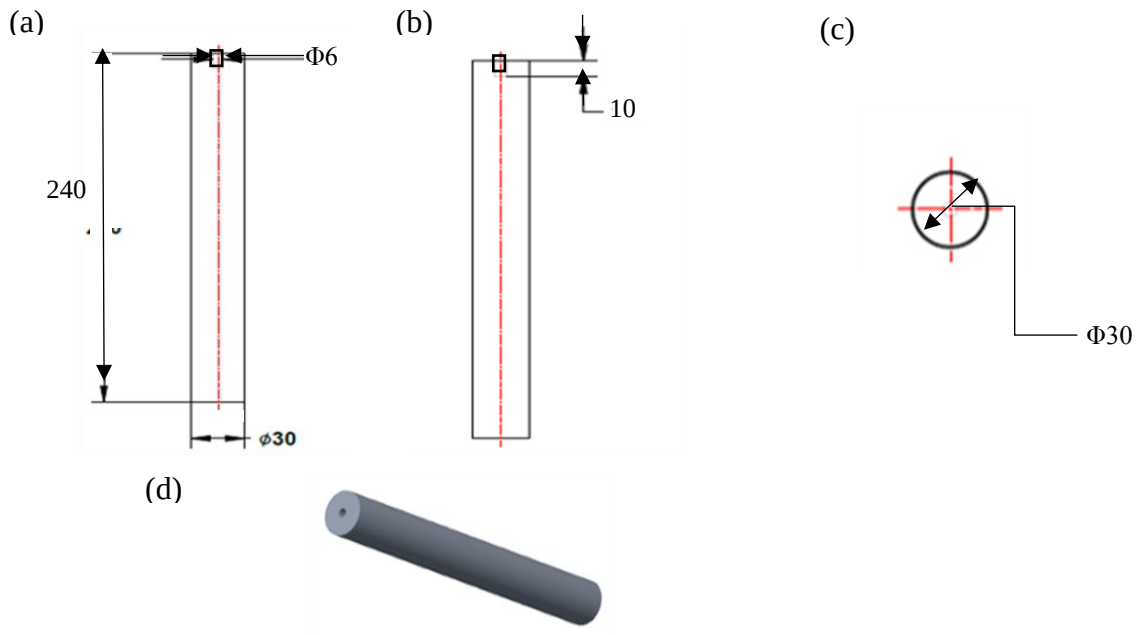


**Fig. 3.22.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the guide rail for the height adjustment system (all dimensions in mm).

The height adjustment system's guide rails allow the top system to move along these guides while providing support. The dimensions of the guide rail can be seen in Figs. 3.22(a,b,c) from the front, side, and top views respectively. Figure 3.22(d) shows the guide rail in a 3-D CAD model. The bottom plate is supported by two guide rails, one on each side. Steel guides with a smooth surface and corrosion-resistant characteristics make up the guides. These guides are made with the 240 mm in length which is long enough to adjust a uniform gap between the magnetorheological finishing tool surface and the different polymer workpiece surfaces at any position in the given height range.

#### 3.2.1.4. Top plate of the height adjustment system

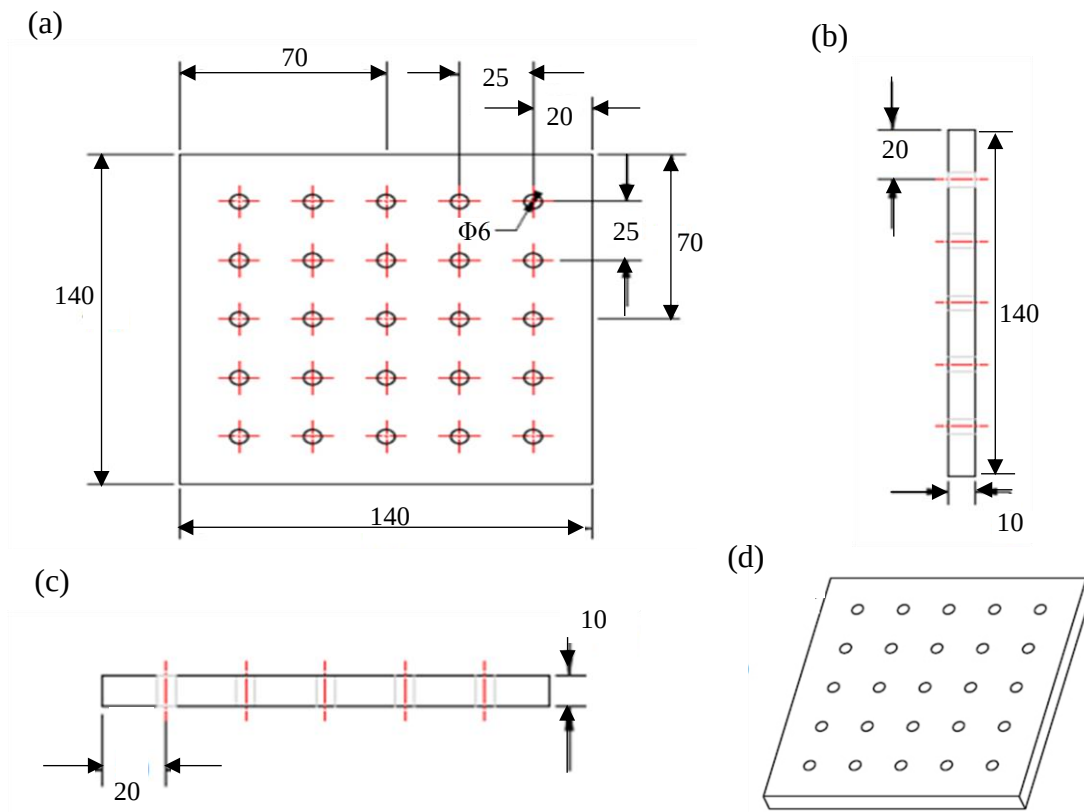


**Fig. 3.23.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the top plate for the height adjustment system (all dimensions in mm).

The top plate used in the height adjustment system helps to hold the plunger blocks using the M6 Allen bolt. The dimension of the top plate is selected in such a way that the plunger block can be properly tighten over the plate. The thickness of the top plate is also kept as 10 mm. The material used for making the top plate is aluminum. The dimensions of the top plate can be observed from

the front view, side view, and top view in Fig. 3.23(a–c). The 3-D CAD model of the top plate can be observed in Fig. 3.23(d). The top plate is also fixed to the slider table using the bolt. This plate holds the rotating polymer workpiece in its position while the finishing process is performed.

### 3.2.1.5. End plate of the height adjustment fixture

The height adjustment system's end plate serves to limit the slide table's motion up to the guide rail's maximum height. Aluminium is the material used to create the end plate. The dimensions of the end plate can be seen in Fig. 3.24(a–c) from the front, side, and top views. Figure 3.24(d) shows the end plate in a 3-D CAD model.

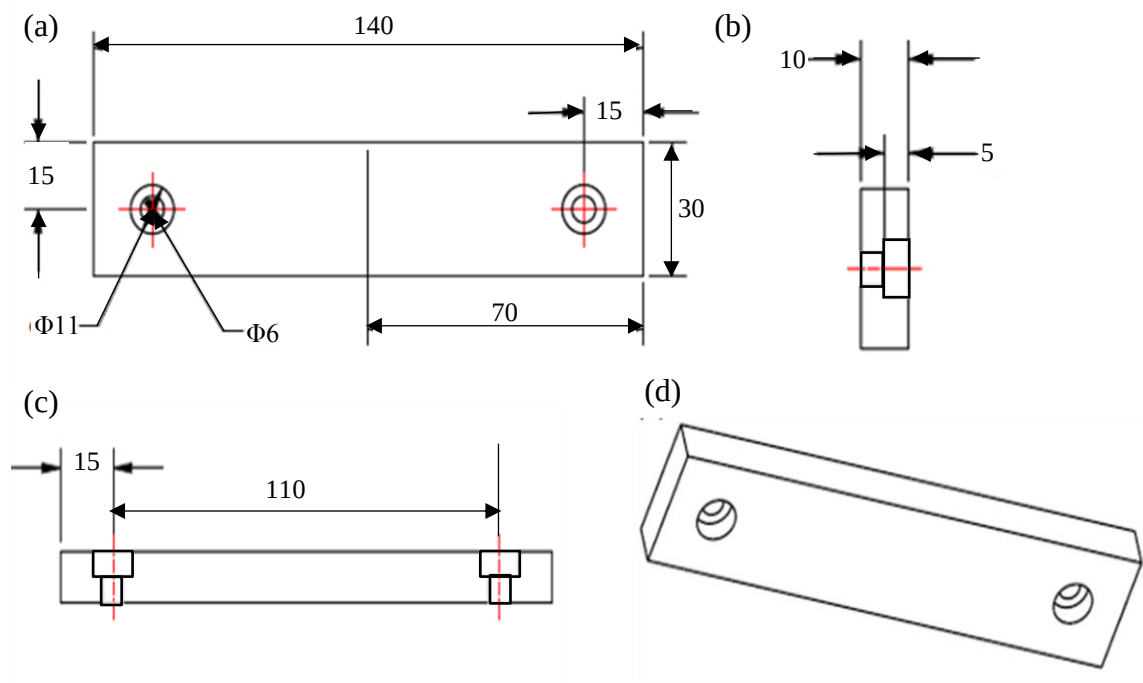


**Fig. 3.24.** (a) Projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the end plate of the height adjustment system (all dimensions in mm).

### 3.2.2 Block shape height adjustment fixture

Figure 3.25 (a) and (b) depict the 3-D CAD model and fabricated block shape height adjustment fixture, respectively. This fixture comprises the base plate, top plate, holding plate. The present fixture was made so that rigidity can be maintained at higher speeds. The block shape height adjustment fixture is used to adjust the workpiece sample up and down as per the requirement with the help of the holding plate, plummer block, nut, and bolts. The plummer block is attached horizontally to the top plate. Most of the parts of the fixture are made of mild steel which makes it

rigid. The block-shape fixture is mostly used when the workpiece is rotated at a higher speed. The plummer blocks are tightened on the top plate using the M6 bolts and the workpiece sample is attached using workpiece holders. Further, the fixture is fixed on the breadboard by screwing a nut on the base plate.

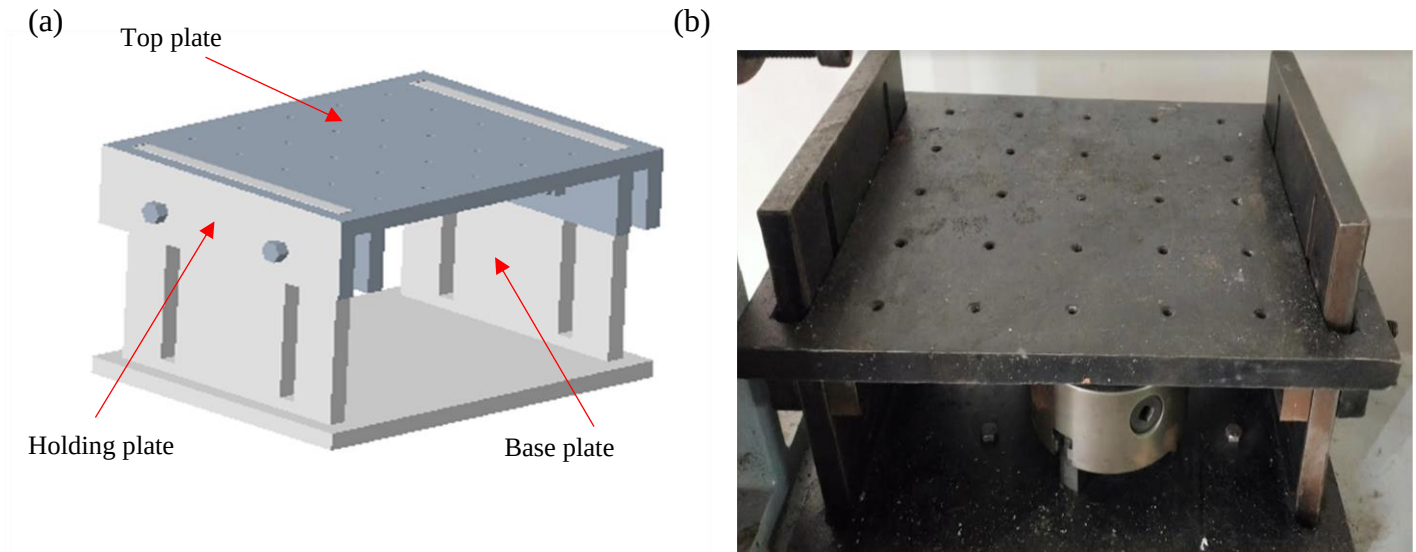


**Fig. 3.25.** (a) 3-D CAD model and (b) fabricated block shape of the height adjustment fixture.

#### *3.2.2.1 Top plate of the block height adjustment system*

The top plate used in the height adjustment system helps to hold the plummer blocks using the M6 Allen bolt. The material used for making the top plate is steel. The dimensions of the top plate can be observed from the front view, side view, and top view in Fig. 3.26(a–c). The 3-D CAD model of the top plate can be observed from Fig. 3.26(d). The thickness of the top plate is 15 mm. This helps in proper tightening of the workpiece on the top plate. The top plate is also fixed to the slider table using the bolt. This plate holds the workpiece holder on its position with the help of the plummer blocks while the finishing process is performed.

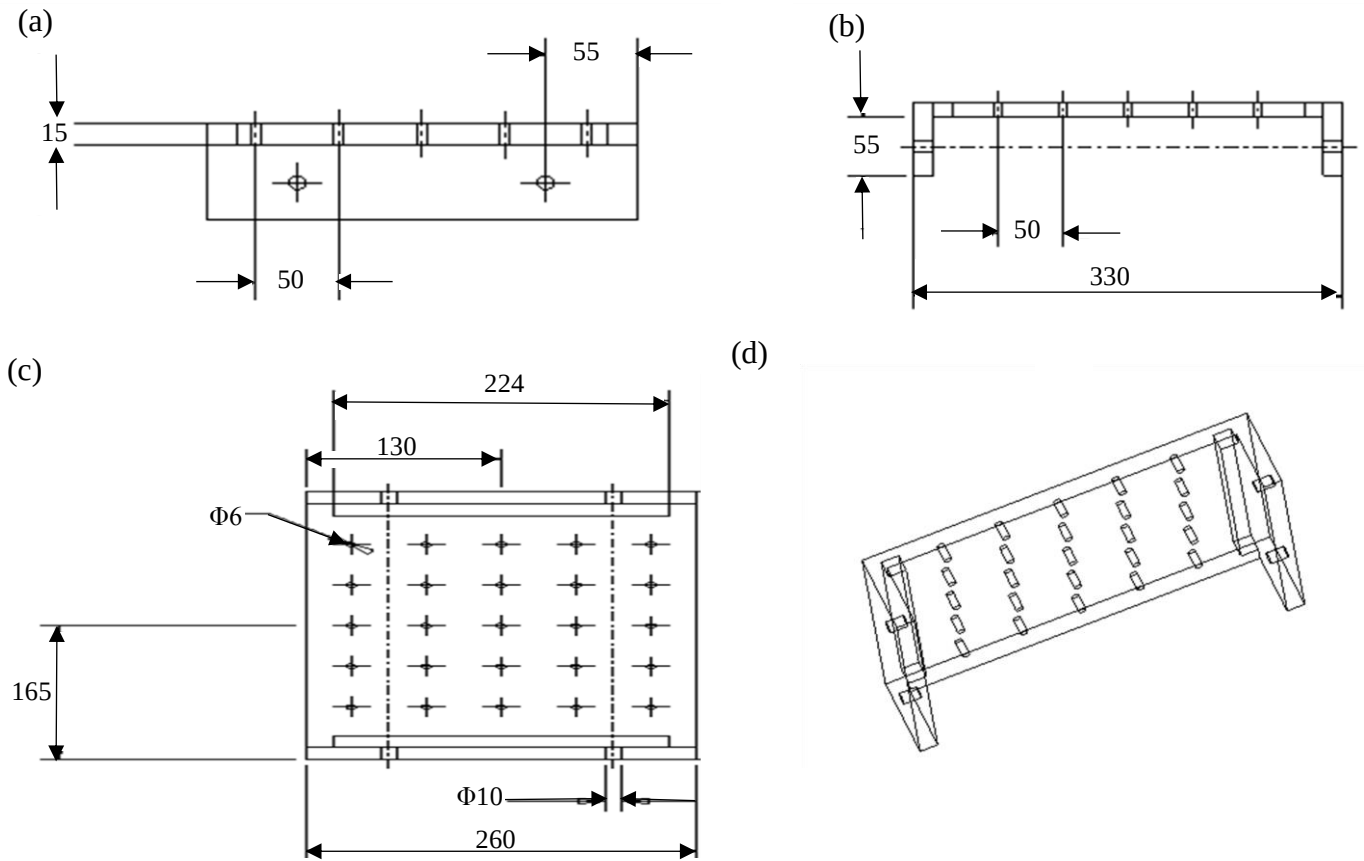


**Fig. 3.26.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the top plate for the block shape height adjustment system (all dimensions in mm).

#### 3.2.2.2 Bottom plate of the block shape height adjustment system

The bottom plate is used for fixing the height adjustment system to the rest of the system. The bottom plate is made of mild steel which is used for making height adjustment fixture rigid. The dimensions of the base plate can be observed from the front view, side view, and top view in Fig. 3.27(a–c). Figure 3.27(d) shows the base plate in a 3-D CAD model. The bottom plate's thickness is set at 15 mm. the bottom plate is screwed to the bread board using the M6 bolts.

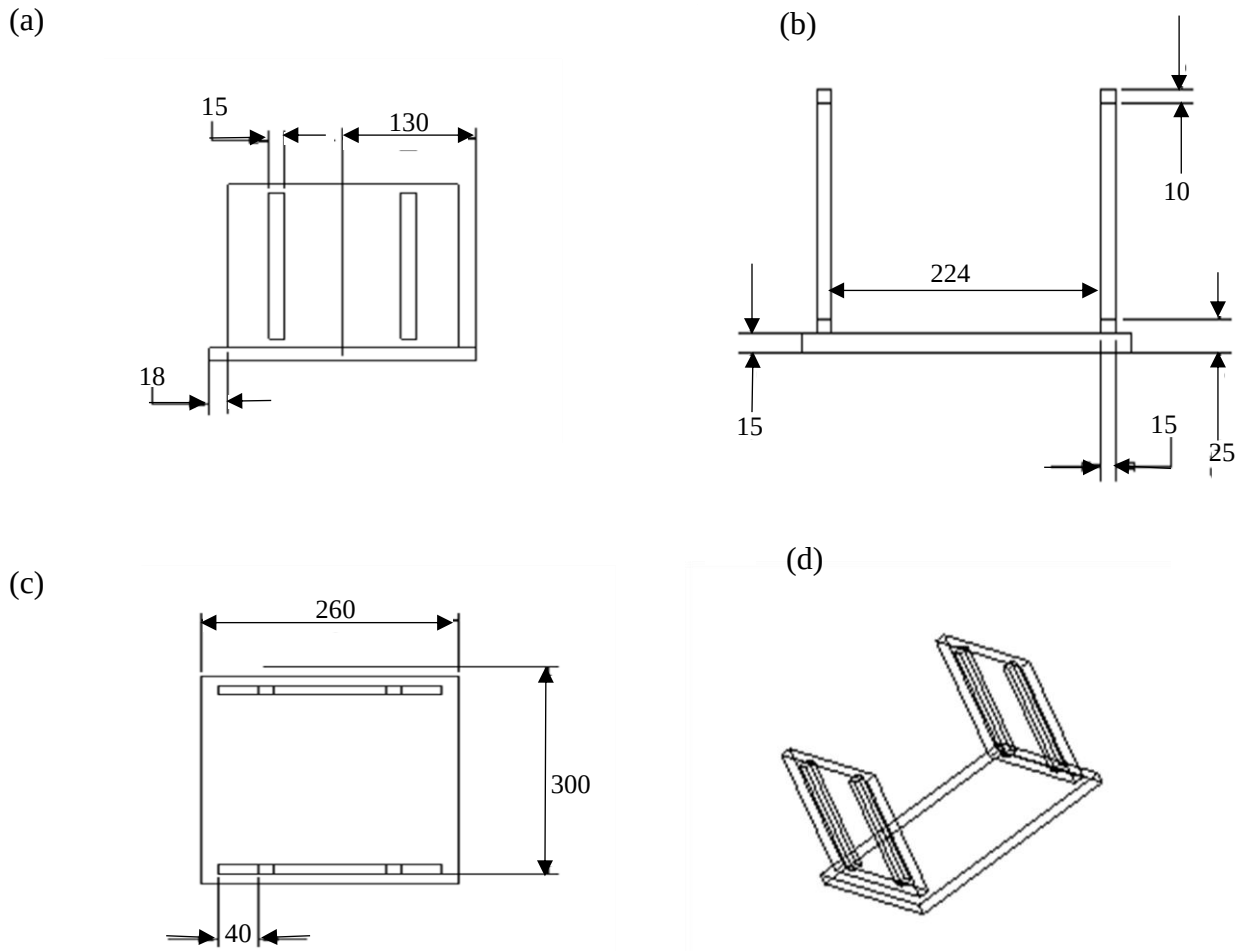


**Fig. 3.27.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the bottom plate for the height adjustment system (all dimensions in mm).

### 3.2.2.3. Holding plate of the block shape height adjustment system

The holding plate is used as a slider which helps in adjusting the height. The holding plate is move up and down as per the requirement and is tighten on the bottom plate using nut and bolt. The holding plate is made of mild steel. The dimensions of the holding plate can be observed from the front view, side view, and top view in Fig. 3.28(a–c). Figure 3.28(d) shows the base plate in a 3-D CAD model. The bottom plate's thickness is set at 15 mm.



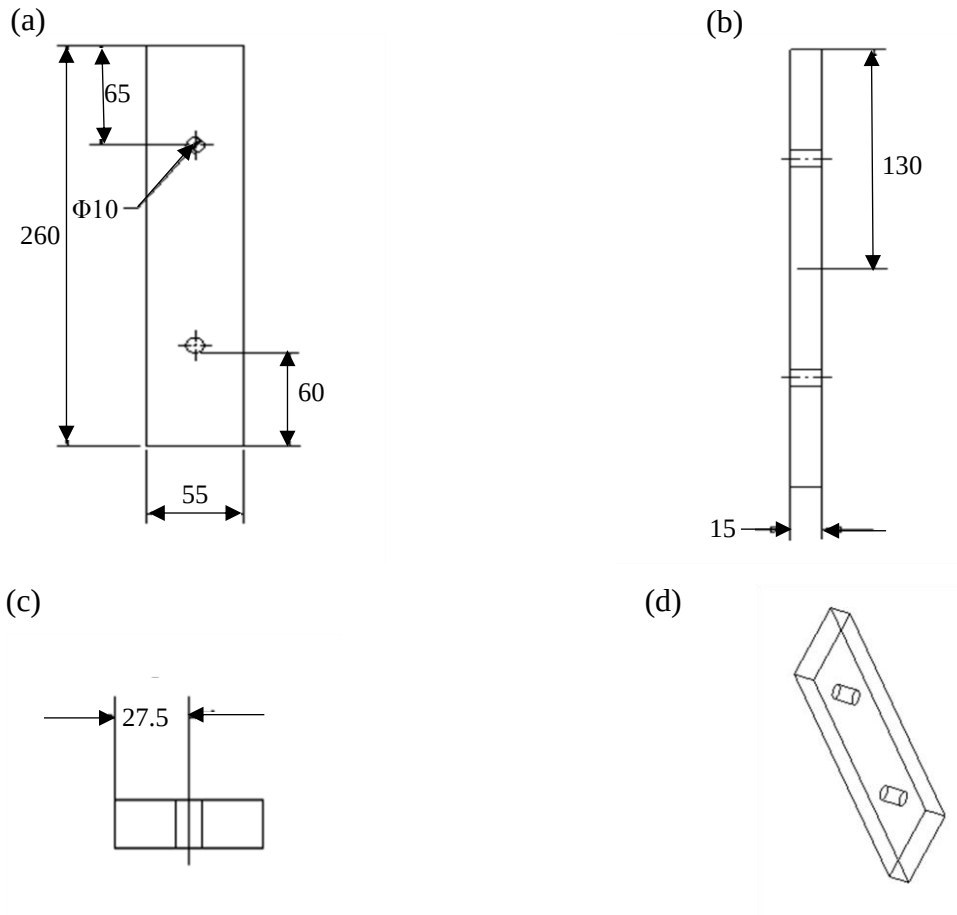


**Fig. 3.28.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the holding plate for the block shape height adjustment system (all dimensions in mm).

### 3.3 Design of fixture for holding the different shapes of the polymer workpieces

To hold the different shapes of the polymer workpieces, the workpiece fixtures are required. These workpiece fixtures must be made in such a way that precisely uniform workpiece rotation can be provided with a constant working gap. Since different shapes of the polymer components are finished in the present work, therefore, the workpiece fixtures are designed and fabricated as per the requirement.

#### 3.3.1 Design of the workpiece holder for polymer bevel gear

The workpiece fixture holder was used to hold the polymer bevel gear workpieces as depicted in Fig. 3.29. The circular plate and the shaft consist of the fixture. Mild steel is used for the workpiece holder as it is wear-resistant and has high strength. The dimensions of the workpiece holder can be seen in Fig. 3.29(a-b) from the front, and side views. Figure 3.29(c) shows the workpiece holder in a 3-D CAD model. The holes in the workpiece holder shown in Fig. 3.29(a) are utilized to keep the inserted workpiece securely in place during rotation. The plummer blocks are fastened to the

workpiece fixture, which is screwed to the polymer workpiece. The final fabricated fixture to hold the polymer bevel gear is depicted in Fig. 3.30.

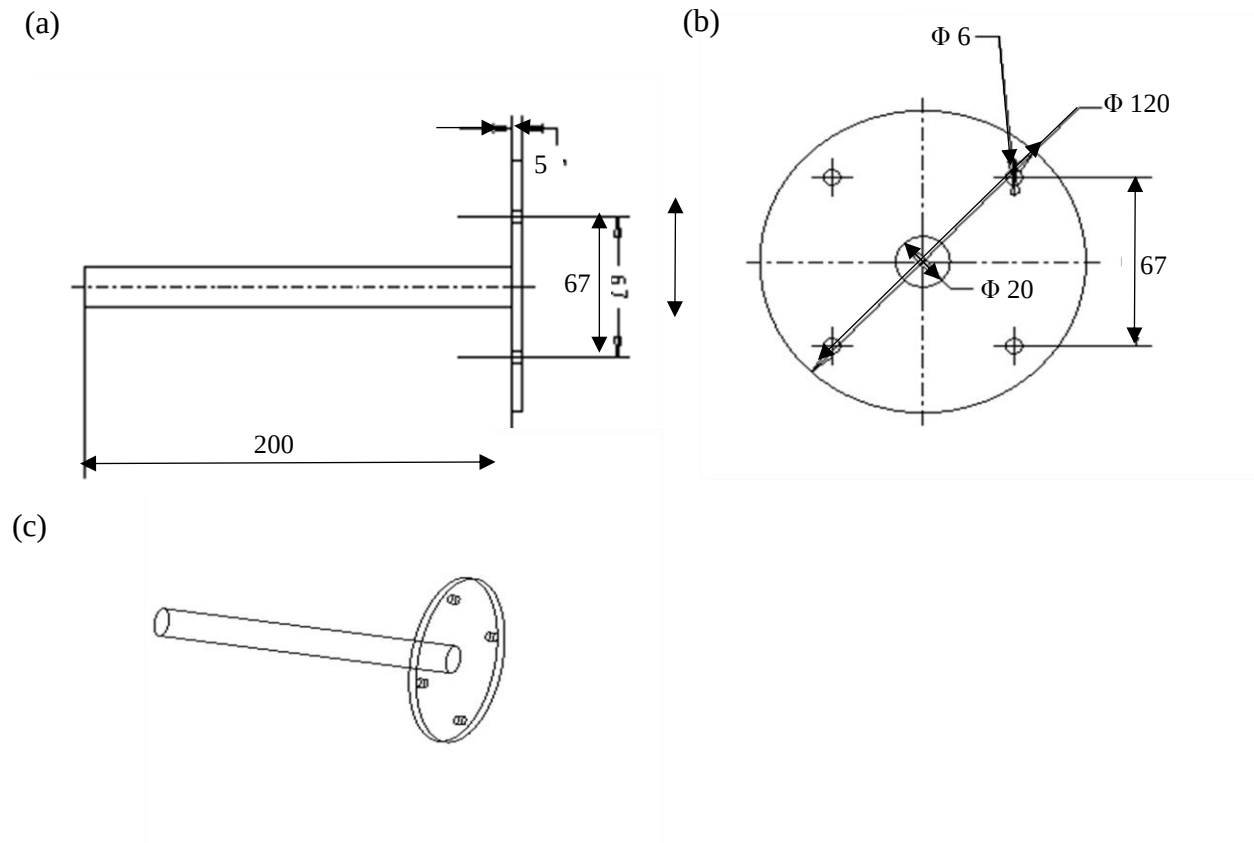


**Fig. 3.29.** 2D drawing of the (a) projected front view, (b) projected side view, and (c) three-dimensional CAD model of the workpiece holder for polymer gear (all dimensions in mm).

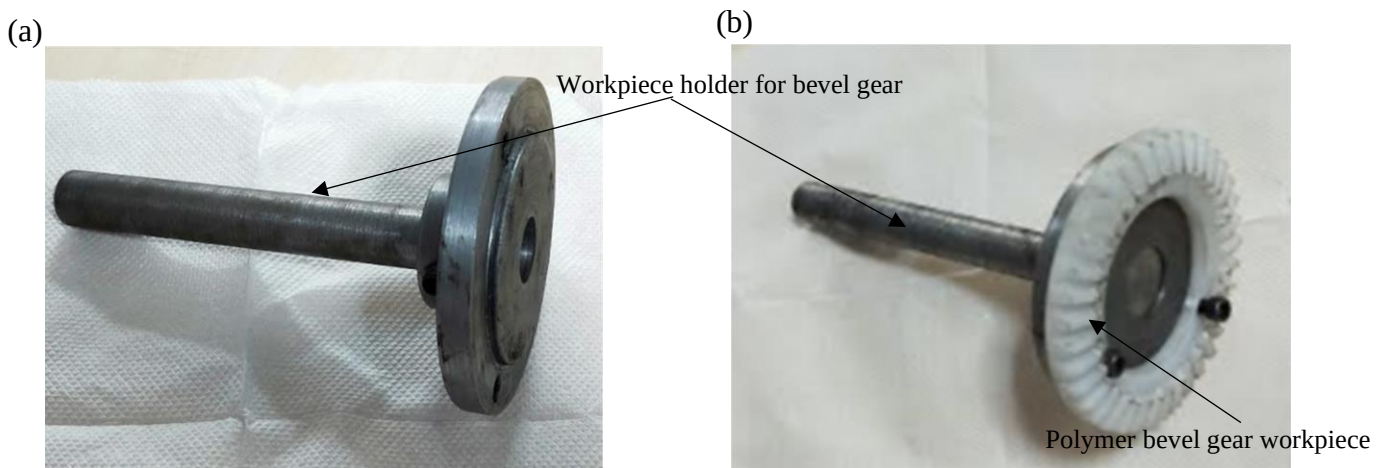


**Fig. 3.30.** Photograph of the fabricated assembly (a) workpiece holder, and (b) workpiece holder along with the polymer bevel gear.

### 3.3.2 Design of the workpiece holder for flat and hemispherical polymer surfaces

The flat and hemispherical cup-type workpieces were held using the workpiece holder. The workpiece holder is made up of mild steel because of its wear resistance and strength. The dimensions of the workpiece holder may be seen in Fig. 3.31(a-c) from the front, side, and top views. Figure 3.31(d) shows a workpiece holder in a 3-D CAD model. To avoid any play or wobbling, the holes in the workpiece holder shown in Fig. 3.31(a) are utilized to tightly retain the inserted workpiece. The shaft that is put into the plummer block is screwed to this workpiece.

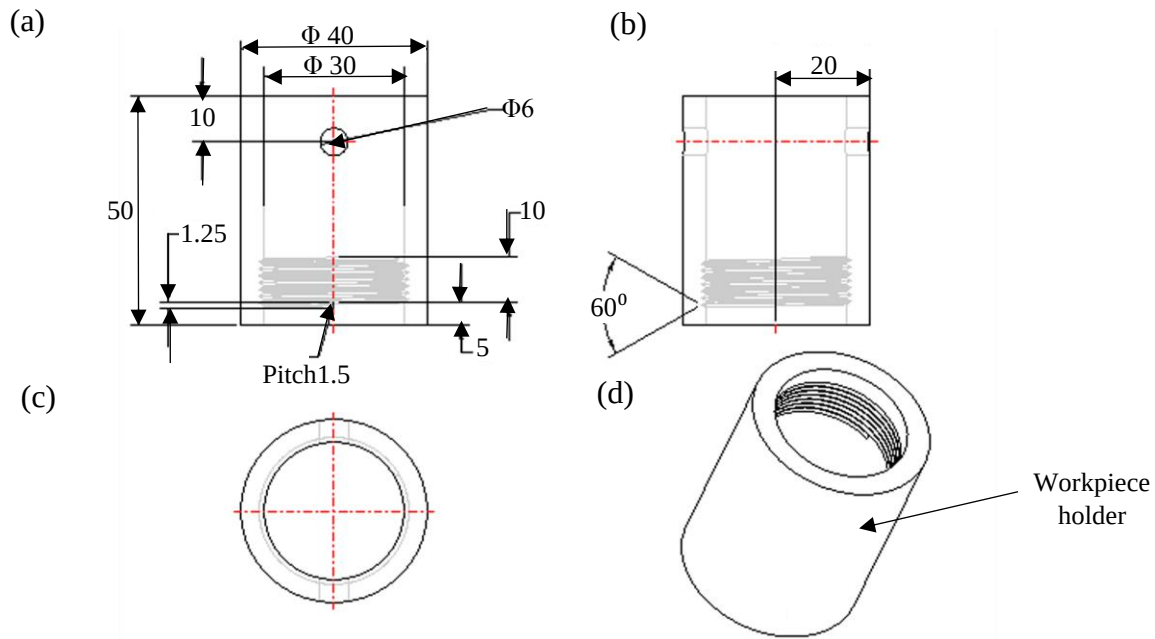


**Fig. 3.31.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional CAD model of the flat and hemispherical workpiece holder (all dimensions in mm).

#### 3.3.2.1 Design of the shaft used to rotate the flat and hemispherical workpiece along with the fixture

The shaft holds the workpiece holder in place and allows it to rotate. To prevent the workpiece holder from wobbling during rotation, a seat with a diameter of 40 mm and a thickness of 5 mm is used. The tolerance inside the threads may be the cause of the wobbling. Due to the bore of the adjustable plummer blocks available on the market, the diameter of the shaft is assumed to be 20 mm. The dimensions of the shaft for the workpiece holder can be observed from the front view, side view, and top view in Fig. 3.32(a) and (b). The 3-D CAD model of the shaft for the workpiece holder can be observed in Fig. 3.32(c).

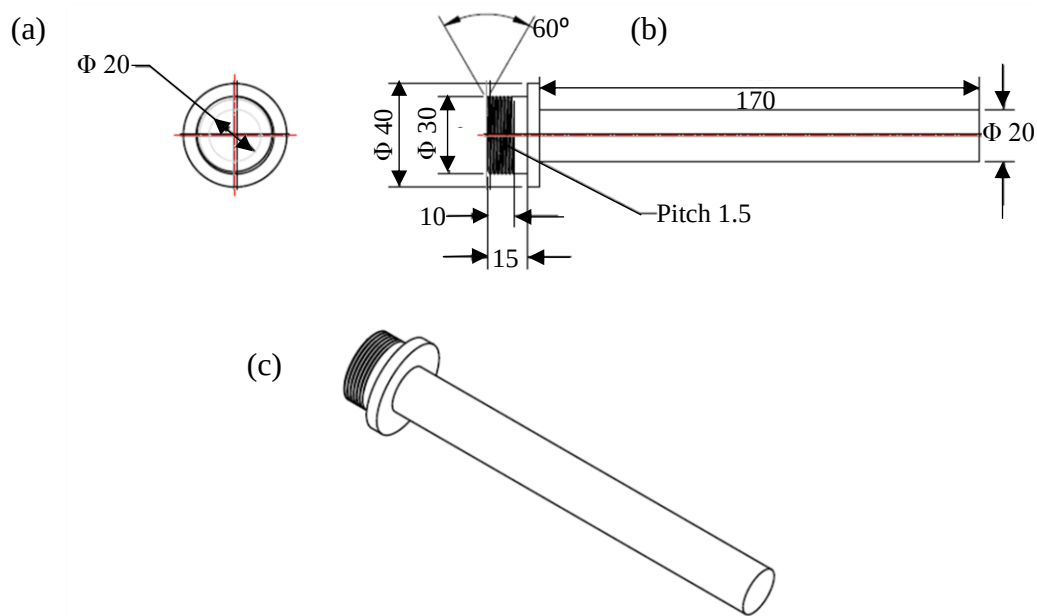


**Fig. 3.32.** 2D drawing of the (a) projected front view, (b) projected side view and (c) three-dimensional CAD model of the shaft for the workpiece holder (all dimensions in mm).

The actual assembled photograph of the workpiece fixture can be observed in Fig. 3.33(a) and the same workpiece holder along with the polymer hemispherical shaped workpiece is shown in Fig. 3.33(b).

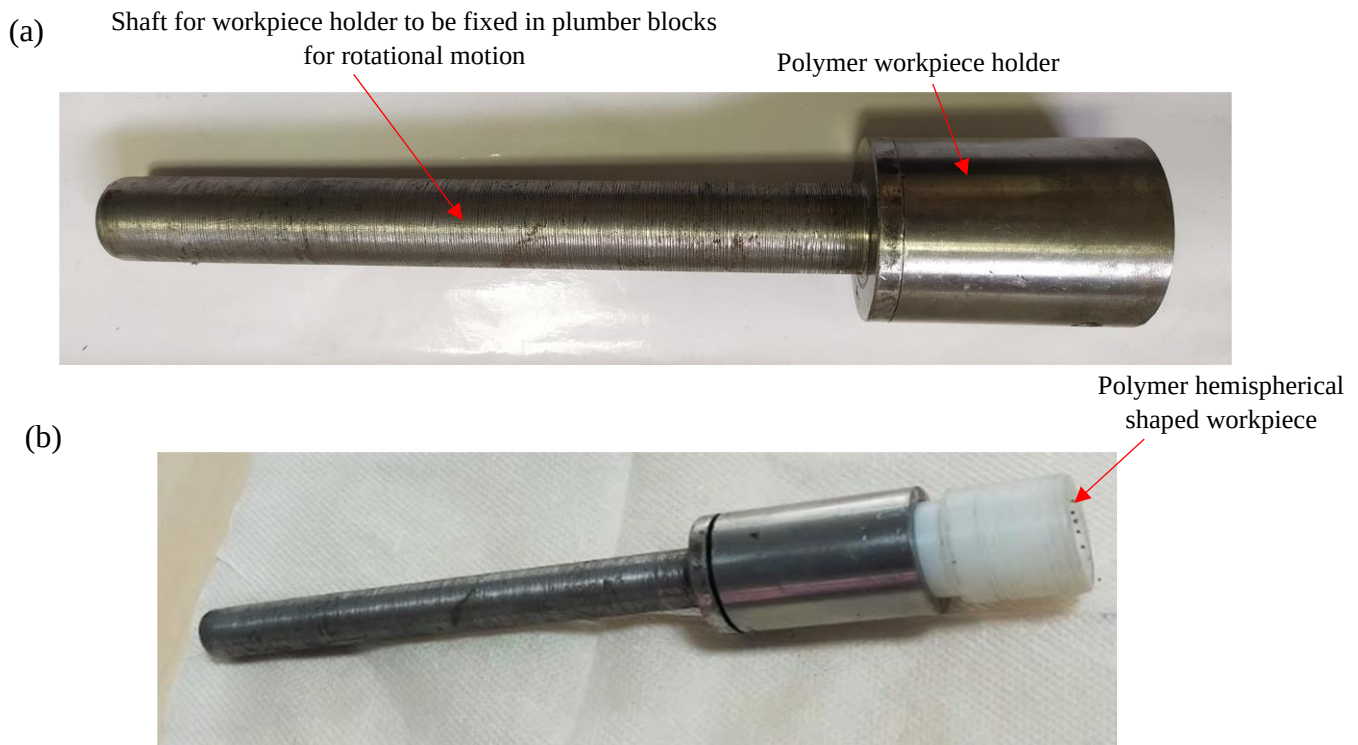


**Fig. 3.33.** Photograph of the fabricated assembly (a) workpiece holder for hemispherical and flat surface, and (b) workpiece holder along with the polymer hemispherical shaped workpiece.

### 3.3.3 Design of the workpiece holder for internal polymer surfaces

For the fine finishing of the internal surface of the polymer workpieces, a specific workpiece fixture is designed and fabricated. The fixture consisted of a rectangular block, a circular plate, a shaft, and a cylindrical block. Since the size of the internal workpieces is different, therefore the workpiece fixtures are designed as per the requirement. The design of the circular plate and shaft has already been discussed in section 3.3.1. Further, the polymer workpiece is inserted into the cylindrical block. The cylindrical block is made up of polymer material owing to its low cost, lightweight and non-ferromagnetic nature. The dimensions of the shaft for the workpiece holder can be observed from the front view, and side view in Fig. 3.34(a-b). The actual photograph of the cylindrical block can be observed in Fig. 3.34(c).

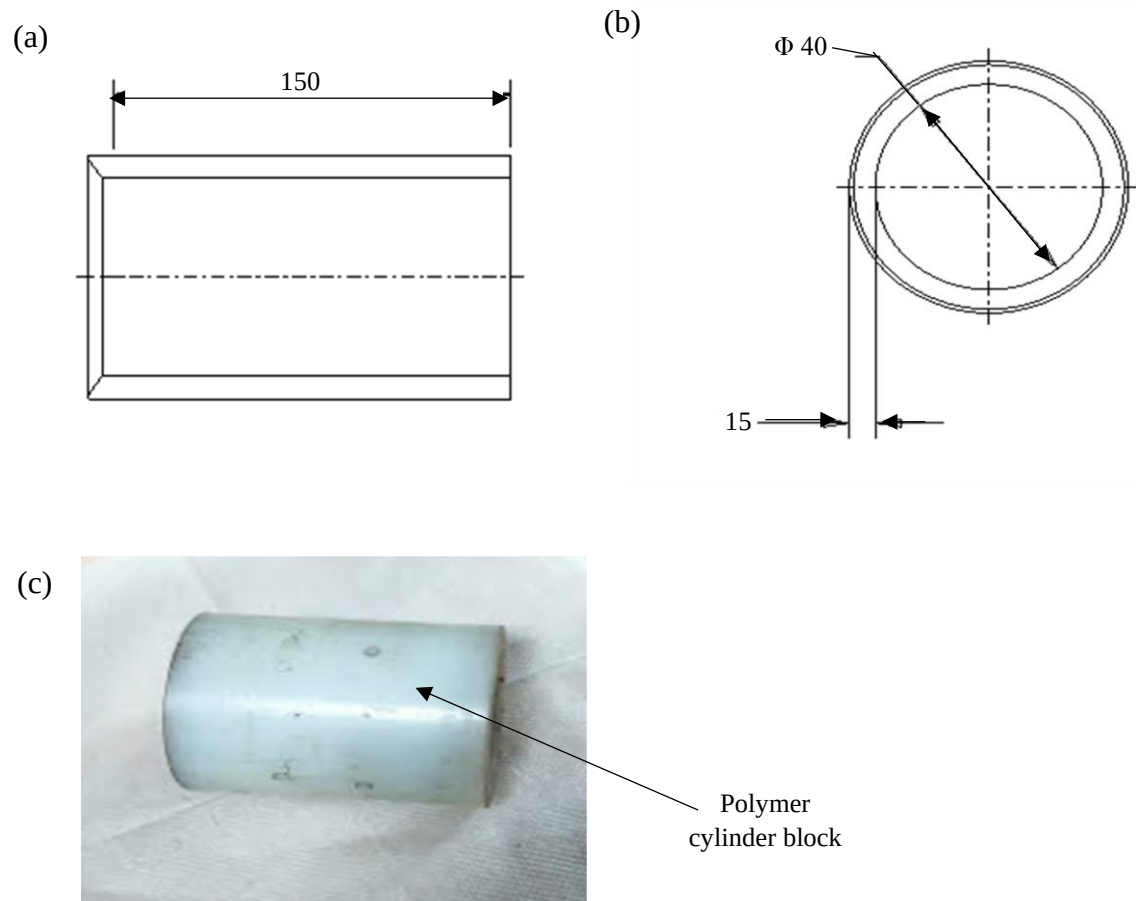


**Fig. 3.34.** 2D drawing of the (a) projected front view, (b) projected side view and (c) fabricated cylindrical block (all dimensions in mm).

Next, the mild steel rectangular block is designed in which four holes are made. The rectangular block is screwed through nuts in the circular plate that is attached to the shaft. The polymer workpiece is rotated owing to this shaft. The dimensions for the rectangular block holder can be observed from the front view, side view, and top view in Fig. 3.35(a-c). The actual photograph of the cylindrical block can be observed in Fig. 3.35(d). The actual assembled photograph of the workpiece fixture can be observed in Fig. 3.36(a) and the same workpiece holder along with the polymer valve seal workpiece is shown in Fig. 3.36(b).

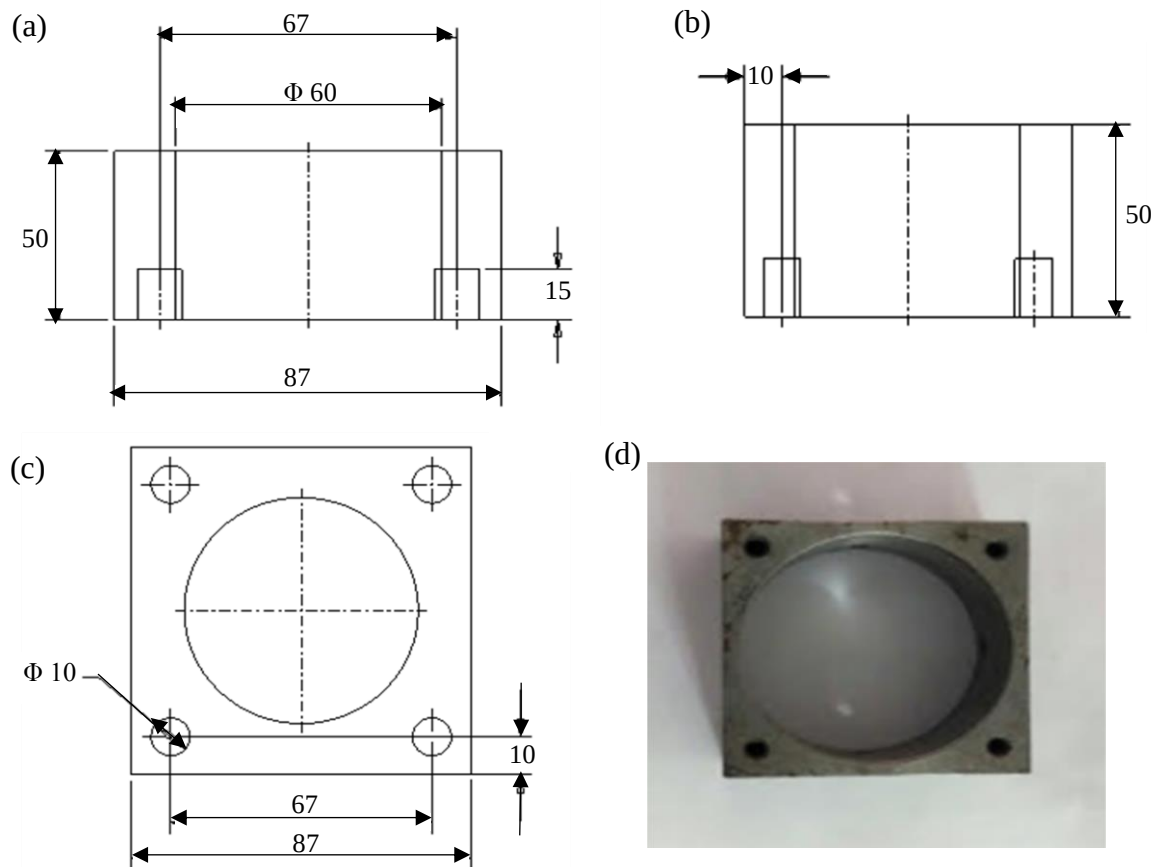


**Fig. 3.35.** 2D drawing of the (a) projected front view, (b) projected side view, (c) projected top view, and (d) three-dimensional fabricated rectangular block (all dimensions in mm).

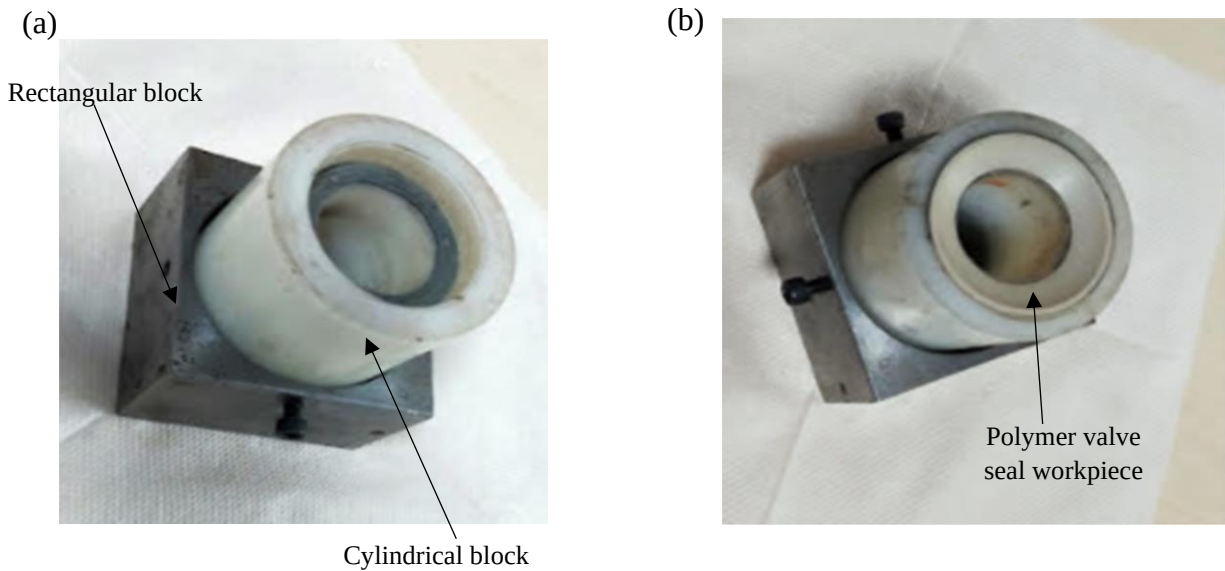


**Fig. 3.36.** Photograph of the fabricated assembly (a) workpiece holder for internal surface, and (b) workpiece holder along with the polymer valve seal workpiece.

### 3.4 Setup to perform finishing over the polymer valve seal surface using the hemispherical magnetorheological finishing tool

The experimental setup for the fine finishing of the polymer valve seal surface is depicted in Fig. 3.37. Since the polymer seat is not flat, therefore, a novel swivel rotating vise fixture is used to provide an angle to the workpiece fixture so that a constant gap is made amid the tool surface and the workpiece surface. The swivel vise is a key component when finishing is performed over the conical truncated polymer valve seal workpiece surfaces. The swivel vise's secondary use is to add height to the workpiece arrangement for the polymer workpiece. The swivel vise dimensions are chosen based on the dimension of the polymer workpieces. The fabricated angular swivel vise is depicted in Fig. 3.37(b). For finishing, initially; the eccentricity is maintained along with the constant gap amid the magnetic tool surface and the finishing surface of the polymer valve seal. This is done so that there is proper alignment amid the tool and valve seal surface while finishing owing to which there is smooth functioning with minimal errors. Further, the MRP fluid is applied manually over the magnetic tool which gets stiffened on the application of the magnetic field. Finally, the finishing process takes place over the finishing surface of the valve seal owing to the simultaneous magnetic tool and workpiece rotation till the fine finishing is achieved.



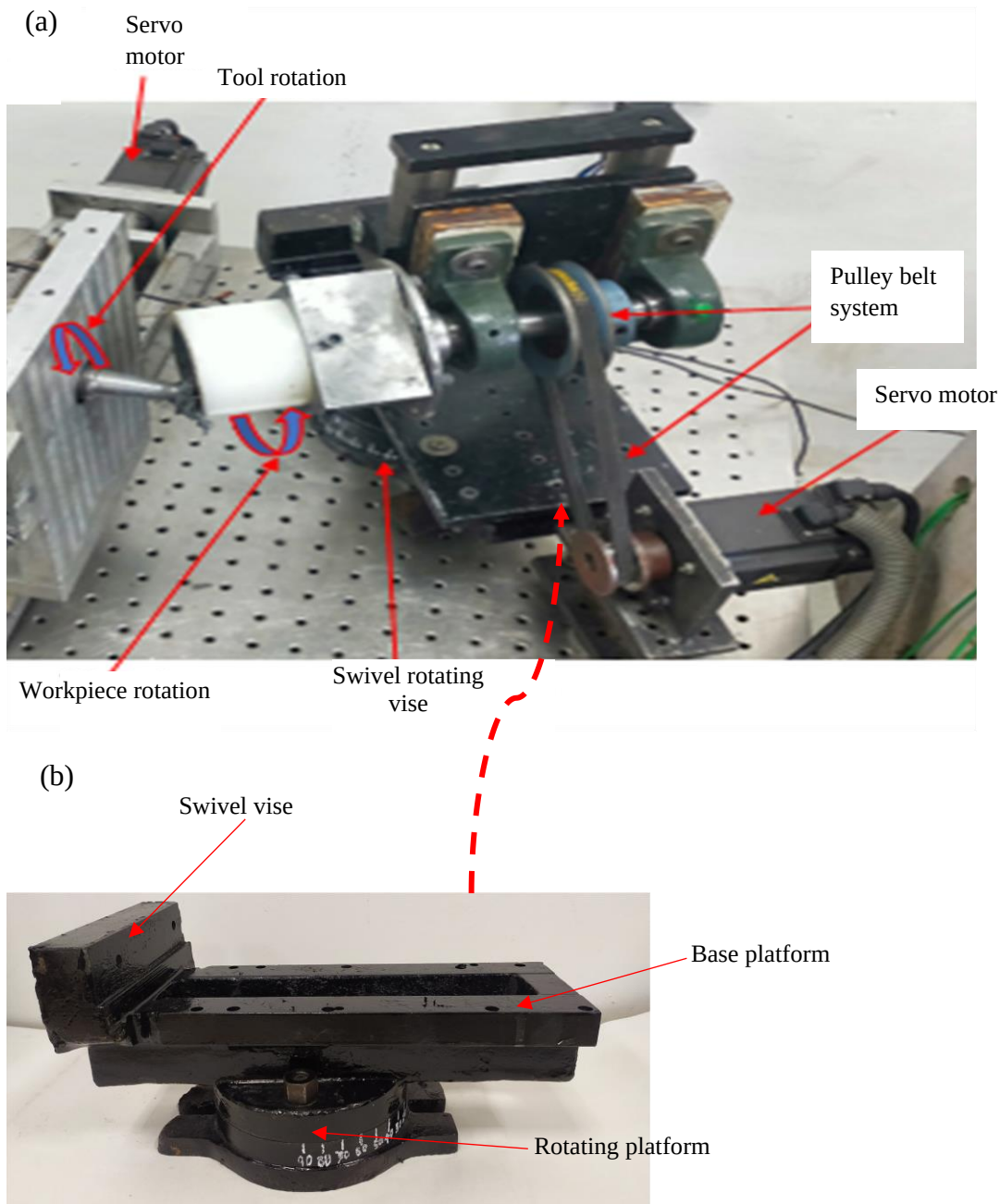


**Fig. 3.37.** (a) Experimental setup, and (b) fabricated swivel vise for maintaining uniform working gap during finishing of the polymer valve seal surface using the hemispherical magnetorheological finishing tool.

The present designed MR finishing tools as well as workpiece fixture holders can be used for the fine finishing of the polymer workpieces with different shapes such as flat, external cylindrical, internal, hemispherical, and gears. The present fabricated MR finishing tools and fixtures can be



used for industries dealing with fine finishing of polymer gears, bearings, medical implants, valve seals, additive manufactured components, etc.

### 3.5 Conclusions

From the design and fabrication of the different novel magnetorheological finishing tools and fixtures for the finishing of the polymer workpiece surface with different shapes, the following conclusions have been drawn.

- The magnetostatic finite element analysis (MFEA) result (0.515 T-0.331 T) for the different finishing tools as per the polymer workpiece shape reveals the ability to retain the magnetorheological polishing (MRP) fluid over the tool surface for fine finishing the various types of polymer workpieces. The decreasing magnetic flux density value amid the working gap ensures that iron particles are retained on the tool surface and abrasive particles present in the MRP fluid perform proper relative motion over the polymer workpiece surface. This concludes that the present developed finishing tools are feasible to provide fine finishing over the different types and shapes of polymer workpiece surfaces.
- The tip surface of the hemispherical tool core is designed as an exact replica of the shape of the workpiece. The higher and uniform concentration of magnetic flux amid the working space as revealed by MFEA leads to the uniform removal of asperities from the work part surface leading to the overall fine finishing of the hemispherical cup surfaces.
- The bevel gear fining tool is designed in such a way proper meshing could take place amid the tool and the polymer bevel gear with predefined working space for the MRP fluid. The decrease in the concentration of magnetic flux from the bevel gear finishing tool surface to the straight bevel gear work part surface ensures that iron particles are on the tool surface and the workpiece surface is always rich with the abrasive particles while finishing. This concludes the effectiveness of the bevel gear finishing tool surface to provide overall fine finishing over the straight bevel gear work part surface.
- The higher and uniform magnetic flux distribution over the novel hexagonal tip-based surface of the tool confirms that abrasive particles are uniformly indented over the FDM fabricated external cylindric surface leading to effective abrading off peaks with the different motions. This concludes the effective finishing of the external FDM fabricated cylindric surface.

- The experimentally measured magnetic field over the different tooltip surfaces reveals the uniform distribution of the magnetic flux density over the surface of the magnetic tool core. This is a necessity in order to get uniform and effective fine finishing over the polymer workpiece surface.
- The fabricated height adjustment fixtures and workpiece holder help in providing a uniform working gap between the tool and different workpiece surfaces owing to which the presently fabricated tool can perform effective finishing over the workpiece surface.

## CHAPTER 4

### ANALYSIS OF THE FINISHING MECHANISM WITH THE DEVELOPED MAGNETORHEOLOGICAL FINISHING TOOLS FOR DIFFERENT POLYMER WORKPIECES

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The material removal mechanism for fine finishing of various polymer components such as acetabular cups, gears, bearings, valve seals, and additive manufactured components has been covered in this chapter. Also, a theoretical analysis has been done to predict the surface roughness value for finishing the polymer workpieces with the newly designed magnetorheological fluid-based finishing tools.

#### **4.1 Theoretical analysis for fine finishing of the ultra-high molecular weight polyethylene (UHMWPE) acetabular cup surface using the novel electromagnetic hemispherical tip-based tool core**

##### **4.1.1 Material removal mechanism**

The material removal mechanism of the present magnetorheological (MR) finishing process is shown in Fig. 4.1. In this process, the finishing takes place due to the indentation of the active abrasive particles (AAPs) on the work part surface and detachment of the material from the locality of the indented AAPs. The material gets detached from the surface asperities of the workpiece mainly due to the abrasion action on surface asperities by the AAPs (Singh *et al.*, 2017). The total time for which the AAPs can perform surface finishing on the work part leads to the abrasion action. From Fig. 4.1(a), it can be seen that the surface asperities of the ultra-high molecular weight polyethylene (UHMWPE) hemispherical shaped acetabular cup work part surface get finished due to the relative motion between the stiffed magnetorheological polishing (MRP) fluid over the magnetized hemispherical tool core tip surface and the UHMWPE work part surface. The tool core and work part rotate in the opposite direction which enhances the relative motion amid the stiffed MRP fluid and the work part surface. This leads to the higher shear stress amid AAPs of the stiffed MRP fluid and surface asperities or roughness peaks of the work part surface owing to which material removal takes place. For the material removal from the surface of the work part, the forces act in this process namely magnetic normal force ( $F_{nm}$ ), and tangential shear force ( $F_{tan}$ ) as shown in Fig. 4.1(b). On the application of the magnetic field, the electrolytic iron particle (EIPs) gets magnetized over the hemispherical tool tip surface and forms a chain-like structure. The active

abrasive particles (AAPs) present in the MRP fluid are tightly gripped in these EIPs chains. The AAPs due to their nonmagnetic nature tend to move towards the low gradient magnetic flux from the high gradient of the magnetic flux i.e., towards the work part surface. This led to the magnetic normal force ( $F_{nrm}$ ) that acts on the work part surface through the AAPs. The AAPs on the work part surface get indented due to the  $F_{nrm}$  as depicted in Fig. 4.1(b). Due to this indentation, there is micro ploughing of the material around the indented area (Grover and Singh, 2018).

Further, the surface asperities of the work part get sheared by the indented AAPs due to the relative motion amid the stiffened MRP fluid and work part surface. During the rotational motion of the tool core and the work part, the AAPs experience the tangential force due to the work part ( $F_{tw}$ ) and tangential force due to the tool core ( $F_{tt}$ ) as shown in Fig. 4.1(b). As the tool rotates, the indented AAPs which are gripped in the EIPs chain structure of the MRP fluid, tend to come outwards tangentially which leads to the clipping of the material from the surface asperities of the work part. Next, the relative motion amid the work part surface and AAPs enhances due to the work part rotational motion. Owing to this relative motion, the work part and AAPs experience the net tangential shear force ( $F_{tan}$ ) which leads to the upsurge in the speed of the clipping of the surface asperities from the work part surface. Hence, to enhance the net relative speed, the rotation motion of the workpiece and tool is kept in the opposite direction simultaneously. Owing to this relative motion, the MRP fluid on the tooltip can easily chip off the surface asperities from the workpiece surface. The net resultant finishing force is the resultant of magnetic normal force ( $F_{nrm}$ ) and tangential shear force ( $F_{tan}$ ). The net finishing forces describe the direction in which the shearing of the surface asperities takes place from the work part surface and predict the magnitude of the net resultant finishing force acting on the active abrasive particle for removing the surface asperities from the UHMWPE acetabular cup work part surface using the present MR finishing process.

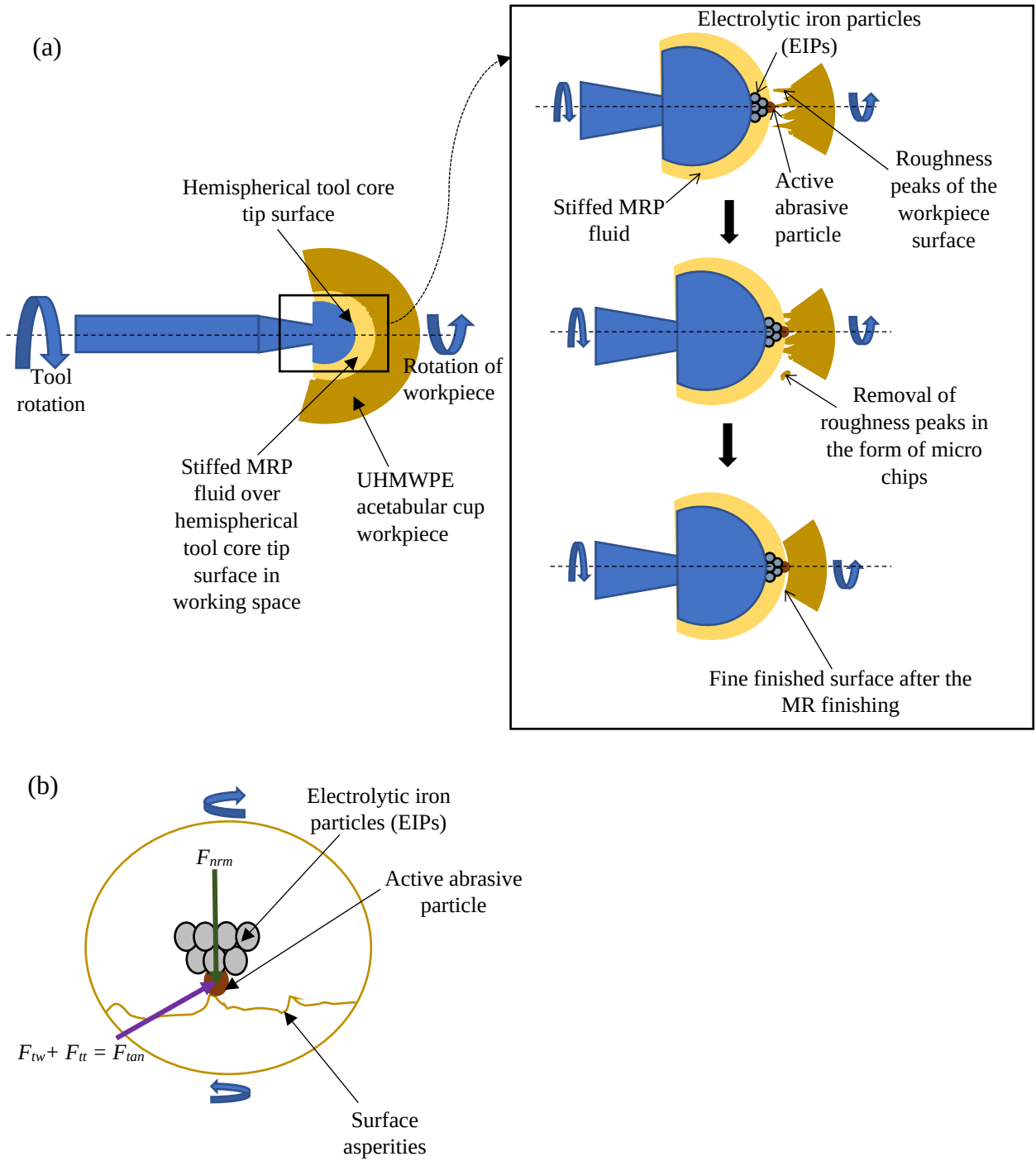


**Fig. 4.1.** (a) Mechanism of material removal by the active abrasive particle over workpiece surface and forces acting on the active abrasive particle during removal of surface asperities, and (b) different forces acting during the material removal.

#### ***4.1.2 Theoretical analysis of reduction in surface roughness during the magnetorheological (MR) finishing of the hemispherical shaped acetabular cup surface***

The hemispherical tip-based electromagnet tool (Chapter 3) can perform fine finishing suitably over the hemispherical shaped workpieces such as acetabular cups. The electromagnetic coil generates the magnetic field over the finishing surface of the novel hemispherical tip-based magnetorheological finishing (MRF) tool. To understand the in-depth process mechanism, a theoretical model for the reduction in surface roughness ( $R_a$ ) of the polymer hemispherical cup is analysed. For the theoretical analysis of the reduction in surface roughness, the following assumptions have been made.

- In the magnetorheological polishing (MRP) fluid, the active abrasive particles (AAPs) and electrolytic iron particles (EIPs) are uniformly distributed.
- The average size of  $\text{CeO}_2$  abrasive particles is assumed to be 19  $\mu\text{m}$  in diameter, and EIPs are assumed to be 30  $\mu\text{m}$  in diameter and both are spherical in shape.
- All other minor forces such as gravitational forces and inertia forces are neglected on the active abrasive particles during the finishing operation.
- Magnetic losses and leakages are not considered in this analysis.

In the present MRF process, the MRP fluid is gripped over the finishing surface of the hemispherical tip-based electromagnetic tool. The magnetic EIPs are present in the MRP fluid and get aligned along the magnetic field line induced in the hemispherical tip-based tool by the electromagnet. Each magnetic EIP tends to retain over the tool's surface under the influence of the magnetic field. Because of this behaviour of the EIPs, the levitation phenomenon occurs among the non-magnetic AAPs that are pushed towards the surface of the hemispherical cup workpiece. Owing to this the workpiece surface always remains abrasive rich till the fine finishing is achieved.

##### ***4.1.2.1 Theoretical analysis of the magnetic flux density induced by the electromagnetic hemispherical tip-based tool surface***

In the present study, for fine finishing of the polymer hemispherical shape cups, a novel magnetic tool is designed and fabricated as the exact replica of the workpiece as shown in Fig. 4.2(a). The gap amid the magnetic hemispherical tool and acetabular cup is filled with the magnetorheological polishing (MRP) fluid as shown in Fig. 4.2(b). The tool is designed such that it can perform a uniform finishing on the overall surface of the hemispherical cup.

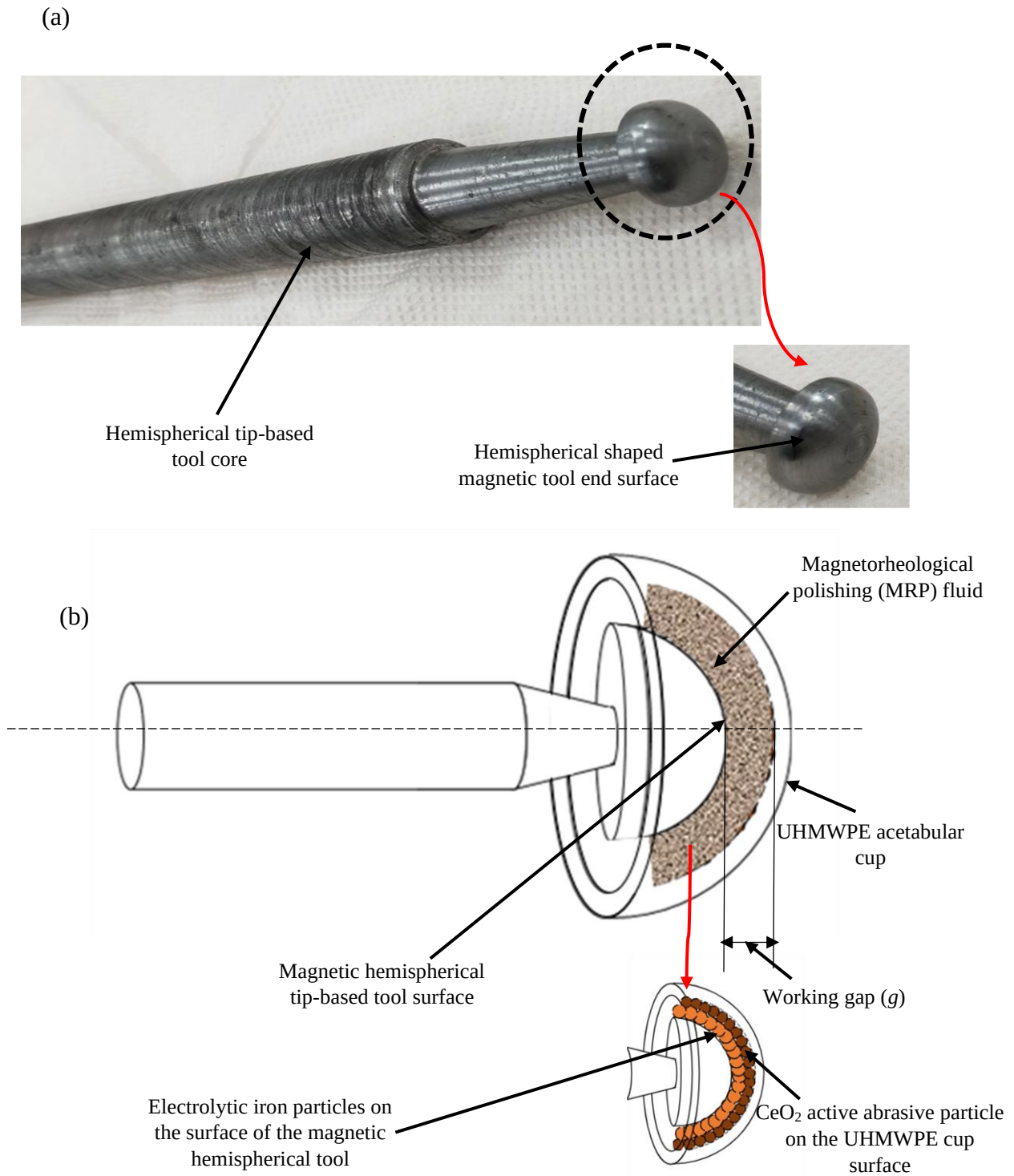


**Fig. 4.2.** (a) Photograph of the fabricated hemispherical tip-based magnetic tool and (b) schematic diagram of the MRP fluid in the predefined gap amid magnetic tool core and acetabular cup surface.

In this work, the core used is in a cylindrical shape, therefore, the electromagnetic coil formed on the core is of the circular geometry. The dimensional specification of the cylindrical core and its shape is reported in Table 4.1.

**Table 4.1.** Dimensional specification of the cylindrical core for the theoretical analysis.

| Parameters                                     | Dimensional specification |
|------------------------------------------------|---------------------------|
| Electromagnet core length                      | 110 mm                    |
| Number of turns of the coil                    | 2600                      |
| Diameter of core                               | 25 mm                     |
| Diameter of the hemispherical tool tip surface | 20 mm                     |
| The gauge of copper wire                       | 1 mm                      |
| Magnetizing current                            | 2 A                       |

The number of turns of the electromagnetic coil which makes the electromagnetic tool for finishing the inner side surface of the hemispherical cup is 2600 and the diameter of the outer surface of the electromagnetic tool is 70 mm.

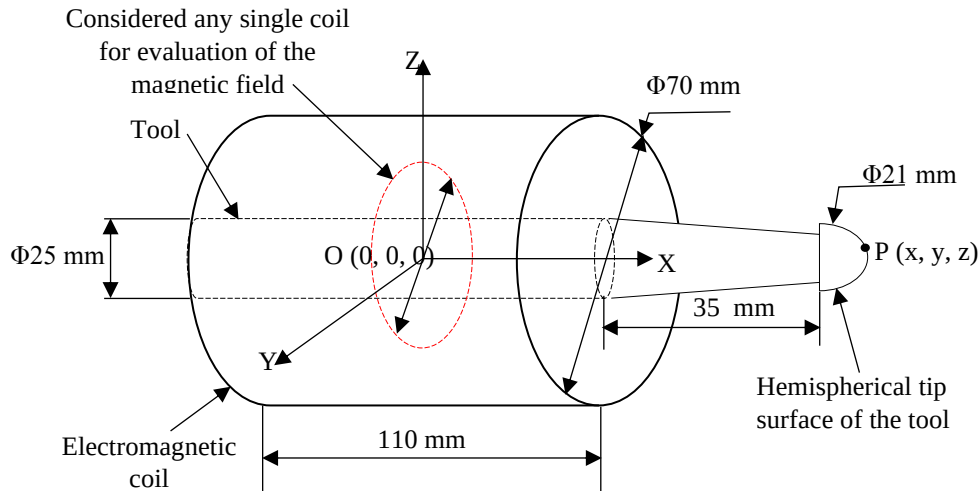


**Fig. 4.3.** The line diagram of the electromagnetic tool coil representing its dimensional and geometrical specification.

Further, the coordinate system used for evaluating the magnetic field generation due to the electromagnetic field is considered as depicted in Fig. 4.3. The X-axis of the considered coordinate system is taken towards the tool end surface and also the working gap. However, Y-axis and Z-axis are taken in such a way that the coil is lying in the YZ plane as shown in Fig. 4.3.

Considering  $Idl$  unit current length of the considered coil which has coordinate point  $P' (x', y', z')$  and position vector is  $r'$  at point  $P'$  as shown in Fig. 4.4. The magnetic field induced at any random point  $P (x, y, z)$  due to the  $Idl$  current length of the coil is  $dB$ . Therefore, the magnetic field



due to the complete coil is found as  $B$  which is obtained by integrating the  $dB$  from zero to  $2\pi r'$ . where,  $r'$  is the radius of the coil as depicted in Fig. 4.4.

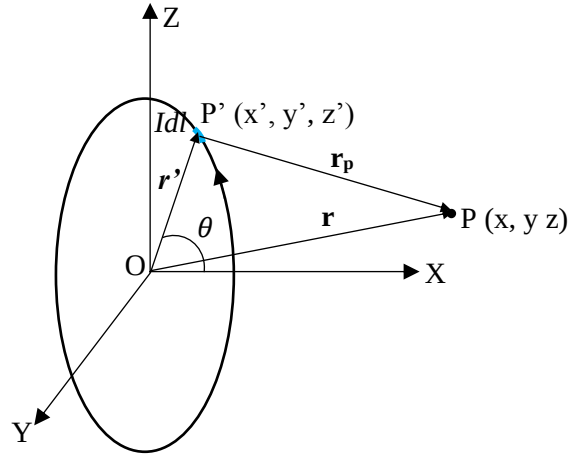


**Fig. 4.4.** Single coil of electromagnetic tool inducing magnetic field at point P (x, y, z).

The magnetic field due to the  $Idl$  current length of the coil at point P which is at distance  $r_p$  and  $r$  from centre O is calculated by the Biot-Savart law. Therefore, as per this law, the magnetic field induced due to the  $Idl$  current length of the coil at point P is expressed in Eq. (4.1).

$$dB = \mu_0 \frac{I \vec{dl} \times \vec{r}}{4\pi r^3} \quad (4.1)$$

On this coil, an elemental length  $dl$  is considered at  $\theta$  angle from X-axis making  $d\theta$  at the center of coil O (0,0,0). As the coil is lying in the YZ plane, the coordinate point of  $dl$  is found as  $x' = 0, y' = r' \cos \theta, z' = r' \sin \theta$ . The  $\theta$  is the angle between the resultant component of the magnetic flux density (MFD) and electric current segment length ( $Idl$ ). Further, the vector length of  $OP'$  is calculated by Eq. (4.2).

$$OP' = (x' - 0)\hat{i} + (y' - 0)\hat{j} + (z' - 0)\hat{k} \quad (4.2)$$

On solving, Eq. (4.2) can be written as Eq. (4.3).

$$OP' = (x')\hat{i} + (y')\hat{j} + (z')\hat{k} \quad (4.3)$$

Further, using the values of  $x', y'$  and  $z'$ , the vector length of  $OP'$  is represented in Eq. (4.4).

$$OP' = (r' \cos \theta)\hat{j} + (r' \sin \theta)\hat{k} \quad (4.4)$$

Next, the unit differential length ( $dl$ ) of the coil is represented in Eq. (4.5).

$$\vec{dl} = OP' d\theta \quad (4.5)$$

Using Eq. (4.4) in Eq. (4.5), the unit differential length ( $dl$ ) is represented as Eq. (4.6).

$$\vec{dl} = r' d\theta (\cos \theta \hat{j} + \sin \theta \hat{k}) \quad (4.6)$$

The position of the point P where the magnetic field is to be calculated is described in Eq. (4.7).

$$\vec{r} = x\hat{i} + (y - r' \cos \theta)\hat{j} + (z - r' \sin \theta)\hat{k} \quad (4.7)$$

The cross product of the unit differential length of the coil ( $\vec{dl}$ ) and the position vector ( $\vec{r}$ ) of the point P is expressed as in Eq. (4.8).

$$\vec{dl} \times \vec{r} = \{r'^2 - r'(z \sin \theta + y \cos \theta)\}d\theta\hat{i} + xr' \cos \theta d\theta\hat{j} + xr' \sin \theta d\theta\hat{k} \quad (4.8)$$

The magnitude of the position vector ( $\vec{r}$ ) of the point of interest of the present study is calculated by the Eq. (4.9).

$$r = \sqrt{x^2 + (y - r' \cos \theta)^2 + (z - r' \sin \theta)^2} \quad (4.9)$$

On using the Eq. (4.8) and Eq. (4.9) in Eq. (4.1), the magnetic field  $dB$  due to the small unit element  $dl$  is obtained in Eq. (4.10).

$$dB = \frac{\mu_0 I \{r'^2 - r'(z \sin \theta + y \cos \theta)\}d\theta\hat{i} + xr' \cos \theta d\theta\hat{j} + xr' \sin \theta d\theta\hat{k}}{\{x^2 + (y - r' \cos \theta)^2 + (z - r' \sin \theta)^2\}^{3/2}} \quad (4.10)$$

As  $dB$  is the magnetic field due to the  $dl$  length of the coil, then the magnetic field ( $B$ ) due to total length of the circular coil ( $2\pi$ ) is calculated in Eq. (4.11).

$$B = \int_0^{2\pi} dB = \frac{\mu_0 I}{4\pi} \int_0^{2\pi} \frac{[\{r'^2 - r'(z \sin \theta + y \cos \theta)\}\hat{i} + xr' \cos \theta\hat{j} + xr' \sin \theta\hat{k}]}{\{x^2 + (y - r' \cos \theta)^2 + (z - r' \sin \theta)^2\}^{3/2}} d\theta \quad (4.11)$$

Let the electromagnetic coil are made up with  $p$  numbers, then total magnetic field ( $B'$ ) due to the all  $p$  numbers of turns of the copper coils is calculated in Eq. (4.12).

$$B' = \frac{\mu_0 p I}{4\pi} \int_0^{2\pi} \frac{[\{r'^2 - r'(z \sin \theta + y \cos \theta)\}\hat{i} + xr' \cos \theta\hat{j} + xr' \sin \theta\hat{k}]}{\{x^2 + (y - r' \cos \theta)^2 + (z - r' \sin \theta)^2\}^{3/2}} d\theta \quad (4.12)$$

The magnetic field strength ( $H'$ ) due to  $p$  number electromagnetic coils can be calculated from the Eq. (4.13).

$$H' = \frac{B'}{\mu_0} \quad (4.13)$$

The complete tool is made with  $n$  numbers of electromagnetic coils and core. Therefore, the magnetic field induced by the tool depends on the magnetic strength induced by the coils, the magnetisation value of the core, and its magnetic permeability.

In the present work, the material of the workpiece is ultra-high molecular weight polyethylene (UHMWPE) polymer which is a non-magnetic material. So, while finishing performs, the magnetic field present in the working space, and on the cup surface is mainly due to the magnetic influence of the electromagnetic coil, tool core and the magnetorheological polishing (MRP) fluid. Since, the MRP fluid is composed of magnetic electrolytic iron particles (EIPs), non-magnetic

cerium oxide (CeO<sub>2</sub>) abrasives, and water base fluid. Therefore, the magnetic behaviour of the MRP fluid is completely dependent on the EIPs as they are only magnetic constituents in the polishing fluid. Hence, the magnetisation of the MRP fluid is taken as the magnetisation of EIPs. However, the relative magnetic permeability of the MRP fluid ( $\mu_{r\_Mrp}$ ) is dependent on all the constituents present in the fluid. The magnetic permeability of the MRP fluid is calculated as given in Eq. (4.14).

$$\mu_{r\_Mrp} = \mu_0 \times \mu_{mr} \quad (4.14)$$

where  $\mu_{r\_Mrp}$  is the MRP fluid's relative magnetic permeability,  $\mu_0$  is absolute magnetic permeability in free space with value  $4\pi \times 10^{-7} \text{ N/A}^2$ , and  $\mu_{mr}$  is magnetic permeability of MRP fluid with value 5 (Paswan and Singh, 2019). Using  $\mu_0$  and  $\mu_{mr}$  in Eq. (4.14),  $\mu_{r\_Mrp}$  is calculated as  $6.28 \times 10^{-6} \text{ H/m}$ .

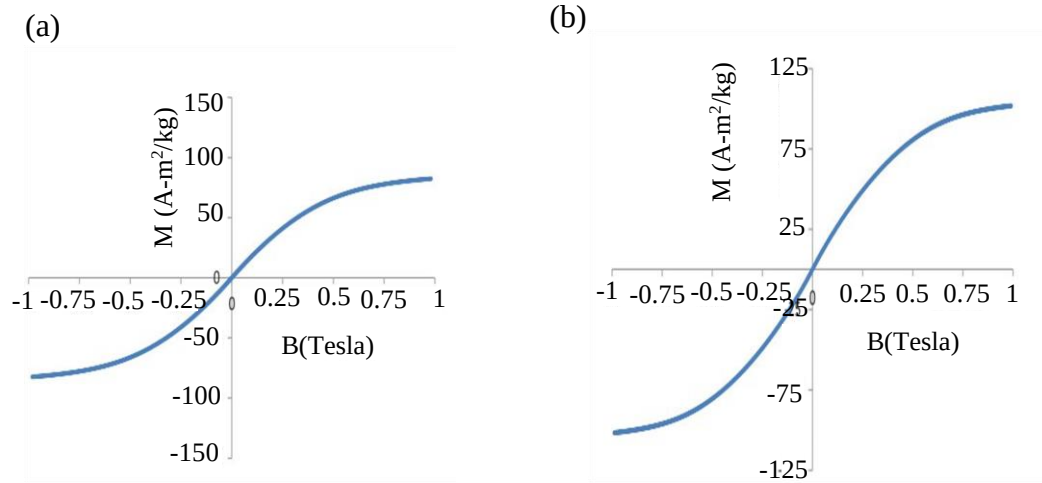


**Fig. 4.5.** Magnetisation- magnetic field curve of (a) electrolytic iron particles and (b) mild steel.

Further, the total magnetic field,  $B_c$  (considering the influence of coils, core and MRP fluid) in the working gap is calculated from the Eq. (4.15) and is reported in Table 4.2.

$$B_c = \mu_0 H' + \mu_{r\_cr} M_{cr} + \mu_{r\_Mrp} M_{eip} \quad (4.15)$$

where  $B_c$  is the total magnetic flux density (T) in the working gap amid tool core and acetabular cup workpiece,  $\mu_{r\_cr}$  is the relative magnetic permeability of the magnetic permeability of the tool core material.  $\mu_{r\_cr}$  is calculated as given in Eq. (4.16).

$$\mu_{r\_cr} = \mu_0 \times \mu_{cr} \quad (4.16)$$

where  $\mu_{cr}$  is magnetic permeability of the tool core material with value of 600 (Singh and Singh, 2019). Using  $\mu_0$  and  $\mu_{cr}$  in Eq. (4.16),  $\mu_{r\_Mrp}$  is calculated as  $7.539 \times 10^{-4}$  H/m,  $M_{eip}$  denotes the magnetisation of the electrolytic iron particles (EIPs) which can be evaluated from magnetisation curve as shown in Fig. 4.5(a).  $M_{cr}$  denotes the magnetisation of the iron particles which can be evaluated from the Fig. 4.5(b).

**Table 4.2.** Magnetic field produced by the electromagnet through tool core and the corresponding magnetization of the EIPs of MRP fluid in the working gap.

| Position in the gap between hemispherical tool and the workpiece surface (m) | Theoretical magnetic field, $B'$ (T) Eq. (4.12) | Magnetisation of EIP, $M_{eip}$ (A-m <sup>2</sup> /Kg) Fig. 4.5 (a) | Magnetisation of tool core, $M_{cr}$ (A-m <sup>2</sup> /Kg) Fig.4.5 (b) | Total theoretical magnetic field, $B_c$ (T) Eq. (4.15) | Total experimental measured magnetic field (T) |
|------------------------------------------------------------------------------|-------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------|------------------------------------------------|
| 0.1001                                                                       | 0.265                                           | 57                                                                  | 49                                                                      | 0.302                                                  | 0.228                                          |
| 0.1002                                                                       | 0.260                                           | 56                                                                  | 48                                                                      | 0.297                                                  | 0.217                                          |
| 0.1003                                                                       | 0.256                                           | 55                                                                  | 47                                                                      | 0.292                                                  | 0.210                                          |
| 0.1004                                                                       | 0.252                                           | 54                                                                  | 46                                                                      | 0.287                                                  | 0.204                                          |
| 0.1005                                                                       | 0.248                                           | 54                                                                  | 45                                                                      | 0.282                                                  | 0.200                                          |
| 0.1006                                                                       | 0.243                                           | 53                                                                  | 43                                                                      | 0.276                                                  | 0.198                                          |

The magnitude of  $B_c$  in the working space is dependent on the of the tool surface magnetization and the EIPs. The higher value of  $B_c$  in the working space leads to the upsurge in the normal magnetic force on the AAPs due to the increase in magnetization of the EIPs chain in the MRP fluid. Further, the variation of the total theoretical magnetic field ( $B_c$ ) is observed by following the linear trend in the working space ( $g$ ) amid the workpiece surface and magnetic tool surface (Table 4.2) as given in Eq. (4.17).

$$B_c(g) = -51.609g + 5.4687 \quad (4.17)$$

where  $g$  is the working gap (m).

The theoretical distribution of the magnetic flux density (MFD) in the working gap ( $g$ ) amid the hemispherical tool surface and the acetabular cup surface is calculated using Eq. (4.17) and shown in Fig. 4.6. Further, the results obtained from the experimentally measured values of MFD are also depicted in Fig. 4.6 and Table 4.2. To measure the experimental values of MFD, the digital gauss meter with the hall effect sensor is utilized. From Fig. 4.6, it can be seen that the trend follow by the experimentally measured values is same as that obtained by the theoretical calculations i.e.,

higher MFD on the tool surface and the lower on work part surface. The experimental and theoretical result ensures that, due to the levitation force, the magnetic electrolytic iron particles (EIPs) are attracted and retained on the surface of the tool and non-magnetic active abrasive particles (AAPs) move towards the lower MFD, i.e., hemispherical cup surface. Due to which the work part always remains abrasives rich during finishing. Owing to this, the roughness asperities get shear off from the surface of the hemispherical cup work part by the movement of the AAPs which leads to the fine finishing.

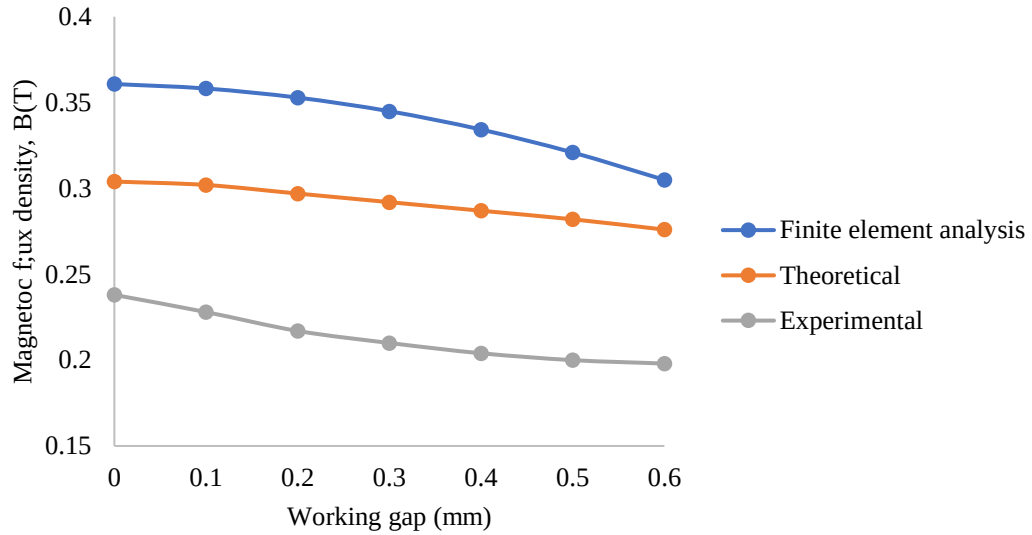


**Fig. 4.6.** Variation of magnetic flux density (MFD) in working gap with theoretical and experimental analysis.

Further, from Fig. 4.6 it can be seen that the value of MFD obtained from the theoretical analysis and finite element analysis (FEA) is higher as compared to the experimental results. This is because, in theoretical analysis, few assumptions are made such as no flux loss, no environmental loss, or effect of temperature. However, in experimentally obtained values, there is actual accessibility to the environment which leads to the decrease in the magnetic flux density. However, their trends are found almost the same (Fig. 4.6).

#### 4.1.2.2 Calculation of the volume of magnetorheological polishing (MRP) fluid and the total number of active abrasive particles (AAPs) present in the working gap

The finishing is performed in the present process by the AAPs present in the MRP fluid in the working space between the acetabular cup surface and the electromagnetic hemispherical tool end surface as shown in Fig. 4.2. Hence, before analysing the reduction in the  $R_a$  value of the cup

surface, it is necessary to analyse the MRP fluid volume and the number of AAPs present in the MRP fluid amid the working gap. For the calculation of the AAPs in the polishing fluid, initially, MRP fluid's total volume ( $V_{mrp}$ ) present in the working space is to be calculated. Since the MRP fluid is placed amid the projected area of the hemispherical tool end surface with the thickness ( $g$ ) as shown in Fig. 4.2. Therefore,  $V_{mrp}$  can be given by Eq. (4.18).

$$V_{mrp} = A_t \times g \quad (4.18)$$

where  $V_{mrp}$  is the MRP fluid's total volume on the magnetized tool end surface in working gap ( $g$ ) in  $m^3$ ,  $A_t$  is the hemispherical tool end surface area in  $m^2$  and  $g$  is the thickness of gap amid the cup surface and hemispherical tool end surface which is considered as  $0.6 \times 10^{-3}$  m in the present work. Further, the area of the hemispherical tool end surface ( $A_t$ ) can be calculated using Eq. (4.19).

$$A_t = 2\pi r_t^2 \quad (4.19)$$

where  $r_t$  is the radius of the hemispherical tool end surface and its value is  $10.5 \times 10^{-3}$  m. Using Eq. (4.19), the  $A_t$  is calculated as  $6.9272 \times 10^{-4}$   $m^2$ . Further, using Eq. (4.19) in Eq. (4.18), the MRP fluid's total volume ( $V_{mrp}$ ) on the tool end surface in the working gap  $0.6 \times 10^{-3}$  m is calculated as  $4.15632 \times 10^{-7}$   $m^3$ . Further in the present work, the composition of the MRP fluid consists of 10 % volume concentration of the  $CeO_2$  abrasive, 30 % volume concentration of the EIPs, and 60 % volume concentration of the water-based carrier fluid (80 % deionized water and 20 % glycerol). The total number of the AAPs ( $N_{aap}$ ) which are responsible for the clipping off the surface asperities are calculated by Eq. (4.20).

$$N_{aap} = \frac{C \times A_t \times d_{aap}}{V_{aap}} \quad (4.20)$$

where  $C$  is the volume concentration of the AAPs (10 %),  $d_{aap}$  is the diameter of single AAP as  $19 \times 10^{-6}$  m and  $V_{aap}$  is the volume of the single AAP. Further, the volume of the single AAP can be calculated using Eq. (4.21).

$$V_{aap} = \frac{4\pi r_{aap}^3}{3} \quad (4.21)$$

where  $r_{aap}$  is the radius of single AAP which is  $9.5 \times 10^{-6}$  m. Using Eq. (4.21), the volume of single AAP is calculated as  $3.591 \times 10^{-15}$   $m^3$ . Using the Eqs. (4.19) and (4.21) in Eq. (4.20), the  $N_{aap}$  is calculated as 366500. These calculated AAPs in the MRP fluid are actually accountable for shearing the asperities from the surface of the hemispherical acetabular cup.

#### 4.1.2.3 Calculation of the path length of the AAP over the acetabular cup during its surface finishing

In this study, first, the AAPs are indented over the roughness peaks of the acetabular cup surface due to the magnetic field. Second, the material separates from the indented AAPs' position as the hemispherical tool and the acetabular cup work component rotate in opposing directions at the same time. As a result, the surface is finished. Since the tool surface and the acetabular cup workpiece are oppositely rotated, therefore, the AAPs form circular paths over the surface of the acetabular cup from top to bottom as shown in Fig. 4.7. As the radius of the hemispherical cup decreases from the top edge to the bottom (point A to B) as shown in Fig. 4.7, therefore at each circumferential level from top to bottom of the hemispherical workpiece, the number of the AAPs decreases. Hence, the removal of the material from the hemispherical cup surface by the AAPs takes place along with the circular path length. Thus, it is important to calculate the circular path length in the present investigation. For the path length ( $L_p$ ) calculation, initially, a single circumferential path length of AAP lying on the hemispherical cup surface from the bottom to the upper edge of the cup is considered as shown in Fig. 4.8. Since all the AAPs are assumed to be uniform in shape (spherical) and size ( $19 \mu\text{m}$ ) and also uniformly lying on the workpiece finishing surface, therefore the number of the AAPs ( $n_c$ ) in a single circumferential line path length can be calculated by dividing the path length of single line AB (Figs. 4.7 and 4.8) with the diameter of abrasive particle ( $d_{aap}$ ) as in Eq. (4.22).

$$n_c = \frac{\pi r_{wp}}{2d_{aap}} \quad (4.22)$$

where,  $r_{wp}$  is the internal radius of hemispherical cup workpiece, and  $d_{aap}$  is the AAP's diameter. The AAPs travel a variable path length over the hemispherical cup surface when the magnetized MRP fluid with the hemispherical tool surface rotates over the rotating hemispherical cup workpiece (Fig. 4.7). The  $n^{\text{th}}$  AAP on the top edge of the circumference in one rotation of the tool completes the  $2\pi r_{wp}$  path length because at this position the abrasive is at  $r_{wp}$  radius of the centre of rotation axis as shown in Fig. 4.8. When the location of  $(n-1)^{\text{th}}$  AAP on the internal surface of the cup is observed, it makes  $\Phi$  angle from the radius of the hemispherical cup as shown in Fig. 4.8. Therefore, the radial position of the  $(n-1)^{\text{th}}$  active abrasive particle changes from  $r_{wp}$  to  $r_{wp} \cos \Phi$ . Similarly, an AAP at  $i^{\text{th}}$  position makes an angle  $\Phi'$  resulting to its radial position from the axis of the tool rotation (Fig. 4.8)  $r_{wp} \cos \Phi'$ . As the  $n_c$  is the total number of the AAPs in

single circumferential path length which make  $90^\circ$  of angle at point of the hemispherical workpiece. Therefore, the angle ( $\Phi'$ ) between the radius of hemispherical cup (radial position of  $n^{\text{th}}$  AAP) and the  $i^{\text{th}}$  AAP can be calculated by Eq. (4.23).

$$\Phi' = 90(1 - \frac{i}{n_c}) \quad (4.23)$$

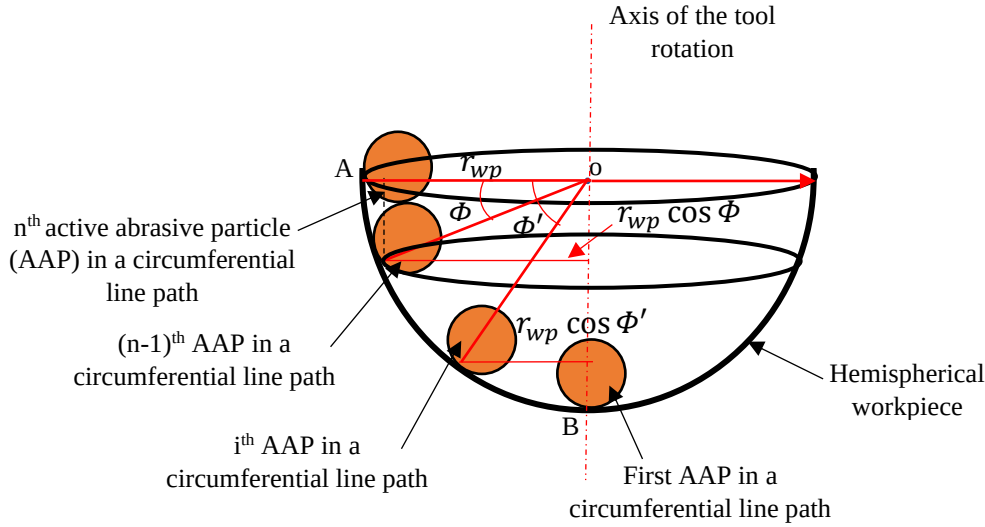


**Fig. 4.7.** Circular path followed by the AAPs due to the simultaneous motion of the tool and workpiece.

Therefore, the total length ( $L_p$ ) covered by the single AAP for shearing off the surface asperities from work part can be evaluated as in Eq. (4.24).

$$L_p = \frac{N_s \times \sum_{i=n}^{i=1} 2\pi r_{wp} \cos \Phi'}{N_{aap}} \quad (4.24)$$

where  $N_s$  is the number of circumferential paths over the hemispherical cup consisting of overall AAPs,  $N_{aap}$  is the total number of active abrasive particles,  $\Phi'$  is the angle subtended by random AAP with the circumferential path length at the centre of the of the hemispherical workpiece o as shown in Figs. 4.7 and 4.8. Further, to get length travelled by the single AAP ( $L_p$ ) lying on the surface of the hemispherical workpiece surface, total number of AAPs circumferential paths ( $N_s$ ) is required. As the radius of the hemispherical workpiece decreases from top to bottom as shown in Figs. 4.7 and 4.8, the number of active abrasive particles (AAPs) reduces at each circumferential level from top to bottom. Therefore, taking average of the number of abrasive particles making line path from top of the hemisphere workpiece to the bottom of the workpiece, total number of path length is calculated from Eq. (4.25).



$$N_s = \frac{C_{top} + C_{bottom}}{2d_{aap}} \quad (4.25)$$

where  $C_{top}$  is the circumference at the top edge of the hemispherical cup work part (point A),  $C_{bottom}$  is the circumference at the bottom of the hemispherical cup (point B) and  $d_{aap}$  is the diameter of the AAP.

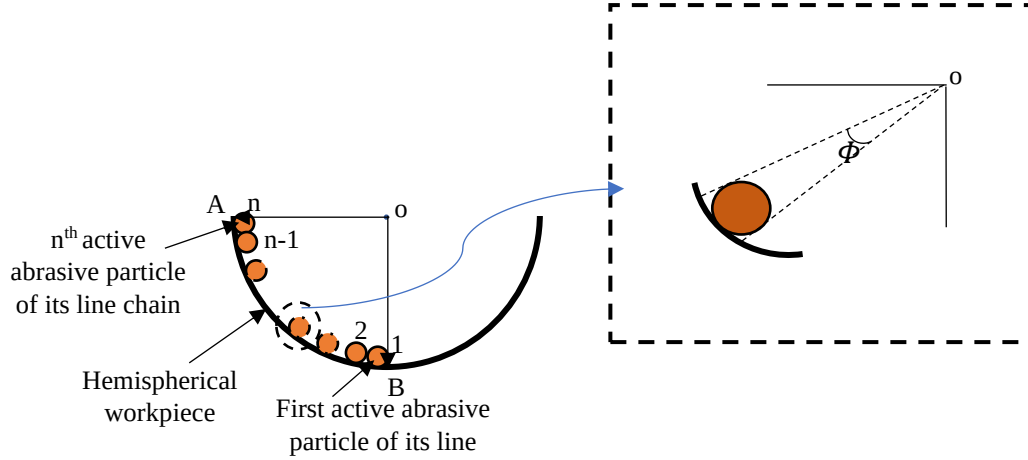


**Fig. 4.8.** Schematic diagram of the path length of active abrasive particles on the finishing surface.

Using Eqs. (4.20), (4.23), and (4.25) in Eq. (4.24), the total path length ( $L_p$ ) covered by the single AAP over the hemispherical cup surface is calculated as  $9.058 \times 10^{-5}$  m. The circular length covered by the single AAP signifies the path length over the acetabular cup surface followed by the AAPs. The clipping off the surface asperities from the cup surface is done by AAPs along the projected length  $L_p$  because of the simultaneous motion of work part and hemispherical shape-based tool surface leading to the fine finishing.

#### 4.1.2.4 Calculation of magnetic normal indentation force on the AAP present over the hemispherical acetabular workpiece surface in the working gap

In the present process, the finishing is performed by the stiffened MRP fluid over the work part surface. The MRP fluid gets stiffened owing to the applied magnetic field as the EIPs present in the fluid forms the columnar structure. As the magnetic flux concentration ( $B$ ) is higher on the tool surface (Fig. 4.6), therefore, the EIPs move towards the tool surface. Further, the nonmagnetic  $CeO_2$  abrasive experiences the normal magnetic force ( $F_{nrm}$ ) which is exerted by the EIPs. This contributes to the penetration of the AAPs into the hemispherical cup surface asperities. As the  $F_{nrm}$  acting on the active abrasive particle (AAP) is responsible for its penetration into the

acetabular workpiece, it is mandate to obtain the magnitude of the magnetic force transferred by an EIP to the AAP. This magnetic force ( $F_{nrm}$ ) acting on the AAP by the EIPs can be calculated from Eq. (4.26).

$$F_{nrm} = \frac{m_e \chi_{eip} B_c \frac{dB_c(g)}{dg}}{\mu_0} \quad (4.26)$$

where  $m_e$  is the mass of the single EIP and its value is  $2.3989 \times 10^{-11}$  kg,  $B_c$  is total magnetic field induced by the magnetic source at positional distance which is calculated by Eq. (4.17),  $\frac{dB_c(g)}{dg}$  is the positional gradient of the magnetic field along working gap and  $\chi_{eip}$  is the mass susceptibility of EIP ( $m^3/kg$ ). Further, the positional gradient of the magnetic field ( $\frac{dB_c(g)}{dg}$ ) can be calculated by using Eq. (4.17) and is given in Eq. (4.27).

$$\frac{dB_c(g)}{dg} = -51.609 \quad (4.27)$$

The negative value of the slope of the magnetic field ( $\frac{dB_c(g)}{dg} = -51.609$  from Eq. 4.27) reveals that the magnetic field is highest on the tool surface and least on the UHMWPE cup surface as depicted in Fig. 4.6. The lower magnetic field on the workpiece hemispherical surface as compared tool surface causes a better relative motion of the non-magnetic  $CeO_2$  abrasives on the finishing cup surface. However, if the higher magnetic field is obtained over the workpiece surface as compared to the tool surface, it may reduce the finishing performance as the EIPs tends to stick on workpiece surface and may resist the motion of the abrasive particles. Hence, this negative slope trend is useful and found in good agreement for finishing the hemispherical cup surfaces. The mass susceptibility of EIP ( $\chi_{eip}$ ) can be evaluated by Eq. (4.28) and reported in Table 4.3.

$$\chi_{eip} = \frac{\mu_0 M_{eip}}{B_c} \quad (4.28)$$

where  $M_{eip}$  denotes the magnetisation of the electrolytic iron particles which can be evaluated from the Fig. 4.5(b).

Using the mass of EIP,  $B_c$ ,  $\frac{dB_c(g)}{dg}$  and  $\chi_{eip}$  in Eq. (4.26), the normal force is calculated and reported in Table 4.3. Since,  $F_{nrm}$  is calculated at the various points in the working space, therefore the net indentation force ( $F_{ind}$ ) is calculated which is the average value of the  $F_{nrm}$  at different points in working gap. The  $F_{ind}$  is found which is equal to  $6.7473 \times 10^{-8}$  N. The  $F_{ind}$  value indicates the indentation of the AAP over the work part surface.

**Table 4.3.** Calculation of magnetic normal force at different points in the working space amid hemispherical tip-based tool and hemispherical cup work part.

| Position in the gap between hemispherical surface tool and the workpiece $g$ (m) | Total theoretical magnetic field, $B_c$ (T)<br>Eq. (4.17) | $\chi_{eip} (m^3/Kg) \times 10^{-4}$<br>Eq. (4.28) | Normal magnetic force ( $F_{nrm}$ )<br>$\times 10^{-8}$ (N)<br>Eq. (4.26) |
|----------------------------------------------------------------------------------|-----------------------------------------------------------|----------------------------------------------------|---------------------------------------------------------------------------|
| 0.1001                                                                           | 0.302                                                     | 2.37                                               | 7.0568                                                                    |
| 0.1002                                                                           | 0.297                                                     | 2.36                                               | 6.9330                                                                    |
| 0.1003                                                                           | 0.292                                                     | 2.36                                               | 6.8092                                                                    |
| 0.1004                                                                           | 0.287                                                     | 2.36                                               | 6.6854                                                                    |
| 0.1005                                                                           | 0.282                                                     | 2.36                                               | 6.5616                                                                    |
| 0.1006                                                                           | 0.276                                                     | 2.36                                               | 6.4378                                                                    |

#### 4.1.2.5 Theoretical analysis of the surface roughness for the present hemispherical tool based magnetorheological finishing process

In the present magnetorheological finishing (MRF) process, the removal of material from the hemispherical acetabular cup work part surface relies on the depth of the indentation ( $d_{in}$ ) of the AAP over the surface of acetabular cup work part surface as shown in Fig. 4.9. Further, the indentation of the AAP on the cup surface asperities relies on the effect of the net indentation force ( $F_{ind}$ ). The effect of the magnetic flux density (MFD) on the tool surface leads to the  $F_{ind}$  acting on the AAP by the EIPs. Further, the normal reactive force ( $F_r$ ) acts on the hemispherical cup surface which opposes the normal indentation force ( $F_{ind}$ ) when the AAP indent on the surface of the cup. Only when the  $F_{ind}$  acting on the AAP overcomes the reactive force ( $F_r$ ), the indentation on the work part takes place. In the present study, for the calculation of the depth of the indentation ( $d_{in}$ ), initially the indentation diameter ( $D_{ind}$ ) indented by the AAP over the work part surface due to normal force is calculated. For the calculation, the Brinell Hardness model is used. The model of hardness number is given by the Eq. (4.29) (Alam and Jha, 2017).

$$9.8 \times H_{BH} = \frac{2 \times 10^{-6} \times F_{ind}}{\pi d_{aap} \left( d_{aap} - \sqrt{d_{aap}^2 - D_{ind}^2} \right)} \quad (4.29)$$

Further, on rearranging, the Eq. (4.29) can be rewritten as the Eq. (4.30).

$$D_{ind} = \sqrt{d_{aap}^2 - \left( d_{aap} - \frac{2 \times 10^{-6} \times F_{ind}}{9.8 \pi H_{BH} d_{aap}} \right)^2} \quad (4.30)$$

where  $H_{BH}$  is the Brinell hardness number and its value is 150 kgf/mm<sup>2</sup> for UHMWPE,  $d_{aap}$  is the diameter of the CeO<sub>2</sub> abrasive particle and its value is  $19 \times 10^{-6}$  m,  $F_{ind}$  is the average magnetic

normal force due to EIPs and its value is  $6.7473 \times 10^{-8}$  N and  $D_{ind}$  is the indentation diameter as indented by the AAP over the hemispherical cup surface. Using these values in Eq. (4.30), the  $D_{ind}$  is calculated as  $7.650379 \times 10^{-9}$  m. Further, from Fig. 4.9, the depth of indentation ( $d_{in}$ ) can be calculated using Eq. (4.31).

$$d_{in} = \frac{d_{aap}}{2} - \frac{1}{2} \sqrt{d_{aap}^2 - D_{ind}^2} \quad (4.31)$$

Using the value of abrasive diameter ( $d_{aap}$ ) and indentation diameter ( $D_{ind}$ ) in Eq. (4.31),  $d_{in}$  by an AAP is evaluated as  $7.70109 \times 10^{-13}$  m. Further, using the Eq. (4.31), the cross-sectional area generated by the AAPs chain over the surface of the acetabular cup ( $A_{in}$ ) is given by Eq. (4.32) (Alam and Jha, 2017).

$$A_{in} = \frac{d_{aap}^2}{4} \sin^{-1} \left\{ \frac{2\sqrt{d_{in}(d_{aap}-d_{in})}}{d_{aap}} - \sqrt{d_{in}(d_{aap}-d_{in})} \left( \frac{d_{aap}}{2} - d_{in} \right) \right\} \quad (4.32)$$

Using Eq. (4.32), the cross-sectional area generated by the AAP of the line chain over the surface of the acetabular cup ( $A_{in}$ ) is calculated as  $9.9317 \times 10^{-12}$  m<sup>2</sup>.

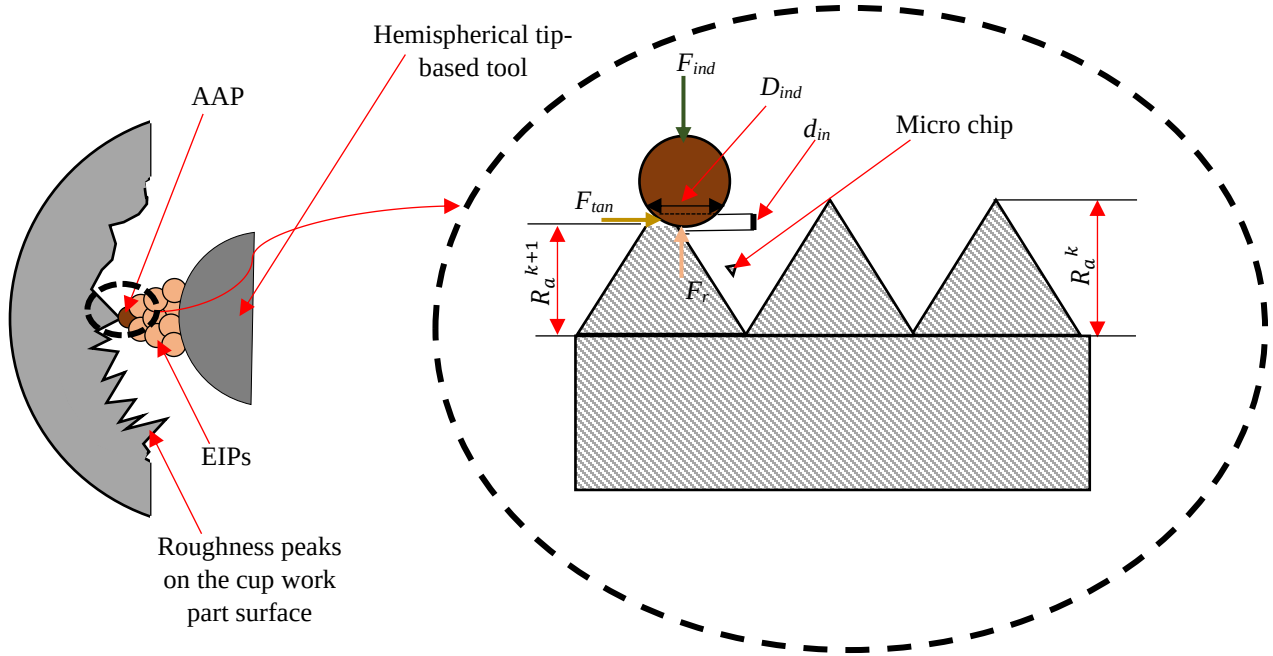


**Fig. 4.9.** Schematic of single active abrasive particle indenting into the surface roughness peaks of the acetabular cup surface during the MR finishing due to the normal magnetic force ( $F_{ind}$ ).

Further, the theoretically calculated volume of the material removed ( $V_{MR}$ ) by the total number of AAP ( $N_{aap}$ ) from the hemispherical acetabular work part during  $k^{th}$  finishing cycle is calculated by Eq. (4.33).

$$V_{MR} = A_{in} \times N_{aap} \times L_p \times k \quad (4.33)$$

where  $A_{in}$  is the indented cross-sectional area ( $m^2$ ),  $N_{aap}$  is the total number of active abrasive particles,  $L_p$  is the total length covered by the single AAP of the chain like structure in a single rotation of the tool (m) and  $k$  is the  $k^{th}$  number for finishing cycle.

Hence in the present work, material removal volume from the acetabular cup surface by the AAPs can be calculated theoretically using Eq. (4.33). Further, according to the continuity equation, the volume of material removed from all trenches made by all indenting active abrasive particles in one finishing cycle ( $V_{MR}$ ) is the equal material cut-out from the finishing surface of the hemispherical work part ( $V_{in}$ ) in a  $k^{th}$  MR finishing cycle. Further,  $V_{in}$  can be calculated by Eq. (4.34).

$$V_{in} = 2\pi r_{wp} \times 2r_{wp} \times k \times d_{in} \quad (4.34)$$

where  $r_{wp}$  is the radius of hemispherical cup workpiece and its value is  $10.5 \times 10^{-3}$  m. Further according to continuity equation, equating  $V_{MR}$  to  $V_{in}$  using Eqs. (4.33) and (4.34), the Eq. (4.35) can be evaluated as

$$A_{in} \times N_{aap} \times L_p \times k = 2\pi r_{wp} \times 2r_{wp} \times d_{in} \times k \quad (4.35)$$

For the calculation of material cut-out from the surface of the acetabular hemispherical cup ( $V_{in}$ ) in a single MR finishing cycle, the total indentation depth by the AAP ( $d_{in}$ ) is found as  $d_{in} = 7(R_a^k - R_a^{k+1})$  (Jain *et al.*, 1999), where  $R_a^k$  is the average surface roughness value in  $(k)^{th}$  finishing cycle of the work part surface and  $R_a^{k+1}$  is the average surface roughness value in  $(k+1)^{th}$  finishing cycle. Using the value of  $d_{in}$ , Eq. (4.34) can be rewritten as Eq. (4.36) (Jain *et al.*, 1999).

$$V_{in} = 2\pi r_{wp} \times 2r_{wp} \times 7(R_a^k - R_a^{k+1}) \quad (4.36)$$

Further, using Eq. (4.36), Eq. (4.35) can be written as Eq. (4.37).

$$A_{in} \times N_{aap} \times L_p \times k = 2\pi r_{wp} \times 2r_{wp} \times 7(R_a^k - R_a^{k+1}) \times k \quad (4.37)$$

On rearranging, Eq. (4.37) can be rewritten as Eq. (4.38).

$$R_a^{k+1} = R_a^k - \left( \frac{A_{in} \times N_{aap} \times L_p}{7 \times 2\pi r_{wp} \times 2r_{wp}} \right) \quad (4.38)$$

Hence in this process mechanism, the reduction in  $R_a$  after every cycle from the hemispherical cup polymer work part by the AAPs can be calculated theoretically using Eq. (4.38). From Eq. (4.38),

it is clearly served that radius of work part, number of AAPs, area of indentation, and circular path length covered by the AAPs effects the finishing performance in this process. On the basis of the involved parameters in the present MR finishing process, the surface roughness can be predicted for the hemispherical shape acetabular cup surface. Further, experimentations are performed and the theoretical model is validated in Chapter 6 (section 6.1).

## **4.2 Theoretical analysis for fine finishing of the polymer gears using the magnetorheological bevel gear finishing (MRBGF) process**

### **4.2.1 Material removal mechanism**

In the present MRBGF process, for the fine finishing, each polymer BG's tooth profile gets meshed properly with the bevel gear finishing (BGF) tool tooth surface as the MRP fluid is within the working space. Further, as the magnetic field gets induced over the electromagnetic BGF tool surface due to direct current ( $I$ ), the EIPs move towards the surface of the tool (higher concentration of magnetic flux) and abrasives being a nonmagnetic move towards the surface of polymer bevel gear (BG) workpiece (lower concentration of magnetic flux). The abrasive particles are entrenched by the magnetic EIPs which form a structure like a chain. These abrasives liable for the clipping of the asperities from the polymer BG surface are known as active abrasive particles (AAPs). Further, the material gets abraded by the indented AAPs from the polymer BG tooth surface locality in the form of microchips due to the BGF tool and the polymer BG simultaneous rotation as shown in Fig. 4.10. In the MRBGF process, the material removal is because the AAP's abrasion action over the polymer BG surface occurs with time. Three different forces act on the AAPs while abrasion of material from the polymer BG surface, naming magnetic normal force ( $F_{nm}$ ), the tangential force due to tool rotation ( $F_{tt}$ ), and tangential force due to workpiece rotation ( $F_{tw}$ ). Owing to the action of these forces, the removal of material from the polymer BG occurs as espied in Fig. 4.10. Firstly, owing to the  $F_{nm}$ , the magnetized EIPs in chains pushes the AAP on the polymer BG workpiece surface in the working gap. Owing to the  $F_{nm}$ , the AAP penetrates over the polymer BG tooth surface.

Further, due to the BGF tool and polymer BG simultaneous rotations, the fine finishing over the polymer BG tooth surface is achieved through abrasion action. As the BGF tool rotates, the firmly clenched AAPs in the EIPs chain also rotate in the same direction and appear to move outwards tangentially.

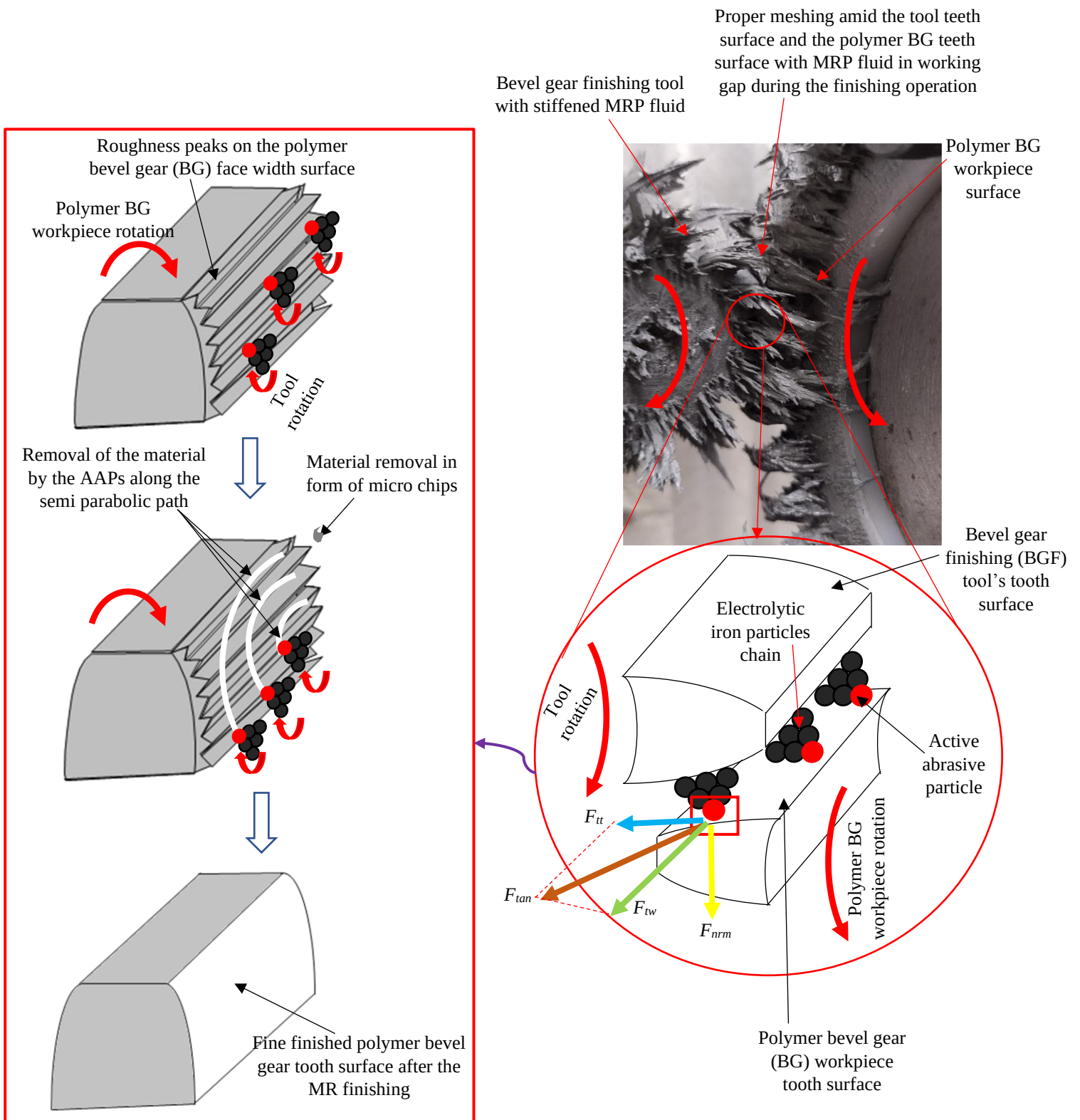


**Fig. 4.10.** Mechanism of material removal by the active abrasive particles over polymer bevel gear workpiece surface with the different forces acting during the MRBGF process.

As a result, the tangential force ( $F_{tt}$ ) acts over the AAP. Due to the  $F_{tt}$ , the shearing takes place in the tangential direction to the asperities present on the polymer BG surface as depicted in Fig. 4.10. Also, as the BGF tool tooth and each polymer BG tooth surface meshes properly with MRP fluid amid working space, the polymer BG rotates along with the BGF tool simultaneously. Owing to this simultaneous rotation, the AAPs tend to rub over the polymer BG surface. This produces the tangential force due to workpiece ( $F_{tw}$ ) along the polymer BG surface. The  $F_{tw}$  acting over the polymer BG surface owing to which roughness peaks get clipped off along the tooth surface (Fig. 4.10). Owing to the  $F_{tt}$  and  $F_{tw}$  acting due to tool and workpiece simultaneous rotation during finishing, the AAPs follow the semi-parabolic path. The clipping off the asperities from the polymer BG surface tends to take place along this semi-parabolic path as depicted in Fig. 4.10. Further, the resultant of the  $F_{tt}$  and  $F_{tw}$  is the net tangential force ( $F_{tan}$ ) which is responsible for abrading the material from the vicinity of the penetrated AAP over the polymer BG surface (Fig. 4.10). Since each tooth of the BGF tool properly meshes with the polymer BG tooth with the MRP fluid in working space, therefore with every tool rotation, each tooth of the polymer BG workpiece is rotated and leading to the overall clipping of asperities from BG surface by the AAPs. This repetitive action of the tangential force (owing to of tool and workpiece rotating simultaneously) over the asperities contributes to the material removal from the polymer BG surface. As a result, the effective finishing of the overall polymer BG is achieved in minimum time using the MRBGF process.

#### ***4.2.2 Theoretical analysis of volume of material removal and surface roughness during the magnetorheological (MR) finishing of the bevel gears (BGs)***

In the present work, an attempt has been made to develop a theoretical mathematical model for the volume of the material removal and surface roughness for the straight bevel gear work part surface using the present MR finishing process. For the development of the mathematical model, following assumptions have been made.

- In the MRP fluid, the abrasive particles are uniformly distributed and also the shape and size of abrasive particles are uniform.
- The average size of  $\text{CeO}_2$  abrasive particles is assumed to be 19  $\mu\text{m}$  in diameter, and electrolytic iron particles is assumed to be 30  $\mu\text{m}$  and both are spherical in shape.
- All other minor forces such as gravitational forces and inertia forces are neglected on the active abrasive particles during the finishing operation.



- Magnetic losses and leakages are not considered in this study.

#### 4.2.2.1. Calculation of number of active abrasive particles in the working gap

In the present work, there is predefined working space amid the straight bevel gear (BG) work part surface and the bevel gear finishing (BGF) magnetic tool surface in which the MRP fluid is placed as shown in Fig. 4.10. Before the study of the theoretical model for removal of material and reduction in surface roughness by the AAPs from the BG work part surface using MR finishing process, it is necessary to analyse the number of the AAPs present in the MRP fluid in the working gap. For the calculation of the AAPs in the MRP fluid, first the total volume of MRP fluid ( $V_{mrp}$ ) present in the working space needs to be calculated. Since, the MRP fluid is placed amid the projected area of the bevel gear work part with thickness ( $g$ ). Therefore,  $V_{mrp}$  can be given by Eq. (4.39).

$$V_{mrp} = (A_{gw}) \times g \quad (4.39)$$

where  $A_{gw}$  is the projected area of the straight bevel gear workpiece ( $\text{mm}^2$ ) on which MRP fluid is placed and  $g$  is the thickness of MRP fluid which is 0.6 mm. Further, the projected area of bevel gear work part ( $A_{gw}$ ) is calculated using Eq. (4.40).

$$A_{gw} = 2(A_{fg}) + A_{bg} \quad (4.40)$$

where  $A_{fg}$  is the projected area of face-flank of the straight bevel gear work part ( $\text{mm}^2$ ) and  $A_{bg}$  is the projected area of the bottom land of the bevel gear work part ( $\text{mm}^2$ ). Further, area of face-flank of the bevel gear ( $A_{fg}$ ) and area of the bottom land of the bevel gear ( $A_{bg}$ ) can be calculated by Eqs. (4.41) and (4.42) respectively (Fig. 4.11).

$$A_{fg} = L_i \times f_w \quad (4.41)$$

$$A_{bg} = L_g \times f_w \quad (4.42)$$

where  $L_i$  is the involute profile length of the bevel gear (mm),  $f_w$  is the face width of the bevel gear (mm) as shown in Fig. 4.11 and  $L_g$  is the bottom gap between two teeth of the bevel gear (mm). The values of the  $f_w$  and  $L_g$  are directly measured using the bevel gear and their values are 14.54 mm and 3.7 mm respectively in the present case. However, length of involute profile of present used straight bevel gear is a curve and not a straight line as shown in Fig. 4.11(a). Therefore, it can be calculated using Eq. (4.43) (Shaikh and Jain, 2014).

$$L_i = r_{iw} \times \alpha \quad (4.43)$$

where  $r_{iw}$  is the involute arc radius of the bevel gear work part (mm) (Fig. 4.11b) and  $\alpha$  is the subtended involute angle at the center. Further, from the Fig. 4.11(b) using  $\Delta ojl$ , the involute arc radius ( $r_{iw}$ ) can be calculated as given in Eq. (4.44).

$$r_{iw} = r_{bw} \times \tan \delta \quad (4.44)$$

where  $r_{bw}$  is the base circle of the bevel gear work part which is 41.7 mm and  $\delta$  is the pressure angle which is  $20^\circ$ , the involute arc radius ( $r_{iw}$ ) is calculated as 15.18 mm (Eq. 4.44). Further in Fig. 4.11(a) from using  $\Delta abd$  and  $\Delta adc$ , the expression can be written as (Eq. 4.45).

$$\sin(\alpha) = \frac{cd}{ac} + \frac{bd}{ab} \quad (4.45)$$

where,  $cd$  and  $bd$  is  $L_{cw}/2$  ( $L_{cw}$  is the chord length of the involute arc) and  $ac$  and  $ab$  is  $r_{iw}$ .

Therefore, Eq. (4.45) can be rewritten as Eq. (4.46).

$$\sin(\alpha) = \frac{L_{cw}}{r_{iw}} \quad (4.46)$$

Further,  $L_{cw}$  can be calculated by the Eq. (4.47) using  $\Delta bce$  in Fig. 4.11(a).

$$L_{cw} = \sqrt{D_d^2 + \left(\frac{D_b - D_t}{2}\right)^2} \quad (4.47)$$

where  $D_d$  is the depth of the bevel gear which is 6.7 mm,  $D_t$  is the top land length of bevel gear which is 2.3 mm and  $D_b$  is the bottom land length of the bevel gear which is 4.8 mm. Using above details, the chord length of involute arc ( $L_{cw}$ ) is calculated as 6.81 mm (Eq. 4.47). Further using Eqs. (4.44) and (4.47) in Eq. (4.46), the subtended involute angle at the center ( $\alpha$ ) is calculated as  $26.65^\circ$ . Using Eqs. (4.44) and (4.46) in Eq. (4.43), the involute length of the bevel gear ( $L_i$ ) is calculated as 7.06 mm.

Further, with the help of the calculated values of the involute profile length of the bevel gear ( $L_i$ ), the face width of the bevel gear ( $f_w$ ) and the bottom gap between two teeth of the bevel gear ( $L_g$ ) in Eqs. (4.41) and (4.42), the projected area of the bevel gear work part ( $A_{gw}$ ) is calculated as  $259.10 \text{ mm}^2$  (Eq. 4.40). Using the values of projected area of the straight bevel gear workpiece on which MRP fluid is placed ( $A_{gw}$ ) as  $259.10 \text{ mm}^2$  and thickness of the MRP fluid ( $g$ ) as 0.6 mm, the volume of the MRP fluid ( $V_{mrp}$ ) amid the bevel gear work part and the BGF tool surface is found as  $155.462 \text{ mm}^3$  (Eq. 4.39). For the present study, the volume concentration of the MRP fluid is taken as 20 %  $\text{CeO}_2$  abrasive particles, 20 % EIPs and 60 % base fluid.

Therefore, the total volume of the abrasive particles ( $V_{ab}$ ) present in the MRP is calculated by the Eq. (4.48).

$$V_{ab} = \frac{20}{100} \times V_{mrp} \quad (4.48)$$

Using the value calculated from Eq. (4.39), the volume of the abrasive particles ( $V_{ab}$ ) is calculated as 31.09 mm<sup>3</sup> (Eq. 4.48).

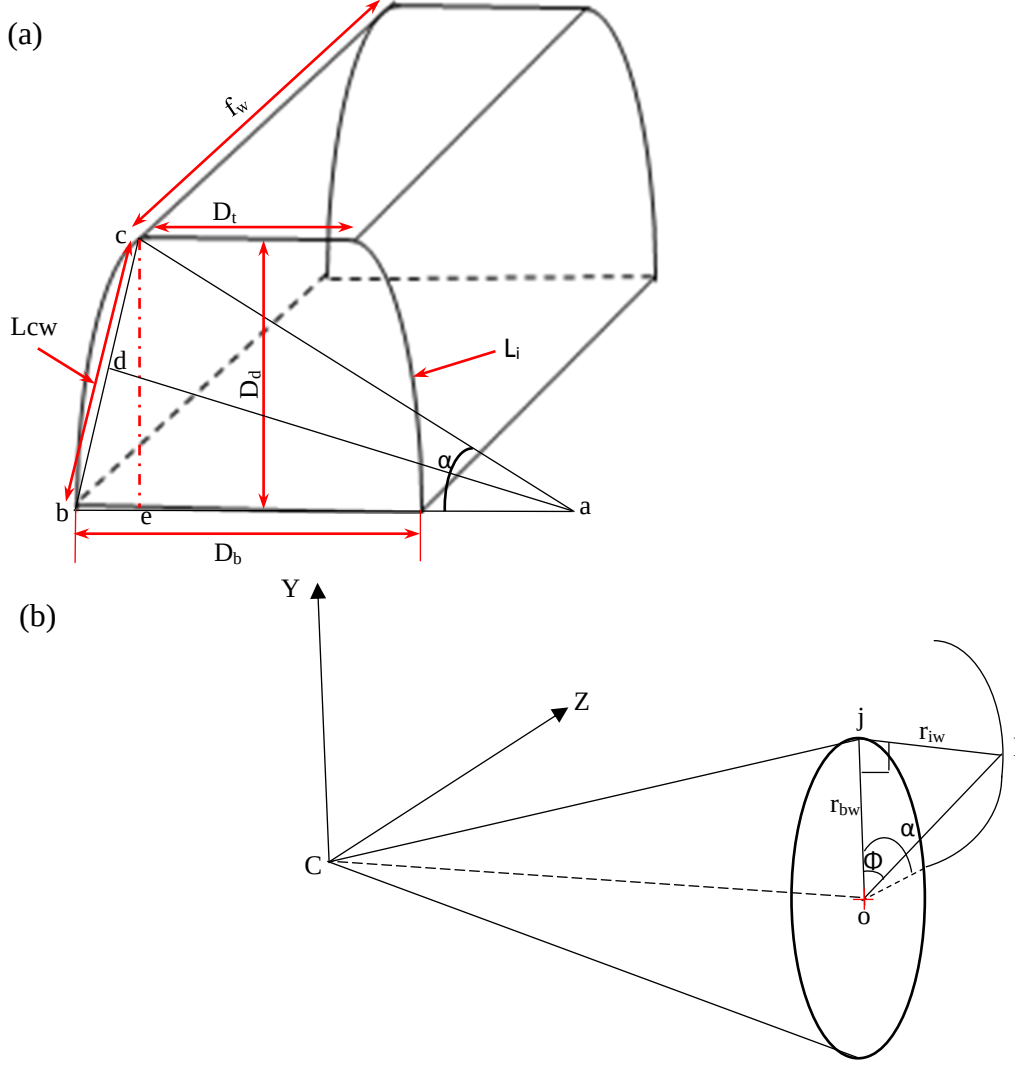


**Fig. 4.11.** (a) Schematic diagram of straight bevel gear with its parameters and (b) involute arc diagram.

Further, the total number of the CeO<sub>2</sub> abrasive particles present in the working space ( $N_{ap}$ ) amid the bevel gear work part surface and the BGF tool is calculated by Eq. (4.49).

$$N_{ap} = \frac{V_{ab}}{V_{aap}} \quad (4.49)$$

where  $V_{aap}$  is the volume of the single CeO<sub>2</sub> abrasive particle which can be calculated by Eq. (4.50).

$$V_{aap} = \frac{4\pi r_{ap}^3}{3} \quad (4.50)$$

where  $r_{ap}$  is the radius of the single CeO<sub>2</sub> abrasive particle which is  $9.5 \times 10^{-3}$  mm. Putting the value of  $r_{ap}$  in Eq. (4.50), the volume of the single CeO<sub>2</sub> abrasive particle ( $V_{aap}$ ) is calculated as  $3.59 \times 10^{-6}$  mm<sup>3</sup>. Next, using the value of the  $V_{ab}$  and  $V_{aap}$  in Eq. (4.49), the total number of the CeO<sub>2</sub> abrasive particles present in the working space ( $N_{ap}$ ) amid the bevel gear work part and the BGF tool is found as 8660167.

Further, the total number of active abrasive particles ( $N_{aap}$ ) which are accountable for shearing of the roughness peaks from the bevel gear work part surface can be calculated by Eq. (4.51).

$$N_{aap} = \frac{20}{100} \times \frac{A_{gw} \times 2r_{ap}}{V_{aap}} \quad (4.51)$$

Using the value of the  $A_{gw}$ ,  $r_{ap}$  and  $V_{aap}$  in Eq. (4.51), the  $N_{aap}$  are found as 274250.

#### 4.2.2.2. Calculation of the path length of the single active abrasive particle over the BG work part during its surface finishing

In the present study, due to the tool rotation, the tangential force ( $F_{tan}$ ) acts owing to which the AAP clips off the surface asperities from the work part and tends to move tangentially outwards as shown in Fig. 4.10.

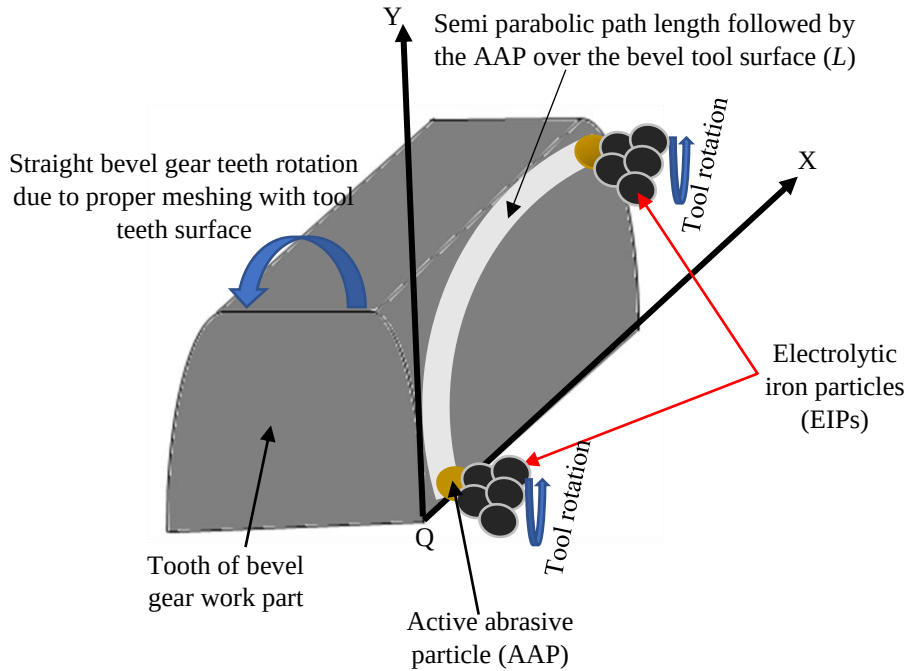


**Fig. 4.12.** Semi parabolic path followed by the AAP over the bevel gear work part tooth surface.

Further, due to the proper meshing amid the tool teeth surface and bevel gear work part teeth surface with the MRP fluid in the predefined space, the bevel gear work part gets rotated with the

rotation of the tool. Due to the simultaneous rotation of the tool and the bevel gear work part, AAP tends to produce rubbing shear force which acts over the width of the bevel gear due to which shearing of surface asperities from the work part surface takes place (Fig. 4.10). This enhances the efficacy of the finishing process and reduces the overall finishing time. Owing to the tangential force and rubbing force acting on the AAP during finishing due to the simultaneous rotation of the tool and the bevel gear work part, the path followed by the single AAP over the bevel gear work part is semi parabolic as shown in Fig. 4.12. The equation of the semi parabolic path covered by AAP over the bevel gear work part is given by Eq. (4.52).

$$\left(\frac{f_w}{L_i^2}\right)y^2 = x \quad (4.52)$$

Further, the length of the arc for the semi parabolic path ( $L$ ) covered by AAP over the bevel gear work part surface is given by Eq. (4.53).

$$\int_0^L dl = \int_0^{f_w} \int_0^{L_i} \sqrt{1 + \left[\left(\frac{dx}{dy}\right)\right]^2} dx dy \quad (4.53)$$

The Eq. (4.53) can be rewritten as Eq. (4.54).

$$L = \int_0^{f_w} \int_0^{L_i} \sqrt{1 + \left[2\left(\frac{f_w}{L_i^2}\right)y\right]^2} dx dy \quad (4.54)$$

Assuming  $\frac{f_w}{L_i^2}$  as constant  $K$ , the Eq. (4.54) can be rewritten as Eq. (4.55).

$$L = \int_0^{f_w} \int_0^{L_i} \sqrt{1 + [2Ky]^2} dx dy \quad (4.55)$$

On solving the Eq. (4.55), the length of the arc for the semi parabolic path ( $L$ ) covered by AAP over the bevel gear work part surface can be calculated using Eq. (4.56).

$$L = \frac{1}{2} \sqrt{f_w^2 + 16L_i^2} + \frac{f_w^2}{8L_i} \ln \left( \frac{4L_i + \sqrt{f_w^2 + 16L_i^2}}{f_w} \right) \quad (4.56)$$

Further, using the calculated values of face width ( $f_w$ ) of straight bevel gear as 14.54 mm and involute length of straight bevel gear ( $L_i$ ) as 7.06 mm, the length of the arc for the path ( $L$ ) covered by AAP over the bevel gear work part surface is evaluated as 21.18 mm (Eq. 4.56).

#### 4.2.2.3. Calculation of the theoretical reduction in surface roughness model for the straight bevel gear during the present MR finishing process

In the MR finishing process, the material removed from the bevel gear (BG) work part surface relies on the depth of the indentation ( $d_{in}$ ) of the active abrasive particle (AAP) over the BG work part surface. Further, the indentation of the active abrasive particles on the surface asperities

present in the bevel gear work part is dependent on the effect of the overall magnetic force ( $F_{nm}$ ). The magnetic force acting on the AAP due to EIPs is owned to the effect of the concentration of the magnetic flux on the tool surface. Owing to the magnetic force when the AAP indents on the BG work part surface, a normal reactive force  $F_r$  as shown in Fig. 4.13 is acted by the work part surface which opposes the normal force. Only when the normal force acting on the AAP overcomes the reactive force, the indentation on the work part takes place. In the present study, for the calculation of the indentation diameter as indented by the AAP over the bevel gear work part surface due to normal force, the Brinell Hardness model is used. The model of hardness number is given by the Eq. (4.29).

Further, indentation diameter ( $D_{ind}$ ) indented by the AAP over the bevel gear polymer work part surface can be evaluated by Eq. (4.30), where  $H_{BH}$  is the Brinell hardness number of polyamide material is  $110 \text{ kgf/mm}^2$ ,  $d_{aap}$  is the diameter of the  $\text{CeO}_2$  abrasive particle and its value is  $19 \times 10^{-6} \text{ m}$ ,  $F_{ind}$  is the overall indentation force due to the magnetization of EIPs and its value is  $4.0698 \times 10^{-7} \text{ N}$  (Singh and Singh, 2020). Using these values in Eq. (4.30), the  $D_{ind}$  is calculated as  $1.224 \times 10^{-8} \text{ mm}$ . Further, from Fig. 4.13, the depth of indentation ( $d_{in}$ ) can be calculated using Eq. (4.31). Using the value of abrasive diameter ( $d_{aap}$ ) and indentation diameter ( $D_{ind}$ ) in Eq. (4.31), the depth of indentation ( $d_{in}$ ) is evaluated as  $1.847 \times 10^{-10} \text{ mm}$ .

Further using Eq. (4.31), the indented cross sectional semi parabolic area generated by the AAP ( $A_{ind}$ ) on the straight bevel gear work part is given by Eq. (4.32). Using Eq. (4.32), the indented cross sectional semi parabolic area generated by the AAP ( $A_{ind}$ ) is calculated as  $1.77 \times 10^{-8} \text{ mm}^2$ . Further, the theoretically calculated volume of the material removed ( $V_{MR}$ ) by the single active abrasive particle (AAP) from the bevel gear work part surface across a semi parabolic path during  $i^{\text{th}}$  finishing cycle is calculated by Eq. (4.33). Using Eq. (4.33), the theoretical volume of material removed ( $V_{MR}$ ) by the total number of AAPs ( $N_{aap}$ ) present on the bevel gear work part surface is calculated by Eq. (4.34).

On rearranging Eq. (4.36) and (4.37), the surface roughness can be calculated by Eq. (4.57).

$$R_a^{i+1} = R_a^i - \left( \frac{N_{aap} \times A_{ind} \times L \times i}{7 \times A_{gw}} \right) \quad (4.57)$$

Hence, the reduction in surface roughness after every cycle from the bevel gear work part by the AAPs can be calculated theoretically using Eq. (4.57). Further, experimentations are performed and the theoretical model is validated in Chapter 6 (section 6.2).

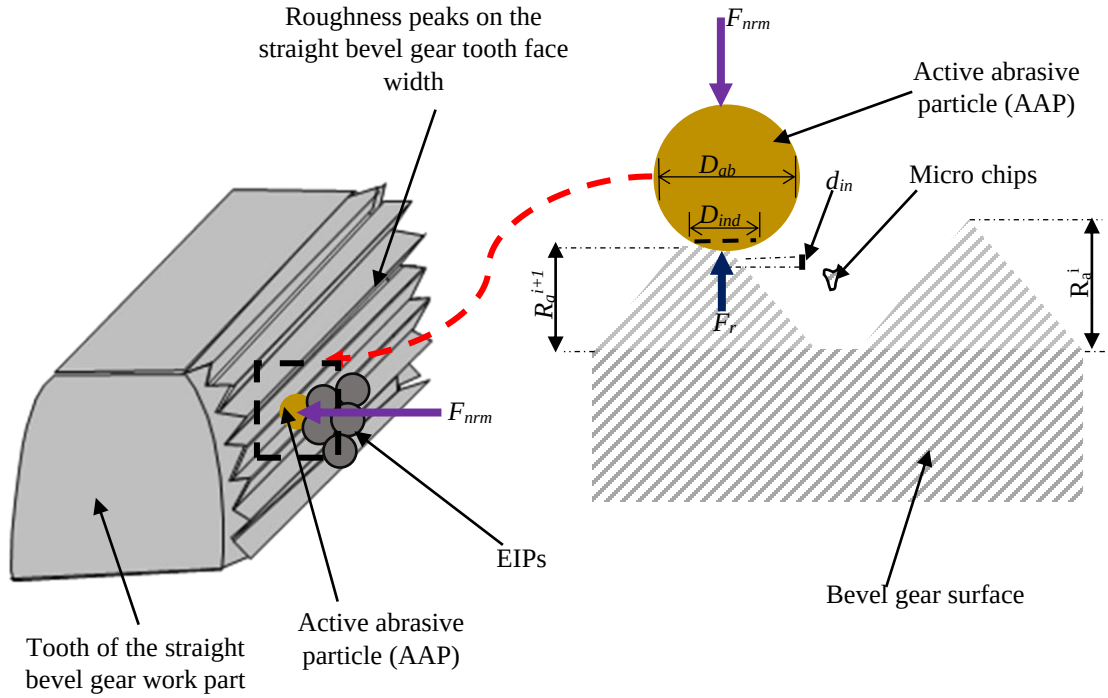


**Fig. 4.13.** Schematic of single active abrasive particle indenting into the surface roughness peaks of the bevel gear during the MR finishing due to the normal force ( $F_{nrm}$ ).

### 4.3 Theoretical analysis for fine finishing of the additive manufactured (AM) typical turbine blade surface using the magnetorheological finishing (MRF) process

#### 4.3.1 Material removal mechanism

MRP fluid comprising of the EIPs, graphene and abrasives are used in this study for fine finishing of the additive manufactured (AM) typical wind turbine blades surface effectively. During the MRF process, various forces act on the AAPs, causing them to indent against the workpiece surface and clip off the roughness peaks. The AAPs are firstly indents over the exterior work part surface owing to the magnetizing current in the present process for fine finishing of the workpiece surface. As the magnetizing current is applied, the electromagnetic hexagonal tool tip surface gets magnetized. As a result, the magnetic EIPs move towards the hexagonal tool tip surface, pushing the non-magnetic abrasives towards the workpiece surface with levitation force. The difference in the gradient of magnetic flux gradient (MFD) which works normally on the AAP through the EIPs chain, generates the normal magnetic force ( $F_{nrm}$ ). The  $F_{nrm}$  causes the AAP to penetrate over the work part surface as shown in Fig. 4.14. The magnetic force produced during the process depends on the current intensity. The MFD increases as the current increases, resulting in an increase in

magnetic force. Furthermore, because to the tool core's rotary and workpiece reciprocatory action, the indented AAPs shear off the surface asperities. As the tool rotates, the indented AAPs retained in the MRP fluid's EIPs chain structure tend to emerge outwards tangentially, clipping the material from the work part's surface asperities as depicted in Fig. 4.14(a).

The indented AAPs that are held in the EIPs chain structure of the MRP fluid tend to come outwards tangentially as the tool rotates, clipping the material from the work part's surface asperities. Owing to this relative motion, the work part and AAPs experience the tangential force due to tool rotation ( $F_{tt}$ ) which leads to the upsurge in the speed of the clipping of the roughness peaks from the work part surface. Next, owing to the reciprocatory movement of the workpiece, an axial force along Z- axis ( $F_{az}$ ) is applied on the active abrasive towards the workpiece along the axial direction as depicted in Fig. 4.14. Owing to the simultaneous rotary motion of tool and reciprocatory motion of workpiece, the AAPs follows the raster path over the workpiece surface along which the shearing of asperities occurs as depicted in Fig. 4.14(b). Next, the tangential shear force ( $F_{tan}$ ) acting over the workpiece surface through the AAP is the resultant of the  $F_{tt}$  and  $F_{az}$ . The repetitive simultaneous action of the tangential shear and axial force over the asperities contributes to the material removal from the workpiece surface, resulting the effective finishing as depicted in Fig. 4.14(c).

In the MR finishing (MRF) process, magnetorheological polishing (MRP) fluid is an essential part to perform fine finishing. The conventional MRP fluid comprises magnetic EIPs, polishing abrasives, and base fluid. For reinforcing the MRP fluid, graphene is introduced for the first time for fine finishing of the AM components. The effect of graphene particles on MRP fluid increases the viscosity under magnetic field influence (Thiyagu *et al.*, 2019).

As illustrated in Fig. 4.15, the effect of the graphene during the material removal mechanism from the AM typical wind turbine blades workpiece surface may be understood. Figure 4.15(a) depicts the removal of material from the workpiece surface with the conventional MRP fluid i.e., EIPs and abrasives. The non-magnetic abrasive particles interact with the workpiece surface in this case, allowing them to participate in the actual material removal process. The abrasive particles are entrenched in the EIPs chain under the magnetic field presence, and the hydrodynamic or fluid pressure created during MRF is transferred to the work surface via the abrasive particles. Due to the stiffened MRP fluid, the AAP penetrates to a specific depth ( $d$ ) (Fig. 4.15a) and tries to remove the material owing to the simultaneous tool rotation and workpiece reciprocation.



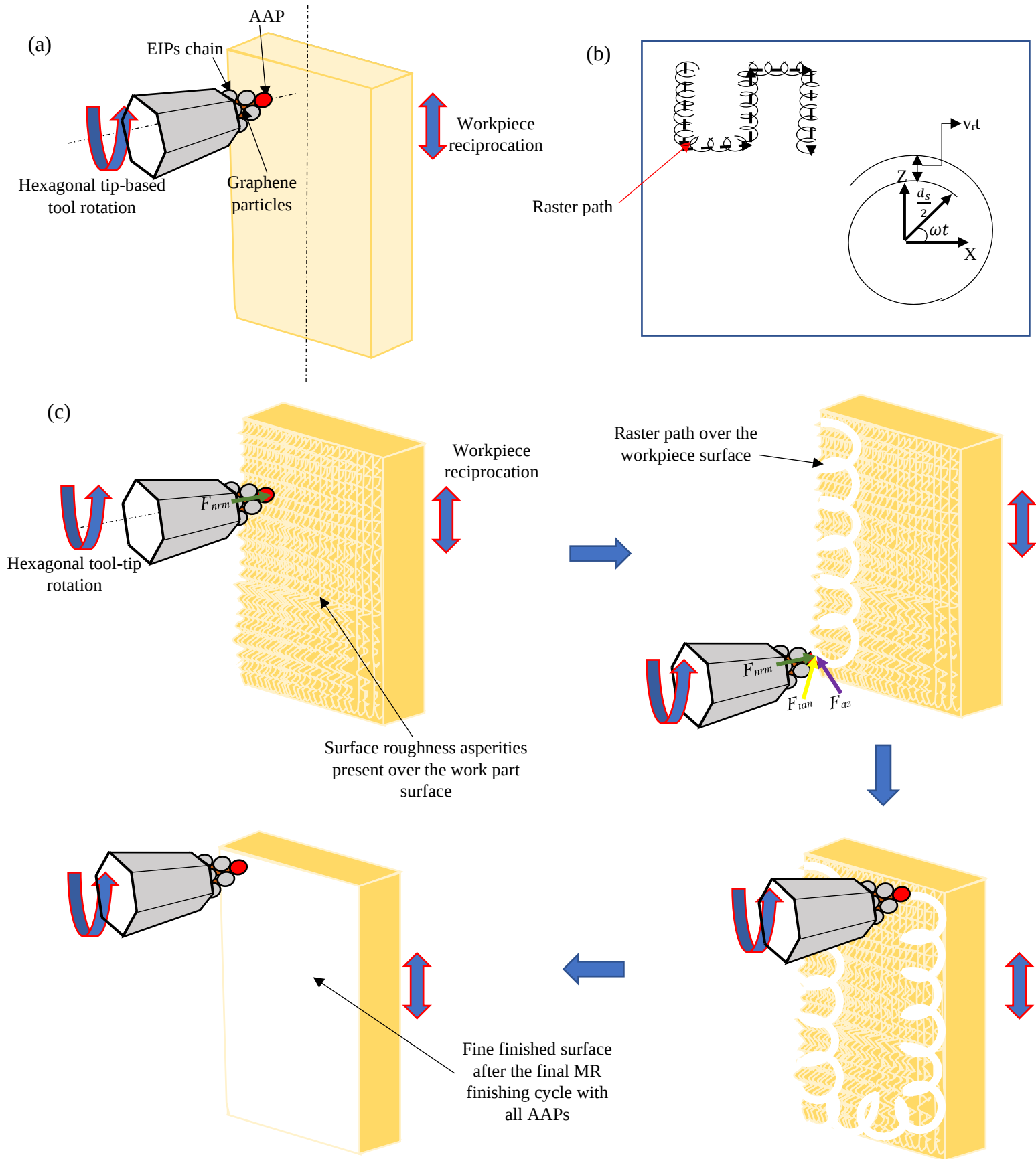


**Fig. 4.14.** (a) Material removal for fine finishing of workpiece surface using novel hexagonal tip-based tool, (b) path followed by AAPs and (c) forces acting while finishing.

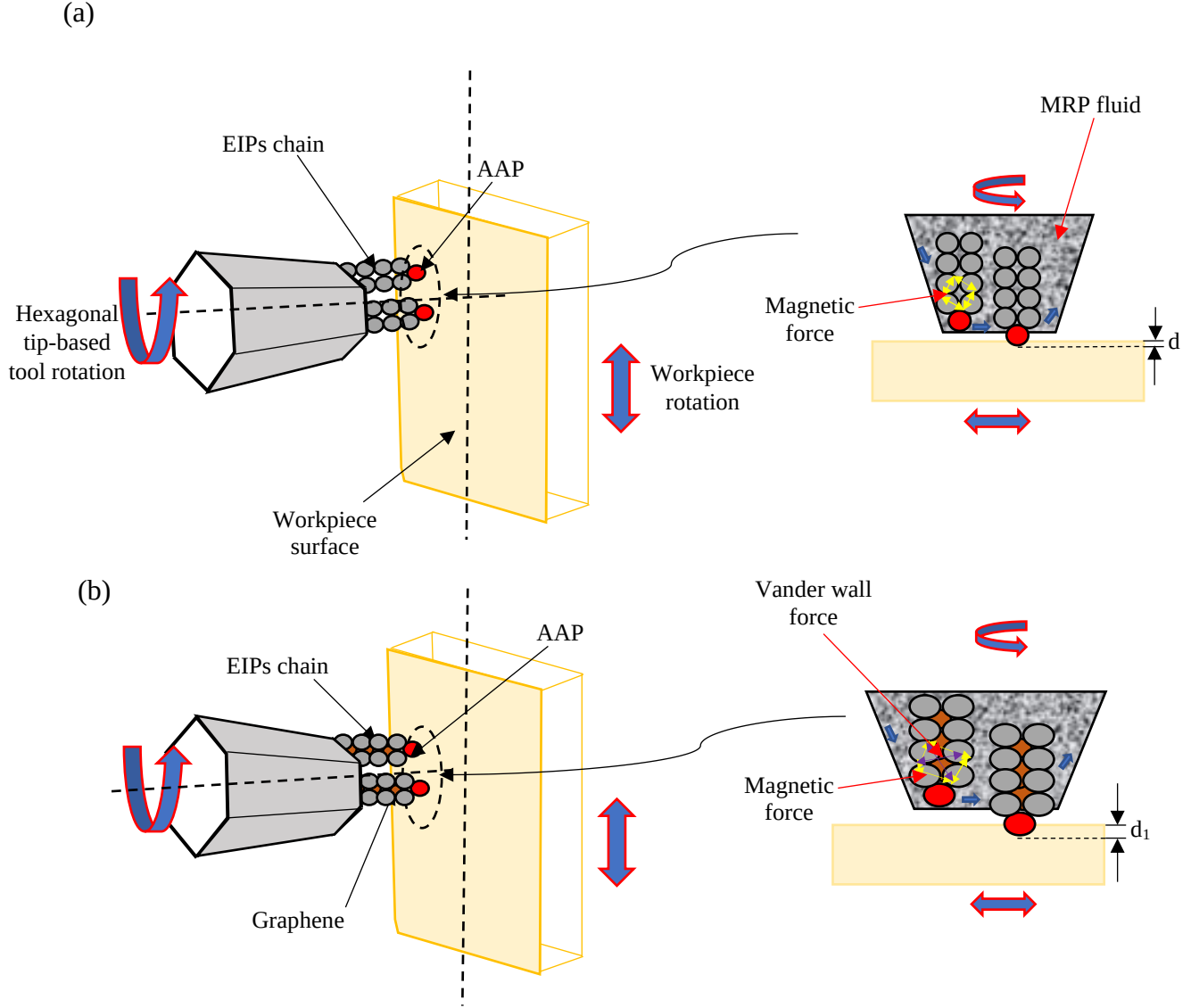


**Fig. 4.15.** Schematic representation of material removal mechanisms in MRF with (a) conventional MRP fluid without graphene and (b) new MRP fluid containing graphene.

Figure 4.15(b) depicts the removal of material from workpiece surface with the new MRP fluid which consists of EIPs, graphene, and abrasives along with the base fluid. The EIPs present in the fluid form a chain-like structure to retain the graphene particles with Vander wall forces, resulting in a rise in shear viscosity (Thiyagu *et al.*, 2019). In the presence of a magnetic field, graphene particles form a chain structure between the two EIPs (Fig. 4.15b), and normal magnetic force pushes the graphene particles inside the micro-voids in the EIPs chain. In this case, abrasives are entrenched amid the graphene and EIPs chain, and they participate in the finishing procedure as a single body. Because of their reciprocal attraction forces, all of those particles actively engage in

the creation of a chain structure in the presence of a magnetic field, as illustrated in Fig. 4.15(b). This indicates that the component particles (EIPs, graphene and abrasives) are subjected to a greater magnetic attraction force in addition to the fluid force. The increased magnetic normal force encourages abrasive particles to penetrate the workpiece surface ( $d_1$ ) as depicted in Fig. 4.15(b). Also, the yield stress of the MRP fluid with graphene tends to have higher shear stress as compared to the MRP fluid without graphene (Prakash *et al.*, 2021). As a result of the increased bonding strength of the magnetic abrasives, higher shear stress is delivered to the workpiece surface. This leads to the enhancement in the surface finishing of the AM typical wind blade workpiece surface.

#### **4.3.2 Theoretical analysis of reduction in surface roughness during the magnetorheological (MR) finishing of the additive manufactured (AM) typical wind turbine blade workpiece**

Further, the prediction of the functional efficacy of the present MRF finishing process with the novel hexagonal tip-based magnetic finishing tool is done on the basis of the theoretically analysis of material removal during AM typical wind turbine blade workpiece. The following assumptions were made for analysis.

- The abrasives are uniformly distributed in the MRP fluid, and also size and shape of AAPs are uniform.
- Magnetic leakages and losses are not considered in this study.

For the shearing off the roughness asperities from the work part surface, the rotary motion of the tool and reciprocatory motion of the workpiece plays an important role. As the tool rotates along with the workpiece reciprocation, the AAPs for the spiral raster path over the work part finishing surface as depicted in Fig. 4.14. The trajectory followed by the AAPs plays a significant role to calculate the material removal from the work part surface. Hence it is important to evaluate the AAPs trajectory. The X-Z co-ordinate of the finishing trajectory (Fig. 4.14) can be evaluated by Eqs. (4.58) and (4.59) respectively.

$$X = \frac{d_s}{2} (\cos \omega t) \quad (4.58)$$

$$Z = Ft + \frac{d_s}{2} (\sin \omega t) \quad (4.59)$$

where,  $F$  is the velocity of the reciprocating tool,  $t$  is the time, and  $\frac{d_s}{2}$  is the radius of raster path (mm). Further, the finishing velocity of AAPs along X and Z direction in the spiral raster path can be calculated by Eqs. (4.60) and (4.61), respectively.

$$V_x = \frac{dX}{dt} = \frac{d_s}{2} \omega(\sin\omega t) \quad (4.60)$$

$$V_z = \frac{dZ}{dt} = F + \frac{d_s}{2} \omega(\cos\omega t) \quad (4.61)$$

Using the Eqs. (4.60) and (4.61), the net velocity ( $V_{net}$ ) of the AAPs can be evaluated by Eq. (4.62).

$$V_{net} = \sqrt{V_x^2 + V_z^2} \quad (4.62)$$

Further, the path length of the raster path ( $L$ ) covered by the AAPs over the AM typical wind turbine blade surface over the time  $T$  is calculated by Eq. (4.63).

$$L = \int_0^T \sqrt{\{F + \frac{d_s}{2} \omega(\cos\omega t)\}^2 + \{\frac{d_s}{2} \omega(\sin\omega t)\}^2} dt \quad (4.63)$$

Hence, the AAP shears off the surface asperities from the work part surface in a single finishing cycle along the projected path length  $L$  and is calculated as 0.384 m at  $\omega = 700$  rpm and  $T = 20$  min. Further, the volumetric removal of material ( $V_{mr}$ ) from the work parts surface is calculated by Eq. (4.64).

$$V_{mr} = L \times A_{in} \quad (4.64)$$

where,  $A_{in}$  is the area of indentation of the AAP on the work part surface. The indentation spiral raster cross section area generated by the AAP over the work part surface is evaluated by Eq. (4.32). The indentation depth and indentation diameter is calculated using Eqs. (4.30) and (4.31) respectively. The Brinell hardness number value is 210 kgf/mm<sup>2</sup>, and  $F_{nrm}$  is the overall magnetic force due to EIPs and its value is taken as  $5.236 \times 10^{-12}$  N (Yadav *et al.*, 2020). Using these values in Eq. (4.30), the indentation diameter is calculated as  $1.586 \times 10^{-9}$  mm. Further, using Eq. (4.31), the indentation depth is evaluated as  $1.039 \times 10^{-11}$  mm and using Eq. (4.32), the area of indentation of the AAP on the work part surface is evaluated as  $1.06 \times 10^{-12}$  mm<sup>2</sup>. Next, the number of the abrasive particles in the single chain ( $N_s$ ) can be calculated by Eq. (4.65).

$$N_s = C \times \frac{A_{hex} \times 2r_{ap}}{V_{aap}} \quad (4.65)$$

where  $C$  is the concentration of the abrasives in the MRP fluid,  $A_{hex}$  is the projected hexagonal area of over the work part surface,  $V_{aap}$  is the volume of single abrasive particle and  $r_{ap}$  is the radius of single abrasive particle. Further,  $V_{aap}$  can be calculated by Eq. (4.21). Putting the value of  $r_{ap}$  in Eq. (4.21), the  $V_{aap}$  is calculated as  $3.59 \times 10^{-6}$  mm<sup>3</sup>. Further  $A_{hex}$  can be calculated by Eq. (4.66).

$$A_{hex} = \frac{3\sqrt{3}s^2}{2} \quad (4.66)$$

where  $S$  is the side of hexagonal tip tool which is 10.5 mm. Using the value of  $S$  in Eq. (4.66), the  $A_{hex}$  is calculated as 286.429 mm<sup>2</sup>. Hence, using Eqs. (4.21) and (4.66) in Eq. (4.65), the number of active abrasives (AAPs) is calculated as 303185. The AAPs are actually responsible for shearing of the surface asperities from the work part surface. Next, the volumetric material removed after  $i^{th}$  rotation can be evaluated by Eq. (4.67).

$$V_{(mr)i} = L \times A_{in} \times N_s \times N \times t' \quad (4.67)$$

where  $N$  is the tool rotational speed (rpm) and  $t'$  is the time taken for one finishing cycle.

Further, for simplifying the present analysis, the surface asperities are assumed to be in triangular shape and are uniformly distributed over the work part surface.  $R_a^0$  is the initial line surface roughness while  $R_a^i$  is the surface roughness after  $i^{th}$  finishing. Hence, the path length covered by the AAPs over the work part surface is expressed as Eq. (4.68) (Ghosh *et al.*, 2021).

$$L = \left(1 - \frac{R_a^i}{R_a^0}\right) l_{fs} \quad (4.68)$$

where  $l_{fs}$  is the finishing spot width over the workpiece surface. Next, the material removed after the  $i^{th}$  finishing cycle can be expressed using Eq. (4.69).

$$V_{(mr)i} = L \times W' \times (R_t^0 - R_t^i) \quad (4.69)$$

where  $R_t$  is the maximum peak to valley height and can be written as  $R_t^0 = 4R_a^0$  (Ghosh *et al.*, 2021). Hence, Eq. (4.69) can be re written as (Eq. 4.70).

$$V_{(mr)i} = L \times W' \times 4(R_a^0 - R_a^i) \quad (4.70)$$

On computing Eqs. (4.67) and (4.70), the surface roughness value after the  $i^{th}$  cycle can be evaluated as Eq. (4.71).

$$R_a^i = R_a^0 - \frac{1}{4} \left( \frac{A_{in}}{W} \times N_s \times N \times t \right) \quad (4.71)$$

The number of active abrasive particles, area of indentation, rotational speed, finishing time, and finishing spot width are the parameters in this process that directly impact the finishing performance as given in Eq. (4.71). Further, experimentations are performed and the theoretical model is validated in Chapter 6 (section 6.5).

#### **4.4 Analysis of the finishing mechanism of the polyamide external cylindrical flat surface using magnetorheological (MR) finishing process**

In the process mechanism, the shearing off the asperities from the polyamide surface occurs in two steps. Initially, the magnetic force induced by the magnetizing current causes the active abrasive particles (AAPs) to indent into the polyamide surface. Secondly, the simultaneous rotations of the

workpiece and tool along with the tool reciprocation cause the material's detachment from the locality of the polyamide workpiece surface by indented AAPs as depicted in Fig. 4.16(a). As a result of these simultaneous motions, the AAPs follow a spiral path along which the asperities are clipped off from the workpiece surface as seen in Fig. 4.16(b). The abrasion action of the AAPs over the polyamide surface causes material removal in the MRF process which happens over time. The abrasion action magnitude is determined by the material hardness, the degree of stiffness of MRP fluid, and the rotational motion of AAPs. As shown in Fig. 4.16(b), three types of forces act in the material removal from the polyamide surface namely normal force ( $F_{nrm}$ ), tangential force ( $F_{tan}$ ), and axial force along Y-axis ( $F_{ay}$ ). The MRP fluid stiffens over the finishing tool surface when a magnetic field is applied. As a result, the EIPs get magnetized, forming a chain-like structure on the tooltip end surface. Due to the magnetic flux density (MFD) gradient, the AAPs entrenched in these EIPs chain push towards the lower gradient i.e., workpiece surface from the higher MFD gradient of tooltip surface. This led to the  $F_{nrm}$ , acting on the polyamide surface by the AAPs. The  $F_{nrm}$  can be calculated using Eq. (4.72) (Yamaguchi et al., 2007).

$$F_{nrm} = m_e \mu_0 \chi_{eip} H' \nabla H \quad (4.72)$$

where  $m_e$  is the single EIP mass in kg,  $\chi_{eip}$  is the EIP's magnetic susceptibility ( $\text{m}^3/\text{kg}$ ),  $\nabla H$  is derivative of magnetic field intensity amid the working space,  $H'$  represents the magnetic field intensity produced by the electromagnet (A/m), and  $\mu_0$  is the air's relative permeability ( $\text{N/A}^2$ ). Further, the plowing mechanism is accountable for the material removal from the polyamide surface by the indented AAPs. The plowing of the material is determined by the shear force produced by the rotary and reciprocatory motion of the indented AAPs.

The simultaneous tool and workpiece rotary motions in opposite direction tend to effectively chip off the asperities which are owned by the tangential shear force ( $F_{tan}$ ). Therefore, the ( $F_{tan}$ ) is the sum of the tangential force due to tool rotation ( $F_{tt}$ ) and the workpiece rotation ( $F_{tw}$ ). The workpiece is rotated in the opposite direction to the tool core to improve the finishing on the polyamide surface. As a result, the relative motion between the polyamide surface and the AAPs increases. The AAP encounters increased  $F_{tan}$  over the work part surface as a result of the higher relative motion. The  $F_{tan}$  operating across the AAPs can be calculated using Eq. (4.73) (Sidpara and Jain, 2012).

$$F_{tan} = A_p \tau_y' \quad (4.73)$$

where  $\tau_y'$  is the viscous fluid shear stress and  $A_p$  is the indented AAP projected area over the polyamide surface.

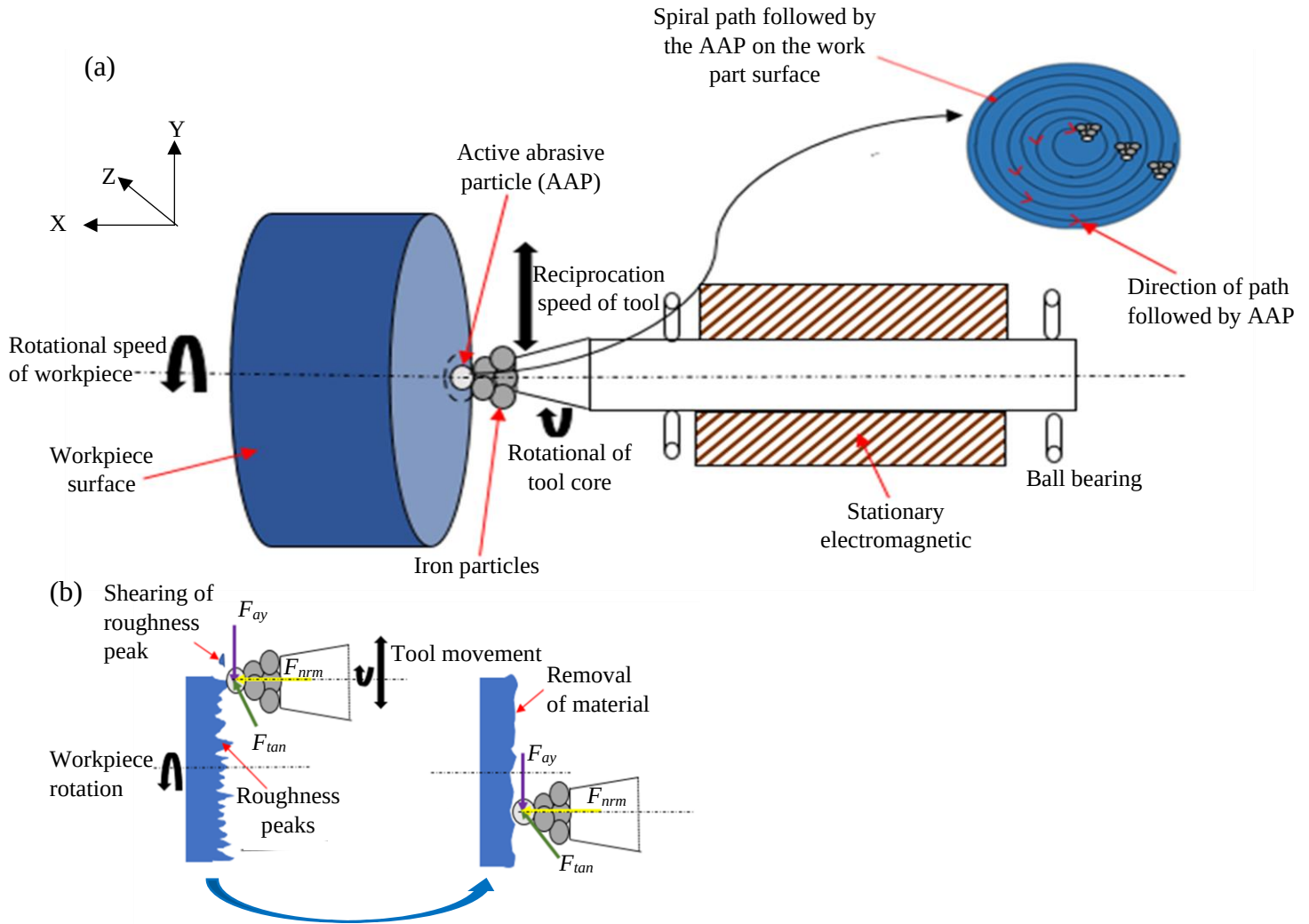


**Fig. 4.16.** (a) Material removal mechanism by the active abrasive particle (AAP) over polyamide workpiece surface, and (b) action of different forces during material removal from the polyamide workpiece.

The AAPs are subjected to axial force ( $F_{ay}$ ) as a result of tool reciprocation which is shown in Fig. 4.16(b). The  $F_{ay}$  aids the AAPs in shearing asperities from the workpiece surface in the axial direction. The  $F_{ay}$  is given by the Eq. (4.74).

$$F_{ay} = \tau_y' w \Delta t \quad (4.74)$$

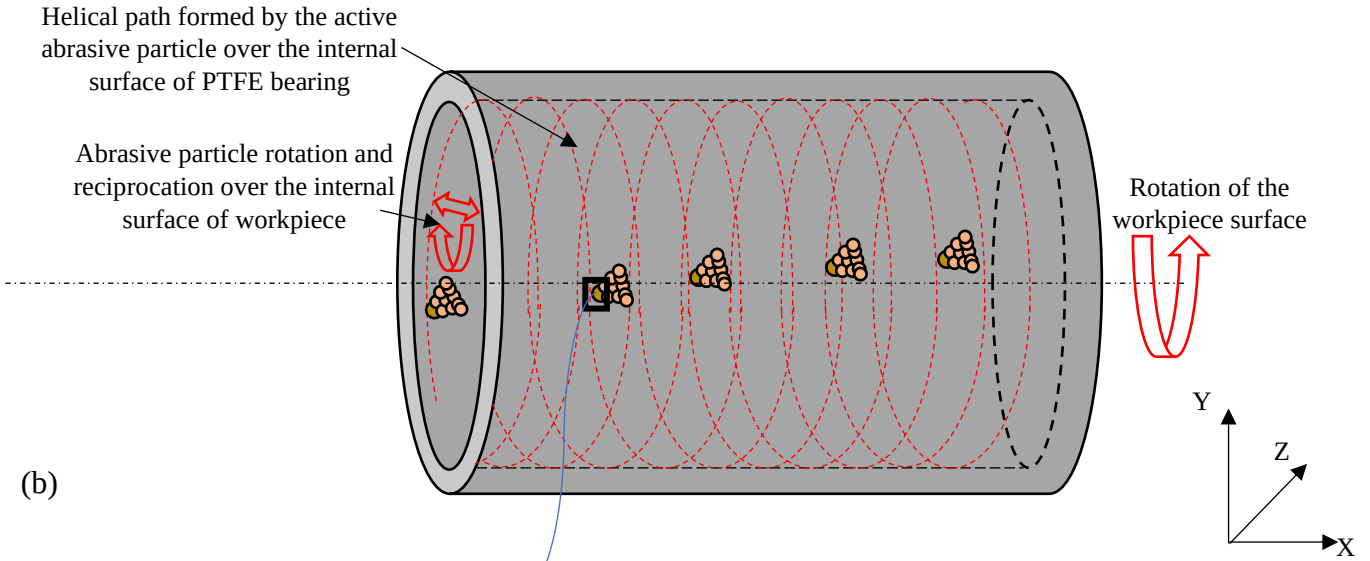
where,  $w$  is the MRP fluid width placed on the tool tip surface and  $\Delta t$  is the reduced MRP fluid thickness due to the squeezing during the reciprocation motion on the polyamide surface. The present work achieves fine surface finishing over the polyamide workpiece as a consequence of the combined effect of  $F_{nrm}$ ,  $F_{tan}$ , and  $F_{ay}$ .

#### **4.5 Analysis of the finishing mechanism of the internal surface of the PTFE bearing using the rotational magnetorheological (R-MR) honing process**

In the present rotational magnetorheological (R-MR) honing process (*Chapter 3*), the simultaneous rotational and reciprocation movement of the active abrasive particles (AAPs) over the polymer bearing (PB) surface leads to the abrasion action. Moreover, owing to the simultaneous rotation to the tool and PB along with reciprocation of the tool, the AAPs tend to follow the helical path as shown in Fig. 4.17(a). The asperities from the bearing surface get sheared off along this helical path only. The MRH tool and workpiece surface are rotated in opposite directions owing to which the length of the helical path and number of turns of the AAP on the helical path upsurges (Paswan and Singh, 2019b). This leads to the fine surface finish of the internal surface of the PTFE bearing. Further, the removal of material from the PTFE bearing surface is due to the three types of forces that act on the AAPs in this process namely tangential shear force ( $F_{tan}$ ), magnetic indentation force ( $F_{nrm}$ ), and axial shear force along X-axis ( $F_{ax}$ ) as depicted in Fig. 4.17(b). The material removal from the bearing surface by the AAPs is due to the action of different forces as depicted in Fig. 4.18. Owing to these different forces, the asperities get sheared off from the bearing surface after each finishing cycle till the finely finished surface is attained. In the present work, during the surface finishing, initially, the EIPs get magnetized and form the columnar structure when the MRP fluid is applied over the surface of the permanent magnet of the magnetorheological honing (MRH) tool. The nonmagnetic AAPs which are gripped in the EIPs chain tend to move towards the low gradient MFD from the high gradient of the MFD i.e., towards the bearing surface. The stiffened columnar structure formed by the EIPs along with the AAPs is on the outer surface of the permanent magnet MRH tool. The stiffened MRP fluid over the tool surface acts as a unibody and these magnetic EIPs apply the magnetic normal force ( $F_{nrm}$ ) over the AAPs (Fig.4.17b).



(a)



(b)

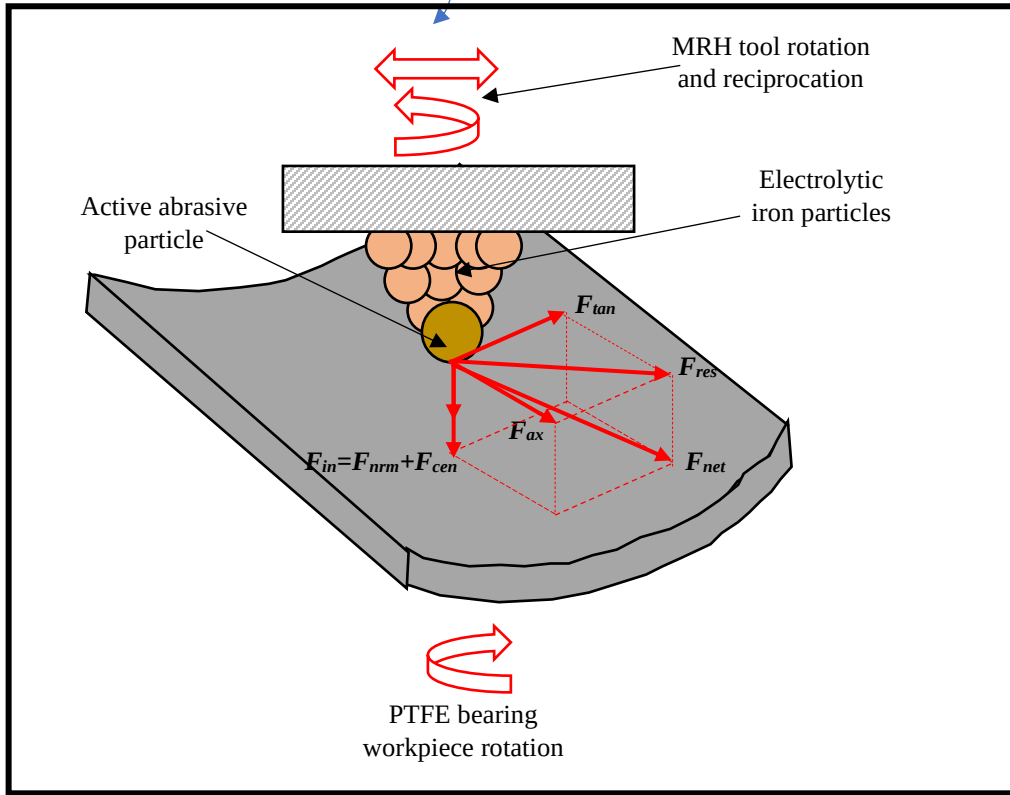


**Fig. 4.17.** (a) Helical path followed by the abrasive particle over the internal surface of the PTFE bearing and (b) different forces acting during material removal from the PTFE bearing workpiece finishing surface.

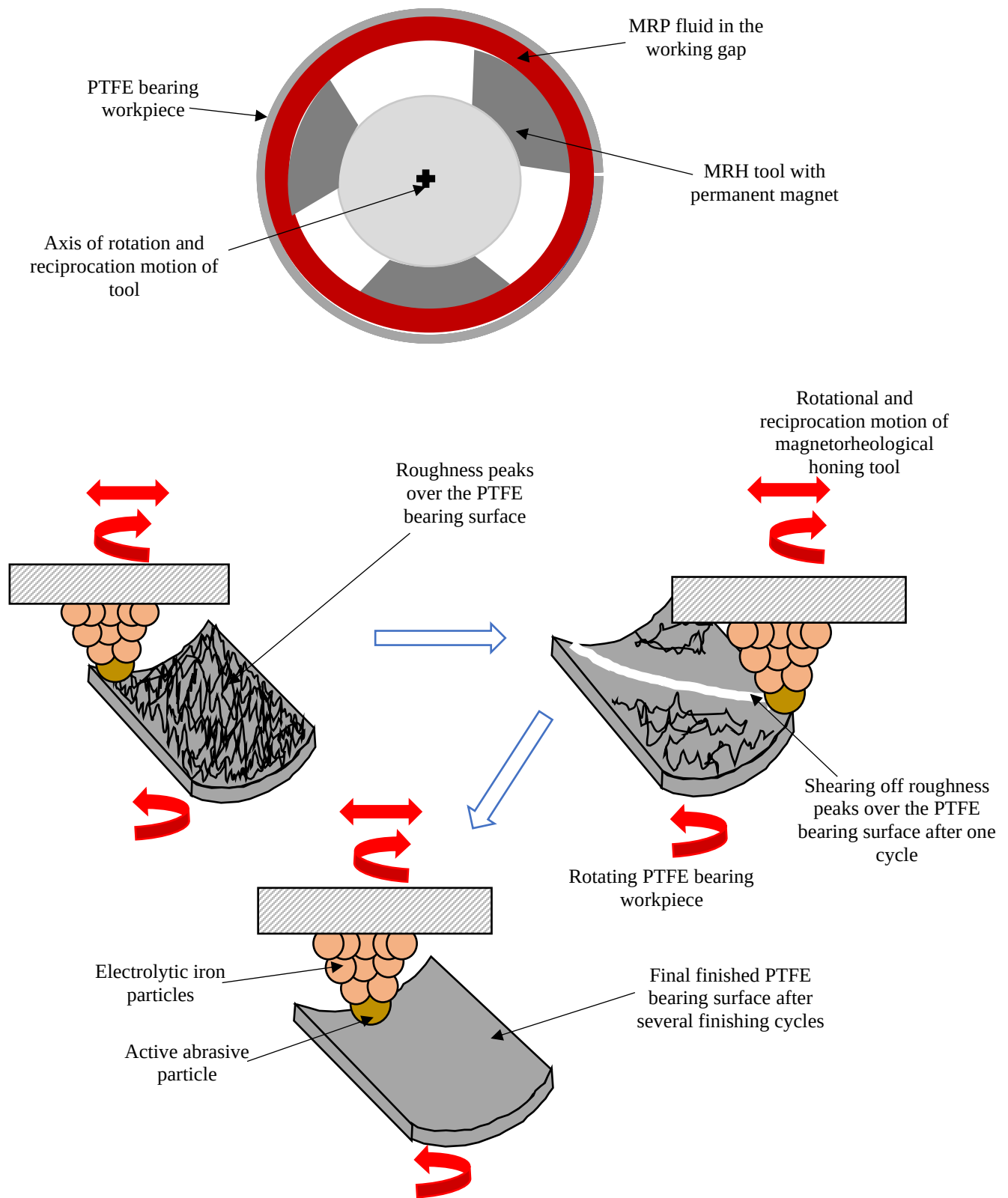


**Fig. 4.18.** Different steps of the removal of material from PTFE bearing work part by single active abrasive particle during the surface finishing using rotational magnetorheological honing process.

Due to this  $F_{nm}$ , the AAP indents on the asperities present on the bearing surface. The indentation of the AAPs leads to the micro ploughing of the material around the indented abrasive marks.

Further, as the MRH tool rotates, the centrifugal force ( $F_{cen}$ ) acts over the AAPs in the same direction as shown in Fig. 4.17(b). As both  $F_{nrm}$  and  $F_{cen}$  are acting in the normal direction, therefore the net indentation force ( $F_{in}$ ) is responsible for the penetration of AAP on the work part surface. Next, as the MRH tool rotates and reciprocates simultaneously along with the bearing rotation, the asperities get sheared off by the AAPs from the internal bearing surface. Owing to the simultaneous rotation and reciprocation of the MRH tool along with bearing workpiece rotation, the AAPs experience the tangential shear force ( $F_{tan}$ ) and the axial shear force ( $F_{ax}$ ) as shown in Fig.4.17(b). The  $F_{tan}$  is due to the simultaneous rotation of the tool and the bearing surface.

As the tool and workpiece rotate simultaneously, the AAPs shear off the surface asperities tangentially as shown in Fig. 4.17(b). Further, the MRP fluid follows the Bingham plastic fluid, therefore, the tangential and axial shear force is calculated considering the MRP as Bingham plastic fluid. Further, with the simultaneous rotation of the tool and workpiece, the MRH tool also have the reciprocation motion. Owing to the reciprocation of the MRH tool, the AAP experience the axial shear force ( $F_{ax}$ ) as depicted in Figure 4.17(b). Next, the shearing of asperities from the bearing surface relies on the resultant shear force ( $F_{res}$ ) of the  $F_{tan}$  and the  $F_{ax}$ . The removal of the asperities from the bearing surface in the form of microchips occurs due to the repetitive action of the  $F_{res}$  over the surface as shown in Figure 4.17(b). Moreover, the net resultant finishing force ( $F_{net}$ ) is the combination of the net indentation force ( $F_{in}$ ) and the resultant shear force ( $F_{res}$ ) as depicted in Fig. 4.17(b). The net resultant finishing force help to describe the direction in which the asperities are getting sheared off from the work part surface.

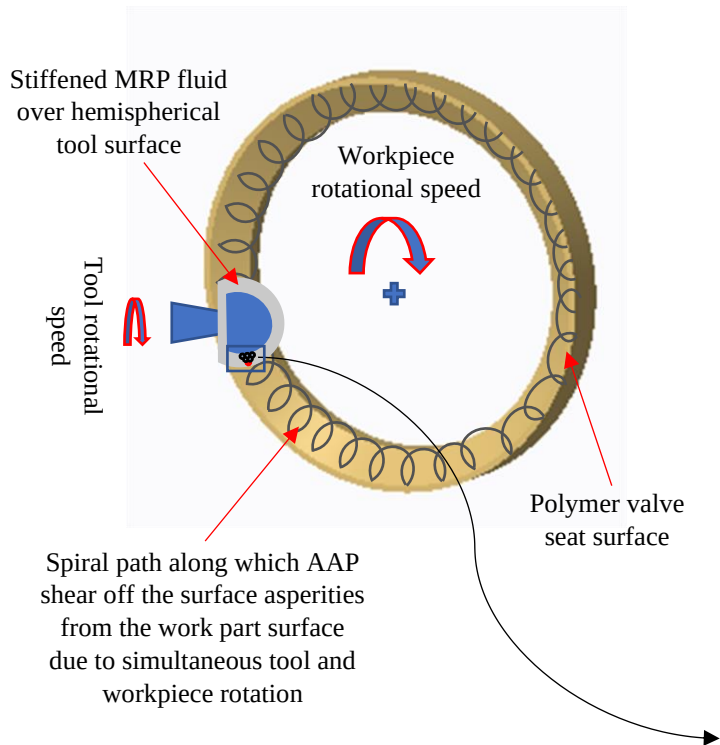
#### **4.6. Analysis of the finishing mechanism of the polymer valve seat surface using the magnetorheological finishing process**

In this work, the magnetorheological polishing (MRP) fluid is used for the fine finishing of the polymer valve seats. The hemispherical designed electromagnetic tool (*Chapter 3*) can be suitable for fine finishing of the polymer valve seal surface. the current study, due to the magnetizing current, the MRP fluid gets stiffened. The asperities from the valve seat surface get sheared off along this spiral path owing to the simultaneous rotation of the tool and workpiece as depicted in Fig. 4.19. The electromagnetic tool and workpiece surface are rotated in opposite directions owing to which the length of the spiral path and number of turns of the AAP on the spiral path upsurges. This leads to the fine surface finish of the polymer valve seat surface. Further, two types of forces act on the AAPs for material removal from the polymer valve seat surface, namely magnetic

normal force ( $F_{nrm}$ ) and tangential shear force ( $F_{tan}$ ). The tangential shear force is the combination of the tool rotation ( $F_{tt}$ ) and workpiece rotation ( $F_{tw}$ ). The removal of material from the surface of the polymer valve seat is owing to the action of these forces as depicted in Fig. 4.19(a). Initially, as the magnetic field gets induced over the electromagnetic tool surface on the application of the magnetization current ( $I$ ), the EIPs present in the stiffened MRP fluid are magnetized. Owing to this the EIPs form columnar structure like a chain over the tool surface. The nonmagnetic AAPs which are gripped in the EIPs chain tend to move towards the low gradient from the high gradient of the magnetic flux density (MFD). Owing to this difference in MFD's gradient the  $F_{nrm}$  acts normally on the AAPs by the EIPs chains. The normal force helps the AAP to penetrate the polymer valve seat surface as depicted in Fig. 4.19(b).

Further, as the tool rotates simultaneously along with the workpiece, the roughness asperities get sheared off by the indented AAPs from the valve seat surface. Owing to the simultaneous rotations the AAPs experience the tangential shear force ( $F_{tan}$ ) as shown in the Fig. 4.19(b). As the tool core rotates, the indented AAPs present amid the working gap tend to rotate in the same direction. Owing to this, the  $F_{tw}$  tends to act over the AAPs. As a result, the AAPs tend to move tangentially outwards leading to the shearing off the asperities from the valve surface as shown in Fig. 4.19(a). Further, as the polymer valve seat workpiece is rotated in the opposite direction to the tool core, the indented AAPs experiences shear force ( $F_{tw}$ ). The  $F_{tw}$  tends to enhance the relative speed of the firmly clenched indented AAPs in the EIPs chain. This enhances the efficacy of the present finishing process and leads to the overall uniform finishing of the polymer valve seat as depicted in Fig. 4.19(b). Further, the resultant of the  $F_{tt}$  and  $F_{tw}$  is the net tangential shear force ( $F_{tan}$ ) which is responsible for abrading the material from the vicinity of the penetrated AAP present on the polymer valve seat surface (Fig. 4.19b). As the tool core and workpiece are rotated simultaneously in opposite direction, the net relative speed of the AAPs upsurges leading to the increase in the tangential shear force ( $F_{tan}$ ). Further, the net resultant force ( $F_{res}$ ) is the resultant of the normal magnetic force and the net tangential shear force as depicted in Fig. 4.19(b). The net resultant force describes the direction in which the shearing of the asperities takes place from the polymer valve seat surface.

(a)



(b)

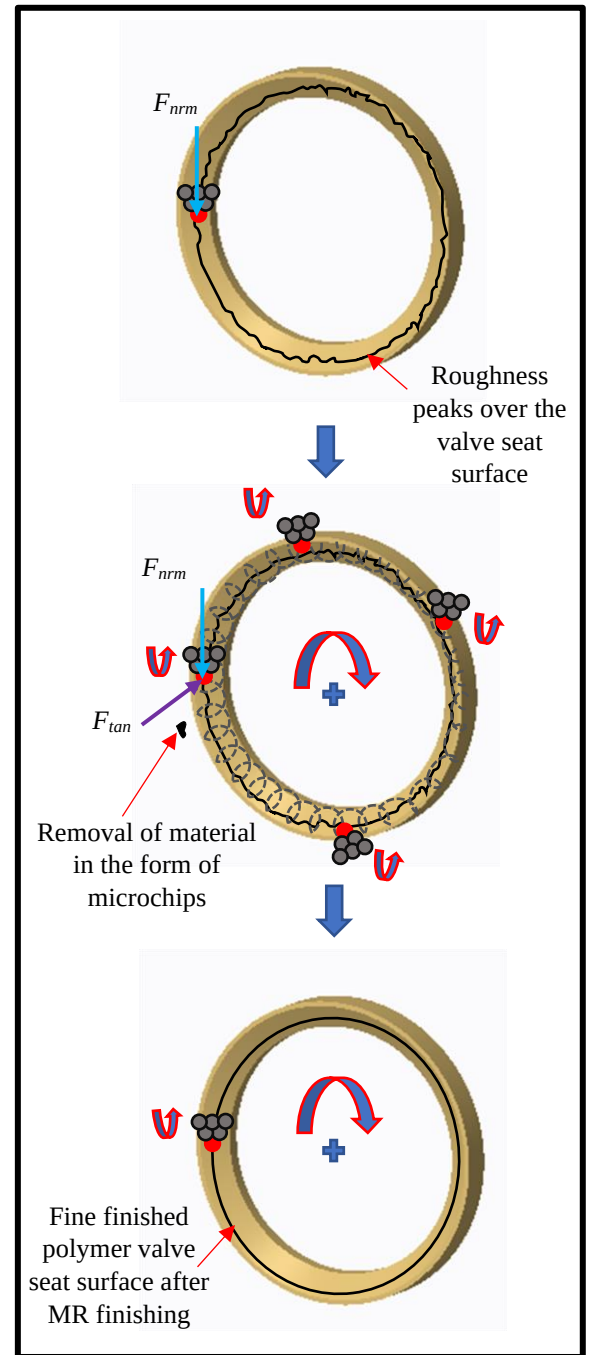
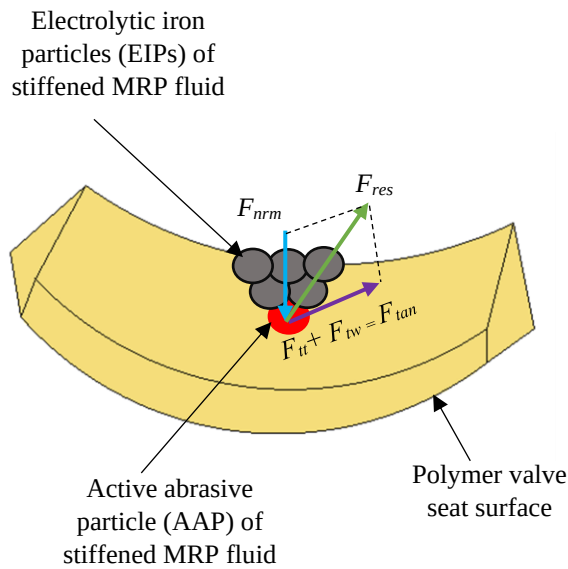


**Fig. 4.19.** (a) Spiral path followed by the abrasive particle over the internal surface of the polymer valve seat (seal) and (b) different forces acting during material removal from the polymer valve seal workpiece surface.

#### **4.7 Analysis of the finishing mechanism of the external cylindric FDM work parts surface using the magnetorheological finishing process**

The hexagonal tip-based electromagnet tool surface (*Chapter 3*) performs finishing suitably over the external cylindric FDM work parts. As the magnetizing current is applied, the electromagnetic hexagonal tool tip surface gets magnetized. Owing to this, the magnetic EIPs move towards the hexagonal tool tip surface and pushes the non-magnetic abrasives with levitation force towards the workpiece surface. The normal magnetic force ( $F_{nm}$ ) is generated by the difference in the gradient of magnetic flux density (MFD), which operates normally on the AAP via the EIPs chain. The AAP penetrates the work part surface due to the magnetic normal force as shown in Fig. 4.20. The magnetic force produced during the process depends on the current intensity. With the rise in current, the MFD upsurge, resulting in an increase of the magnetic force. The  $F_{nm}$  acting over the electrolytic iron particles (EIPs) in the presence of the magnetic field towards the external cylindrical surface (Yamaguchi *et al.*, 2007) as shown in Fig. 4.20. Furthermore, the indented AAPs shear off the surface asperities owing to the tool core's simultaneous rotational and reciprocatory action, as well as the rotation of the workpiece. The indented AAPs that are held in the EIPs chain structure of the MRP fluid tend to come outwards tangentially as the tool rotates, clipping the material from the work part's surface asperities. Further, the relative motion amid the workpiece surface and AAPs enhances due to the rotary motion of workpiece. Owing to this relative motion, the AAPs experience the tangential shear force ( $F_{tan}$ ) which leads to the upsurge in the speed of the clipping of the roughness peaks from the work part surface. The tool and workpiece are rotated in opposing directions to enhance the relative motion of the AAPs. Further, owing to the reciprocatory movement along X-axis of the rotating hexagonal tip-based magnetic tool, an axial shear force ( $F_{ax}$ ) is applied on the external cylindrical surface through AAPs. The depth of indentation depends on the magnitude of the  $F_{nm}$ . The axial shear force ( $F_{ax}$ ) owing to the tool reciprocation and the tangential shear force ( $F_{tan}$ ) due to simultaneous tool and work part rotation are accountable for material removal from the external surface of the FDM component. Next, the resultant shear force acting over the external cylindrical surface through the AAP is the resultant of the  $F_{tan}$  and  $F_{ax}$ . The repetitive simultaneous action of the tangential shear and axial force over the asperities contributes to the material removal from the workpiece surface, resulting the effective finishing as depicted in Fig. 4.20. Further, the outer surface of the workpiece is

cylindric, therefore, the working gap amid hexagonal tool tip surface and workpiece varies as illustrated in Fig. 4.21.

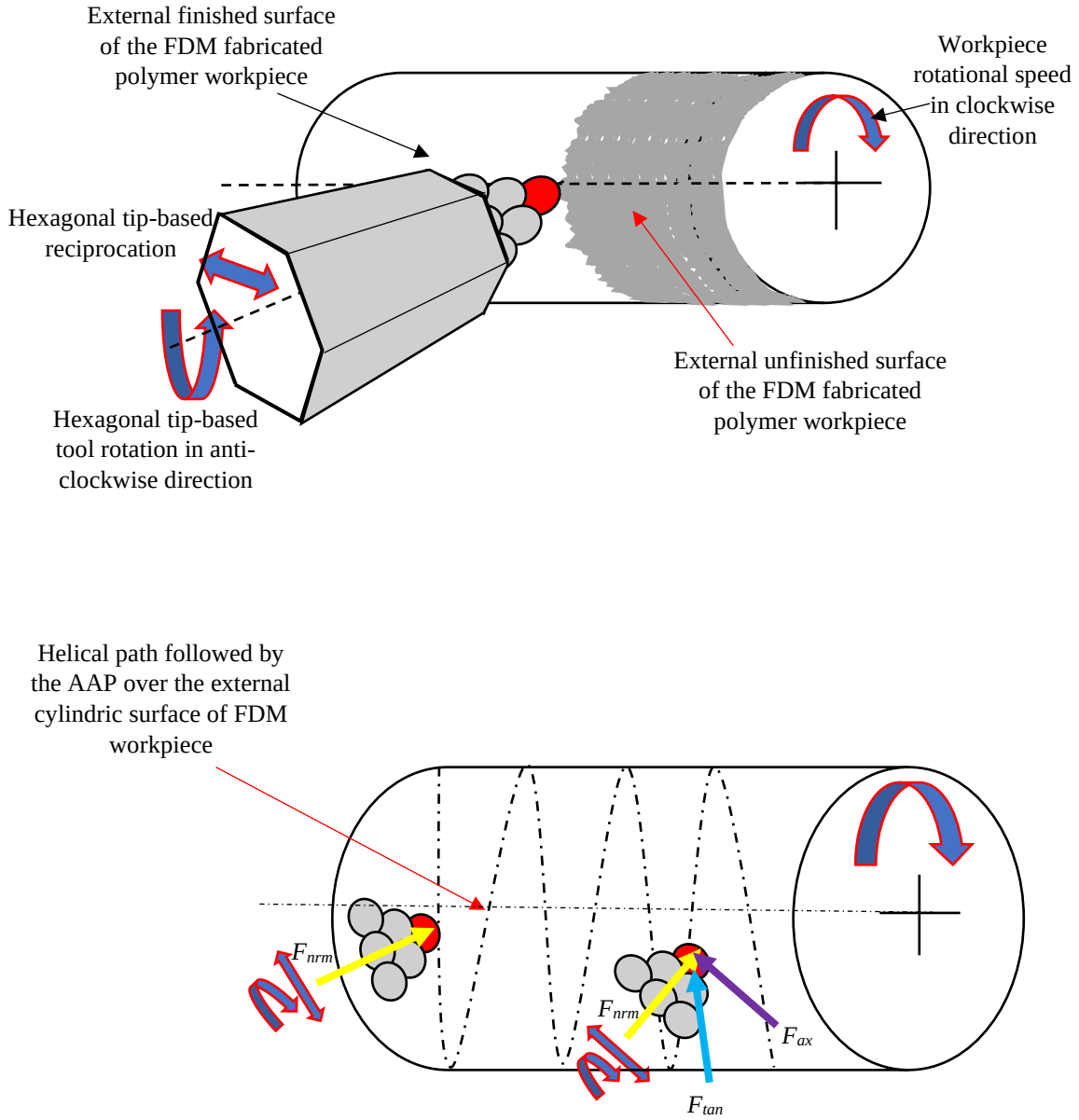


**Fig. 4.20.** Material removal mechanism along with the forces acting while fine finishing of FDM fabricated external cylindric surface using novel hexagonal tip-based tool.

The strength of magnetic field decreases with the rise in the working gap and vice versa. Assuming the hexagonal tool tip of the is divided in six parts naming A, B, C, D, E, and F as depicted in Fig 4.21. From the Fig. 4.21, it can be seen that edge B-E is initially at minimum working gap and

edges A-F and C-D are at maximum working gap. Consider the two sets of EIP chains 1 and 2, which are initially at points A and B of the hexagonal tip surface (Fig. 4.22a).

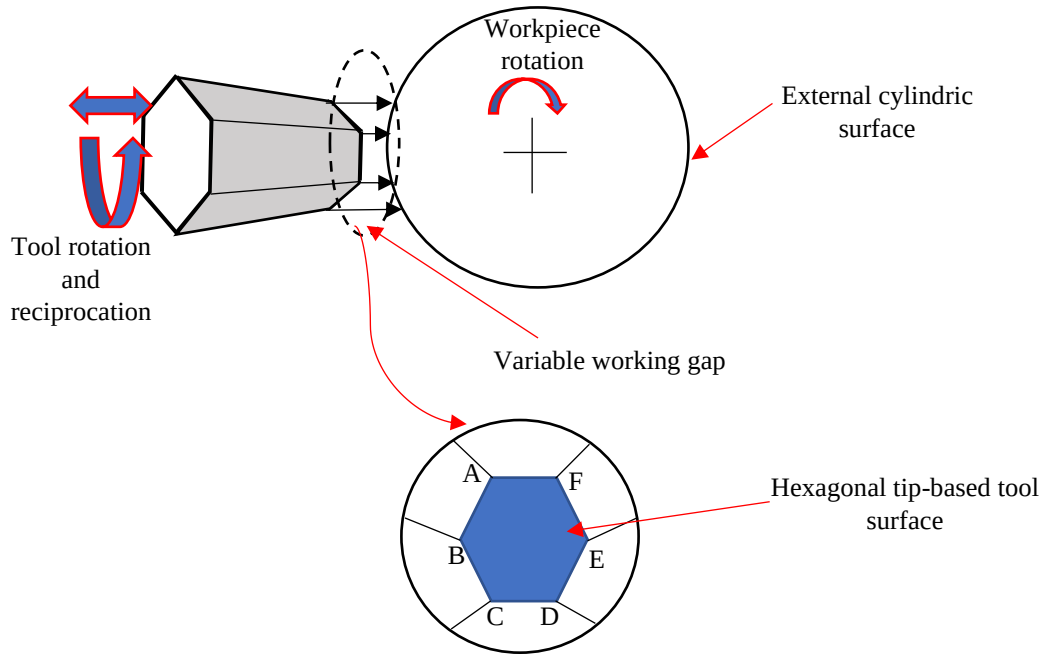


**Fig. 4.21.** Variable working gap amid the hexagonal tool tip and cylindric workpiece surface.

As shown in Fig. 4.22(a), at position A, the working gap is more where the EIP chains (1) is presented, and at position B, the working gap is less where EIP chains (2) is presented. Hence the magnetic field strength is lower at position A as compared to position B. Owing to this, AAPs are held loosely in the EIPs chain (1) and strongly gripped in the EIPs chain (2). As the hexagonal tool tip surface rotates anticlockwise, the EIPs chain rotates along with it. and EIP chain (2) moves from location B to C (Figs. 4.20a and b). Hence, the loosely gripped EIPs chain (1) at location A changes the orientation of the AAPs cutting edges as it travels from location B. New cutting edges of the same AAPs come into contact with the cylindric work part surface when abrasives arrive at position B from A. After the hexagonal tip-based tool rotates by  $60^\circ$  the EIPs chain (1) moves from location A to B, and EIP chain (2) moves from location B to C (Figs. 4.22a and b). Hence, the loosely gripped EIPs chain (1) at location A changes the orientation of the AAPs cutting edges as it travels from location B. New cutting edges of the same AAPs come into contact with the cylindric work part surface when abrasives arrive at position B from A. Furthermore, position B has a smaller gap and a stronger magnetic field.



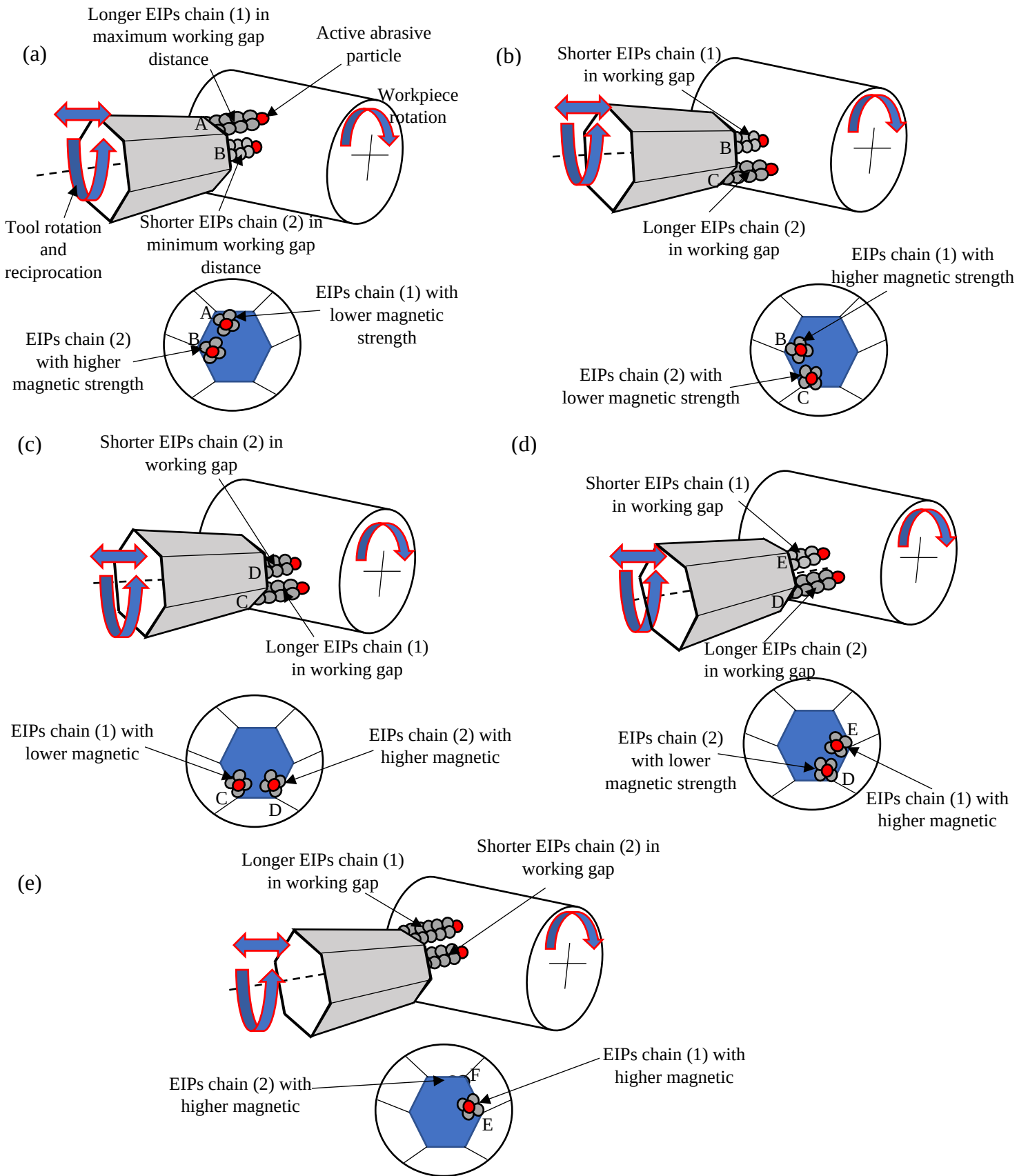


**Fig. 4.22.** Schematic representation of a rotation of AAP with EIPS chain during rotation of the hexagonal tool tip surface in high and low magnetic field strengths (a) A-B, (b) B-C, (c) C-D (d) D-E and (e) E-F.

As a result, with the new cutting edges, AAPs tightly gripped by EIPs chain (1) performs fine finishing at position B. Simultaneously, EIP chains (2) rotate to position C (Fig. 4.22b), where the working gap is more and lower magnetic field strength owing to which the AAPs in the EIPs chain gets loosen. Further, the hexagonal tip tool rotates by another  $60^\circ$ , the EIPs chain (1) moves to position C and the EIPs chain (2) moves to location D as depicted in Fig. 4.22(c). As the EIPs chain travel from location B to C and C to D (Fig. 4.22c), the orientation of the cutting edges of the loosely bonded AAPs held in the EIPs chain changes. Hence at position C, the fresh cutting abrasive edges are present for finishing with less working gap as depicted in Fig. 4.22(c). After the hexagonal tip-based tool rotates by  $60^\circ$  the EIPs chain (1) moves from location A to B, Simultaneously, EIPs chain (1) moves from position C to position D with a higher working gap and lower magnetic strength. The same process is followed as the hexagonal tip-based tool rotated by  $60^\circ$  i.e., from C-D to D-E (Fig. 4.22d), and from D-E to E-F (Fig. 4.22e). From Fig. 4.22(a-e), it can be observed that the cutting edges of AAPs are continually shifted from a lower to higher magnetic field strength, and vice versa. Due to the fluctuation in the magnetic field strength, the AAPs cutting edges change their orientation which increases the cross-cutting effect of abrasives and enhances the polishing efficiency (Wu *et al.*, 2020).

#### 4.8 Conclusions

The following conclusions have been drawn after the analysis of the finishing mechanism with developed magnetorheological finishing tools for different polymer workpieces.

- Based on the process mechanism for fine finishing of hemispherical shaped workpieces, the magnetic normal force along with the forces produced by the rotating tool and the rotating workpiece helps to shear off material from the polymer hemispherical shaped workpiece surfaces. The material removed by shearing off the asperities provides fine finishing over the hemispherically shaped workpiece surface which tends to enhance the functional efficacy of the polymer components such as acetabular cups.
- The net magnetic flux density induced in the working gap through the electromagnetic tool core also includes the magnetic flux density due to the magnetization of the iron particles of MRP and tool core.
- The negative slope of the theoretically calculated and experimentally measured magnetic field from the MR finishing tool surface ensured that the active abrasive particles of MRP

fluid can perform relative motion over the polymer workpiece surface as iron particles of the MRP fluid get attracted toward the higher magnetic field.

- The rotary motion of the tool core and proper meshing amid the magnetic tool teeth and the teeth of the straight bevel gear work part with MRP fluid in the predefined working space leads to the rotary motion of the bevel gear work part. Owing to this each tooth of straight bevel gear comes in the contact with the MRP fluid present on the magnetized tool teeth surface. This leads to the overall finishing of the straight bevel gear in the minimum time.
- The magnetic normal force along with the forces produced while the reciprocation motion of the rotating tool and the rotating workpiece helps to shear off material from the external cylindrical and flat polymer workpiece surfaces. The material removed by shearing off the asperities provides fine finishing over the workpiece surface which tends to enhance the functional efficacy of the polymer components.
- Based on the process mechanism for fine finishing of internally shaped workpieces, the magnetic normal force along with the forces produced by the reciprocation of the rotating tool and the rotating workpiece helps to shear off material from the internal cylindric shaped polymer surfaces. The material removed by shearing off the asperities provides fine finishing over the polymer internal cylindric surface which tends to enhance the functional efficacy of the polymer components such as bearings.
- The process mechanism due to the different motions reveal the removal of material from the different shapes of the polymer workpieces which tends to provide fine finishing to the various polymer applications such as acetabular cups, bearings, gears, valve seal, etc.

## **CHAPTER 5**

### **DEVELOPMENT OF MAGNETORHEOLOGICAL POLISHING FLUIDS AND PRELIMINARY EXPERIMENTATIONS TO EVALUATE THEIR EFFECTIVENESS FOR FINISHING THE DIFFERENT POLYMER MATERIALS**

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In the magnetorheological finishing (MRF) process, the magnetorheological polishing (MRP) fluid as a finishing medium plays an important role which comprises polishing grade abrasives, carrier fluid, additives, and electrolytic iron particles (EIPs) (Niranjan and Jha, 2014). The MRP fluid is also known as smart fluid because applying the magnetic field changes its property from Newtonian fluid to non-Newtonian fluid. (Khatri *et al.*, 2018); Sidpara *et al.*, 2009).) The MRP fluid alters its rheological properties and becomes viscoplastic in the MRF process by applying a magnetic field. The EIPs are magnetized during the MRF process due to the magnetic field's influence. Owing to this, MRP fluid gets stiffened, forming a columnar structure due to the upsurge in the rheological properties (viscosity and yield stress). The MRP fluid changes into a semi-solid as a result of the increasing yield stress. This is a finishing media that is used in the MRF process to clip asperities from polymer materials during surface finishing. As a result, the surface of the polymer workpiece is finely finished. In this chapter, various magnetorheological polishing (MRP) fluids are developed for the fine finishing of the different polymer materials. Further, the parametric experimentations were done to test their effectiveness for fine finishing of the polyamide material.

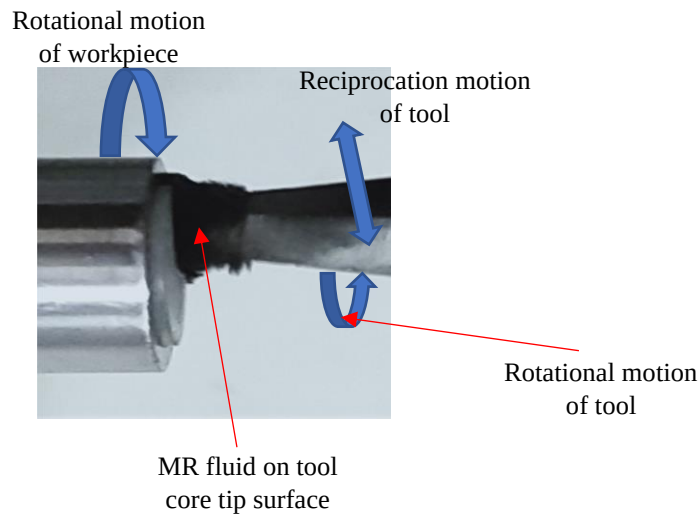
#### **5.1 Development of the magnetorheological polishing fluid (MRP) for fine finishing of the polyamide workpieces**

Owing to the limited literature available for the MRP fluid for finishing the polyamide work part, the initial trials were done using two different types of carrier fluid, naming water-based carrier (WBC) fluid and oil-based carrier (OBC) fluid. OBC uses grease and paraffin oil as a carrier media, whereas WBC uses glycerol and deionized water as a carrier media. Further, the abrasives used in MRP fluid for the trial experimentations are SiO<sub>2</sub>, CeO<sub>2</sub>, and Al<sub>2</sub>O (800 mesh size). Further, the electrolytic iron particles (500 mesh size) are used. In a DC-controlled stirring machine, the mixture of abrasives, EIPs, and carrier fluid is further combined. The time required to stir the MRP fluid in the mixer varies between 30 and 45 min. The MRP fluid composition is reported in Table 5.1.

**Table 5.1.** Composition of the MRP fluid for experimentation.

| Parameter             | Electrolytic iron particles | Abrasive's type (800 mesh size) |                  |                                | Base fluid                                       |                                           |
|-----------------------|-----------------------------|---------------------------------|------------------|--------------------------------|--------------------------------------------------|-------------------------------------------|
|                       |                             | SiO <sub>2</sub>                | CeO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | WBC                                              | OBC                                       |
| %Volume concentration | 15 %                        | 15 %                            | 15 %             | 15 %                           | 70 %<br>(80 % deionized water and 20 % glycerol) | 70 %<br>(80 % paraffin oil + 20 % grease) |

The experimentations are performed for 20 min over the polyamide workpiece surface as depicted in Fig. 5.1. The parameter for the initial trials is reported in Table 5.2.

**Fig. 5.1.** MR finishing of the polyamide workpiece with the different controlled motions.

The parameters for the selection of the abrasives and base fluid are done based on a literature review (Alam *et al.*, 2018). After the trials, it is found that MRP fluid WBC is better for polyamide workpieces as compared to the MRP fluid with OBC as reported in Fig. 5.2. The roughness values are found to be lower for water-based fluid as compared to the oil-based fluid (Fig. 5.2). This is because the water molecules present in water-based MRP fluid chemically react with polyamides which may result in softening of the surface of the polymers Eq. (5.1) (Cook 1990; Das 2014).

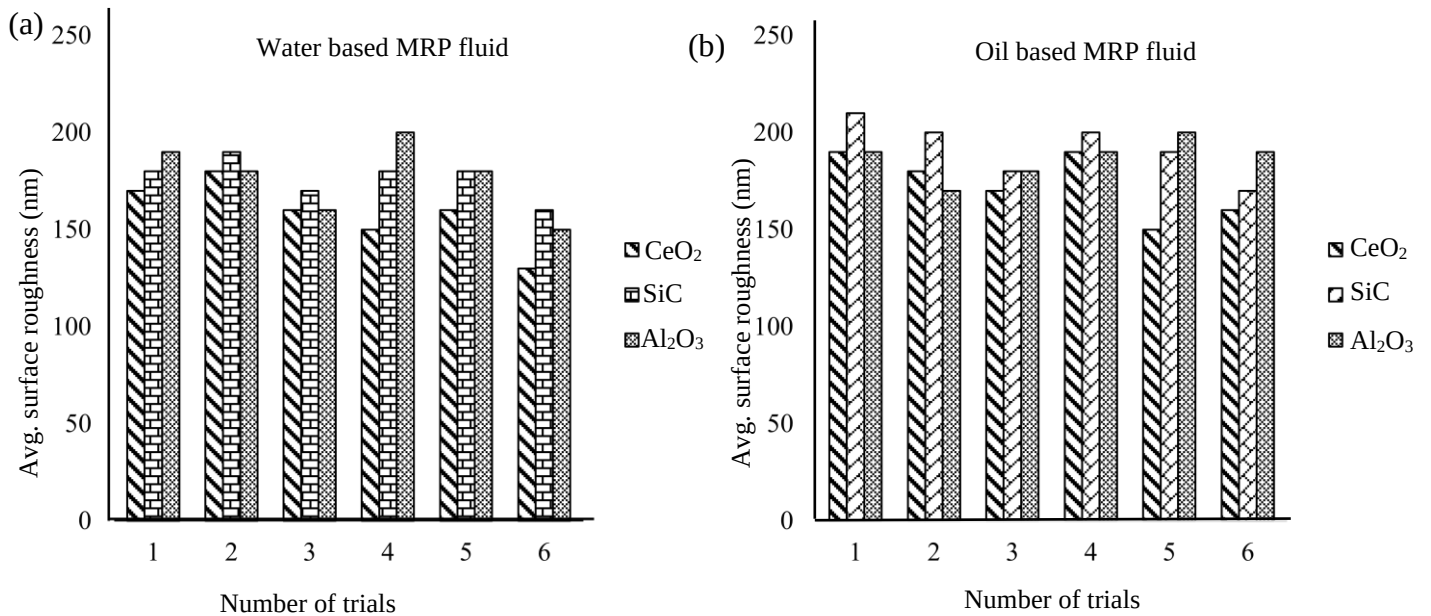


Further, glycerol acts as a protective layer around solid particles, reducing the oxidation of iron particles. Due to these reasons, water-based type MRP fluid is used for experimentation (Sidpara and Jain, 2014). Further, to attain high polishing, the pH value of the fluid should be kept below 9 (Das, 2014).

**Table 5.2.** Initial trials for the selection of the abrasive and carrier fluid.

| S. No | Tool rotation, $T$ (rpm) | Workpiece rotation, $W$ (rpm) | Tool reciprocation, $F$ (cm/min) | Current, $I$ (A) | Initial $R_a$ value (nm) | Final $R_a$ value (nm) with types of abrasives in MRP fluid |     |     |     |                                |     |
|-------|--------------------------|-------------------------------|----------------------------------|------------------|--------------------------|-------------------------------------------------------------|-----|-----|-----|--------------------------------|-----|
|       |                          |                               |                                  |                  |                          | CeO <sub>2</sub>                                            |     | SiC |     | Al <sub>2</sub> O <sub>3</sub> |     |
|       |                          |                               |                                  |                  |                          | WBC                                                         | OBC | WBC | OBC | WBC                            | OBC |
| 1.    | 100                      | 50                            | 10                               | 2                | 240                      | 170                                                         | 190 | 180 | 210 | 190                            | 190 |
| 2.    | 100                      | 100                           | 15                               | 1.5              | 230                      | 180                                                         | 180 | 190 | 200 | 180                            | 170 |
| 3.    | 300                      | 50                            | 5                                | 2.5              | 250                      | 160                                                         | 170 | 170 | 180 | 160                            | 180 |
| 4.    | 200                      | 150                           | 10                               | 3                | 230                      | 150                                                         | 190 | 180 | 200 | 200                            | 190 |
| 5.    | 400                      | 200                           | 25                               | 1                | 220                      | 160                                                         | 150 | 180 | 190 | 180                            | 200 |
| 6.    | 500                      | 100                           | 10                               | 1.5              | 230                      | 130                                                         | 160 | 160 | 170 | 150                            | 190 |

This is because if the pH of the fluid is less than 9 it can move towards an acidic nature due to which there can be an increase in the  $H^+$  ions and a decrease in  $OH^-$  ions. Hence, it's important to keep up the right amount of hydroxyl ions in fluid for a higher polishing rate. The pH strips were utilized in this study to determine the pH value of the MRP fluid. The pH strips were immersed in the solution for 10 sec. The color of the pH strip shifts from yellow to green, indicating that the pH of the water-based MRP fluid is between 8 and 9.

**Fig. 5.2.** Experimental result of the initial trials (Table 5.2) for (a) water based, and (b) oil based magnetorheological polishing fluid.

Further, out of the three abrasives used, the best result (minimum surface roughness) is shown by the CeO<sub>2</sub> abrasives (Fig. 5.2). This might be due to CeO<sub>2</sub>'s exceptional high polishing efficiency, suspension particles, and scratch-free surface quality. Furthermore, the CeO<sub>2</sub> abrasive chemically

strengthens the bonding with the polymer, resulting in increased material removal (Sidpara and Jain, 2014). Therefore, the MRP fluid with WBC is to be utilized for the experiments on polymer workpieces. The composition of MRP fluid used was 15 % by volume of EIPs (500 mesh size), 15 % by volume of CeO<sub>2</sub> abrasive (800 mesh size), and 70 % by volume of WBC fluid (the carrier fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol) for fine finishing of the polyamide workpieces.

## 5.2 Development of the magnetorheological polishing (MRP) fluid for fine finishing of the ultra-high molecular weight polyethylene (UHMWPE) acetabular cup surface

For the fine finishing of the hemispherical shape UHMWPE acetabular cup, water-based magnetorheological polishing fluid is utilized. Since there is no literature available for fine finishing of UHMWPE material using magnetorheological polishing fluid, therefore, three different types of MRP fluids were made with a different type of abrasives named SiC, CeO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> while other components were kept constant to check the effectiveness of these abrasives for finishing the UHMWPE workpiece. The composition of the magnetorheological polishing fluid is reported in Table 5.3. Finally, the required mixture of abrasives, EIPs, and WBC fluid is mixed in a DC-controlled stirring machine for 30 to 45 min. Thus, MRP fluid gets prepared indigenously which has been used in conducting the present experimental analysis. The experimentations are performed for 20 min over the polyamide workpiece surface as depicted in Fig. 5.3.

**Table 5.3.** Composition of the magnetorheological polishing fluid for experimentation.

| Parameter              | Electrolytic iron particles (500 mesh size) | Abrasive's type (800 mesh size) |                  |                                | Base fluid (WBC)                                 |
|------------------------|---------------------------------------------|---------------------------------|------------------|--------------------------------|--------------------------------------------------|
|                        |                                             | SiO <sub>2</sub>                | CeO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> |                                                  |
| % Volume concentration | 30 %                                        | 15 %                            | 15 %             | 15 %                           | 55 %<br>(80 % deionized water and 20 % glycerol) |

For the initial trials, current and working space was kept constant at 2 A and 0.6 mm respectively. Further, the obtained surface roughness values with the SiC, CeO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> abrasives in MRP fluid at the different hemispherical tip-based tool surface and UHMWPE cup work part rotations are reported in Table 5.4. From the experimentations, the best results are found with the MRP fluid containing CeO<sub>2</sub> abrasive particles (800 mesh size) with 15 % volume

concentration providing the minimum surface roughness over the UHMWPE workpiece (Table 5.4). This could be because of the  $\text{CeO}_2$  offers extraordinary suspension particles, and high polishing efficacy (Singh *et al.*, 2012). The results of the initial trials for selecting the suitable abrasive particles are reported in Table 5.4. Therefore, in the further parametric experimental analysis,  $\text{CeO}_2$  is used as the abrasive particles in the MRP fluid for finishing the UHMWPE workpiece. In the present work, the water-based carrier (WBC) fluid (80 % deionized water and 20 % glycerol) is used with % volume concentration of 55 %. The WBC fluid is used in the present process because water-based MR fluid responds faster to the magnetic field (Sidpara and Jain, 2014).

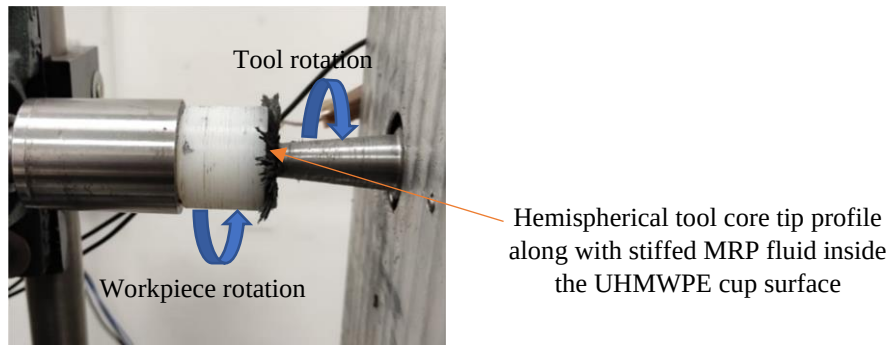


**Fig. 5.3.** MR finishing of the UHMWPE cup with stiffed MRP fluid with the different controlled motions.

The water-based carrier fluid consists of deionized water and glycerol as a carrier medium. The deionized water is used in WBC fluid because water molecules react chemically with UHMWPE can be reduced (Sidpara and Jain, 2014).

**Table 5.4.** Initial trials and results for selecting the suitable type of abrasives in MRP fluid.

| S. No. | Tool rotation,<br>$T$ (rpm) | Workpiece<br>rotation,<br>$W$ (rpm) | Initial $R_a$<br>value<br>(nm) | Final $R_a$ value<br>(nm) with abrasives type in MRP fluid |     |                         |
|--------|-----------------------------|-------------------------------------|--------------------------------|------------------------------------------------------------|-----|-------------------------|
|        |                             |                                     |                                | $\text{CeO}_2$                                             | SiC | $\text{Al}_2\text{O}_3$ |
| 1.     | 100                         | 50                                  | 220                            | 170                                                        | 180 | 190                     |
| 2.     | 100                         | 100                                 | 230                            | 180                                                        | 200 | 180                     |
| 3.     | 300                         | 50                                  | 250                            | 160                                                        | 170 | 160                     |
| 4.     | 200                         | 150                                 | 230                            | 140                                                        | 180 | 200                     |
| 5.     | 400                         | 200                                 | 220                            | 160                                                        | 180 | 180                     |
| 6.     | 500                         | 100                                 | 210                            | 150                                                        | 160 | 170                     |



### 5.2.1 Experiments to finalize the best volume concentration of the constituents of the MRP fluid for fine finishing of UHMWPE acetabular cups

For fine finishing of the UHMWPE acetabular cup, preliminary experimentations were done using the water-based MRP fluid with CeO<sub>2</sub> abrasives. The range of % volume concentration of electrolytic iron particles (EIPs) varies from 25-35 % and % volume concentration of CeO<sub>2</sub> abrasives varies from 5-15 %. The initial average roughness values ( $R_a$ ) of the UHMWPE workpieces range between 240-290 nm for preliminary experimentation. The other process parameters are reported in Table 5.5.

**Table 5.5.** Process parameters and their values used during experimentation.

| S. No. | Process parameters       | Value   |
|--------|--------------------------|---------|
| 1.     | Magnetizing current      | 2 A     |
| 2.     | Tool core rotation speed | 300 rpm |
| 3.     | Workpiece rotation       | 100 rpm |
| 4.     | Working gap              | 0.6 mm  |

The experimental trials were done for 40 min and after every 20 min of the finishing cycle, the MRP fluid is changed on the hemispherical tool tip surface so that the abrasive particles work effectively. A total of 10 experiments are performed to assess the outcomes of the selected MRP fluid composition on the % improvement in surface finish (%  $\Delta R_a$ ). After the experiments, the %  $\Delta R_a$  was calculated by Eq. (5.2).

$$\% \Delta R_a = \frac{(Initial\ Ra - Final\ Ra)}{Initial\ Ra} \times 100 \quad (5.2)$$

Further, the results of the experiments are reported in the Table 5.6. Next, the effect of the % volume concentration of EIPs and abrasives on the %  $\Delta R_a$  has been discussed.

**Table 5.6.** Experimentations for selecting the best % volume concentration of the constituents of the MRP fluid.

| S. No. | % vol of EIPs, $E$ | % vol of CeO <sub>2</sub> abrasives, $C$ | % vol of water based carrier fluid | Initial $R_a$ value (nm) | Final $R_a$ value (nm) | % $\Delta R_a$ (Eq. 5.2) |
|--------|--------------------|------------------------------------------|------------------------------------|--------------------------|------------------------|--------------------------|
| 1.     | 27.5               | 12.5                                     | 60                                 | 260                      | 150                    | 42.30                    |
| 2.     | 25                 | 15                                       | 60                                 | 270                      | 230                    | 14.81                    |
| 3.     | 30                 | 12.5                                     | 57.5                               | 290                      | 150                    | 48.27                    |
| 4.     | 27.5               | 7.5                                      | 65                                 | 280                      | 140                    | 50                       |
| 5.     | 30                 | 10                                       | 60                                 | 260                      | 120                    | 53.84                    |
| 6.     | 32.5               | 7.5                                      | 60                                 | 270                      | 130                    | 51.85                    |
| 7.     | 30                 | 10                                       | 60                                 | 270                      | 120                    | 55.55                    |
| 8.     | 35                 | 10                                       | 55                                 | 280                      | 160                    | 42.71                    |
| 9.     | 30                 | 10                                       | 40                                 | 260                      | 130                    | 50                       |
| 10     | 32.5               | 12.5                                     | 45                                 | 270                      | 140                    | 48.18                    |

Further, the effect of the % volume concentration of EIPs and abrasives on the % improvement of surface finish has been discussed. Fig. 5.4(a) depicts the effect of % volume concentration of electrolytic iron particles (EIPs)  $E$  on %  $\Delta R_a$ . The  $C$  was kept constant at 10 %. It can be seen that as the  $E$  increases up to the value of 30 %, the trend %  $\Delta R_a$  increases. This is because, at a lower  $E$ , the columnar structure of EIPs becomes thinner and weaker. This weak structure of EIPs is not able to grip the  $\text{CeO}_2$  abrasives rigidly while finishing. However, as the  $E$  increases, the normal and shear forces increase (Huang *et al.*, 2005). Also, with an increase in the % volume concentration of EIPs, the magnetic permeability of the MRP fluid increases owing to which the EIPs chains become continuous (Khan and Jha, 2017). Further, EIPs tend to form thicker and stronger chains along the magnetic flux lines owing to which yield stress of the MRP fluid upsurge. This leads to the strong gripping of the active abrasive particles (AAPs) in the EIPs chain. These firmly gripped abrasives perform more cutting the surface asperities during finishing and increase the %  $\Delta R_a$ . However, when the % volume concentration of EIPs goes beyond 30 %, the trend of %  $\Delta R_a$  decreases. This is because upto 30 % volume concentration of the EIPs, all the AAPs are gripped sufficiently in the EIPs chain, and further adding more EIPs only aggregates outside the already existing EIP chains which leads to a decrease in the number of overall cutting edges of AAPs which are used for the surface finishing. This leads to a decrease in the removal of material from the work part surface. Owing to this, there is a decrease in the trend %  $\Delta R_a$ . The maximum value of the %  $\Delta R_a$  was achieved at 30 % of the volume concentration of EIPs.

Fig. 5.4(b) depicts the effect of % volume concentration of  $\text{CeO}_2$  abrasives ( $C$ ) on % improvement in surface finish (%  $\Delta R_a$ ). The %  $E$  was kept constant at 30 %. It can be observed that as the %  $C$  increases upto the value of 10 %, the trend %  $\Delta R_a$  increases. This is because as the %  $C$  abrasive increases initially, the  $\text{CeO}_2$  abrasives get trapped in the EIPs chain structure. Owing to this the active abrasive particles (AAPs) are tightly held by the EIPs during the finishing operation as there are less discontinuous chains. This led to the upsurge in the trend of the %  $\Delta R_a$ . However, as the %  $C$  abrasives increase further, the number of active abrasives that get tangled between the EIPs increases. This led to the weaker EIPs lattice structure which leads to the reduction in the shear strength of the MRP fluid (Kumar *et al.*, 2019). Further, with an increase in the % volume of concentration  $\text{CeO}_2$  abrasives, the distance between the two EIPs increases which reduces the magnetic interaction force. This leads to a decrease in the strength of the MRP fluid. Owing to this there is a reduction in material removal rate which decreases the trend of %  $\Delta R_a$ . The maximum

value of the  $\% \Delta R_a$  was achieved at 10 % of the volume concentration of  $\text{CeO}_2$  abrasives. From the experimentations, the best MRP fluid was found as 30 % volume concentration of electrolytic iron particles (EIPs) and 10 % volume concentration of the  $\text{CeO}_2$  abrasive particles, and 60 % of the water-based carrier fluid for fine finishing of the UHMWPE acetabular cup surface.

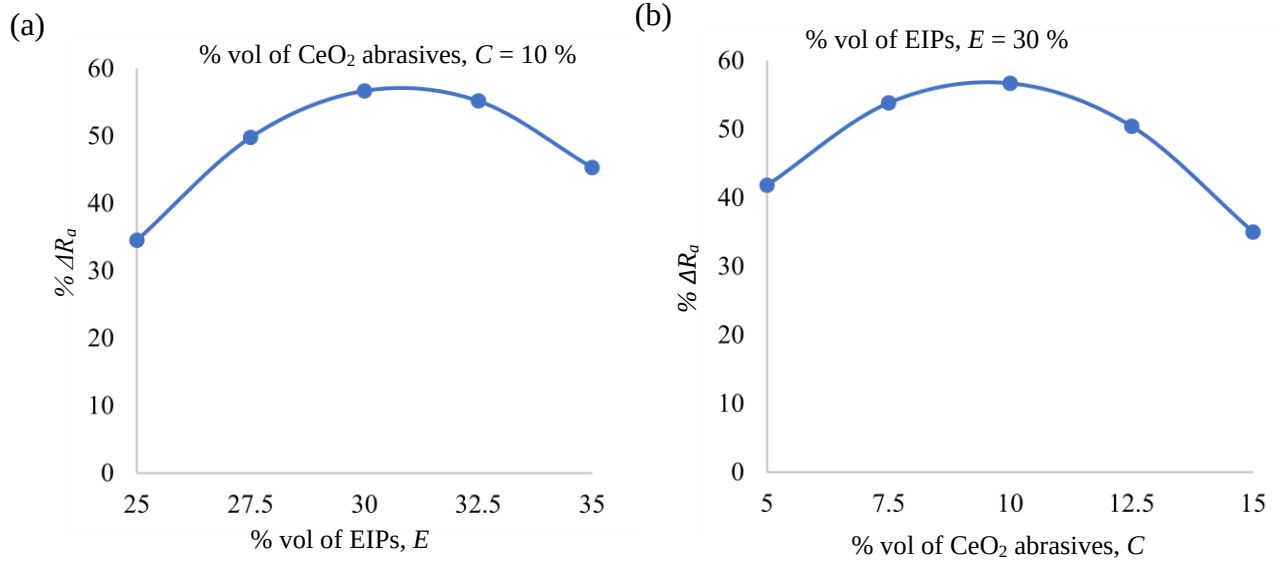


**Fig. 5.4.** Effect of (a) % volume of EIPs ( $E$ ) and (b) % volume of  $\text{CeO}_2$  abrasives ( $C$ ) on %age improvement in the surface finish ( $\% \Delta R_a$ ).

### 5.3 Development of the magnetorheological polishing fluid for fine finishing of the Polytetrafluoroethylene (PTFE) surface

The magnetorheological polishing (MRP) fluid plays an important role in the fine finishing of the PTFE bearing internal surface. The MRP fluid comprises magnetic EIPs, polishing abrasives, and base fluid. Since there is no literature available for the fine finishing of the PTFE polymers using the MRF process, therefore, initially, four different types of abrasives are used for making the MRP fluid naming alumina, cerium oxide, silicon carbide, and silicon oxide (each 800-mesh size). The selection of the abrasive is done by performing the preliminary experimentations on the PTFE polymer bearing surface using the different abrasives (800 mesh size) mixed with the EIPs (500 mesh size) and base fluid. For performing the preliminary experimentations, the volume % concentration of abrasives and EIPs are kept constant at 20 % each and the base fluid as 60 %. The experimentations are performed for 20 min over the polyamide workpiece surface as depicted in Fig. 5.5. Further, the obtained surface roughness values with the  $\text{SiC}$ ,  $\text{CeO}_2$ ,  $\text{SiO}_2$ , and  $\text{Al}_2\text{O}_3$

abrasives in MRP fluid at the different rotations of the hemispherical tip-based tool surface and UHMWPE cup work part are reported in Table 5.7.

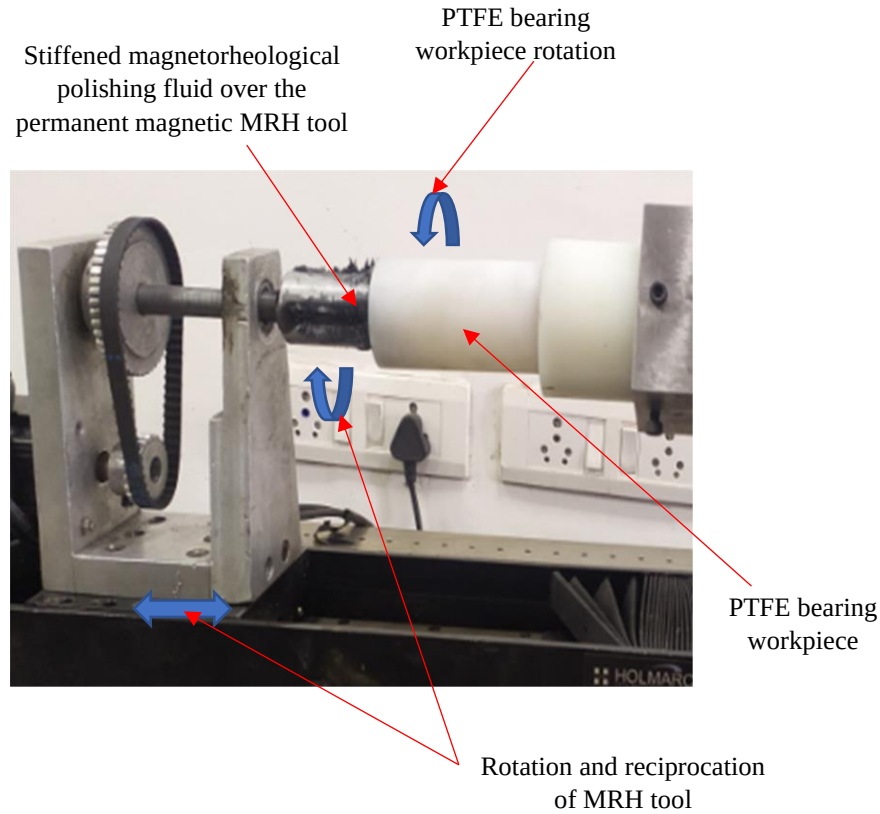


**Fig. 5.5.** MR finishing of the PTFE bearing with the different controlled motions.

**Table 5.7.** Preliminary experimentation for selecting the abrasive's type in magnetorheological polishing (MRP) fluid.

| S. No. | Tool rotation (rpm) | Tool reciprocation (mm/min) | Workpiece rotation (rpm) | Initial $R_a$ (nm) | Final $R_a$ (nm) with different types of abrasives in MRP fluid |           |         |         |
|--------|---------------------|-----------------------------|--------------------------|--------------------|-----------------------------------------------------------------|-----------|---------|---------|
|        |                     |                             |                          |                    | SiC                                                             | $Al_2O_3$ | $CeO_2$ | $SiO_2$ |
| 1.     | 300                 | 10                          | 20                       | 400                | 330                                                             | 290       | 290     | 300     |
| 2.     | 300                 | 10                          | 20                       | 380                | 310                                                             | 250       | 260     | 300     |
| 3.     | 300                 | 10                          | 20                       | 410                | 340                                                             | 320       | 330     | 310     |
| 4.     | 300                 | 10                          | 20                       | 400                | 330                                                             | 280       | 280     | 310     |
| 5.     | 300                 | 10                          | 20                       | 390                | 320                                                             | 270       | 260     | 310     |

From the preliminary experimentations,  $Al_2O_3$  and  $CeO_2$  both are found suitable for finishing the PTFE bearing surface as compared to the SiC, and  $SiO_2$  (Table 5.7). Since PTFE is a softer grade polymer, therefore it is vulnerable to sleeks and scratches, and the  $CeO_2$  can impart defects into

the surface resulting in scratch-dig failures and higher than expected surface roughness values (Hooper *et al.*, 2015). Therefore, for the experimentation for MR finishing of PTFE,  $\text{Al}_2\text{O}_3$  is used as an abrasive. Further, the base fluid used in the present work is the water-based carrier (WBC) fluid which comprises 80 % deionized water and 20 % glycerol. Owing to this, the surface asperities get easily shear off from the polymer internal surface by the AAPs leading to the fine surface finish.

### 5.3.1 Experiments to finalize the best volume concentration of the constituents of the MRP fluid for fine finishing of PTFE internal bearing surface

For fine finishing of the PTFE internal bearing, preliminary experimentations were done using the water-based MRP fluid with  $\text{Al}_2\text{O}_3$  abrasives. The range of % volume concentration of electrolytic iron particles (EIPs) varies from 15-35 % and % volume concentration of  $\text{Al}_2\text{O}_3$  abrasives varies from 10-20 %. The initial average roughness ( $R_a$ ) values of the PTFE workpieces range between 380-410 nm for preliminary experimentation. The other process parameters are reported in Table 5.8.

**Table 5.8.** Process parameters and their values used during experimentation.

| S. No. | Process parameters       | Value     |
|--------|--------------------------|-----------|
| 1.     | Tool reciprocation speed | 70 mm/min |
| 2.     | Tool core rotation speed | 300 rpm   |
| 3.     | Workpiece rotation       | 15 rpm    |
| 4.     | Working gap              | 1 mm      |

**Table 5.9.** Experimentations for selecting the best % volume concentration of the constituents of the MRP fluid.

| S. No. | % vol of EIPs, $E$ | % vol of $\text{Al}_2\text{O}_3$ abrasives, $C$ | % vol of water based carrier fluid | Initial $R_a$ value (nm) | Final $R_a$ value (nm) | % $\Delta R_a$ (Eq. 5.2) |
|--------|--------------------|-------------------------------------------------|------------------------------------|--------------------------|------------------------|--------------------------|
| 1.     | 25                 | 10                                              | 65                                 | 390                      | 270                    | 30.76                    |
| 2.     | 20                 | 12.5                                            | 67.5                               | 410                      | 220                    | 45                       |
| 3.     | 30                 | 17.5                                            | 52.5                               | 380                      | 140                    | 63.15                    |
| 4.     | 35                 | 15                                              | 60                                 | 380                      | 170                    | 55.26                    |
| 5.     | 30                 | 17.5                                            | 52.5                               | 390                      | 150                    | 61.53                    |
| 6.     | 25                 | 20                                              | 55                                 | 410                      | 210                    | 48.78                    |
| 7.     | 30                 | 17.5                                            | 52.5                               | 400                      | 160                    | 60                       |
| 8.     | 15                 | 15                                              | 70                                 | 400                      | 270                    | 32.50                    |
| 9.     | 20                 | 17.5                                            | 62.5                               | 410                      | 220                    | 46.34                    |
| 10     | 25                 | 15                                              | 60                                 | 410                      | 170                    | 58.53                    |

The experimental trials were done for 60 min and after every 20 min of the finishing cycle, the MRP fluid is changed on the MR finishing tool tip surface so that the abrasive particles work

effectively. A total of 10 experiments are performed to assess the outcomes of the selected best volume concentration of the MRP fluid's constituents on the % improvement in surface finish (%  $\Delta R_a$ ). The experimental process the %  $\Delta R_a$  was calculated by the Eq. (5.2). Further, the results of the preliminary experiments are reported in Table 5.9. Further, the effect of the % volume concentration of EIPs and abrasives on the % improvement of surface finish has been discussed. The effect of the % volume concentration of abrasives ( $C$ ) on %  $\Delta R_a$  is depicted in Fig. 5.6(a). The % volume concentration of EIPs ( $E$ ) was kept constant at 30 %. It can be seen that as the %  $C$  increases upto 17.5 %, there is an upsurge in the trend of %  $\Delta R_a$ . However, after the optimum value of the %  $C$ , there is a decrease in the trend %  $\Delta R_a$ . The AAPs are responsible for the shearing off the asperities from the bearing surface. As the concentration of the AAPs increase in the MRP fluid initially, the number of the AAPs performing the shearing action upsurges. This leads to the increase in the trendline of the %  $\Delta R_a$ . However, after the optimum value of the %  $C$ , the number of AAPs becomes so high that the abrasives start to get tangled in the EIPs columnar structure. Owing to this, the EIPs lattice structure gets weaken leading to the lower shear strength of the MRP fluid. These weak EIPs chains under lower shear strength led to the lower material removal from the work parts surface leading to the decrease in the trend of the %  $\Delta R_a$ .

The effect of % volume concentration of EIPs ( $E$ ) on %  $\Delta R_a$  is depicted in Fig. 5.6(b). The tool rotational speed ( $T$ ), tool reciprocation speed ( $F$ ), workpiece rotational speed ( $W$ ), and % volume concentration of AAPs ( $C$ ) are kept constant at 300 rpm, 15 rpm, 70 mm/min, and 17.5 % respectively. It can be seen that as the %  $E$  increases initially, there is an upsurge in the trendline of %  $\Delta R_a$ . However, after the optimum value of the 30 % of %  $E$  there is a decrease in the trendline of %  $\Delta R_a$ . This is due to the fact that as the %  $E$  upsurges, the normal magnetic force acting of the AAPs upsurges. Also, there is an increase in the magnetic permeability of the MRP fluid which leads to the strong and continuous EIP columnar structure. This leads to the higher shear strength of the EIPs chain due to which there is strong gripping of the AAPs in these chains. These tightly gripped AAPs perform higher shearing off the asperities from the bearing surface and increases the trend of the %  $\Delta R_a$ . However, beyond the optimum limit of the %  $E$ , the trendline of the %  $\Delta R_a$  decreases. This is because, after the optimal value, all the AAPs are tightly gripped sufficiently in the EIPs chain, and further adding more EIPs only aggregate outside the existing chains which decreases the overall cutting edges of the AAPs used for the surface finishing. From the experimentations, the best % volume concentration of MRP fluid was found as 30 % of electrolytic

iron particles (EIPs), and 17.5 % volume concentration of the  $\text{Al}_2\text{O}_3$  abrasive particles and 52.5 % of the base fluid.

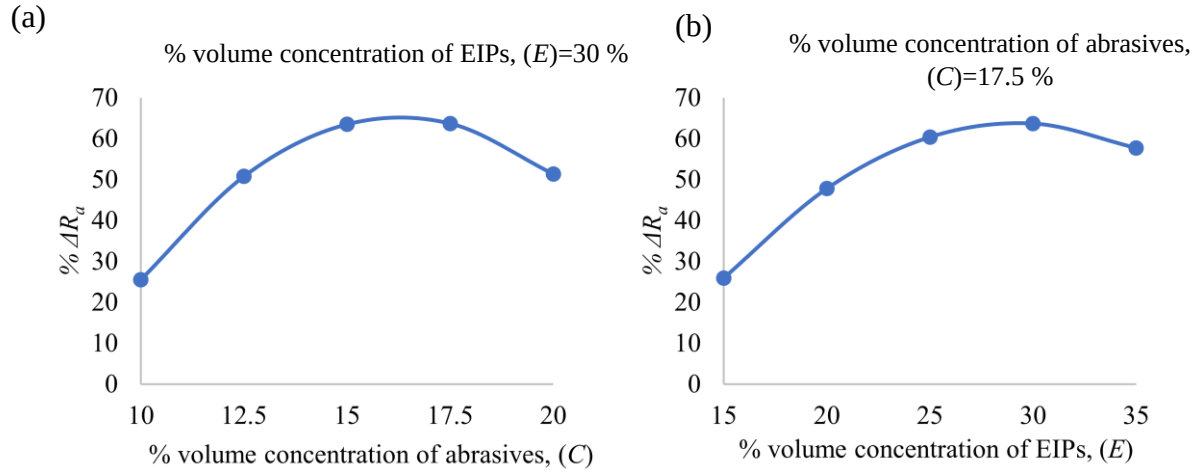


**Fig. 5.6.** (a) % volume concentration of abrasive ( $C$ ) and (b) % volume concentration of EIPs ( $E$ ) on %age improvement in the surface finish ( $\% \Delta R_a$ ).

#### 5.4 Development of the magnetorheological polishing fluid for fine finishing of the acrylonitrile butadiene styrene (ABS) surface

The MRP fluid is an essential part of the fine finishing of the ABS material workpiece using the MRF process. The MRP fluid comprises magnetic EIPs, polishing abrasives, and base fluid. Since very little literature is available for the fine finishing of the acrylonitrile butadiene styrene (ABS) polymer components using the MRF process. Therefore, four different types of abrasives are used to make the MRP fluid in this study naming titanium oxide, cerium oxide, alumina, and silicon oxide (each 800-mesh size). For the abrasive selection, the preliminary experimentations are performed on the FDM fabricated polymer cylindrical external surface using the different abrasives mixed with the EIPs and base fluid. For performing the preliminary experimentations, the volume % concentration of abrasive ( $C$ ) and EIPs ( $E$ ) are kept constant at 20 % each and base fluid as 60 %. Table 5.10 reports the other varied process parameters. The experimentations are performed for 20 min over the polyamide workpiece surface as depicted in Fig. 5.7. From the initial trials, cerium oxide ( $\text{CeO}_2$ ) is found more suitable for finishing the FDM fabricated polymer cylindrical external surface as compared to the alumina, titanium oxide, and silicon oxide (Table 5.10). This might be because  $\text{CeO}_2$  provides great polishing efficiency and excellent suspension particles. For the experimentations, the composition of MRP fluid used was 25 % by volume of EIPs (500 mesh size), 15 % by volume of  $\text{CeO}_2$  abrasive (800 mesh size), and 60 % by volume of

WBC fluid (the carrier fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol).

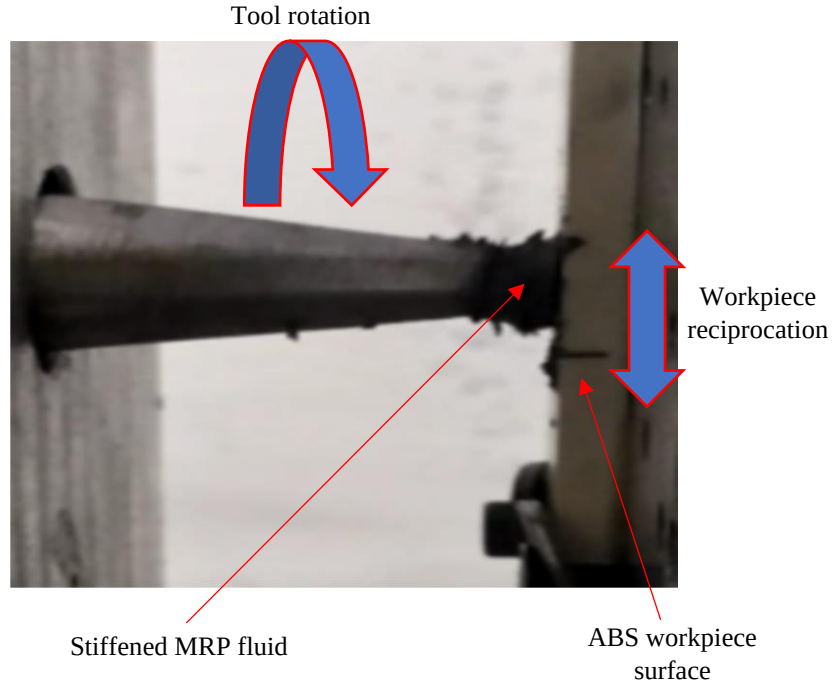


**Fig. 5.7.** MR finishing of the additive manufactured (AM) typical turbine blade with the different controlled motions.

**Table 5.10.** Initial trials for the selection of the abrasives.

| S. No | Tool rotation, (rpm) | Workpiece rotation, (rpm) | Tool reciprocation, (cm/min) | Current, (A) | Initial $R_a$ value (nm) | Final $R_a$ value (nm) with different types of abrasives in MRP fluid |                  |                  |                                |
|-------|----------------------|---------------------------|------------------------------|--------------|--------------------------|-----------------------------------------------------------------------|------------------|------------------|--------------------------------|
|       |                      |                           |                              |              |                          | CeO <sub>2</sub>                                                      | TiO <sub>2</sub> | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> |
| 1.    | 100                  | 50                        | 10                           | 2            | 590                      | 360                                                                   | 420              | 430              | 390                            |
| 2.    | 100                  | 200                       | 15                           | 4            | 630                      | 390                                                                   | 440              | 450              | 400                            |
| 3.    | 300                  | 150                       | 5                            | 2.5          | 600                      | 310                                                                   | 400              | 410              | 340                            |
| 4.    | 200                  | 100                       | 10                           | 3.5          | 620                      | 330                                                                   | 380              | 400              | 350                            |
| 5.    | 400                  | 200                       | 25                           | 1            | 610                      | 300                                                                   | 390              | 410              | 330                            |

#### **5.4.1 Development of the graphene-based MRP fluid for the fine finishing of the acrylonitrile butadiene styrene (ABS) surface**

For enhancing the finishing rate of the present MRF process, new MRP fluid namely EIPs-CeO<sub>2</sub>-graphene is introduced for the fine finishing of the ABS workpieces. The EIPs present in the fluid form a chain-like structure to retain the graphene particles with the Vander wall forces, resulting in a rise in shear viscosity (Thiyagu *et al.*, 2019). In the presence of a magnetic field, graphene



particles form a chain structure between the two EIPs, and normal magnetic force pushes the graphene particles inside the micro-voids in the EIP chains. In this case, abrasives are entrenched amid the graphene and EIPs chain, and they participate in the finishing procedure as a single body. Because of their reciprocal attraction forces, all of those particles actively engage in the creation of a chain structure in the presence of a magnetic field. This indicates that the component particles (EIPs, graphene, and abrasives) are subjected to a greater magnetic attraction force. Also, the yield stress of the MRP fluid with graphene tends to have higher shear stress as compared to the MRP fluid without graphene (Prakash *et al.*, 2021). As a result of the increased bonding strength of the magnetic abrasives, higher shear stress is delivered to the workpiece surface. This leads to the enhancement in the surface finishing of the workpiece surface.

Further, to analyze the efficacy of the graphene in the MRP fluid, preliminary experimentations were performed. The range of the graphene was selected as 1 % - 2.5 %. The EIPs composition varies from 22.5 % - 24 % and % volume composition of abrasives is 15 %. Further, the initial average roughness values ( $R_a$ ) of the ABS workpieces range between 590-610 nm for preliminary experimentation. The other process parameters are reported in Table 5.11.

**Table 5.11.** Process parameters and their value during experimentation.

| S. No. | Process parameters       | Value     |
|--------|--------------------------|-----------|
| 1.     | Tool reciprocation speed | 15 cm/min |
| 2.     | Tool core rotation speed | 700 rpm   |
| 3.     | Magnetizing current      | 4 A       |
| 4.     | Working gap              | 0.6 mm    |

The experimental trials were done for 60 min and after every 20 min of the finishing cycle, the MRP fluid is changed on the hemispherical tool tip surface so that the abrasive particles work effectively. A total of 5 preliminary experiments are performed to assess the outcomes of the selected best % volume concentration of the constituents of the MRP fluid on the % improvement in surface finish ( $\% \Delta R_a$ ). After the experimentation, the  $\% \Delta R_a$  was calculated using the Eq. (5.2). Further, the results of the preliminary experiments are reported in the Table 5.12.

**Table 5.12.** Experimentations for selecting the best % volume concentration of the constituents of the MRP fluid.

| S. No. | % vol of graphene, $G$ | % vol of EIPs, $E$ | % vol of $CeO_2$ abrasives, $C$ | % vol of base fluid | Initial $R_a$ value (nm) | Final $R_a$ value (nm) | % $\Delta R_a$ (Eq. 5.2) |
|--------|------------------------|--------------------|---------------------------------|---------------------|--------------------------|------------------------|--------------------------|
| 1.     | 1                      | 24                 | 15                              | 60                  | 590                      | 280                    | 52.54                    |
| 2.     | 1.5                    | 23.5               | 15                              | 60                  | 610                      | 240                    | 60.65                    |
| 3.     | 2                      | 23                 | 15                              | 60                  | 600                      | 210                    | 65                       |
| 4.     | 2.5                    | 22.5               | 15                              | 60                  | 590                      | 240                    | 59.32                    |
| 5.     | 3                      | 22                 | 15                              | 60                  | 610                      | 320                    | 47.54                    |

The effect of the percent volume concentration of graphene ( $G$ ) on the %  $\Delta R_a$  is depicted in Fig. 5.8. It can be seen that as the parameter  $G$  initially increases, the trend of the %  $\Delta R_a$  increases. However, the trend of the %  $\Delta R_a$  decreases after a 2 % vol concentration of graphene particles. Increasing  $G$ , upsurges the MRP fluid shear strength of the MRP fluid. This results in the strong gripping of the AAPs in the EIPs chain which results in enhancement in shearing off the roughness asperities from the work part surface. Hence, the material removal rate increases which lead to the trendline of the %  $\Delta R_a$ .

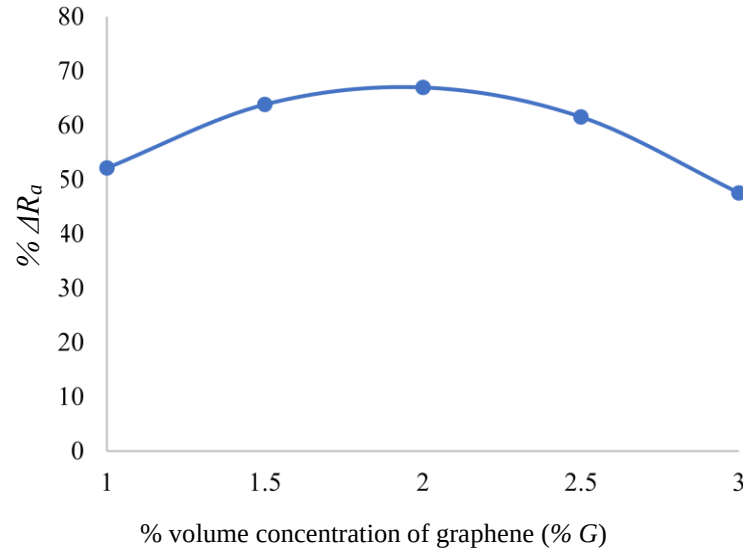


**Fig. 5.8.** % volume concentration of graphene ( $G$ ) on %age improvement in the surface finish (%  $\Delta R_a$ ).

However, as the  $G$  further increases beyond optimum value, the number of graphene particles that become tangled between the EIPs and abrasive increases. As a result, the EIPs lattice structure became weaker, lowering the shear strength of the MR fluid. This leads to a decrease in the MRP

fluid's strength. Owing to this there is a reduction in material removal rate which decreases the trend of  $\% \Delta R_a$ .

Further, the experimentation is performed with graphene-based MRP fluid and without graphene-based MRP fluid. Three experiments were performed for 20 min each and the process parameters used for experiments is reported in Table 5.13. The other process parameter used are reported in Table 5.11. The results of the experimentation are depicted in Fig. 5.9. From the figure, it can be seen that the MRP fluid with graphene provides fine finishing (lower surface roughness) as compared to the MRP fluid without graphene. Hence, it can be concluded that the addition of graphene to the MRP fluid tends to enhance the surface finishing of the polymer surface.

**Table 5.13.** MRP fluid composition with and without graphene used for experimentation.

| MRP fluid without graphene |                   |                     | MRP fluid with graphene |                |                 |                  |
|----------------------------|-------------------|---------------------|-------------------------|----------------|-----------------|------------------|
| vol % of EIPs              | vol % of abrasive | vol % of base fluid | vol % EIPs              | vol % graphene | vol % abrasives | vol % base fluid |
| 25                         | 15                | 60                  | 23                      | 2              | 15              | 60               |

The present developed different MRP fluids are used for the fine finishing of the different types of polymer workpieces with different shapes. Thus, these MRP fluids in the MRF process are to be useful for industries dealing with fine finishing of polymer gears, bearings, medical implants, valve seals additive manufactured components, etc.

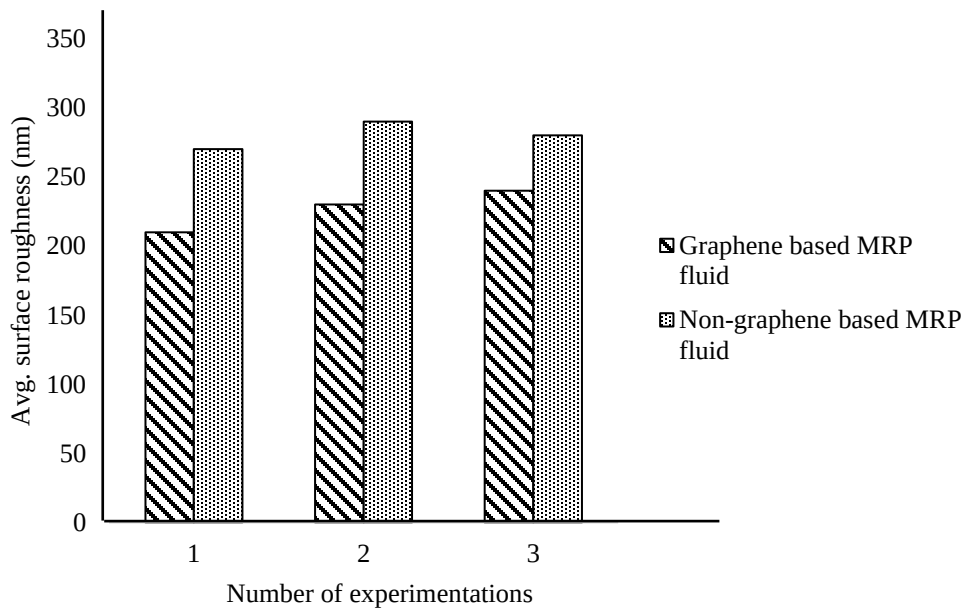


**Fig. 5.9.** Experimental results with and without graphene based MRP fluid over ABS workpiece.

## 5.5 Conclusions

From the development of the magnetorheological polishing (MRP) fluids for the finishing of the different types of polymer materials with different shapes, the following conclusions have been drawn.

- The water-based magnetorheological polishing fluid show effectively finishing over polyamide surface with 15 % by volume of EIPs (500 mesh size), 15 % by volume of CeO<sub>2</sub> abrasive (800 mesh size), and 70 % by volume of base fluid (the base fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol).
- The water-based MRP fluid with CeO<sub>2</sub> abrasives reveals more effective for fine finishing the UHMWPE polymer acetabular cup as compared to the SiC and Al<sub>2</sub>O<sub>3</sub> abrasives.
- The study of the different abrasives used in the magnetorheological polishing fluid reveals that the Al<sub>2</sub>O<sub>3</sub> abrasives are more suitable for the fine finishing of the PTFE bearings as compared to the SiC, CeO<sub>2</sub>, and SiO<sub>2</sub> abrasives.
- The MRP fluid with cerium oxide (CeO<sub>2</sub>) abrasives reveals a more effective MR finishing of the acrylonitrile butadiene styrene (ABS) workpiece surface than SiO<sub>2</sub>, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> abrasives.
- Graphene-based magnetorheological polishing fluid results in the increased bonding strength of the magnetic abrasives, and higher shear stress is delivered to the workpiece surface. This leads to the enhancement in the surface finishing of the polymer workpiece surface.

## 5.6 Experimental investigation to examine the fine finishing of the polyamide surface using the magnetorheological finishing process

The polyamides are replacing most metal alloys in the marine, molding, and tooling industries (Guo *et al.*, 2018). However, poor surface finish increases the volumetric wear rate and reduces fracture loading, owing to which polyamides tend to have poor flexural (bending) strength as compared to metals (Hoskins *et al.*, 2011). Due to these drawbacks, there is a delay in the implementation of polyamide components in many industries. As a result, a high-grade surface finishing is required to enhance the functional effectiveness of polyamide components with improved service life and minimal wear and friction. For uniform finishing of the polyamide surface, the magnetorheological finishing (MRF) process with a rectangular tip-based tool (Singh and Singh, 2019) is utilized. As a result, the MR finished polyamide workpiece surface can

improve service life, shape, and geometrical correctness. The optimum process parameters for fine finishing polyamide workpieces are finally predicted. Microhardness, wear test, surface morphology, and waviness of the polyamide workpiece are investigated further to determine the current MRF process performance.

#### **5.6.1 Material selection and workpiece preparation**

Lightweight materials play an important role in various industries nowadays. Automobile, medical, defense are some sectors where polyamides are used as alternatives to lightweight alloys due to their property of lightweight, non-corrosive, and extremely good formability. Polyamides are utilized in a variety of applications, including gears, bushes, and bearings. The surface finishing plays an important role in these components.

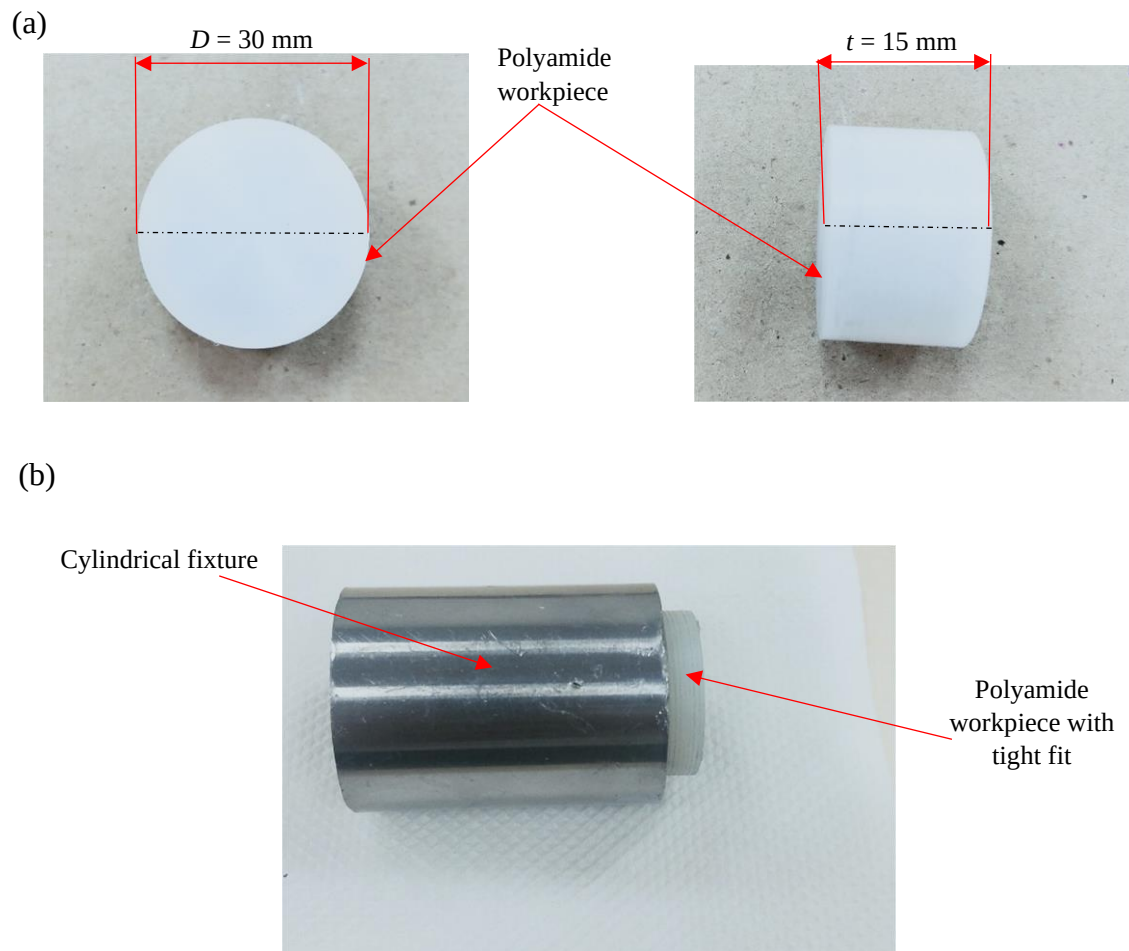


**Fig. 5.10.** (a) Dimension of the polyamide workpiece and (b) cylindrical fixture to hold the workpiece.

Therefore, finely finished polyamide workpiece surface tends to reduce wear and friction which enhances the quality in molding tool industry. Hence, in the present study, polyamides are used as the material for experimentation. Cylindrical rods of polyamides are used to make workpiece samples of diameter ( $D$ ) 30 mm and 15 mm thickness ( $t$ ) as depicted in Fig. 5.10(a). Turning was done on the lathe for the initial machining to make samples in required dimensions. Following that, workpiece samples were subjected to conventional grinding. Before MR finishing, the workpieces were cleaned with acetone and regular maintenance was performed to keep the surface clean. Further, to hold the sample on the workpiece table, a cylindrical sample holder was made with a diameter of 32 mm and a length of 50 mm as shown in Fig. 5.10(b).

### **5.6.2 Experimentation**

For the effective polyamide workpiece finishing, the rotary core-based MRF (magnetorheological fluid) process is utilized as depicted in Fig. 5.11. To perform the finishing operations, two types of motions are used in this work. Rotary motion by the workpiece ( $W$ ), rotary motion by the tool core ( $T$ ), and reciprocatory motion of tool ( $F$ ) are rotated in the opposite direction as depicted in Fig. 5.11. In the absence of the magnetic field, the MRP fluid is not stiffened as depicted in Fig. 5.11(a). However, as the magnetic field is applied, the MRP fluid becomes stiffened as depicted in Fig. 5.11(b). The working space amid the work part surface and tooltip surface is kept constant at 0.6 mm. Further, due to the constant supply of current through the electromagnetic coil of the tool, the temperature tends to rise which may reduce the viscosity of MRP fluid in the working space, and hence due to this effect, the process performance gets slower. Therefore, the transformer oil circulates inside the cooling jacket to cool the electromagnet coil during the finishing process. Fig. 5.11(c) depicts the actual finishing of the polyamide workpiece due to the different motions.

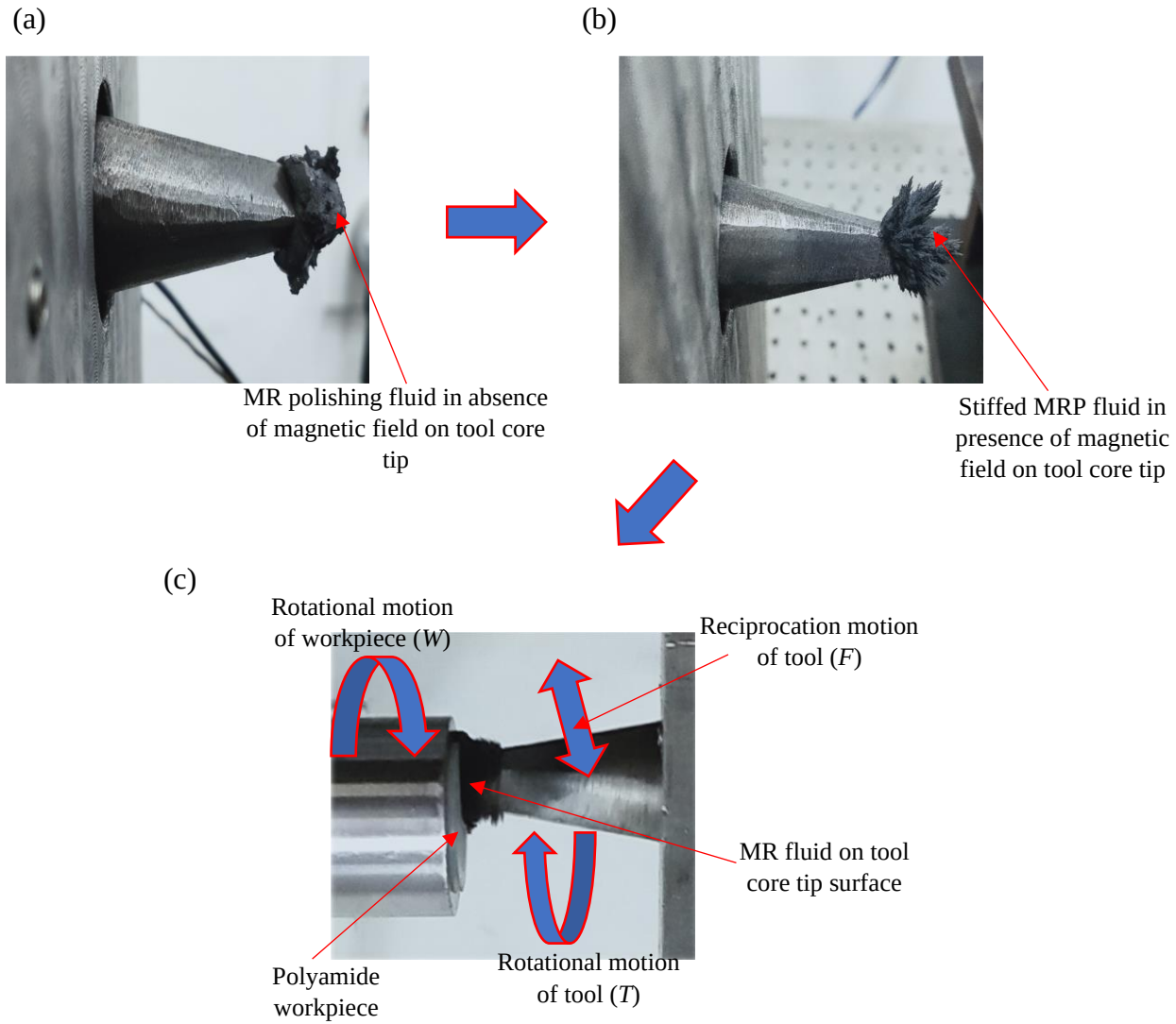


**Fig. 5.11.** Magnetorheological polishing fluid on tool tip surface (a) in the absence of magnetic field, (b) in the presence of the magnetic field, and (c) MR finishing of polyamide workpiece with the different controlled motions.

#### 5.6.2.1 Selection of finishing process parameters

The various process parameters were chosen based on the effective finishing required over the polyamide exterior workpiece surface using the rotary core-based MRF process as depicted in Fig. 3.1 (*Chapter 3*). The process parameters employed in this study include magnetizing current ( $I$ ), tool rotary speed ( $T$ ), work part rotary speed ( $W$ ), and tool reciprocatory speed ( $F$ ). Since the polyamide external surface is to be fine finished with an electromagnetic rectangular tip-based rotary tool in this study. The magnetic flux density (MFD) can be controlled during the MRF process by the magnetizing current ( $I$ ). Furthermore, the tool rotational speed ( $T$ ) and work part rotational speed ( $W$ ) that operate on the AAPs control the tangential shear force. The  $T$  and  $W$  additionally control the relative movement between the AAPs and the work section. Next, the axial

shear force exerted on the particles is controlled by the reciprocating tool speed ( $F$ ). It controls the AAPs collision with the asperities on the workpiece's surface.

### 5.6.3 Design of experiments

For performing the experiments on the flat surface of a cylindrical polyamide workpiece, the response surface methodology (RSM) technique was used to check the outcome of parameters on the response. The RSM is a group of various technologies such as statistical, mathematical, and graphical methods, it develops the relationship between output and input. The main aim of the regression model is to study the  $\% \Delta R_a$  by reducing the variability in the process and improving the finishing of the polyamide surface. In the RSM, the central composite design (CCD) with five levels and four parameters design is utilized in the present work. In RSM, CCD is appropriate for fitting second-order polynomial equations and has been frequently used for optimization. A CCD has three groups of design points (Asadollahzadeh *et al.*, 2014). The first one is two-level factorial or fractional factorial design points ( $2^k$ ), consisting of possible combinations of +1 and -1 levels of the factor, the second is  $2k$  axial points (sometimes called star points) fixed axially at a distance say  $\alpha$  from the center to generate quadratic terms, and third is center points which represent replicate terms; center points provide a good and independent estimate of the experimental error. Considering these points, the number of experiments designed by CCD is given by Eq. (5.3)

$$N_e = 2^k + 2k + q \quad (5.3)$$

where  $N_e$  is the total number of experiments,  $k$  is the number of factors studied, and  $q$  is the number of replicates.

Further, the Design of Expert 6.0.8 software is used for designing the experimentations. The range of variable process parameters is based on preliminary experiments. Table 5.14 summarizes the process parameter range used for experimentation.

**Table 5.14.** Process parameter and their range.

| S. No. | Parameters                             | Range |     |     |     |     |
|--------|----------------------------------------|-------|-----|-----|-----|-----|
| 1.     | Tool rotational speed, $T$ (rpm)       | 100   | 200 | 300 | 400 | 500 |
| 2.     | Workpiece rotational speed, $W$ (rpm)  | 50    | 100 | 150 | 200 | 250 |
| 3.     | Magnetizing current $I$ , (A)          | 1     | 1.5 | 2   | 2.5 | 3   |
| 4.     | Tool reciprocation speed, $F$ (cm/min) | 5     | 10  | 15  | 20  | 25  |



The preliminary experimental results were utilized to select the range of process parameters in the parametric analysis in order to effectively finish the polyamide workpiece. Further, to study the outcome of the different process parameters on the %  $\Delta R_a$ , RSM was utilized. Statistical, analytical and graphical techniques of the RSM were used for the process optimization. The Eq. (5.4) specifies the relationship amid responses and variables.

$$Y = f(I, T, F, W) \quad (5.4)$$

where  $Y$  is the response for the %  $\Delta R_a$  and  $f(I, T, F, W)$  is the function of the process parameters used. The outcomes of the process parameters were examined using the second-order polynomial response. As the initial surface roughness ( $R_a$ ) values for each sample were different, therefore %  $\Delta R_a$  was taken as the output response. A total 30 experiments were performed and their parametric details are reported in Table 5.15 Each experiment was done for 20 min. The composition of the magnetorheological polishing (MRP) fluid used for experiments is discussed in *Section 5.1*. The composition of MRP fluid used was 15 % by volume of EIPs (500 mesh size), 15 % by volume of CeO<sub>2</sub> abrasive (800mesh size), and 70 % by volume of WBC fluid (the carrier fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol). The effectiveness of the model was verified at the 95 % of confidence level. The F-level test from analysis of variance (ANOVA) was further used to determine the implications of the regression equation for amplification of the relationship between (%  $\Delta R_a$ ) and controlled process parameters. After the experimental process, the %  $\Delta R_a$  was calculated using Eq. (5.2)

The surface asperities value of the workpieces was measured with the assistance of SJ-400 Mitutoyo surface roughness tester with 0.25 mm cut off length. The surface characteristics of the polyamide samples were observe by scanning electron microscopy (SEM) JSM-6510LV and the waviness is measured with the help of the Tylor Hobson profilometer. Further, the wear rate is measured using in the Pin-on-Disc Tribometer (Contech, CAS-304), and microhardness tests using the microhardness tester machine Mitutoyo HM-210 model.

#### **5.6.4 Results and discussion**

Experimental trials were carried out in this study to assess the effects of various process factors on the %  $\Delta R_a$ . The experimental validation was done by the developed model so that the accuracy of the process can be checked. The experimental response data is reported in Table 5.15. Further, on each parametric condition two trials are done ( $X_1$  and  $X_2$ ), and after that average value of  $X_1$  and  $X_2$  is obtained to get the final  $R_a$  which is used in Eq. (5.2) to get %  $\Delta R_a$ . The experimental data

was utilized to do ANOVA as depicted in Table 5.16. The p-value of the model was determined to be less than 0.05 after performing ANOVA on the basis sequential model. The p-value for lack of fit is more than 0.05, suggesting that the lack of fit is not significant.

The F-value of the model is 19.22, as seen in the ANOVA table. Further, the model's Adj R-square value is 88.29 % and R-square value obtained from the model is 93.14 %, which shows the accuracy of the model. This concluded that there is not much variation amid the experimental and the calculated values from the developed model.

**Table 5.15.** Experimentation plans and results.

| Run order | Std. order | Current, $I$ (A) | Tool rotation speed, $T$ (rpm) | Workpiece rotation speed, $W$ (rpm) | Tool reciprocating speed, $F$ (cm/ min) | Initial $R_a$ (nm) | Final $R_a$ (nm) |      |                    | % $\Delta R_a$ Eq. (5.2) |
|-----------|------------|------------------|--------------------------------|-------------------------------------|-----------------------------------------|--------------------|------------------|------|--------------------|--------------------------|
|           |            |                  |                                |                                     |                                         |                    | $X1$             | $X2$ | Average $R_a$ (nm) |                          |
| 1         | 13         | 2                | 300                            | 150                                 | 15                                      | 580                | 260              | 240  | 250                | 56.89                    |
| 2         | 17         | 1.5              | 400                            | 200                                 | 10                                      | 630                | 360              | 350  | 355                | 43.65                    |
| 3         | 16         | 1.5              | 200                            | 200                                 | 20                                      | 580                | 350              | 330  | 340                | 41.37                    |
| 4         | 10         | 2.5              | 400                            | 100                                 | 20                                      | 620                | 330              | 310  | 320                | 48.38                    |
| 5         | 6          | 2.5              | 200                            | 200                                 | 10                                      | 600                | 330              | 350  | 340                | 43.33                    |
| 6         | 12         | 2                | 300                            | 250                                 | 15                                      | 570                | 390              | 310  | 350                | 38.59                    |
| 7         | 15         | 1.5              | 400                            | 100                                 | 20                                      | 590                | 300              | 320  | 310                | 47.45                    |
| 8         | 11         | 1.5              | 200                            | 100                                 | 20                                      | 610                | 320              | 370  | 345                | 43.44                    |
| 9         | 25         | 2.5              | 400                            | 100                                 | 10                                      | 600                | 340              | 300  | 320                | 46.67                    |
| 10        | 14         | 1                | 300                            | 150                                 | 15                                      | 590                | 360              | 340  | 350                | 40.67                    |
| 11        | 8          | 1.5              | 400                            | 200                                 | 20                                      | 630                | 260              | 280  | 270                | 57.14                    |
| 12        | 21         | 2                | 300                            | 150                                 | 25                                      | 590                | 310              | 330  | 320                | 45.76                    |
| 13        | 7          | 2                | 300                            | 150                                 | 15                                      | 580                | 270              | 280  | 275                | 52.58                    |
| 14        | 5          | 2.5              | 200                            | 100                                 | 20                                      | 590                | 320              | 340  | 330                | 44.06                    |
| 15        | 19         | 1.5              | 200                            | 100                                 | 10                                      | 620                | 310              | 330  | 320                | 48.38                    |
| 16        | 27         | 2                | 100                            | 150                                 | 15                                      | 580                | 360              | 340  | 350                | 39.65                    |
| 17        | 26         | 2                | 500                            | 150                                 | 15                                      | 610                | 350              | 310  | 330                | 45.90                    |
| 18        | 29         | 2.5              | 200                            | 200                                 | 20                                      | 570                | 320              | 340  | 330                | 42.10                    |
| 19        | 1          | 2.5              | 400                            | 200                                 | 20                                      | 620                | 350              | 330  | 340                | 45.16                    |
| 20        | 2          | 1.5              | 400                            | 100                                 | 10                                      | 590                | 340              | 350  | 345                | 41.52                    |
| 21        | 23         | 3                | 300                            | 150                                 | 15                                      | 610                | 320              | 310  | 315                | 48.36                    |
| 22        | 22         | 2.5              | 200                            | 100                                 | 10                                      | 590                | 330              | 320  | 325                | 44.91                    |
| 23        | 18         | 2                | 300                            | 150                                 | 15                                      | 580                | 240              | 260  | 250                | 56.89                    |
| 24        | 3          | 2.5              | 400                            | 200                                 | 10                                      | 570                | 290              | 310  | 300                | 47.36                    |
| 25        | 30         | 2                | 300                            | 150                                 | 15                                      | 590                | 270              | 290  | 280                | 52.54                    |
| 26        | 20         | 1.5              | 200                            | 200                                 | 10                                      | 590                | 350              | 330  | 340                | 42.37                    |
| 27        | 24         | 2                | 300                            | 150                                 | 5                                       | 590                | 310              | 330  | 320                | 45.76                    |
| 28        | 28         | 2                | 300                            | 150                                 | 15                                      | 590                | 290              | 270  | 280                | 52.54                    |
| 29        | 4          | 2                | 300                            | 50                                  | 15                                      | 590                | 280              | 300  | 290                | 50.84                    |
| 30        | 9          | 2                | 300                            | 150                                 | 15                                      | 620                | 310              | 290  | 300                | 51.61                    |

This demonstrates that the model is significant and only 0.01 % possibility is that model can be insignificant because of noise. Table 5.16 shows the ANOVA after the non-significant factors have

been removed. For the following factors specifically  $I$ ,  $T$ ,  $W$ ,  $F$ ,  $I^2$ ,  $T^2$ ,  $F^2$ ,  $W^2$ ,  $IT$ ,  $IF$ ,  $TF$ , and  $TW$ , the p-value are less than 0.05 and for the remaining factors, the p-value is more than 0.05. Therefore, the insignificant factors were eliminated.

**Table 5.16.** ANOVA analysis for % improvement in surface finish (%  $\Delta R_a$ ).

| Source      | Sum of squares | DOF | Mean square | F value | Prob>F   | Remark                                      | PC (Eq. 5.6) |
|-------------|----------------|-----|-------------|---------|----------|---------------------------------------------|--------------|
| Model       | 790.42         | 12  | 65.87       | 19.22   | < 0.0001 | $F_{(0.05,12,17)}=1.957$<br>Significant     |              |
| $I$         | 28.17          | 1   | 28.17       | 8.22    | 0.0107   |                                             | 2.761        |
| $T$         | 32.67          | 1   | 32.67       | 9.53    | 0.0067   |                                             | 3.202        |
| $W$         | 80.67          | 1   | 80.67       | 23.54   | 0.0001   |                                             | 7.907        |
| $F$         | 16.67          | 1   | 16.67       | 4.86    | 0.0415   |                                             | 1.634        |
| $I^2$       | 198.11         | 1   | 198.11      | 57.82   | < 0.0001 |                                             | 19.419       |
| $T^2$       | 257.25         | 1   | 257.25      | 75.08   | < 0.0001 |                                             | 25.216       |
| $W^2$       | 216.96         | 1   | 216.96      | 63.32   | < 0.0001 |                                             | 21.266       |
| $F^2$       | 116.68         | 1   | 116.68      | 34.05   | < 0.0001 |                                             | 11.437       |
| $IT$        | 25.00          | 1   | 25.00       | 7.30    | 0.0151   |                                             | 2.45         |
| $IF$        | 16.00          | 1   | 16.00       | 4.67    | 0.0453   |                                             | 1.568        |
| $TW$        | 16.00          | 1   | 16.00       | 4.67    | 0.0453   |                                             | 1.568        |
| $TF$        | 16.00          | 1   | 16.00       | 4.67    | 0.0453   |                                             | 1.568        |
| Residual    | 58.25          | 17  | 3.43        |         |          |                                             |              |
| Lack of fit | 49.42          | 12  | 4.12        | 2.33    | 0.1800   | $F_{(0.05,12,17)}=1.957$<br>Not significant |              |
| Pure error  | 8.83           | 5   | 1.77        |         |          |                                             | 0.4          |
| Total       | 848.67         | 29  |             |         |          |                                             |              |

The quadratic equation for the improved response surface is provided in Eq. (5.5).

$$\% \Delta R_a = -39.104 + 43.667I + 0.085T + 0.24W + 2.508F - 10.75I^2 - 3.06 \times 10^{-4}T^2 - 1.125 \times 10^{-3}W^2 - 8.25 \times 10^{-2}F^2 + 2.5 \times 10^{-2}IT - 0.40IF + 2 \times 10^{-4}TW + 2 \times 10^{-3}TF \quad (5.5)$$

The predicted %  $\Delta R_a$  is calculated using Eq. (5.5) and compared to the experimental %  $\Delta R_a$  readings. Furthermore, the % error demonstrated the similarity between the calculated and experimental values.

#### 5.6.4.1 Effect of significant parameters on the performance of the process

The percentage contribution (PC) of each factor and their interaction is reported in Table 5.16. The PC depicts individual parameter weight in the regressional study of the %  $\Delta R_a$ . Using ANOVA Table 5.16, the values of each parameter's weightage are computed. The Eq. (5.6) is used to compute PC.

$$PC = \frac{\text{Sum of square of parameter}}{\text{Total sum of square}} \times 100 \quad (5.6)$$

It can be observed that the percentage contribution of workpiece rot ary speed ( $W$  and  $W^2$ ) is 29 %, tool rotary speed ( $T$  and  $T^2$ ) is 28.5 %, magnetizing current ( $I$  and  $I^2$ ) is 22 % and reciprocating

speed of tool ( $F$  and  $F^2$ ) is 13 % . The results of the significant parameters have been discussed further in this section.

#### 5.6.4.2 Individual effect of significant parameters on the % $\Delta R_a$

The effect of current ( $I$ ) on %  $\Delta R_a$  is depicted in Fig. 5.12(a). The tool rotary motion ( $T$ ), workpiece rotational speed ( $W$ ), and tool reciprocation speed ( $F$ ) are kept constant at 300 rpm, 150 rpm, and 15 cm/min respectively. It can be seen that when  $I$  increase, the %  $\Delta R_a$  upsurges as well, eventually reaching an optimal value of 2 A. This is because, as the  $I$  upsurge initially, the magnetic flux density (MFD) of the MRP fluid rises. As a result, abrasives in the EIPs chain have a strong grip. Further, the finishing pressure generated by the EIPs in the working space is given by Eq. (5.7) (Saraswathamma *et al.*, 2015).

$$P = \frac{B^2(1-\frac{1}{\mu_e})}{\mu_x} \quad (5.7)$$

where  $P$  is the finishing pressure,  $B$  is the MFD,  $\mu_x$  is relative permeability in vacuum and  $\mu_e$  is relative permeability in EIPs. From Eq. (5.7), it is clear that with the upsurge in  $B$ , the finishing pressure increases which upsurges the chipping off the asperities from the polyamide external surface. Hence, due to this strong gripping action and increase in finishing pressure, there is a rise in the finishing action leading to higher material abrasion. Owing to this the %  $\Delta R_a$  trend line increases. However, as  $I$  reach its optimal value, the trend in %  $\Delta R_a$  decreases. This is due to the excess increase in indentation force that comes with an upsurge in the current ( $I$ ). Now, as the  $I$  upsurge, there is an excess increment in the MFD due to which indentation force by AAPs on the polyamide external surface increases. The indentation force that acts on the AAPs becomes so high that it does not only chip off the asperities but also deteriorates the workpiece surface which leads to the formation of the pits. Owing to this formation of pits, there is a decrease in %  $\Delta R_a$  after 2 A. The influence of tool rotating speed ( $T$ ) on %  $\Delta R_a$  is shown in Fig. 5.12(b). The  $I$ ,  $W$ , and  $F$  were kept constant at 2 A, 150 rpm, and 15 cm/min respectively. It can be seen that %  $\Delta R_a$  upsurge up to an optimized value of  $T$  at 300 rpm. However, beyond the optimum rotation value of the  $T$ , the trend line of the %  $\Delta R_a$  decreases. This is because when the  $T$  rises initially, there is an upsurge in the abrasion speed of AAPs rotating over the polyamide external surface asperities. As a result, the tangential force due to tool ( $F_t$ ) increases as discussed in *Chapter 4 (section 4.4)*. The AAPs, which are tightly entrenched in the EIPs chain, clip off the asperities from the polyamide external surface due to the greater  $F_t$ . As a result, there is an increase in material removal, hence the %  $\Delta R_a$

trendline upsurges. However, as the  $T$  upsurge over the 300 rpm value, the  $F_{tt}$  becomes so high that may lead to a loosening in the grip of AAPs in the EIPs chain. Owing to this there is a reduction in the influence of a magnetizing force that acts on EIPs. As a result, the AAPs are unable to clip off the asperities effectively, leading to less material removal and a decrease in surface quality. As a result, the decrease in  $\% \Delta R_a$  after 300 rpm is due to an excessive rise in  $F_{tt}$  acting on the EIPs as the rotation of tool ( $T$ ) increases. At 300 rpm of  $T$ , the maximum value of  $\% \Delta R_a$  was obtained. The influence of workpiece rotary motion ( $W$ ) on  $\% \Delta R_a$  is shown in Fig. 5.12(c). The magnetizing current ( $I$ ), the tool rotary motion ( $T$ ), and reciprocatory speed of the tool ( $F$ ) were kept constant at 2 A, 300 rpm, and 15 cm/min respectively. The  $\% \Delta R_a$  trend-line upsurges as the  $W$  increases until it reaches the optimized value of 150 rpm. However, after the optimum  $W$  value, the trendline of the  $\% \Delta R_a$  starts decreasing. This is because, as the  $W$  rises, the collision between a workpiece's surface asperities and AAPs increases due to the AAPs' increased net relative velocity. As a result, the AAPs can clip off the polyamide work part surface asperities at a higher rate. As a result, the trendline of the  $\% \Delta R_a$  increases. When the  $W$  is increased beyond 150 rpm, however, the  $\% \Delta R_a$  trend decreases. This is because when the  $W$  increases, the net relative velocity of AAPs increases to the point where interaction time amid asperities and AAPs decreases. Because of the shorter interaction time, the abrasive is unable to clip off the asperities, resulting in a decrease in  $\% \Delta R_a$ . The influence of tool reciprocation motion ( $F$ ) on  $\% \Delta R_a$  is shown in Fig. 5.12(d). The  $T$ ,  $I$ , and  $W$  are constant at 300 rpm, 2 A, and 150 rpm respectively. As the  $F$  rises, the  $\% \Delta R_a$  trend-line upsurges until it reaches the optimum value of 15 cm/min, at which point the  $\% \Delta R_a$  trend-line begins to decrease. This is because the number of finishing cycles rotating over the work part surface rise as the  $F$  rises (up to 15 cm/min). As a result, the asperities sheared off from the polyamide surface by the AAPs rise. Also, with an initial upsurge in the  $F$ , the axial shear force acting on the AAPs upsurges. This results in the quick removal of asperities axially from the work part surface, resulting in good finishing and thereby upsurging the  $\% \Delta R_a$  trend-line. However, when the  $F$  goes beyond the optimum value, the EIPs chain gets disturbed due to the very fast motion of the electromagnetic tool over the polyamide external surface. This causes deformation in the EIPs chain, causing the EIPs to lose their grip on the AAPs. Furthermore, at a higher  $F$ , the MRP fluid interacts with the surface more quickly, giving AAPs less time to shear surface asperities from the polyamide external surface. As a result, the AAPs are unable to effectively finish the polyamide workpiece surface adequately, resulting in a decrease in  $\% \Delta R_a$ .

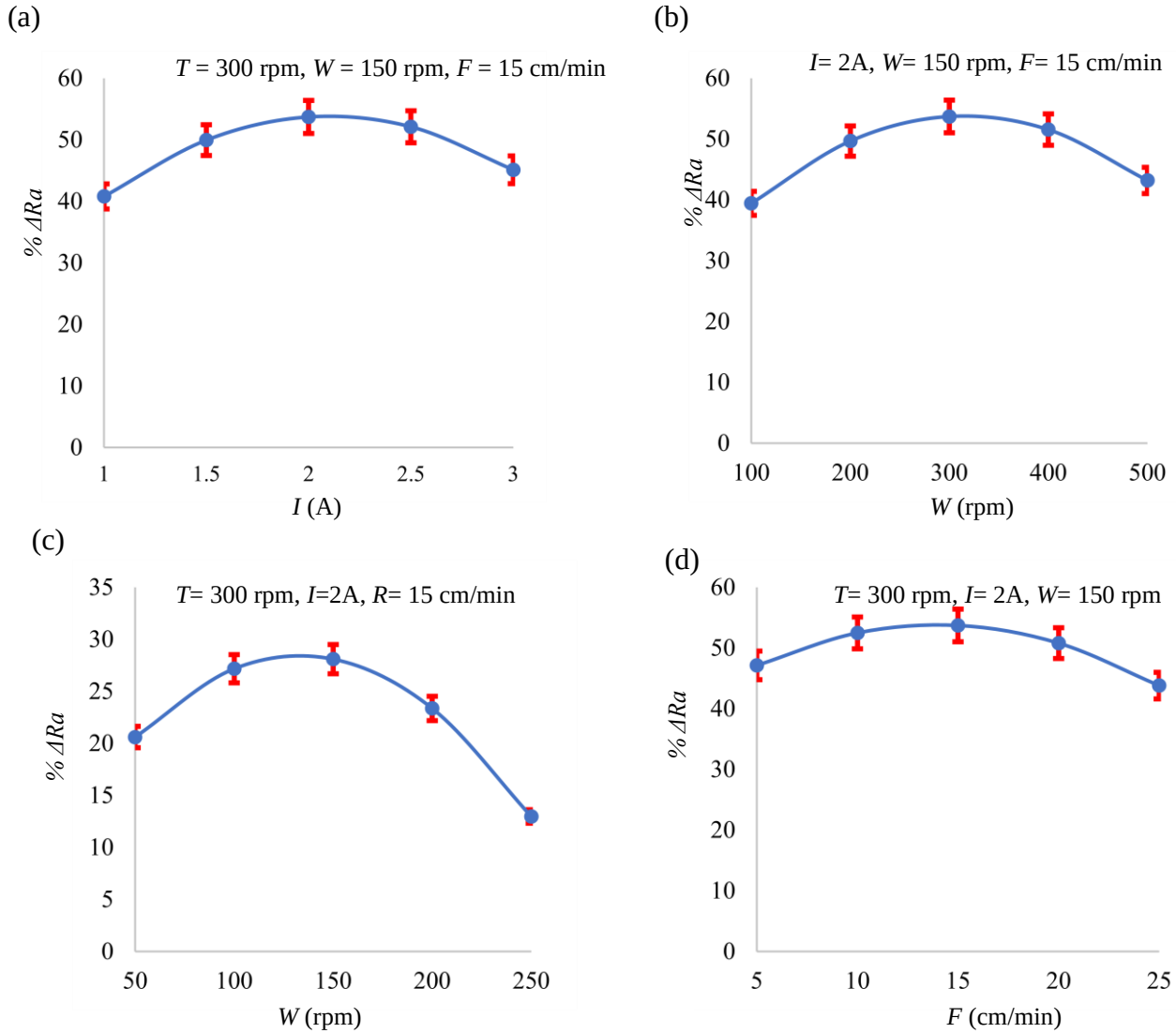


**Fig. 5.12.** Effect of (a) magnetizing current ( $I$ ), (b) rotational speed of tool ( $T$ ), (c) rotational speed of workpiece ( $W$ ) and (d) reciprocating speed of tool ( $F$ ) on %age improvement in the surface finish ( $\% \Delta R_a$ ).

#### 5.6.4.3 Combined effect of significant parameters on the $\% \Delta R_a$

In Fig. 5.13(a), the effect of  $I$  and  $F$  on  $\% \Delta R_a$  is shown. The  $T$  and  $W$  are kept constant at 300 rpm and 150 rpm respectively. The trend line of  $\% \Delta R_a$  rises first as  $F$  upsurges along with  $I$ . However, after the optimal value of  $I$  and  $F$ , the trendline of the  $\% \Delta R_a$  decreases. This is because there is an increase in the MFD along with the rise in the axial force when the  $I$  and  $F$  both increase simultaneously. As a result, the number of finishing cycles of the AAPs that are strongly gripped in the EIPs chains over the work part surface has increased. This leads to the higher interaction time between the roughness peaks present on the polyamide workpiece and the AAP. As a result,

the number of asperities sheared off the polyamide work part surface by the AAPs rises. Hence there is the rise in the trendline of  $\% \Delta R_a$ . However, once the  $F$  and  $I$  values are exceeded the optimum value, the MFD and axial force become so strong that the gripping of AAPs in the EIPs columnar structure loosens during surface finishing. Furthermore, the tool may have a quick interaction with roughness asperities, resulting in AAPs interacting with the roughness peaks present on the polyamide workpiece surface in a relatively short length of time. As a result, the clipping off of asperities by AAPs from the polyamide workpiece surface decreases, resulting in a drop in the  $\% \Delta R_a$  trendline. Further, the maximum improvement in  $\% \Delta R_a$  was attained at 2 A magnetizing current and 15 cm/min reciprocation speed of the tool.

The simultaneous effect of  $T$  and  $F$  on  $\% \Delta R_a$  is depicted in Fig. 5.13(b). The  $I$  and  $W$  were kept constant at 2 A and 150 rpm respectively. It can be observed that when the  $T$  and  $F$  rise, the  $\% \Delta R_a$  trend line increases. However, after the optimal value of  $T$  and  $F$ , the trendline of the  $\% \Delta R_a$  decreases. This trend occurs because with the simultaneous rise in the  $T$  and  $F$ , the tangential ( $F_{tan}$ ) and axial force upsurges initially. As a result, the firmly held AAPs in EIPs chains start to rotate across the work part surface as the finishing cycles increase. This leads to shear off the surface asperities from the workpiece as the tightly gripped AAPs get high interaction time to rotate with high speed over the polyamide workpiece surface leading to higher material abrasion. Hence, the trendline of  $\% \Delta R_a$  increases. However, beyond the optimal values of  $T$  and  $F$ , the influence of  $F_{tan}$  becomes so strong that it may cause AAPs in the EIPs chain to relax their grasp. The magnetizing force is also reduced as a result of this. The AAPs may also interact quickly with roughness peaks on the workpiece surface at higher  $T$  and  $F$ . However, above the ideal values of  $T$  and  $F$ , the influence of centrifugal force becomes so strong that it may cause AAPs in the EIPs chain to loosening their grip. The magnetizing force is also reduced as a result of this. Also at higher  $T$  and  $F$ , the AAPs may have quick interaction with roughness peaks present on the polyamide external surface. Because of this quick interaction, AAPs do not get much time to chip off the roughness asperities from the polyamide external surface. As a result, improper chipping of roughness asperities from the surface occurs, resulting in a reduction in the  $\% \Delta R_a$ . Therefore, the overall change in trend is because of the combined effect of  $F_{tan}$  on abrasive particles and the less time available for AAPs to remove the peaks at a higher current. The maximum improvement in  $\% \Delta R_a$  was achieved at 300 rpm of  $T$  and 15 cm/min of  $F$ .

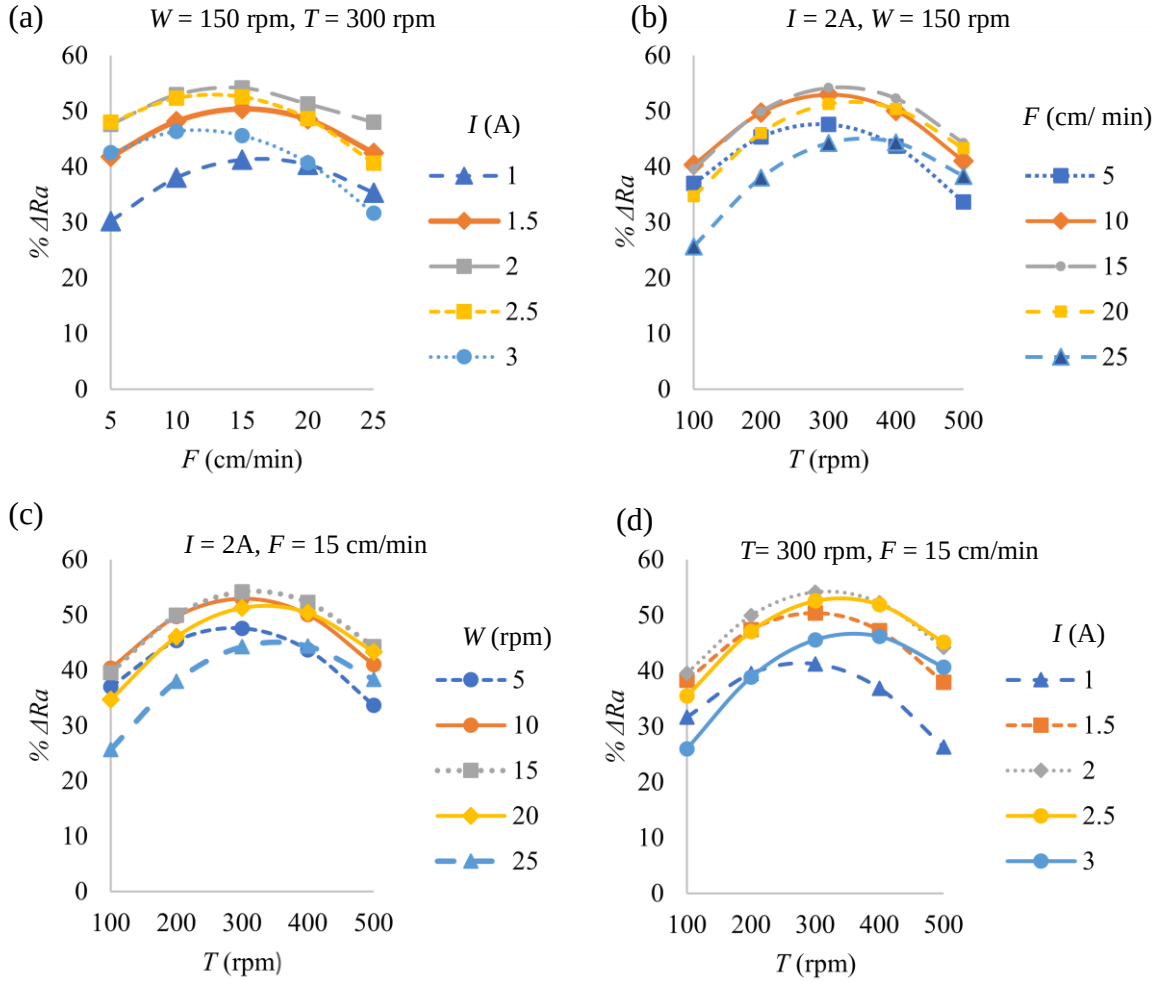


**Fig. 5.13.** Effect of (a) reciprocating speed of tool ( $F$ ) at different magnetizing current ( $I$ ), (b) rotational speed of tool ( $T$ ) at different reciprocating speed of tool ( $F$ ), (c) rotational speed of tool ( $T$ ) at different workpiece speed of tool ( $W$ ), and (d) rotational speed of tool ( $T$ ) at different magnetizing current ( $I$ ) on percentage improvement in the surface finish ( $\% \Delta R_a$ ).

The effect of the  $T$  and  $W$  on the percent improvement in the surface finish ( $\% \Delta R_a$ ) is shown in Fig. 5.13(c). The  $F$  and  $I$  remain constant at 15 cm/min and 2 A, respectively. It is observed that the trend-line of  $\% \Delta R_a$  increases initially as the  $T$  and  $W$  increase. However, with the simultaneous further increment in the  $T$  and  $W$  beyond their optimized values, the trend-line of  $\% \Delta R_a$  starts decreasing. As  $T$  and  $W$  are increased at the same time, the AAPs' net relative rotational speed rises. This increases the net tangential force acting over the polyamide workpiece surface. Due to the enhanced AAPs relative rotary speed, there is a rapid upsurge in the clipping off asperities from the workpiece surface. However, after the parameters go beyond their optimal values ( $T=300$



rpm and  $W = 150$  rpm), the relative motion of AAPs becomes very high owing to which there is very little time for AAP to interact with the polyamide surface. Owing to which, there is a rapid decrease in the clipping off the peaks from the workpiece surface. Also, at the higher net relative speed of the AAPs, the net cutting force becomes so high that the EIPs present in the columnar structure of MRP fluid becomes unstable which reduces the finishing performance. As a result, the rate of material removal decreases, lowering the surface quality.

The effect of  $T$  and  $I$  on  $\% \Delta R_a$  is depicted in Fig. 5.13(d). The  $W$  and  $F$  are kept constant at 150 rpm, and 15 cm/min respectively. As the  $T$  and  $I$  upsurge, there is an increment in the trendline of the  $\% \Delta R_a$ . However, after the optimal value of  $T$  and  $I$  (300 rpm and 2 A), the trendline of the  $\% \Delta R_a$  decreases. This trend occurs because initially with the simultaneous upsurge in  $T$  and  $I$  there is an upsurge in the normal magnetic force along with the relative speed of the AAP over the polyamide workpiece. This leads to the higher shear strength of the EIPs columnar structure in which the AAPs are tightly entrenched. Owing to this, the removal rate of the material from the workpiece surface upsursges leading to the increase in the trendline of  $\% \Delta R_a$ . However, beyond the optimal values of  $T$  and  $I$  the relative speed of the AAP overcomes overall magnetic force which leads to the loosening in the gripping of the EIPs columnar structure during surface finishing. As a result, the shearing off of roughness asperities from the finishing surface is reduced, lowering the rate of material removal. As a result, the  $\% \Delta R_a$  trend line is decreasing.

### 5.6.5 Process parameter optimization and validation

After the regression analysis, the process parameters were modified to produce the best feasible outcome for the  $\% \Delta R_a$ . To obtain the minimal value of the surface asperities ( $R_a$ ), a mathematical model is created using regression analysis. The maximum  $\% \Delta R_a$  can be calculated using Eq. (5.5). To maximize the  $\% \Delta R_a$ , parameters were subjected to

$$1\text{ A} \leq I \leq 3\text{ A}$$

$$100\text{ rpm} \leq T \leq 500\text{ rpm}$$

$$50\text{ rpm} \leq W \leq 250\text{ rpm}$$

$$5\text{ cm/min} \leq F \leq 25\text{ cm/min}$$

The prediction of the optimizing machining parameters was done based on the outcome of the various significant parameters on  $\% \Delta R_a$ . Regression analysis was utilized to analyze the equation that is employed to maximize  $\% \Delta R_a$  in the quadratic mathematical model. The optimal parameter values were predicted  $I$  as 2 A,  $T$  as 300 rpm,  $W$  as 150 rpm, and  $F$  as 15 cm/min, which are discovered within the experimental range of the process parameters. Further, three experiments

were carried out to test the model's validity using Eq. (5.5). The data attained from predicted and their comparison with the experimental results has been depicted in Table 5.17.

**Table 5.17.** Confirmation tests and their comparison with the results.

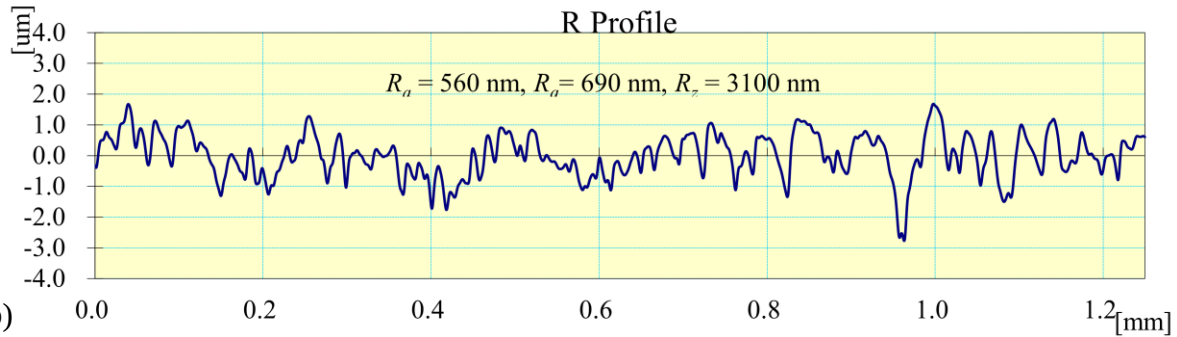
| Time<br>(mins) | Optimal<br>experimental<br>parameters<br>with<br>condition |           |           |              | Experimental<br>$\% \Delta R_a$ | Predicted<br>$\% \Delta R_a$<br>Eq (5.5) | Error<br>% |
|----------------|------------------------------------------------------------|-----------|-----------|--------------|---------------------------------|------------------------------------------|------------|
|                | $I$ (A)                                                    | $T$ (rpm) | $W$ (rpm) | $F$ (cm/min) |                                 |                                          |            |
| 20             | 2                                                          | 300       | 150       | 15           | 52.50                           | 53.71                                    | -2.30      |
| 20             | 2                                                          | 300       | 150       | 15           | 48.21                           | 53.71                                    | -11.21     |
| 20             | 2                                                          | 300       | 150       | 15           | 53.33                           | 53.71                                    | -0.71      |

The discrepancy between the experimental and theoretical values of  $\% \Delta R_a$  was determined to be in the range of -11.21 % to -0.71 % after investigation. This confirms that the current work's outcome is repeatable.

#### 5.6.5.1 Effect of significant parameters on process performance over the polyamide surface

The surface finishing was performed by the MRF process on the polyamide work part with a surface area of 706.5 mm<sup>2</sup> for 100 min.

(a)



(b)

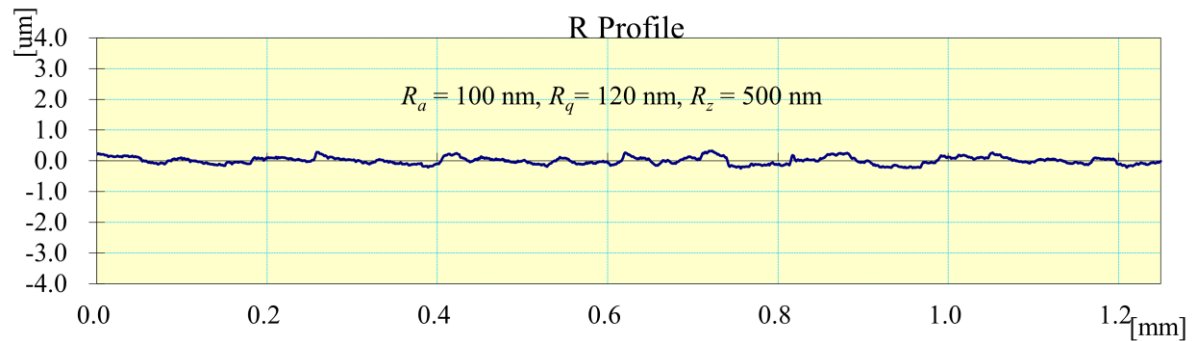


**Fig. 5.14.** Surface roughness profiles for (a) initial surface and (b) after 100 min of MRF on polyamide surface at  $T = 300$  rpm,  $I = 2$  A,  $W = 150$  rpm and  $F = 15$  cm/min.

Figure 5.14(a) and (b) show the initial and final surface asperities ( $R_a$ ) profiles, respectively. The initial ground  $R_a$  profile parameters are measured as  $R_a = 560$  nm,  $R_z = 3100$  nm, and  $R_q = 690$  nm while the final finished polyamide surface after 100 min of MRF with best process parameters over polyamide surface is measured as  $R_a = 100$  nm,  $R_z = 500$  nm,  $R_q = 120$  nm. Further, after 100 min, the workpiece surface showed no substantial improvement. The maximum %  $\Delta R_a$ , %  $\Delta R_z$ , and %  $\Delta R_q$  using optimum parameters are found as 82.14 %, 83.87 %, and 82.60 % respectively. In addition, the waviness has a longer sample length than the roughness profile which provides information on the linear surface. The arithmetic mean waviness ( $W_a$ ) value of the initial ground polyamide work part surface was  $0.19 \mu\text{m}$  and  $W_a$  value of the final polyamide surface after MR finishing of 100 min was  $0.09 \mu\text{m}$  as measured with the assistance of Tylor Hobson profilometer.

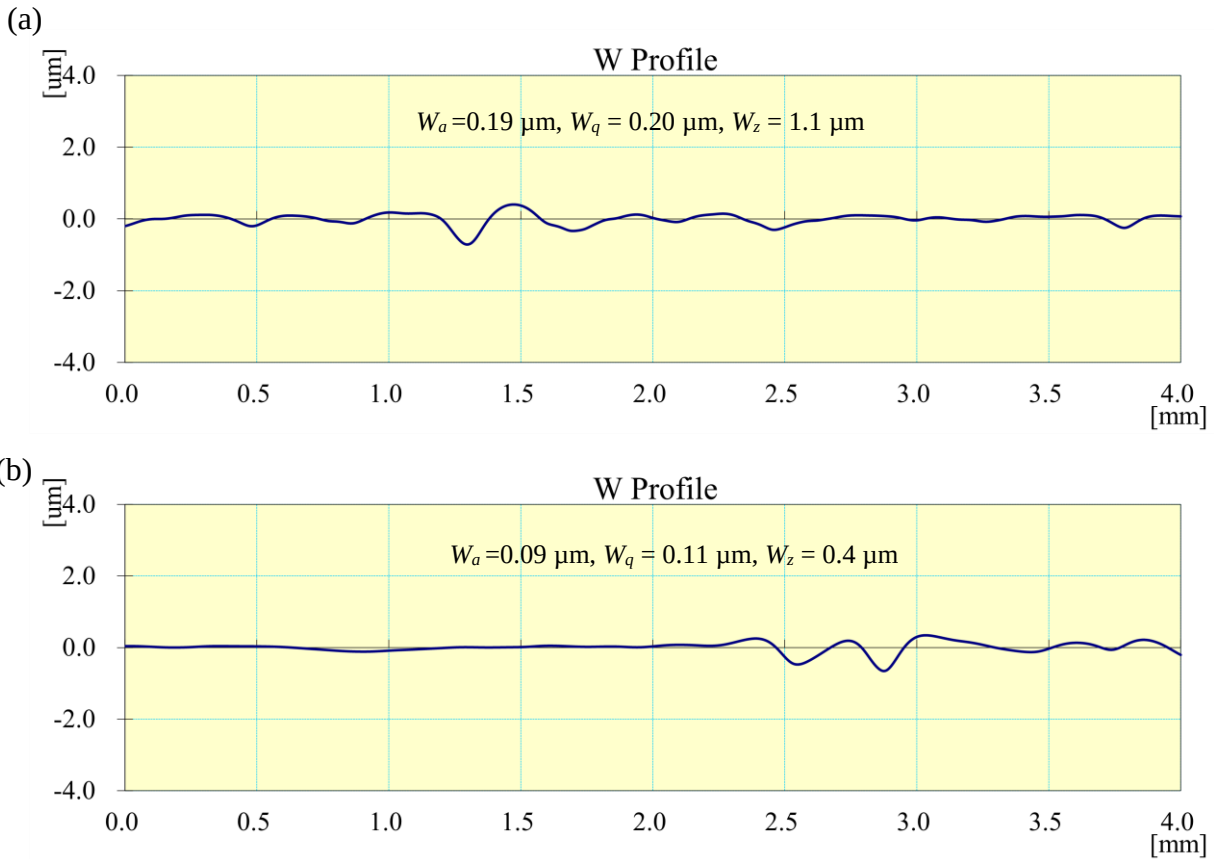
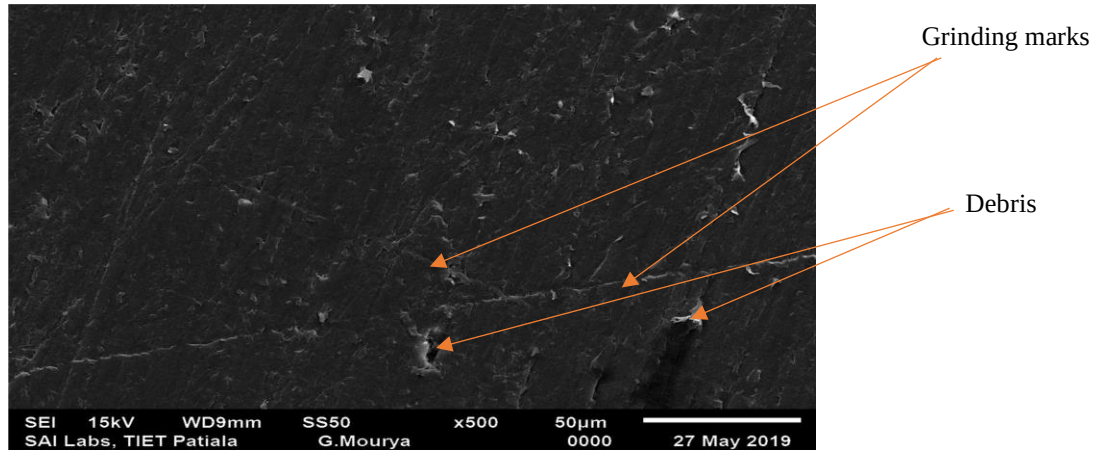


**Fig. 5.15.** Waviness profiles for (a) initial surface and (b) after 100 min of MRF on polyamide surface at  $T = 300$  rpm,  $I = 2$  A,  $W = 150$  rpm and  $F = 15$  cm/min.

Figure 5.15(a) and (b) show the initial ground waviness profile and the MR finished surface profile with the best parametric conditions, respectively. After 100 min of MRF with optimum process parameters on the polyamide work part surface, the %  $\Delta W_a$  was found to be 52.63 %, indicating

that the straightness of the polyamide work part's external surface has improved. After 100 min of MRF, the polyamide workpiece surface shows a substantial reduction in roughness and waviness. The present process involves two steps for fine finishing the polyamide surface. The magnetic normal force (*Chapter 4, section 4.4*) indents the AAPs on the workpiece surface in the first step. The indented AAPs clip-off peaks from the polymer workpiece surface in the second stage, which is caused by the simultaneous rotations of the tool and workpiece along with the tool reciprocation. These simultaneous rotations and reciprocation lead to the finishing force. The roughness results reveal that the present MRF process is capable of providing uniform and fine finishing of the polyamide surface material.

(a)



(b)

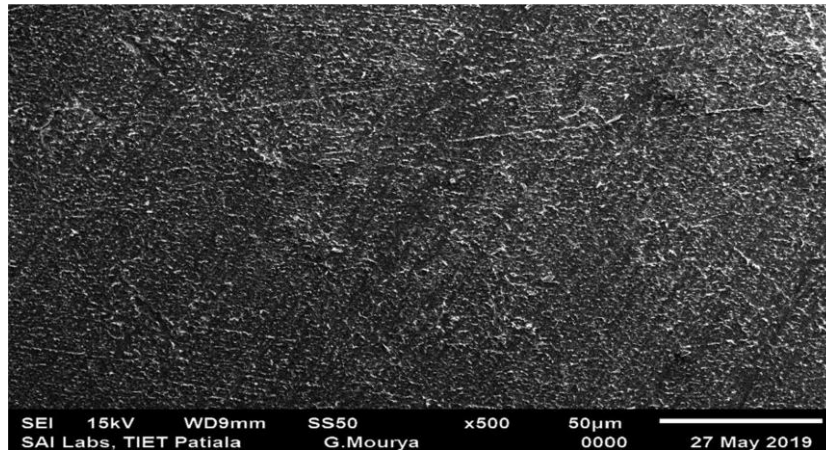


**Fig. 5.16.** SEM images for (a) initial surface and (b) after 100 min of MRF on polyamide surface at  $T = 300$  rpm,  $I = 2$  A,  $W = 150$  rpm and  $F = 15$  cm/min.

A scanning electron microscope (SEM) was further used to investigate the surface characteristics of the polyamide work component. Figure 5.16 shows the surface morphologies of the initial and final polyamide workpiece surfaces. In Fig. 5.16(a) grinding marks with some debris on the initial surface can be seen. Initially grinding was done to make the smooth surface. However, during the grinding process grinding marks are left on the surface by the abrasives used in the process which can be seen in the image. Further, the debris on the surface is due to the abrasion property of the material. However, following the MRF, the grinding marks get aloof gradually over time due to the properties of the MRP fluid, and a better even surface was achieved as illustrated in Fig. 5.16(b). The MRF process does not leave any scratches or pits on the surface. In the MRF process, the shear stress delivered to the work part by abrasives flowing in a converging gap determines the material removal rate. The normal forces acting on abrasives are very low and this leads to a damage-free and clean workpiece surface.

#### 5.6.2 *Effect of significant parameters on functional performance over the polyamide surface*

The present water-based MRP fluid provides fine finishing of the polyamides by reducing the surface asperities. Due to this reduction in the surface asperities, the life span of polyamides is upsurges owing to the increase in microhardness. This leads to a reduction in wear rate. For functional improvement of polyamides, surface finish plays a significant role because as the asperities decrease, there is a decrease in the frictional coefficient, owing to which there is a functional improvement. Further, the volumetric wear rate of the polyamide material leads to a decrease in stiffness or rigidity of the polymer leading to lower resistance to deformation. For calculating the volumetric wear rate, Archard sliding wear theory is used which is given by the Eq. (5.8) (Zhang *et al.*, 2020).

$$W' = \frac{k_a F' L'}{H} \quad (5.8)$$

where  $W'$  is the volumetric wear rate,  $k_a$  is Archard coefficient,  $L'$  is sliding distance,  $F'$  is the normal load, and  $H$  is the material hardness. Further, the microhardness and wear test are experimentally done on the initial and final MR finished polyamide workpieces. To study the load-bearing capability of the polyamide workpiece, the micro-hardness test is done before and after the MRF on the polyamide surface. For a dwell time of 20 sec, three indents were made at 25 g load over the ground and final MR finished polyamide workpiece surface. The average hardness value was obtained for 25 g of load is analysis. The average microhardness of the initial polyamide workpiece surface for the 25 g load was determined to be 12.56 HV. However, after MRF process

on the polyamide workpiece surface, the average microhardness for the 25 g load was determined to be 14.85 HV. The hardness results reveal the increase in hardness of the polyamide surface following the MRF process. This is because asperities peaks are higher height (Fig. 5.14a) and have a lower concentration area on the initial surface area. As a result, the load-carrying capability of the polyamide component reduces, resulting in decreased hardness. After the MRF process, however, the surface asperities become more flattened (Fig. 5.14b), enhancing the concentration region and load-bearing capacities. This increases the hardness of the workpiece surface, which increases the load-bearing capacity of the polyamide workpiece surface. Thus, the upsurge in the hardness on the MR finished polyamide work part tends to reduce the volumetric wear rate according to Eq. (5.8).

Wear is also a dynamic process in polyamide components, that involves the continuous loss of material from surfaces that are moving relative to one another. Wear is the gradual loss of material in various manufactured components that cannot be avoided but may be significantly reduced by using fine finishing techniques. The study of wear caused by the dynamic interaction of two sliding surfaces with regard to one another is critical for polyamide workpieces because material loss from the work parts reduces the component's reliability and durability.

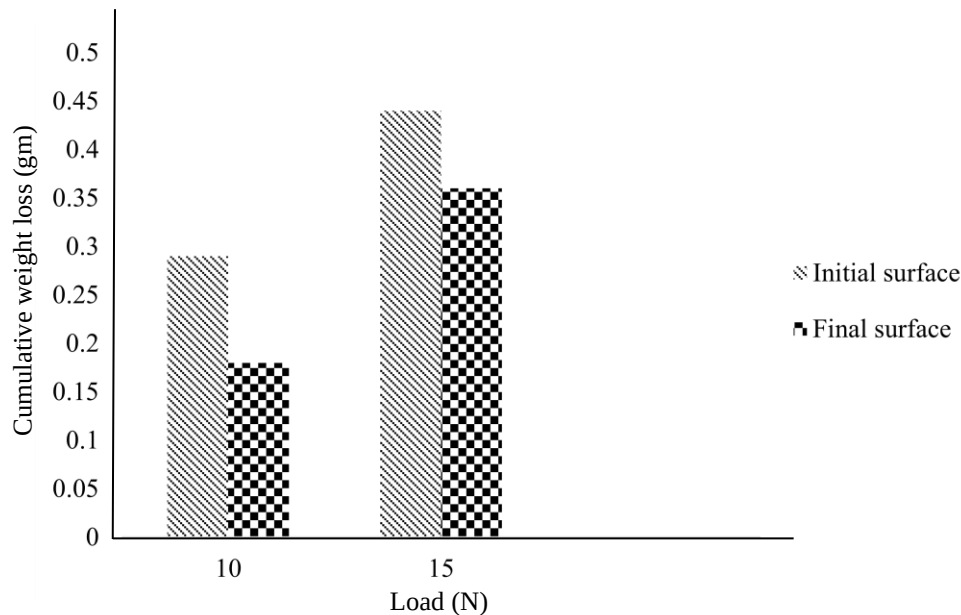


**Fig. 5.17.** Wear results at different loads for the initial ground surface, and final finished surface using MR-finishing on the polyamide workpiece with 100 min of finishing.

Wear testing on the initial and final MR polished surfaces was done utilizing a pin on disk setup in dry sliding conditions at room temperature. Further, the initial and MR finished samples were cleaned with acetone. The weight of the polyamide pins was measured using a weighing machine before and after the wear test. At different loads, Fig. 5.17 illustrates the effect of applied load on wear rate for the initial and MR completed workpiece surfaces. The wear rate on the ground surface is higher for the loads (10 N, and 15 N) as compared to the final MR finished polyamide workpiece surface. The higher wear on the initial surface may occur because of the lower hardness of the surface owing to higher surface roughness. However, there is a significant decrease in surface roughness following MR finishing across the polyamide workpiece using the optimum parameters, increasing the hardness of the finishing surface. Hence, the wear rate decreases which may enhance the reliability and durability of the polyamide components.

Clinically, an increase in hardness and flexural strength tends to increase the resistance in abrasion action which leads to a decrease in wear and increases the life span of the workpiece. Hence, the present water-based MRP fluid tends to offer a fine finish that improves the functional life of polyamide components such as gears, and bushings.

### **5.6.6 Conclusions**

The MRF process with a rotary rectangular tip-based tool is used for the fine finishing of the polyamide workpieces. The following conclusions show the efficacy of the water-based MR finishing process on polyamides surface.

- The predicted optimal parameters using the regression analysis as 2 A magnetizing current, tool rotational speed of 300 rpm, work part rotational speed of 150 rpm, and the reciprocating tool speed of 15 cm/min reveal fine finishing over the polyamide work part surface.
- The significant % reduction in surface roughness parameters  $R_a$ ,  $R_z$ , and  $R_q$  by 82.14 %, 83.87 %, and 82.60 %, respectively over polyamide surface in 100 min of finishing cycle with predicted optimal process parameters reveals the improved finishing of the polyamide workpiece which can further enhance its functional efficacy on industrial components.
- The reduction of surface asperities from 560 nm to 100 nm and waviness from 0.19  $\mu\text{m}$  to 0.09  $\mu\text{m}$  in 100 min of finishing time for the surface area of 706.5 mm<sup>2</sup> by the present water-based magnetorheological finishing confirms the functional improvement in the polyamide components used in industries.

- The enhancement in microhardness and reduction in wear rate can upsurge the functional efficacy and also it can improve the functional life of polyamide components such as gears, and bushings.
- In the present work, the error obtained between the experimental and the predicted  $\% \Delta R_a$  is found within -11.21 % to -0.71 %, which concludes that the developed regression model is decently accurate, therefore, the predicted optimized process parameters for finishing the polyamide workpieces are found in good order.
- The overall experimentation results reveal that the water-based magnetorheological finishing process can be highly suitable for improving performance of various manufactured polyamide components such as polymer gears, bushings etc. which are in high demand in various industries.



## CHAPTER 6

### PARAMETRIC INVESTIGATION OF THE DEVELOPED DIFFERENT MAGNETORHEOLOGICAL FINISHING TOOLS IN FINE FINISHING THE VARIOUS TYPES OF POLYMER WORKPIECES

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In this chapter, various typical industrial polymer applications are fine finished using the presently developed different magnetorheological finishing tools. The typical industrial polymer applications like polymer gears, bearings, acetabular cups, valve seats, and additive manufactured components required fine finishing. The fine finishing of these polymer components enhances the functional performance of their process application in industries. In today's era, polymers are playing a crucial role due to the high demand for lightweight objects in various industries. Automotive, defense and aerospace are the few industries where polyamide usage is increasing rapidly because of their low weight as compared to metals (Kumar *et al.*, 2013).

#### **6.1 Parametric investigation of typical ultra-high molecular weight polyethylene (UHMWPE) acetabular cup is for improving its functional performance in hip implants**

In the modern medical implant industry, ultra-high molecular weight polyethylene (UHMWPE) is most commonly used in the joint replacement prosthesis (Pace *et al.*, 2013). Properties such as good mechanical strength, high hardness, good chemical resistance, excellent biocompatibility, and low-cost increase its importance even more in the medical field for making sockets in the hip, knee, and spline implants (Steinberg and Marcin, 2014). In hip implants, the acetabular cup component consists of the UHMWPE liner in an alloy shell (mostly titanium alloy). During the stiffness measurement of the UHMWPE cup by the rim compression, it was found that the UHMWPE liner is less stiffened as compared to metals and ceramics (Chaudhury *et al.*, 2018). Further, the lower stiffness leads to the balanced load distribution owing to which there is a low surface strain (Small *et al.*, 2013). This further adds up to the advantage of using a UHMWPE cup liner. However, in the joint replacement prosthesis, the limiting factor is the functionality and longer life span of the implant which is due to the wear (Chaudhury *et al.*, 2018). The wear is generated due to the inaccuracy in the dimensional constraints and poor surface finish of the tribological pair of implants (Souza *et al.*, 2016). In young and active patients, UHMWPE wear often leads to the loosening of the acetabular cup liner. This is one of the main reasons for

the long-term revision in total hip arthroplasty (THA). In the UHMWPE acetabular cup, there are many factors that contribute to the wear and debris. Hence, for improving the life span of the implant, reducing the chances of the osteolysis, and having high engagement stability of the UHMWPE cup when patients take a different kind of motions, the acetabular cups need the high grade of the surface (Souza *et al.*, 2016). Therefore, an attempt is made to improve the finishing of the UHMWPE acetabular cup surface with the help of the magnetorheological finishing (MRF) process. The novel hemispherical shape tip-based tool is utilized for improving the acetabular cup surface using the MRF process. Further, the optimum parameters of the MRF process are predicted for the effective finishing of the UHMWPE acetabular cup surface, and to check the effectiveness of the present process, surface morphology, circularity, and microhardness test are performed on the UHMWPE acetabular cup. Also, the theoretical model for surface roughness developed in Chapter 4 (section 4.1) has been experimentally validated.

#### 6.1.1 Material selection and workpiece preparation

Ultra-high molecular weight polyethylene (UHMWPE) is the most commonly used polymer for joint replacement prostheses in the modern medical implant industry. The surface finishing has significant importance in these components.

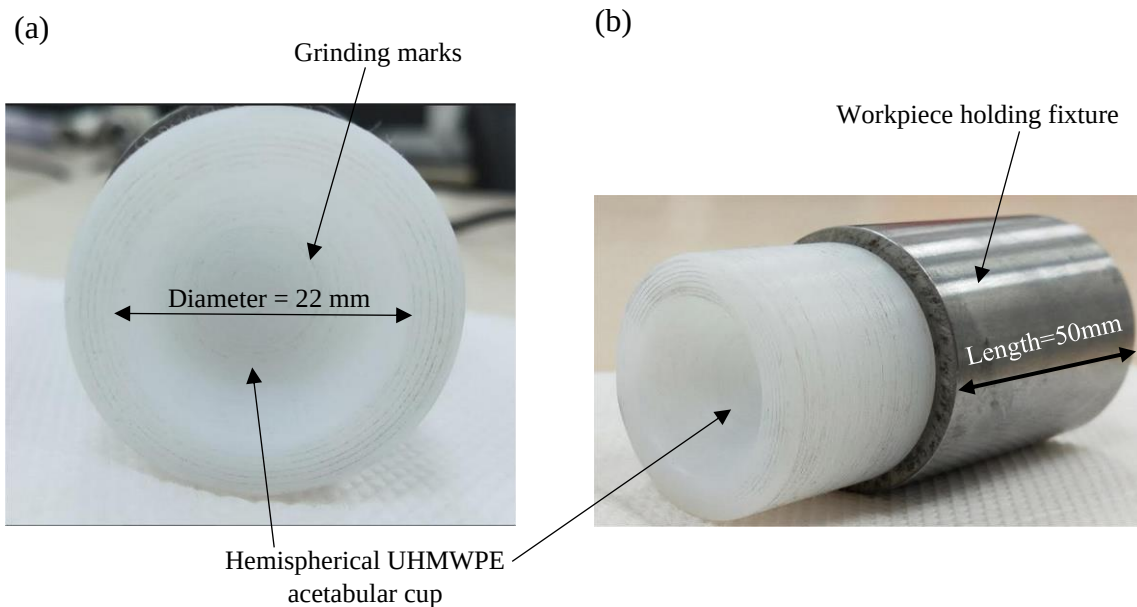


**Fig. 6.1.** (a) Dimension of the UHMWPE hemispherical acetabular cup workpiece and (b) cylindrical fixture to hold the workpiece.

For example, in hip-joint implants, a fine finish acetabular cup leads to a decrease in the coefficient of friction due to which there is proper relative motion can be found amid the acetabular cup and the femoral head. This further tends to decrease the osteolysis and increases the life span of hip-joint implants. Similarly, in knee and spine implantation, a fine finish UHMWPE is essential for the proper functioning of implants. Hence, UHMWPE is used as the workpiece in the present experimentation. In the present work, the UHMWPE hemispherical cups are manufactured as depicted in Fig. 6.1(a). Initially, a turning operation is done on the UHMWPE rod for making samples as per the dimension required. Further, traditional grinding is done on workpiece samples to eliminate the uneven marks from the hemispherical cup surface. After that the workpieces are cleaned using acetone and maintained properly before the magnetorheological (MR) fluid-based finishing. Further, a fixture of length 50 mm is made to hold the workpiece sample on the table as depicted in Fig. 6.1(b).

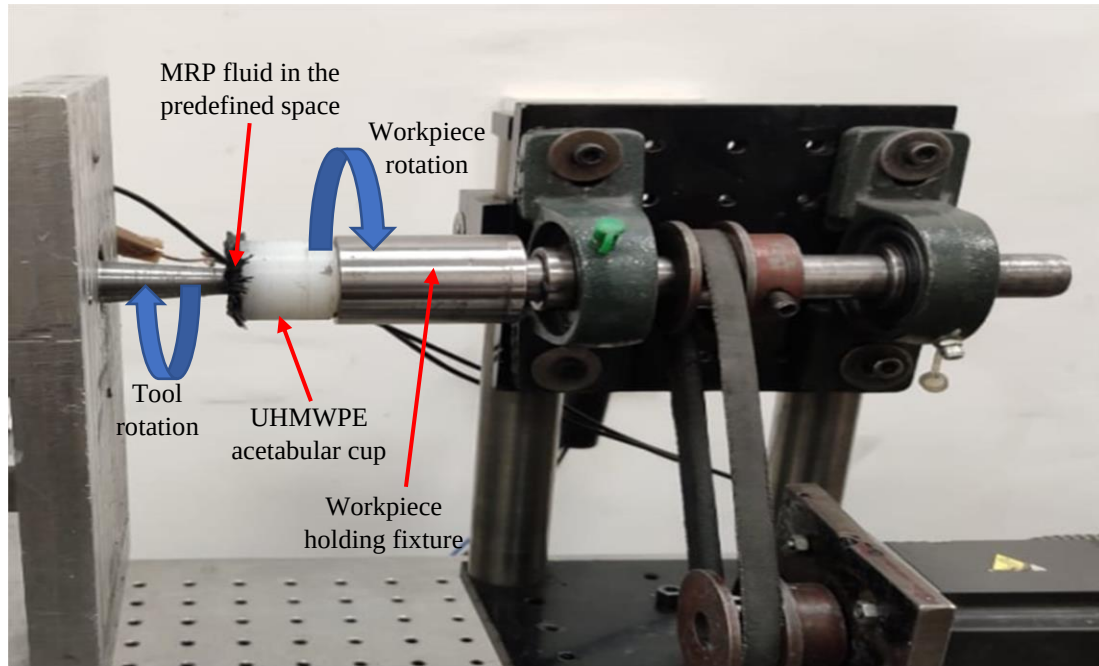
### **6.1.2 Experimentation**

The experimental setup of the presently used magnetorheological finishing (MRF) process is shown in Fig. 6.2(a). For the fine finishing of the hemispherical acetabular cup, a novel hemispherical tip-based tool is used. The design of the electromagnetic hemispherical tool core tip surface has already been discussed in *Chapter 3 (section 3.1.1)*. To perform the finishing operations, two types of motions are used in this work. Rotary motion by the workpiece (W) and rotary motion by the tool core (T) is rotated in the opposite direction as depicted in Fig 6.2(b). The working space amid the work part surface and tooltip surface is kept constant at 0.6 mm.

#### **6.1.2.1 Selection of process parameters**

In the present work, the developed magnetorheological (MR) finishing process with a hemispherical profile tool core tip surface is utilized in the detailed study of the various parameters for effectively finishing the UHMWPE acetabular cup liner. To analyze the parametric study for the fine finishing of the acetabular cup liner, the design of experiments (DOE) is used. Further, for analyzing the outcome of various parameters on the % improvement in the surface finish ( $\% \Delta R_a$ ), response surface methodology (RSM) is used. The effect of the different process parameters and their combined effects are studied. The preliminary experimentations were conducted for the 20 min finishing cycle at 2 A current and 0.6 mm working space with the different range of the selected variable parameters.

(a)



(b)

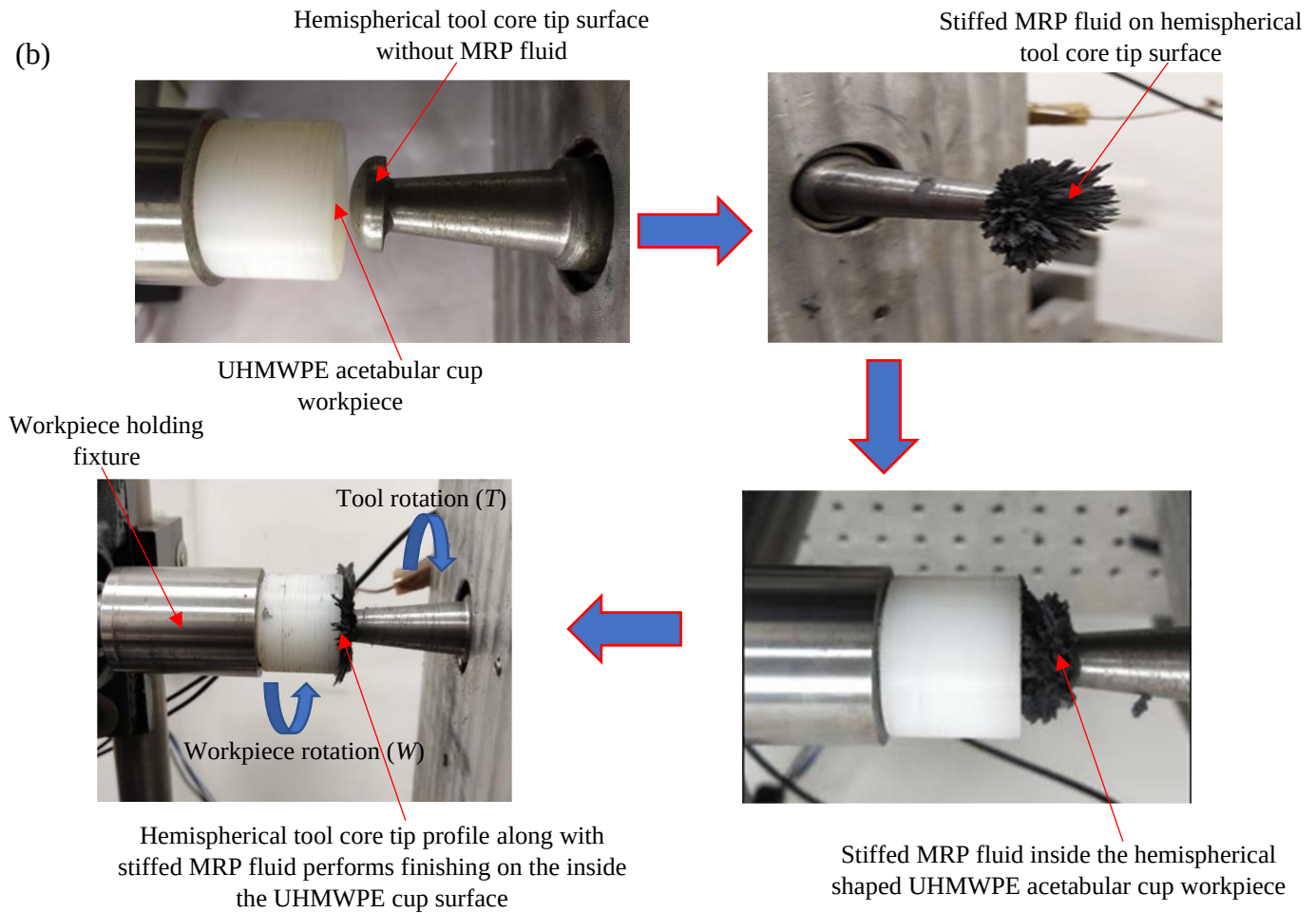


**Fig. 6.2.** (a) Setup of the presently used magnetorheological (MR) finishing process and (b) different steps followed to finish the hemispherical shape UHMWPE acetabular cup surface with the stiffed MR polishing (MRP) fluid.

The values of surface roughness obtained after preliminary experimentations (Table 5.2) are shown in Fig. 5.2 (*Chapter 5*). The results obtained from the preliminary experimentations are used for selecting the range of the process parameters for effectively fine finishing of the UHMWPE acetabular cup liner. The selected range for parameters is reported in Table 6.1.

**Table 6.1.** Process parameters and their range.

| S. No. | Parameters                                                    | Range |      |     |      |     |
|--------|---------------------------------------------------------------|-------|------|-----|------|-----|
| 1.     | Tool rotational speed, $T$ (rpm)                              | 100   | 200  | 300 | 400  | 500 |
| 2.     | Workpiece rotational speed, $W$ (rpm)                         | 50    | 100  | 150 | 200  | 250 |
| 3.     | Volume % of EIPs (500 mesh number), $E$                       | 25    | 27.5 | 30  | 32.5 | 35  |
| 4.     | Volume % of CeO <sub>2</sub> abrasives (800 mesh number), $C$ | 5     | 7.5  | 10  | 12.5 | 15  |

### 6.1.3 Design of experiments

In the present research, the initial average  $R_a$  value of the work parts ranges between 220-290 nm, therefore, % improvement in the surface finish ( $\% \Delta R_a$ ) is taken as an output response. The surface roughness was measured using the Mitutoyo SJ-410 instrument. The cut-off length of the instrument is kept at 0.25 mm. To analyze the effects of the various selected parameters on the  $\% \Delta R_a$ , the design of the experiment is used. Further, the RSM technique is utilized to evaluate the outcome of parameters on the response. The foremost objective of a regression model is to analyze the reduction in the process variability in  $\% \Delta R_a$  and to enhance the efficacy of the presently used MR finishing process. In the present model the relationship between the  $\% \Delta R_a$  and independent input parameters are given in Eq. (6.1) (Jamal *et al.*, 2019).

$$\% \Delta R_a = f(T, W, E, C) \quad (6.1)$$

where  $f$  is the function of response,  $T$  is tool rotation in rpm,  $W$  is workpiece rotation in rpm,  $E$  is % volume concentration of electrolytic iron particles (EIPs) and  $C$  is % volume concentration of CeO<sub>2</sub> abrasives. Further, to inspect the response of the process parameters on the outcomes, the second-order polynomial response is utilized. The analysis is done on the central composite design (CCD) in the design of expert (DOE) 6.0.8. The five levels and four parameters design were created. A total 30 experiments are planned by the CCD as reported in Table 6.2. Each experimentation is performed on the UHMWPE workpiece for 40 min and after every 20 min of the finishing cycle, the MRP fluid is changed on the hemispherical tool tip surface so that the

abrasive particles work effectively. The confidence level of the model is 95 % to verify its effectiveness of the model.

**Table 6.2.** Experimentation plans and their results.

| Run order | Std no. | Process Parameters             |                                     |                  |                                  | Initial value<br>$R_{ai}$<br>(nm) |      | Final value<br>$R_a$<br>(nm) | Final average $R_{af}$<br>value (nm) | % $\Delta R_a$<br>Eq. (5.2) |
|-----------|---------|--------------------------------|-------------------------------------|------------------|----------------------------------|-----------------------------------|------|------------------------------|--------------------------------------|-----------------------------|
|           |         | Tool rotation speed, $T$ (rpm) | Workpiece rotation speed, $W$ (rpm) | % vol. EIPs, $E$ | % vol. of $CeO_2$ abrasives, $C$ |                                   | $X1$ | $X2$                         |                                      |                             |
| 1         | 12      | 400                            | 200                                 | 27.50            | 12.50                            | 270                               | 180  | 160                          | 170                                  | 37.04                       |
| 2         | 19      | 300                            | 50                                  | 30.00            | 10.00                            | 290                               | 140  | 160                          | 150                                  | 48.27                       |
| 3         | 11      | 200                            | 200                                 | 27.50            | 12.50                            | 230                               | 130  | 150                          | 140                                  | 39.13                       |
| 4         | 18      | 500                            | 150                                 | 30.00            | 10.00                            | 220                               | 120  | 130                          | 125                                  | 43.18                       |
| 5         | 16      | 400                            | 200                                 | 32.50            | 12.50                            | 250                               | 130  | 160                          | 145                                  | 42.00                       |
| 6         | 4       | 400                            | 200                                 | 27.50            | 7.50                             | 270                               | 150  | 160                          | 155                                  | 42.59                       |
| 7         | 22      | 300                            | 150                                 | 35.00            | 10.00                            | 280                               | 160  | 180                          | 170                                  | 39.29                       |
| 8         | 21      | 300                            | 150                                 | 25.00            | 10.00                            | 260                               | 150  | 170                          | 160                                  | 38.46                       |
| 9         | 15      | 200                            | 200                                 | 32.50            | 12.50                            | 250                               | 180  | 170                          | 175                                  | 30.00                       |
| 10        | 10      | 400                            | 100                                 | 27.50            | 12.50                            | 230                               | 130  | 140                          | 135                                  | 41.30                       |
| 11        | 6       | 400                            | 100                                 | 32.50            | 7.50                             | 230                               | 120  | 130                          | 125                                  | 45.65                       |
| 12        | 2       | 400                            | 100                                 | 27.50            | 7.50                             | 270                               | 170  | 160                          | 165                                  | 38.89                       |
| 13        | 29      | 300                            | 150                                 | 30.00            | 10.00                            | 280                               | 130  | 150                          | 140                                  | 50.00                       |
| 14        | 1       | 200                            | 100                                 | 27.50            | 7.50                             | 270                               | 160  | 150                          | 155                                  | 42.59                       |
| 15        | 5       | 200                            | 100                                 | 32.50            | 7.50                             | 250                               | 130  | 140                          | 135                                  | 46.00                       |
| 16        | 9       | 200                            | 100                                 | 27.50            | 12.50                            | 270                               | 160  | 180                          | 170                                  | 37.03                       |
| 17        | 7       | 200                            | 200                                 | 32.50            | 7.50                             | 270                               | 160  | 200                          | 180                                  | 33.33                       |
| 18        | 23      | 300                            | 150                                 | 30.00            | 5.00                             | 250                               | 160  | 170                          | 165                                  | 34.00                       |
| 19        | 28      | 300                            | 150                                 | 30.00            | 10.00                            | 250                               | 120  | 140                          | 130                                  | 48.07                       |
| 20        | 26      | 300                            | 150                                 | 30.00            | 10.00                            | 270                               | 150  | 130                          | 140                                  | 48.14                       |
| 21        | 3       | 200                            | 200                                 | 27.50            | 7.50                             | 240                               | 170  | 150                          | 160                                  | 33.33                       |
| 22        | 14      | 400                            | 100                                 | 32.50            | 12.50                            | 230                               | 130  | 150                          | 140                                  | 39.13                       |
| 23        | 13      | 200                            | 100                                 | 32.50            | 12.50                            | 250                               | 140  | 150                          | 145                                  | 42.00                       |
| 24        | 8       | 400                            | 200                                 | 32.50            | 7.50                             | 270                               | 160  | 180                          | 170                                  | 37.04                       |
| 25        | 17      | 100                            | 150                                 | 30.00            | 10.00                            | 260                               | 150  | 180                          | 165                                  | 36.54                       |
| 26        | 27      | 300                            | 150                                 | 30.00            | 10.00                            | 260                               | 130  | 120                          | 125                                  | 51.92                       |
| 27        | 24      | 300                            | 150                                 | 30.00            | 15.00                            | 230                               | 130  | 150                          | 140                                  | 39.13                       |
| 28        | 30      | 300                            | 150                                 | 30.00            | 10.00                            | 260                               | 130  | 150                          | 140                                  | 46.15                       |
| 29        | 25      | 300                            | 150                                 | 30.00            | 10.00                            | 270                               | 130  | 140                          | 135                                  | 50.00                       |
| 30        | 20      | 300                            | 250                                 | 30.00            | 10.00                            | 250                               | 150  | 140                          | 145                                  | 42.00                       |

The F-level test from analysis of variance (ANOVA) is done to identify the implication of the regression equation for strengthening the relation amid the %  $\Delta R_a$  and controlled process parameters. The % improvement in surface finish (%  $\Delta R_a$ ) value after the experimentation is calculated by using Eq. (5.2). Further, the study of the surface characteristics of the UHMWPE samples and dimensional accuracy are observed with the help of scanning electron microscopy and a co-ordinate measuring machine respectively. Also, the hardness of the UHMWPE acetabular

cup is measured with the help of the microhardness tester Mitutoyo HM-210 model. The diamond indenter is utilized to measure the micro-hardness on the ground and MR finished surface of the UHMWPE cup. The hardness value obtained after the test is in Vickers Pyramid Number (HV).

#### 6.1.4 Results and discussion

In the present research, a total of 30 experiments are performed to assess the outcomes of the selected process parameters on the % improvement in the surface finish (%  $\Delta R_a$ ). The experimental response data is tabulated in Table 6.2. After the experimentation, the value of  $R_a$  ( $X1$  and  $X2$ ) is obtained using the surface roughness profilometer. To get the final value  $R_a$ , the average of  $X1$  and  $X2$  is calculated which is further used in Eq. (5.2) to obtain %  $\Delta R_a$ . Further, an analysis of variance (ANOVA) is utilized to develop the quadratic theoretical statistical model. The finishing process parameters which have a p-value less than 0.05 are significant parameters and process parameters that have a p-value greater than 0.05 are insignificant parameters. The insignificant parameters are ignored and the significant parameters are found namely  $T$ ,  $W$ ,  $E$ ,  $C$ ,  $T^2$ ,  $W^2$ ,  $E^2$ ,  $C^2$ ,  $TW$ ,  $TE$ ,  $WC$ , and  $EC$  as their p-value is less than 0.05. The experimental response data were used to perform ANOVA as reported in Table 6.3. The factors ( $T$ ,  $W$ ,  $E$ , and  $C$ ) influence the response (%  $\Delta R_a$ ) linearly. The significant parameters  $T^2$ ,  $W^2$ ,  $E^2$ , and  $C^2$  influence the %  $\Delta R_a$  non-linearly. Further, the interaction of  $TW$ ,  $TE$ ,  $WC$ , and  $EC$  also influences the output response (%  $\Delta R_a$ ). After performing ANOVA on the basis of the sequential model, the p-value of the model is less than 0.05, this shows that the model is significant. For lack of fit, the p-value is higher than 0.05 (0.1643) which signifies that the lack of fit is not significant. From the ANOVA table, it can be seen that the F-value of the developed quadratic model is 59.13 which is greater than the actual F value (1.957). Hence, the model is significant and the chances of the model being insignificant due to noise is only 0.01 %. The obtained response surface quadratic equation is given in Eq. (6.2).

$$\begin{aligned} \% \Delta R_a = & -583.1 + 0.127T - 0.024W + 38.09E + 8.791C - 4.2 \times 10^{-4}T^2 - \\ & 6.12 \times 10^{-4}W^2 - 0.665E^2 - 0.725C^2 + 2.12 \times 10^{-4}TW + 3.75 \times 10^{-3}TE + 9.5 \times 10^{-3}WC + \\ & 0.13EC \end{aligned} \quad (6.2)$$

Using Eq. (6.2), the %  $\Delta R_a$  is calculated and compared with the experimental %  $\Delta R_a$  values. Percentage error reveals the closeness between the experimental and calculated values. The variation in experimental and calculated values are shown in Fig. 6.3. From the figure, it can be concluded that there is not much variation amid the experimental and the calculated values from the developed model. It can also be validated from the model as the R-square predicted value is

92.13 %, Adj R-square value is 96.01 % and the R-square value obtained from the model is 97.66 %, which shows the accuracy of the model. Further, the percentage contribution of each significant factor (linear and non-linear) and their interaction have been calculated. The percentage contribution depicts parameters of significance in the regression analysis of the %  $\Delta R_a$ . The weightage of each parameter is calculated by using the ANOVA Table 6.3. The percentage contribution is calculated by using Eq. (5.6).

**Table 6.3.** ANOVA analysis for % improvement in surface finish (%  $\Delta R_a$ ).

| Source                | Sum of squares | Degree of freedom (DOF) | Mean square | F value | Prob>F   | Remark                                        | Percentage contribution (Eq. 5.6) |
|-----------------------|----------------|-------------------------|-------------|---------|----------|-----------------------------------------------|-----------------------------------|
| Model                 | 1538.99        | 12                      | 128.25      | 59.13   | < 0.0001 | $F_{(0.05,12,17)} = 1.957$<br>Significant     |                                   |
| <i>T</i>              | 51.04          | 1                       | 51.04       | 23.53   | 0.0001   |                                               | 2.61                              |
| <i>W</i>              | 145.04         | 1                       | 145.04      | 66.87   | < 0.0001 |                                               | 7.43                              |
| <i>E</i>              | 57.04          | 1                       | 57.04       | 26.30   | < 0.0001 |                                               | 2.92                              |
| <i>C</i>              | 22.04          | 1                       | 22.04       | 10.16   | 0.0054   |                                               | 1.13                              |
| <i>T</i> <sup>2</sup> | 507.74         | 1                       | 507.74      | 231.77  | <0.0001  |                                               | 25.78                             |
| <i>W</i> <sup>2</sup> | 64.31          | 1                       | 64.31       | 29.65   | <0.0001  |                                               | 3.29                              |
| <i>E</i> <sup>2</sup> | 473.81         | 1                       | 473.81      | 218.44  | <0.0001  |                                               | 24.30                             |
| <i>C</i> <sup>2</sup> | 563.17         | 1                       | 563.17      | 259.63  | <0.0001  |                                               | 28.88                             |
| <i>TW</i>             | 18.06          | 1                       | 18.06       | 8.33    | 0.0103   |                                               | 0.92                              |
| <i>TE</i>             | 14.06          | 1                       | 14.06       | 6.48    | 0.0209   |                                               | 0.72                              |
| <i>WC</i>             | 22.56          | 1                       | 22.56       | 10.40   | 0.0050   |                                               | 1.15                              |
| <i>EC</i>             | 10.56          | 1                       | 10.56       | 4.87    | 0.0414   |                                               | 0.54                              |
| Residual              | 36.88          | 17                      | 2.17        |         |          |                                               |                                   |
| Lack of fit           | 31.54          | 12                      | 2.63        | 2.46    | 0.1643   | $F_{(0.05,12,17)} = 1.957$<br>Not significant |                                   |
| Pure error            | 5.33           | 5                       | 1.07        |         |          |                                               | 0.33                              |
| Total                 | 1575.87        | 29                      |             |         |          |                                               |                                   |

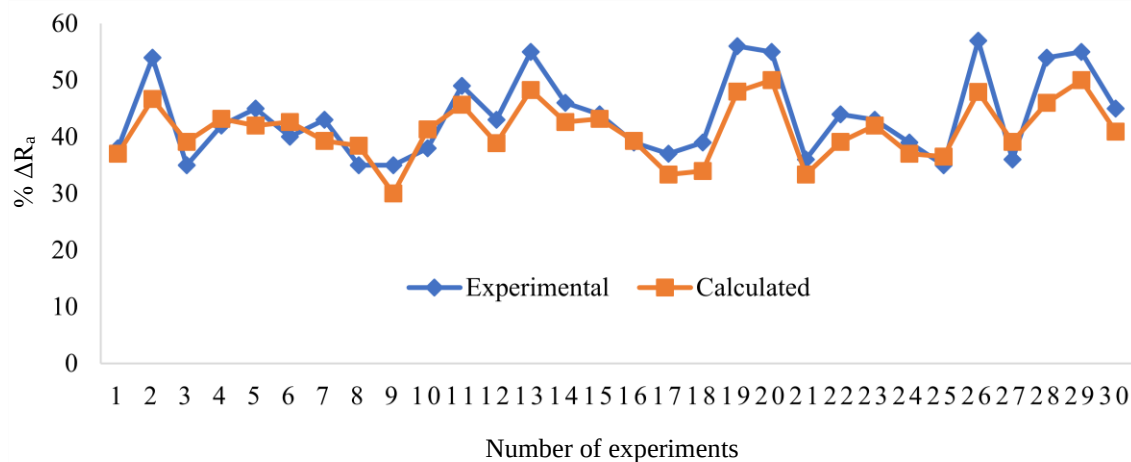


**Fig. 6.3.** Variation between the experimental and the calculated values on output %  $\Delta R_a$ .



Using the Eq. (5.6), the percentage contribution of each significant parameter is calculated and depicted in Table 6.3. After the regression analysis of the process parameters on the  $\% \Delta R_a$ , the outcome of the significant parameters has been conferred in this section.

#### 6.1.4.1 Individual effect of significant parameters on the $\% \Delta R_a$

Fig. 6.4(a) depicts the effect of tool rotation speed ( $T$ ) on  $\%$  improvement in the surface finish ( $\% \Delta R_a$ ). The workpiece rotation speed ( $W$ ),  $\%$  volume concentration of electrolytic iron particles (EIPs) ( $E$ ), and  $\%$  volume concentration of  $\text{CeO}_2$  abrasives ( $C$ ) was kept constant at 100 rpm, 30 %, and 10 % respectively. It can be seen that with the upsurge in  $T$ ,  $\% \Delta R_a$  upsurge up to a value of 300 rpm, and then the trend starts decreasing. This is because as the  $T$  increases up to 300 rpm, there is an increase in the rotational speed of the active abrasive particles (AAPs) that rotates over the surface asperities of the work part surface which leads to an increase in the tangential force. Owing to this, there is an upsurge in the shearing of the surface asperities from the work part surface by the tightly gripped AAPs present in the EIPs chain which provides an improvement in finishing. Hence, the trend of  $\% \Delta R_a$  upsurge. However, when the tool rotational speed exceeds 300 rpm, there is an excessive increase in centrifugal force due to which the active abrasive particles tend to loosen their grip in the EIPs chain during finishing. Owing to this, AAPs are unable to shear off the surface asperities properly from the work part surface which results in a decrease in the trend of the  $\% \Delta R_a$  at higher tool rotation. Hence, the decrease in the trend of  $\% \Delta R_a$  after 300 rpm is due to the excess increase of tangential shear force that acts on the AAPs with an upsurge in tool rotation. The maximum value of the  $\% \Delta R_a$  was attained at the 300 rpm of tool rotation.

Fig. 6.4(b) depicts the effect of workpiece rotational motion ( $W$ ) on  $\%$  improvement in the surface finish ( $\% \Delta R_a$ ). The  $T$ ,  $E$ , and  $C$  were kept constant at 300 rpm, 30 %, and 10 %, respectively. It can be seen that as the workpiece rotational speed increases up to the value of 100 rpm, there is an upsurge in shear force. Owing to this, the shearing of the surface asperities by AAPs on the work part region increases. This leads to an increase in  $\% \Delta R_a$ . However, when the workpiece rotation speed goes beyond 100 rpm, there is a decrease in the trend of  $\% \Delta R_a$ . This is due to the fact that as the workpiece rotational speed increases further, there may decrease in the interaction time for which the surface asperities and active abrasive particles (AAPs) collide. Due to this reduced interaction time, the AAPs are not able to shear off the surface asperities properly in a short moment of time which leads to a decrease in  $\% \Delta R_a$ .

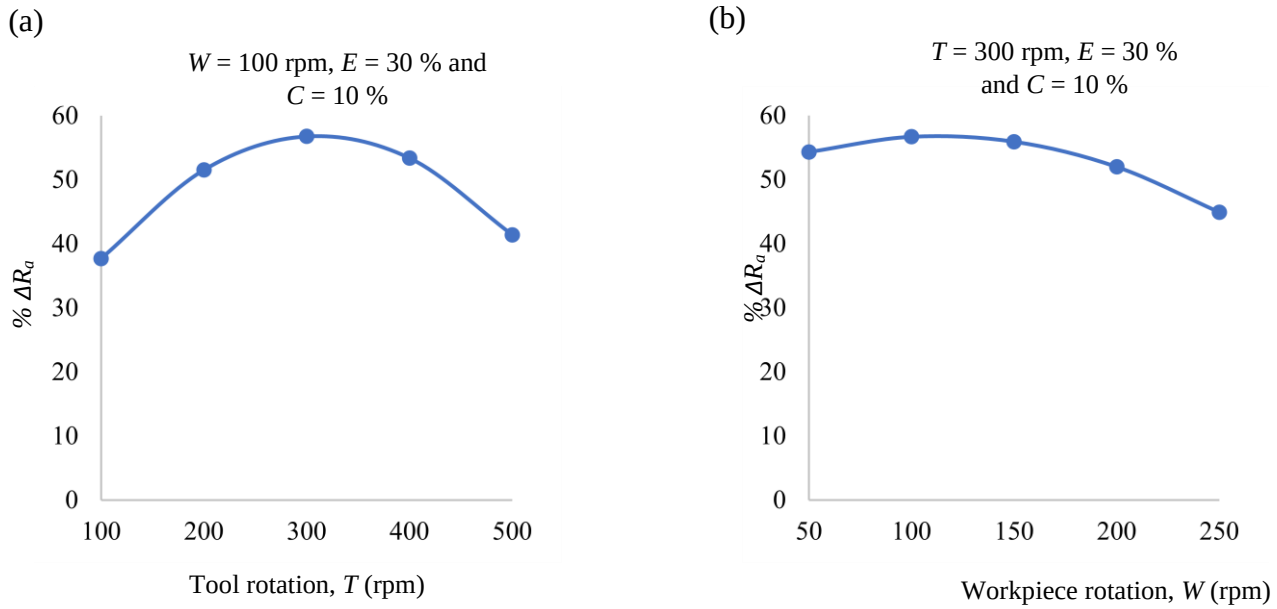


**Fig. 6.4.** Effect of (a) tool rotation ( $T$ ), and (b) workpiece rotation ( $W$ ) on %age improvement in the surface finish ( $\% \Delta R_a$ ).

Further, the effect of the % volume concentration of EIPs ( $E$ ) and % volume of  $\text{CeO}_2$  abrasives ( $C$ ) on the  $\% \Delta R_a$  has been discussed in *Chapter 5 (section 5.2)*. the maximum value for  $\% \Delta R_a$  was achieved at 30 % volume concentration of EIPs and 10 % volume concentration of abrasives.

#### 6.1.4.2 Combined effect of significant parameters on the $\% \Delta R_a$

Fig. 6.5(a) depicts the effect of tool rotation speed ( $T$ ) and workpiece rotation speed ( $W$ ) on the % improvement in the surface finish ( $\% \Delta R_a$ ). The % volume concentration of EIPs ( $E$ ) and % volume of  $\text{CeO}_2$  abrasives ( $C$ ) was kept constant at 30 % and 10 %, respectively. It can be seen that as the  $T$  and  $W$  increase initially, the trend of the  $\% \Delta R_a$  increases. However, after achieving the 300 rpm of tool rotation and 100 rpm of work part rotation there is a decrease in the trend of the  $\% \Delta R_a$ . Increasing both the parameters simultaneously leads to the enhancement in the net relative motion of the AAPs that act on the work part surface. This enhances the surface finish of the work part due to which there is an increase in the trend of the  $\% \Delta R_a$ . However, beyond the 300 rpm of rotational motion of the tool and 100 rpm of work part rotation, the net relative motion between active abrasives and the workpiece becomes so high that the interaction time amid the AAPs and the workpiece surface decreases. Further, the finishing action on the work part surface due to the relative motion amid AAPs and workpiece dominates initially at a lower tool and workpiece rotational speeds. However, at the high tool and workpiece rotation, a significant amount of centrifugal force destabilizes the EIPs columnar chain in the MRP fluid. This adversely affects the finishing action. Due to these reasons, there is a decrease in the trend of  $\% \Delta R_a$  as depicted in Fig

6.5(a). The maximum value of the  $\% \Delta R_a$  was achieved at the 300 rpm of tool rotational motion and 100 rpm of work part rotation.

Fig. 6.5(b) depicts the effect of  $E$  and  $T$  on the  $\%$  improvement in surface finish ( $\% \Delta R_a$ ). The  $W$  and  $C$  were kept constant at 100 rpm and 10 %, respectively. It can be observed that as the  $T$  and  $E$  upsurge initially there is an increase in the trend of the  $\% \Delta R_a$ . However, after achieving the 300 rpm of tool rotation and 30 % volume of  $E$ , there is a decrease in the trend of the  $\% \Delta R_a$ . This is because, as the  $T$  and volume % of  $E$  increase simultaneously, there is an increase in the centrifugal and normal force in MR polishing (MRP) fluid which leads to the increase in the shearing of the surface asperities. This is because the strength of the EIPs chain structure increase which provides more stiffness to the MRP fluid which leads to the finishing of the workpiece. Hence the increase in the trend of the  $\% \Delta R_a$ . However, after achieving 300 rpm of tool rotation and 30 % volume of EIPs, there is a decrease in the trend of the  $\% \Delta R_a$  if both the parameters increase simultaneously. This is due to the excessive increase in centrifugal force due to which the active abrasive particles may tend to loosen their grip in the EIPs chain during finishing. Also, there is a decrease in the overall cutting edges of AAPs which are used for the surface finishing as more EIPs aggregate outside the already existing EIPs chains in which the AAPs are tightly gripped. Owing to this there is improper chipping off surface asperities from the workpiece surface which leads to a decrease in the trend  $\% \Delta R_a$ . The maximum value of the  $\% \Delta R_a$  was achieved at the 300 rpm of tool rotation and 30 % volume of iron particles.

Fig. 6.5(c) depicts the simultaneous effect of  $W$  and  $C$  on the  $\%$  improvement in surface finish ( $\% \Delta R_a$ ). The  $T$  and  $E$  were kept constant at 300 rpm and 30 % respectively. It can be seen that as the parameters  $W$  and  $C$  increased simultaneously, there is an upsurge in the trend of the  $\% \Delta R_a$ . However, after the 100 rpm of workpiece rotation and 10 % volume concentration of  $\text{CeO}_2$  abrasives, there is a decrease in the trend of the  $\% \Delta R_a$ . An increase in the  $W$  and  $C$  simultaneously upto 100 rpm and 10 % lead to the upsurge in the shear force as the net relative speed between AAPs and work part surface increases. Also, there may be less discontinuous EIPs chains with the 10 % volume concentration of  $\text{CeO}_2$  abrasives, and the active abrasive particles (AAPs) are tightly held by the EIPs during the surface finishing. Owing to this there is an increase in the clipping of the surface asperities from the work part.

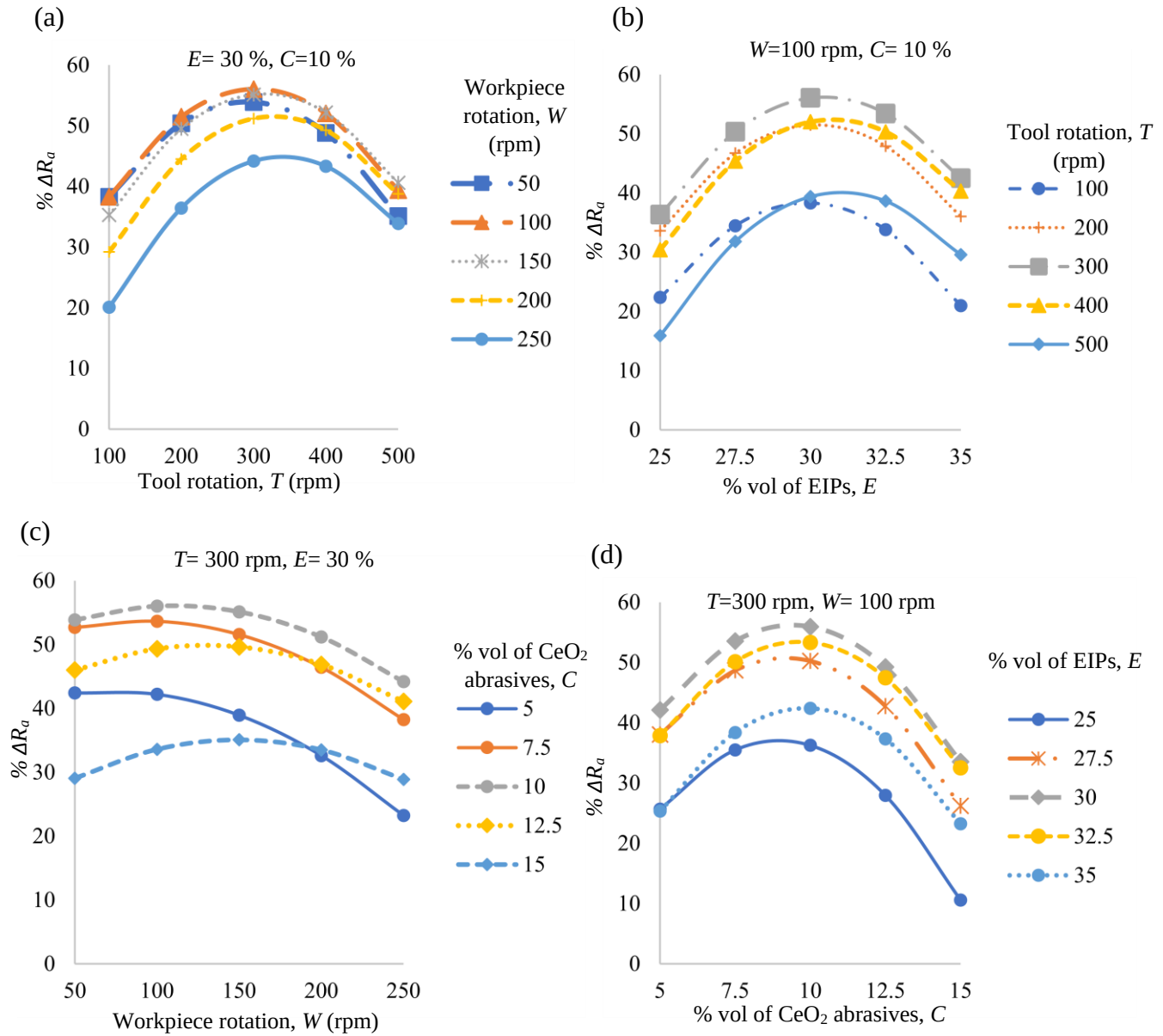


**Fig. 6.5.** Effect of (a) tool rotation ( $T$ ) at different workpiece rotations ( $W$ ), (b) % volume of EIP ( $E$ ) at different rotational speeds of tool ( $T$ ), (c) workpiece rotation ( $W$ ) at different % volume of  $\text{CeO}_2$  abrasives ( $C$ ) and (d) % volume of  $\text{CeO}_2$  abrasives ( $C$ ) at different % volume of EIPs on percentage improvement in the surface finish ( $\% \Delta R_a$ ).

However, after the 100 rpm of workpiece rotation and 10 % volume concentration of the  $\text{CeO}_2$  abrasives, there is a decrease in the trend of  $\% \Delta R_a$  if the  $W$  and  $C$  are further increasing simultaneously. This is because, at higher  $W$  and  $C$ , there may decrease in the interaction time for which the surface asperities and AAPs collide. Due to the reduced interaction time, the AAPs are not able to shear off the surface asperities properly in a short moment of time. Also, the AAPs in an extra amount get trapped amid the EIPs chains. This increases the distance between two EIPs. Owing to this there is a reduction in the magnetic interaction force between the EIPs leading to a

decrease in the MRP fluid strength as given in Eq. (5.7). Hence this decreases the strength of MRP fluid leading to a decrease in the trend of the  $\% \Delta R_a$ . The maximum value of the  $\% \Delta R_a$  was achieved at the 100 rpm of workpiece rotation and 10% volume concentration of CeO<sub>2</sub> abrasives. Fig. 6.5(d) depicts the simultaneous effect of  $C$  and  $E$  on the  $\%$  improvement in surface finish ( $\% \Delta R_a$ ). The  $W$  and  $T$  were kept constant at 100 rpm and 300 rpm respectively. It can be observed that as the parameters  $C$  and  $E$  increase simultaneously, there is an upsurge in the trend of the  $\% \Delta R_a$ . However, after the 10 % volume concentration of CeO<sub>2</sub> abrasive particles and 30 % volume concentration of EIPs, there is a decrease in the trend of the  $\% \Delta R_a$ . Increasing both the parameters simultaneously upto 10 % and 30 % leads to the enhancement in the MRP fluid shear strength as there is an increase in the normal force of the active abrasives. Owing to this there is an increase in the clipping of the asperities from the work part surface. Due to this there is an increase in the trend of the  $\% \Delta R_a$ . However, beyond the 10 % volume concentration of CeO<sub>2</sub> abrasive particles and 30 % volume of EIPs tends to decrease the shear strength of the MRP fluid. This is because the higher % volume concentration of abrasive increases the distance between the EIPs which decreases the magnetic interaction force as given in Eq. (5.7). Also, at higher % vol of the EIPs, more EIPs aggregate outside the already existing EIP chains in which AAPs are tightly gripped. Owing to this there is a decrease in the number of overall cutting edges of AAPs which are used for the surface finishing. This leads to the reduction in the removal of material, due to which  $\% \Delta R_a$  decreases. The maximum value of the  $\% \Delta R_a$  was achieved at the 10 % volume concentration of CeO<sub>2</sub> abrasive particles and 30% volume concentration of EIPs.

In the present work, the main aim is to get a minimum  $R_a$  value and maximum  $\% \Delta R_a$  for MR finishing the UHMWPE acetabular cup liner. To get the best possible outcome for the  $\% \Delta R_a$ , the prediction of the optimum parameters was done after the regression analysis. The model developed from the regression analysis is used to get the minimum value of the surface asperities ( $R_a$ ). Equation (5.2) was used to calculate the maximum  $\% \Delta R_a$ .

In order to maximize the  $\% \Delta R_a$ , the parameters were subjected to

$$100 \text{ rpm} \leq T \leq 500 \text{ rpm}$$

$$50 \text{ rpm} \leq W \leq 250 \text{ rpm}$$

$$25 \% \leq E \leq 35 \%$$

$$5 \% \leq C \leq 15 \%$$

To predict the optimum parameters, the outcomes from different process parameters on  $\% \Delta R_a$  are analyzed. The quadratic model equation after the regression analysis (Eq. 6.2) is used to maximize the  $\% \Delta R_a$ . The optimized parameter values were found as tool rotational speed of 300 rpm, workpiece rotational speed of 100 rpm, 30 % volume concentration of electrolytic iron particles (EIPs) and 10 % volume concentration of the  $\text{CeO}_2$  abrasive particles. Hence, the optimum composition of MR polishing (MRP) fluid for finishing the UHMWPE acetabular cup workpieces with the present process is predicted as 30 % volume concentration of EIPs, 10 % volume concentration of the  $\text{CeO}_2$  abrasives and remaining 60 % volume concentration of water-based carrier fluid (80 % deionized water and 20 % glycerol).

#### 6.1.4.3 Observation of reduction in surface roughness of the hemispherical shaped acetabular cup surface

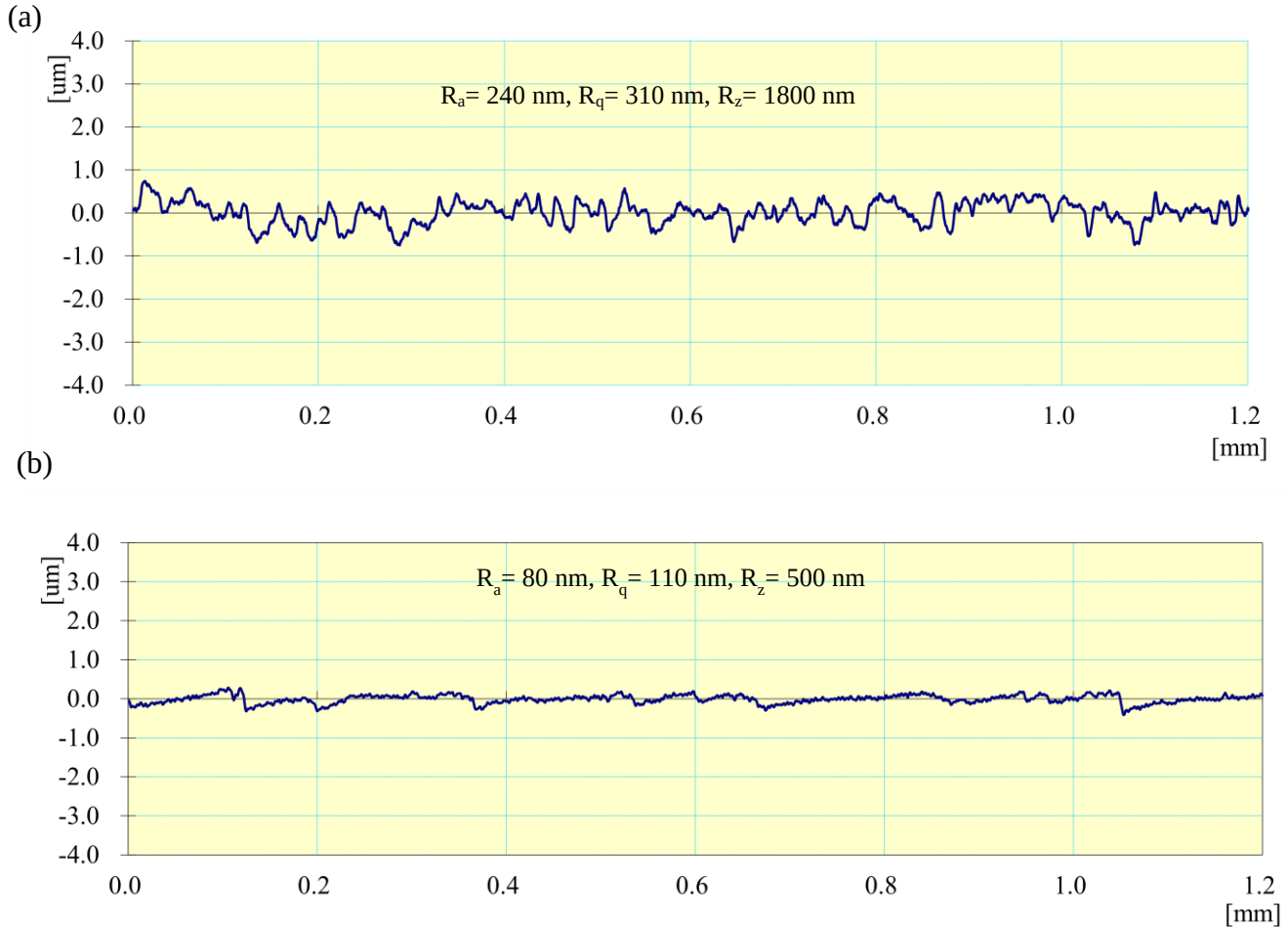


**Fig. 6.6.** Surface roughness profiles for (a) initial surface and (b) after 80 min on MR finishing of final surface at  $T= 300$  rpm,  $W= 100$  rpm,  $E= 30$  % and  $C= 10$  %.

Further, experimentations are performed using optimized parameters on the UHMWPE acetabular cup surface. The minimum surface roughness ( $R_a$ ) value of 80 nm was achieved from the ground roughness values of 240 nm in 80 min of MR finishing for 1140 mm<sup>2</sup> surface area. After 80 min, no significant improvement was observed on the work part surface. The total improvement in %  $\Delta R_a$  of the UHMWPE acetabular cup after the magnetorheological finishing was found as 66.67 % on 1140 mm<sup>2</sup> hemispherical surface area. The surface asperities profiles for initial and final are depicted in Fig. 6.6(a) and (b) respectively. The initial ground  $R_a$  profile parameters are measured as  $R_a = 240$  nm,  $R_z = 1800$  nm, and  $R_q = 310$  nm while the final finished polyamide surface after 100 min of MRF with best process parameters over the polyamide surface is measured as  $R_a = 80$  nm,  $R_z = 500$  nm,  $R_q = 110$  nm. The reduced surface roughness parameters validate the fine finishing of the hemispherical shaped acetabular cup surface using the presently designed tool.

#### *6.1.4.4 Observation of surface characteristics of the hemispherical shaped acetabular cup surface*

In the present work, for analyzing the surface characteristics of the UHMWPE acetabular cup, scanning electron microscopy (SEM) was utilized. The initial and MR finished UHMWPE cup surface images of the SEM are depicted in Fig. 6.7. From Fig. 6.7(a) it can be seen that there are various defects on the initial acetabular cup surface such as grinding lays, scratches, and deep feed marks. During the grinding process, these defects are due to the lack of control over finishing forces which results in the removal of non-uniform material. Owing to these defects, the dimensional accuracy of the acetabular cup decreases and the wear rate upsurges. This may lead to osteolysis which may decrease the service life and functional efficacy of the implant. However, after the magnetorheological finishing (MRF) over the UHMWPE acetabular cup surface for 80 min of the finishing cycle, there is a significantly enhancement in the final finished acetabular cup surface characteristics as shown in Fig. 6.7(b). This is because in the MRF process, normal forces acting on the cup surface are comparatively low and the removal of material occurs in the form of microchips. Also, in the MR finishing process, the external forces can be controlled magnetically which also improves its surface characteristics. Owing to this improvement in surface characteristics, the wear rate may decrease which further tends to enhance the service life and functional efficacy of the implants.

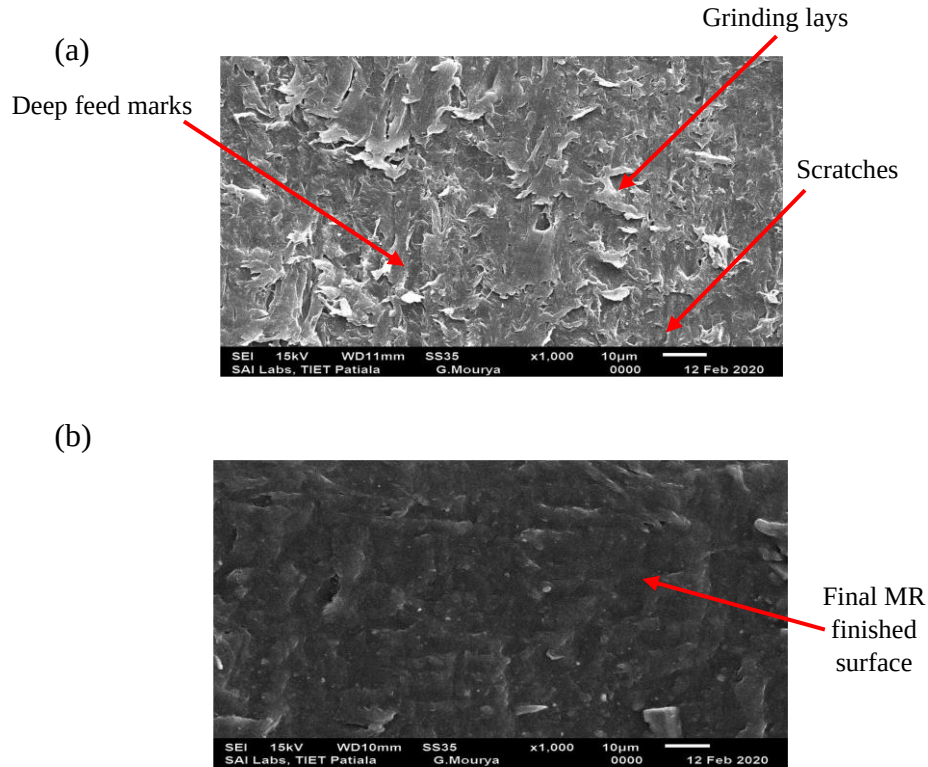


**Fig. 6.7.** Surface morphology images of (a) initial surface and (b) final surface after 80 min on MR finishing of final surface at  $T= 300$  rpm,  $W= 100$  rpm,  $E= 30$  % and  $C= 10$  %.

Further to confirm the dimensional accuracy on the hemispherical UHMWPE acetabular cup, the circularity test was done on the initial surface and the final MR finished surface with the help of the coordinate measuring machine (CMM). The circularity test predicts the closeness of the real circle to the true circle of the acetabular cup. The closeness of the real circle to the true circle determines the dimensional accuracy of the work part (Martorelli *et al.*, 2017). To reduce the wear in the tribological implants, the accuracy in dimensional parameters is essential. The circularity was measured and depicted in Fig. 6.8(a) and (b). Fig. 6.8(a) shows the circularity image of the initial ground surface and the value was found as 0.0780 mm. It can be observed from Fig. 6.8(a) that most of the recorded points on the real circle have deviated from the true circle. However, in Fig. 6.8(b), it can be seen that there is a significant enhancement in the circularity as most of the recorded points are lying close to the true circle. Also, the value of circularity was found as 0.0171 mm. Hence, on the basis of Fig. 6.6, it can be concluded that the MR fluid-based finishing process is useful for improving the dimensional accuracy of the hemispherical UHMWPE acetabular cup.



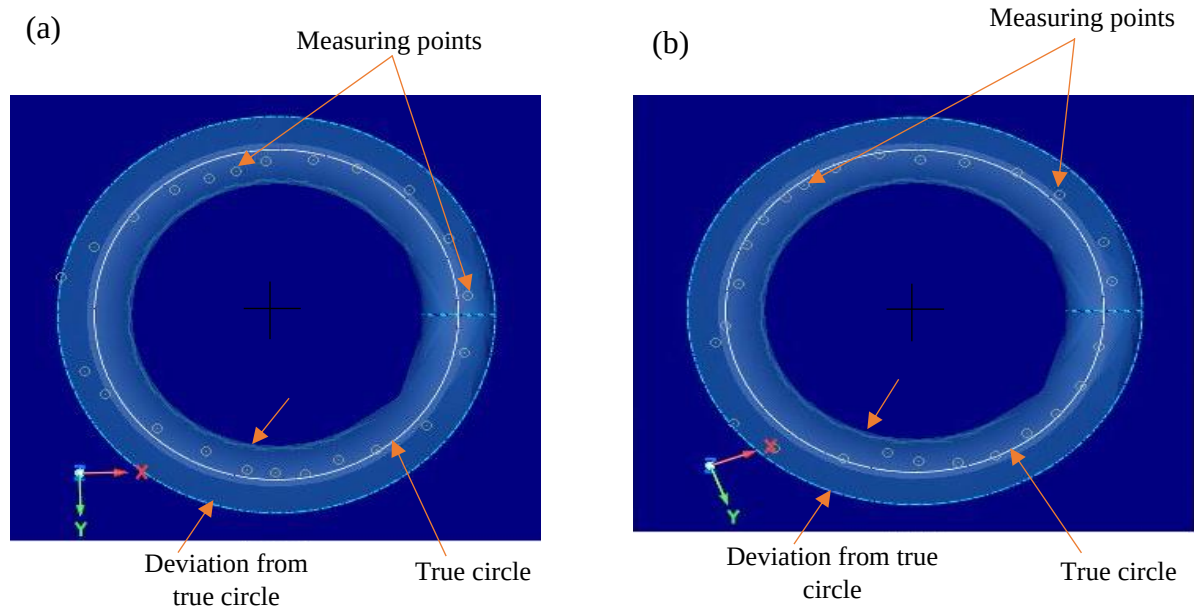


**Fig. 6.8.** Circularity image of (a) initial ground surface and (b) final MR finished surface at  $T= 300$  rpm,  $W= 100$  rpm,  $E= 30$  % and  $C= 10$  %.

Further, at the initial condition after the grinding, the hardness of the UHMWPE acetabular cup surface was found as 4.8 HV. After the MR finishing, the hardness of the UHMWPE acetabular cup was found as 8.2 HV. Thus, the results of the micro-hardness test reveal that the hardness value gets increased after the MR finishing. If the surface of the UHMWPE acetabular cup is found rough after the grinding process, the peaks of surface asperities on the of the UHMWPE acetabular cup have low area concentration owing to which the peaks are not able to the bear load and hence gets break which lowers its hardness. However, after the MR finishing, the peaks of surface asperities on the UHMWPE acetabular cup get more flattened due to the further removal of the surface asperities peaks owing to which the area concentration increases and leads to the increase in the workpiece hardness (Singh and Singh 2019). This result in an increase in the load-bearing capability of the UHMWPE acetabular cup surface. Hence, the decrease in the creep rate and wear rate volume of UHMWPE acetabular cup after the presently used hemispherical tool core tip-based MR finishing process tends to enhance the functional application of the UHMWPE acetabular cups with a decrease in the chances of osteolysis which may make the medical implants more efficient and may increase their total life span.

#### 6.1.4.5 Experimental validation of the theoretical analysis for the reduction in surface roughness of UHMWPE acetabular cup using the hemispherical tip based electromagnetic tool

Experiments are carried out to validate the theoretical model (*Chapter 4, section 4.1*) for a reduction in surface roughness of the hemispherical cup work part utilizing the MR finishing process. The experiment is carried out in four cycles, each of which lasts 20 min. The experimentally obtained surface roughness values are compared with theoretically calculated surface roughness values as reported in Table 6.4. The range of error amid the experimentally obtained and theoretically calculated surface roughness is reported in Table 6.4. The % error is evaluated using Eq. (6.3).

$$\% \text{ error} = \frac{|\text{Experimental measured Ra value} - \text{Theoretical calculated Ra value}|}{\text{Experimental measured Ra value}} \times 100 \quad (6.3)$$

After the experimentation, the value of  $R_a$  ( $X1$  and  $X2$ ) is obtained and further final average  $R_a$  value was taken as reported in Table 6.4. The % error range lies amid 15.55 % to 1.71 %. The % error in the experimentally and theoretically measured volumetric material removal value after the 80 min of finishing time shows a close agreement except for the last finishing cycle. The error is high in the last cycle (15.55 %) because the theoretical calculated surface roughness value reduces with the constant rate for each finishing cycle (Eq. 4.38). However, after each finishing cycle, the roughness peaks present on the hemispherical cup work part surface starts to get flattened due to the decrease in the surface roughness. Owing to the flattening of the surface asperities, the surface roughness value varies after each finishing cycle as reported in Table 6.4.

**Table 6.4.** Validation of the theoretical value and the experimental value of surface roughness with different number of finishing cycles.

| Finishing time<br>(min) | Theoretical surface<br>roughness (nm)<br>Eq. (4.38) | Experimental surface roughness (nm) |      |                  | % error<br>Eq. (6.3) |
|-------------------------|-----------------------------------------------------|-------------------------------------|------|------------------|----------------------|
|                         |                                                     | $X1$                                | $X2$ | Final avg. $R_a$ |                      |
| 0                       | 240                                                 | 240                                 | 240  | 240              | 0.00                 |
| 20                      | 206                                                 | 210                                 | 190  | 200              | 3.00                 |
| 40                      | 172                                                 | 180                                 | 170  | 175              | 1.71                 |
| 60                      | 138                                                 | 130                                 | 140  | 135              | 2.22                 |
| 80                      | 104                                                 | 80                                  | 100  | 90               | 15.55                |

#### 6.1.5 Conclusions

The magnetorheological (MR) finishing process with the newly fabricated hemispherical tool core tip surface has been found potential to provide fine finishing on the hemispherical UHMWPE

acetabular cup surface which further tends to enhance their functional performance. The response surface methodology is used for obtaining the optimum process parameters in effectively MR finishing the hemispherical UHMWPE acetabular cup surface. Further, to validate the developed theoretical model, the experimentations have been performed on the hemispherical-shaped acetabular cup. The fine finished UHMWPE acetabular cups can be used in various joint implants like hip joints and knee joints. The reduction in wear rate and the creep rate validates the functional efficacy of the MR finished UHMWPE acetabular cups owing to the decrease in the coefficient friction after reduction in surface roughness values. The following conclusions are drawn from the MR fluid-based finishing process on the UHMWPE acetabular hemispherical cup surface.

- The regression analysis with response surface methodology reveals that the effectively finishing over the UHMWPE acetabular cup surface is achieved with optimized parameters as tool rotational speed of 300 rpm, workpiece rotational speed of 100 rpm, 30 % volume concentration of electrolytic iron particle and 10 % volume concentration of CeO<sub>2</sub> abrasive particles with the 60 % volume concentration of water-based carrier fluid (80 % deionized water and 20 % glycerol).
- The reduction in roughness value from 240 nm to 80 nm after MR finishing with the optimized parameters on the 1140 mm<sup>2</sup> hemispherical surface area of the UHMWPE acetabular cup workpiece reveals the effectiveness of the present MR finishing process with the newly fabricated hemispherical tool tip surface for the UHMWPE acetabular cup workpieces. Also, the reduction in circularity of the hemispherical UHMWPE acetabular cup surface from 0.0780 to 0.0171 and the increment in microhardness from 4.8 HV to 8.2 HV reveals the improvement in dimensional accuracy and functionality of the UHMWPE acetabular cup surface after the MR finishing.
- The improvement in the surface characteristics, dimensional accuracy, and reduction in surface roughness of the hemispherical UHMWPE acetabular cup surface reduces the coefficient of friction and increases the hardness. This may lead to the reduction in wear rate and the creep rate of the UHMWPE acetabular cup surface during their actual use for different motions
- The error amid experimentally obtained surface roughness values and theoretically determined roughness values ranges between 1.71 and 15.55 %. This validates the

effectiveness of the present developed mathematical model for fine finishing of the hemispherical cups.

- The reduction in the wear rate and creep rate of the UHMWPE acetabular cup can enhance the functionality of the hip-joint implant. Also, it may reduce the chance of osteolysis which can increase the life span of the hip-joint implant.

## **6.2 Parametric investigation of typical polymer gear for improving their functional performance**

Gear is a mechanical component which is commonly utilized in machining components for transmitting motion, torque, or both amid two shafts. On comparing to belts and chain drives, the gear drive offers better transmission owing to the lower slipping effect (Petare *et al.*, 2020). In today's era, polymer gears do offer unique advantages over metal gears owing to which their demands are increasing rapidly in different industries such as automobile, marine, office machines, medical devices, and food and textile (Snyder, 2010; Fernandes *et al.*, 2019). Polymer gears are also quoted as the no-noise components which even adds up to their advantages in various medical equipment. In industries, different types of polymer gears are used depending on the shaft's relative position. Polymer bevel gears (BGs) are one such gear that is generally used in the sectors of the aviation industry, micro and macro devices, automotive equipment, farm and agricultural equipment, electrical toys, marine transmission, biomedical devices, etc. (Gupta *et al.*, 2017). Owing to the high demand for polymer BGs in these sectors, gear manufacturers have focused on making gears with low cost, high transmission efficiency, and fine quality. However, in comparison with the other types of gears, the manufacturing and design of polymer BGs are complex. Owing to this the polymer bevel gear (BG) finishing becomes very difficult for accomplishing the requirements such as higher transmission efficiency, better gear surface quality, and longer service life. Further, the poor surface finish may lead to heat generation during the meshing of polymer gears. This causes wear and contact stresses in the BGs which is apparent in the form of lower accuracy, gear system efficacy, and loss in involute profile resulting in the eventual failure of polymer bevel gears. Hoskins *et al.* (2011) highlighted that with the rise in temperature due to friction, the elastic modulus of polymer material changes. This alters the stiffness of the gear teeth leading to a reduction in service life. Hence, for enhancing the functional performance of polymer bevel gears with improved service life, and minimal wear and friction, a high-grade surface finishing is essential.

Therefore, the magnetorheological bevel gear finishing (MRBGF) process is utilized to enhance the overall polymer BGs teeth finishing in the minimum time. The process parameters with an optimum surface finish of the polymer BGs using the present MRBGF process are predicted. The surface roughness reduction, surface characteristics, and gear run out parameter are investigated after MR finishing over polymer BGs. Also, the theoretical model for fine finishing of bevel gear developed in *Chapter 4 (section 4.2)* is experimentally validated. Further, to study the effectiveness of MR finishing on the polymer gears, the gear functional testing setup is developed and demonstrated. The present gear testing setup offers a lot of flexibility when it comes to studying different operating circumstances, but its biggest advantage is that it allows for continuous monitoring of gear surface temperature on the test gears regardless of tooth wear. The purpose is to compare the effects of surface finishing on surface wear, and temperature. The present MRBGF process tends to enhance the polymer gears service life by providing fine finishing in minimum time with improved functional efficacy.

#### **6.2.1 Material selection and workpiece preparation**

In this work, for manufacturing the polymer bevel gears (BGs) polyamide material is used. Properties of a polyamide such as low-cost, low weight, corrosive resistance, and ability to work in either presence or absence of external lubrication make them beneficial for various industrial components.

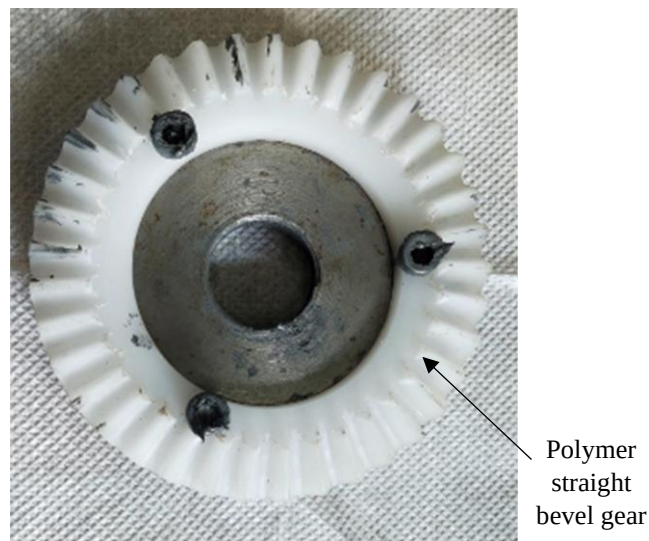


**Fig. 6.9.** Photographic image of the polymer straight bevel gear work part.

In this study, the typical standard size of polymer BG is manufactured which is used in the automobile industry as shown in Fig. 6.9. Initially, the milling process is used for manufacturing the straight bevel gears (BGs) and further, the profile grinder is utilized to get the necessary dimensions of the gear teeth and initial finishing. The polymer BG's and dimensional specifications are stated in Table 6.5.

**Table 6.5.** Straight bevel gear work part and tool specification.

| Specification        | Workpiece dimension | Tool dimension  |
|----------------------|---------------------|-----------------|
| Pressure angle       | 20 <sup>0</sup>     | 20 <sup>0</sup> |
| Base circle diameter | 83.4 mm             | 37 mm           |
| No. of teeth         | 36                  | 12              |
| Module               | 2                   | 2               |

### 6.2.2 Experimentation

In the current work, for polymer bevel gears (BGs) finishing, a novel designed magnetorheological bevel gear finishing (MRBGF) tool is used as espied in Fig. 6.10. The design of the hemispherical tool used has been discussed in *Chapter 3 (section 3.1.2)*. The variation of the magnetic field between the working space occurs due to magnetizing current, which is controlled by the DC source. The working gap amid the bevel gear finishing (BGF) tool and polymer BG tooth is kept constant and MRP fluid is used in it. The novel BGF tool core is given rotation to accomplish the finishing over the polymer BG. The polymer bevel gear (BG) is placed in such a way that with each BGF tool core rotation, each polymer BG's tooth profile gets meshed properly with a working gap filled with the MRP fluid as shown in Fig. 6.10. As a result, the polymer BG workpiece rotates with the tool core rotation. Every tooth of the polymer BG comes into contact with MRP fluid that is placed on the magnetized BGF tool owing to the simultaneous polymer gear and BGF tool rotations. As a result, polymer gear teeth get finished simultaneously, hence reducing the overall finishing time.

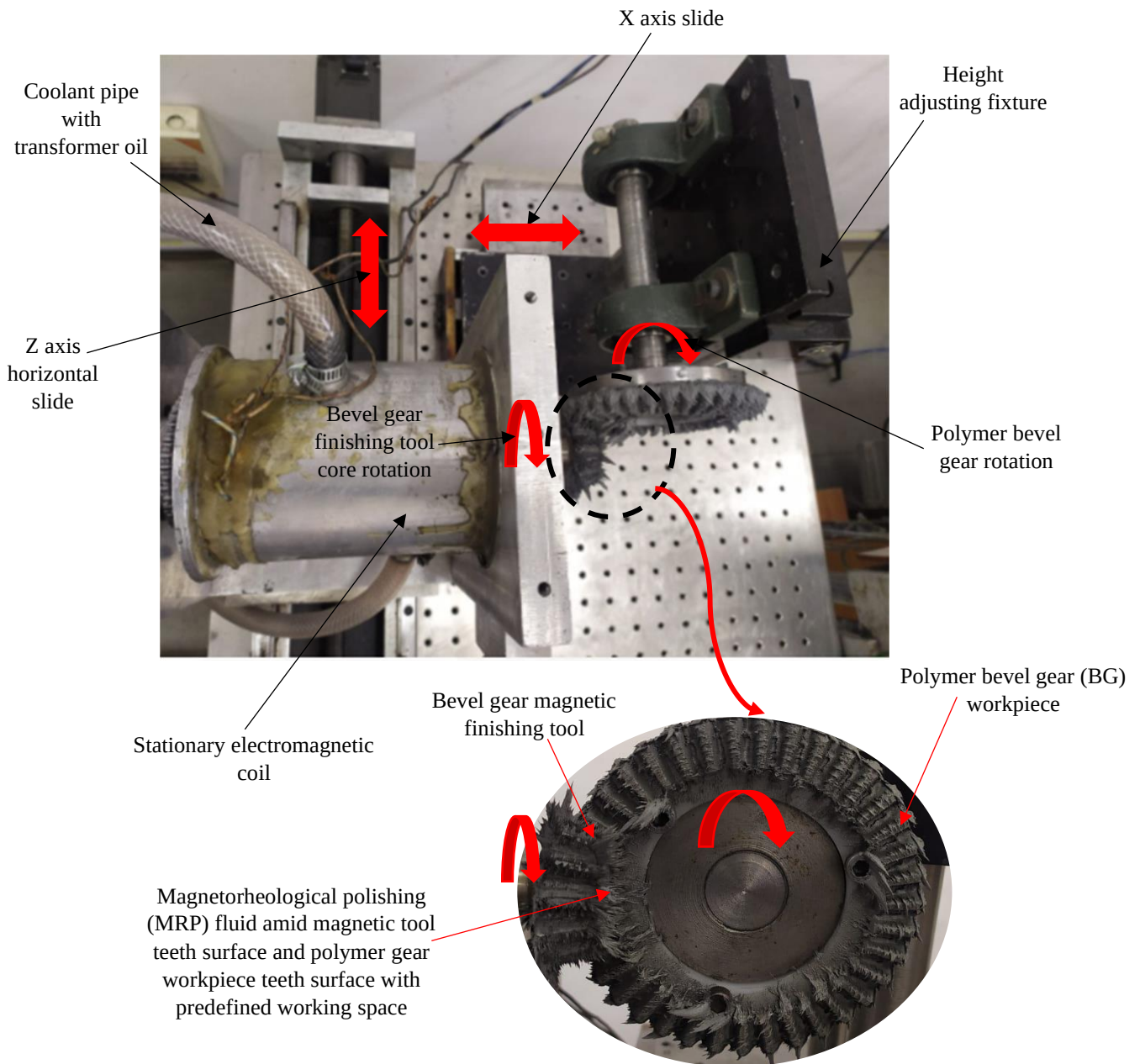


**Fig. 6.10.** Photograph of the finishing of polymer bevel gear using the presently designed bevel gear magnetorheological (MR) finishing setup.

#### 6.2.2.1 Selection of process parameters

In this study, a newly developed MRBGF process with the bevel gear finishing (BGF) tool is used in the detailed analysis for the effective finishing of the polymer BGs. In the present analysis, three parameters naming the BGF tool rotational speed ( $T$ ), magnetizing current ( $I$ ), and working space or gap ( $S$ ) are used. Each of the parameters has its own influence on the present MRBGF process. Since with the BGF tool rotation ( $T$ ), the polymer BG also rotates simultaneously,

therefore the tangential shear force and rubbing force that acts over AAPs is governed by the tool rotational speed ( $T$ ). Similarly, magnetizing current ( $I$ ) and working gap ( $S$ ) control the magnetic flux density (MFD) which governs the indentation of the active abrasive particles (AAPs) over the polymer BG surface. Hence both  $I$  and  $S$  play key roles in the present MRBGF process. The output response is taken as % improvement in surface finish or % reduction in surface roughness ( $\% \Delta R_a$ ). Further, the composition of MRP fluid used was 15 % by volume of electrolytic iron particles (EIPs) (500 mesh size), 15 % by volume of  $\text{CeO}_2$  abrasive (800 mesh size), and 70 % of carrier fluid by volume (the carrier fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol). Based on the primary experiments, the MRP fluid's concentration is decided in *Chapter 5 (section 5.1)*.

Further, to decide the various process parameters range for the effective finishing of the polymer BG with the MRBGF process, the initial trials were performed. The value of average surface roughness ( $R_a$ ) of initial polymer BG has measured between 360-390 nm, using the Mitutoyo SJ-410 instrument. The cut-off length of the instrument is kept at 0.25 mm. The process parameters selected range is reported in Table 6.6. To analyze the individual and combined outcome of the various process parameters on the polymer BG, the design of experiments (DOE) with response surface methodology (RSM) is used.

**Table 6.6.** Process parameters and their range.

| S. No. | Parameters                       | Range |     |     |     |     |
|--------|----------------------------------|-------|-----|-----|-----|-----|
| 1      | Tool rotational speed, $T$ (rpm) | 49    | 84  | 119 | 154 | 189 |
| 2      | Working gap, $S$ (mm)            | 0.6   | 1   | 1.4 | 1.8 | 2.2 |
| 3      | Magnetizing current, $I$ (A)     | 1     | 1.5 | 2   | 2.5 | 3   |

In the present study, the RSM technique central composite design (CCD) is utilized to analyze experiments. The CCD is a good choice among the typical designs used in RSM because of its high efficiency in terms of the number of necessary runs. The main objective of the current predicted model is to provide the analysis of variation in the enhancement of  $\% \Delta R_a$  and to improve the efficiency of the present MRBGF process. The relation amid the output ( $\% \Delta R_a$ ) and the input independent parameters is given by Eq. (6.4).

$$\% \Delta R_a = f(I, T, S) \quad (6.4)$$



where  $f$  is the response function,  $I$  is the magnetizing current,  $S$  is the working gap, and  $T$  is the BGF tool rotational speed.

In the current research, with five levels and three parameters central composite design (CCD) is utilized to plan and analyze the experiments. CCD is planned for a total of 20 experiments as stated in Table 6.7. Each experiment is conducted for 60 min and the MRP fluid is changed over the BGF tool surface after every 20 min of the finishing.

**Table 6.7.** Experimentation plan and their results.

| Run | Tool rotation, $T$ (rpm) | Working gap, $S$ (mm) | Magnetizing current, $I$ (A) | Average initial $R_{ai}$ value (nm) | Final $R_a$ value (nm) |       |       | Average final $R_{af}$ value ( $\mu\text{m}$ ) | % $\Delta R_a$ Eq. (5.2) |
|-----|--------------------------|-----------------------|------------------------------|-------------------------------------|------------------------|-------|-------|------------------------------------------------|--------------------------|
|     |                          |                       |                              |                                     | $X_1$                  | $X_2$ | $X_3$ |                                                |                          |
| 1   | 119                      | 1.40                  | 2.00                         | 390                                 | 180                    | 180   | 170   | 176                                            | 54.87                    |
| 2   | 154                      | 1.80                  | 1.50                         | 370                                 | 210                    | 210   | 200   | 203                                            | 45.13                    |
| 3   | 189                      | 1.40                  | 2.00                         | 380                                 | 240                    | 250   | 240   | 243                                            | 36.05                    |
| 4   | 49                       | 1.40                  | 2.00                         | 360                                 | 270                    | 260   | 260   | 263                                            | 26.94                    |
| 5   | 154                      | 1.80                  | 2.50                         | 370                                 | 210                    | 220   | 220   | 216                                            | 41.62                    |
| 6   | 119                      | 1.40                  | 1.00                         | 380                                 | 290                    | 270   | 270   | 276                                            | 27.36                    |
| 7   | 119                      | 1.40                  | 2.00                         | 390                                 | 190                    | 190   | 170   | 183                                            | 53.07                    |
| 8   | 119                      | 1.40                  | 2.00                         | 360                                 | 180                    | 170   | 180   | 176                                            | 51.11                    |
| 9   | 84                       | 1.00                  | 2.50                         | 370                                 | 220                    | 220   | 240   | 226                                            | 38.91                    |
| 10  | 119                      | 1.40                  | 2.00                         | 370                                 | 190                    | 190   | 200   | 193                                            | 47.83                    |
| 11  | 119                      | 1.40                  | 3.00                         | 380                                 | 240                    | 220   | 240   | 233                                            | 38.68                    |
| 12  | 119                      | 1.40                  | 2.00                         | 360                                 | 200                    | 200   | 210   | 203                                            | 43.61                    |
| 13  | 119                      | 1.40                  | 2.00                         | 380                                 | 190                    | 190   | 180   | 187                                            | 50.78                    |
| 14  | 154                      | 1.00                  | 1.50                         | 380                                 | 280                    | 270   | 280   | 277                                            | 27.10                    |
| 15  | 119                      | 2.20                  | 2.00                         | 360                                 | 210                    | 200   | 200   | 203                                            | 43.61                    |
| 16  | 154                      | 1.00                  | 2.50                         | 370                                 | 220                    | 240   | 240   | 233                                            | 37                       |
| 17  | 84                       | 1.80                  | 2.50                         | 380                                 | 250                    | 250   | 260   | 253                                            | 33.42                    |
| 18  | 119                      | 0.60                  | 2.00                         | 390                                 | 250                    | 250   | 240   | 246                                            | 36.92                    |
| 19  | 84                       | 1.80                  | 1.50                         | 380                                 | 250                    | 250   | 260   | 253                                            | 33.42                    |
| 20  | 84                       | 1.00                  | 1.50                         | 380                                 | 260                    | 260   | 270   | 263                                            | 30.78                    |

This is achieved so that during the surface finishing of the polymer BG, the abrasive cutting edges stay new. Further, the analysis of variance's (ANOVA) F-test is performed to identify of the implied predicted equation to strengthen the relation amid the process parameters and the %  $\Delta R_a$ . The %  $\Delta R_a$  can be calculated using Eq. (5.2). Further, to validate the MRBGF process effectiveness for fine finishing of the polymer BG surface, the surface characteristics using a scanning electron microscopy (SEM), the hardness utilizing the microhardness instrument Mitutoyo HM-210 model, gear run out with DIN standard 3965 at computer numerical controlled (CNC) gear metrology machine (GTB-800) are analyzed. Further, for measuring the temperature, the contact type temperature sensor (Quick sensor LED sensor) is used. The temperature sensor comprises the

probe which is used for the measuring temperature over the polymer teeth surface. Furthermore, the specific wear rates for the before and after MR finished polymer gear teeth surfaces are evaluated experimentally.

### 6.2.3 Results and discussion

In the current work, a total of 20 experimentations are conducted to evaluate the effect on the outcome response ( $\% \Delta R_a$ ) of the process parameters. Since the average initial  $R_a$  values of the polymer BG teeth surface vary from 0.360-0.390  $\mu\text{m}$ , therefore the outcome is taken as  $\% \Delta R_a$  for experimentations. The data of the experimentation is reported in Table 6.7. After each set of experimentations, three values of the surface roughness ( $R_1$ ,  $R_2$ , and  $R_3$ ) are analyzed at three different points over the polymer bevel gear (BG) teeth surface and reported in Table 6.7. Further, the final  $R_{af}$  value is obtained by taking the average of  $X_1$ ,  $X_2$ , and  $X_3$  which is further utilized in Eq. (5.2) for obtaining the  $\% \Delta R_a$ . Next, for developing the statistical model, ANOVA is used and reported in Table 6.8.

**Table 6.8.** ANOVA for  $\%$  reduction in surface roughness ( $\% \Delta R_a$ ).

| Source      | Sum of squares | Degree of freedom (DOF) | Mean square | F value | Prob>F   | Remark                                  | Percentage contribution (PC) (Eq. 5.6) |
|-------------|----------------|-------------------------|-------------|---------|----------|-----------------------------------------|----------------------------------------|
| Model       | 1255.40        | 8                       | 156.92      | 12.71   | 0.0001   | $F_{(0.05,12,17)}=2.948$<br>Significant |                                        |
| $T$         | 76.56          | 1                       | 76.56       | 6.20    | 0.0300   |                                         | 4.64                                   |
| $S$         | 68.06          | 1                       | 68.06       | 5.51    | 0.0386   |                                         | 4.13                                   |
| $I$         | 60.06          | 1                       | 60.06       | 4.87    | 0.0496   |                                         | 3.64                                   |
| $T^2$       | 559.17         | 1                       | 559.17      | 45.29   | < 0.0001 |                                         | 33.93                                  |
| $S^2$       | 185.46         | 1                       | 185.46      | 15.02   | 0.0026   |                                         | 11.25                                  |
| $I^2$       | 501.46         | 1                       | 501.46      | 40.62   | < 0.0001 |                                         | 30.42                                  |
| $TS$        | 78.13          | 1                       | 78.13       | 6.33    | 0.0287   |                                         | 4.74                                   |
| $SI$        | 66.13          | 1                       | 66.13       | 5.36    | 0.0410   |                                         | 4.01                                   |
| Residual    | 135.80         | 11                      | 12.35       |         |          | Not significant                         |                                        |
| Lack of fit | 52.97          | 6                       | 8.83        | 0.53    | 0.7673   |                                         |                                        |
| Pure error  | 82.83          | 5                       | 16.57       |         |          |                                         | 3.24                                   |
| Cor total   | 1391.20        | 19                      |             |         |          |                                         |                                        |

Based on the sequential model upon performing ANOVA, the developed predicted model's p-value (PV) is found less than 0.05. It verifies the significance of the present predicted model. Further, the lack of fit's PV is higher than 0.05 (0.7673) which confirms its non-significance. Similarly, the parameters with PV lesser than 0.05 are significant parameters and parameters having PV higher than 0.05 are non-significant parameters. In the mathematical regression model

(Eq. 6.5), the non-significant parameters are not included and the significant parameters in actual forms are given as namely tool rotational speed ( $T$ ), magnetizing current ( $I$ ), working gap ( $S$ ), square of tool rotational speed ( $T^2$ ), square of working gap ( $S^2$ ), the square of magnetizing current ( $I^2$ ), the combined effect of tool rotational speed and working gap ( $TS$ ) and the combined effect of magnetizing current and working gap ( $IS$ ). It is evident from the ANOVA table that the predicted quadratic model's F-value is 12.71 (Table 6.8), higher than the actual F-value of 2.948. This confirms the significance of the present predicted model with only a 0.01% chance that the model can become insignificant owing to noise. The second-order mathematical regression model equation in terms of actual factors which are utilized for analyzing the effect of the process parameter on  $\% \Delta R_a$  is given by Eq. (6.5).

$$\% \Delta R_a = -135.39 + 0.662T + 54.87S + 95.45I - 3.849 \times 10^{-3}T^2 - 16.971S^2 - 17.86I^2 + 0.223TS - 14.37SI \quad (6.5)$$

where actual factors are presented as  $T$  is the BGF tool rotation (rpm),  $S$  is the working gap amid tool tooth surface and polymer BG tooth surface (mm), and  $I$  is the magnetizing current (A).

The  $\% \Delta R_a$  predicted is calculated for each experimentation trial and is further compared with the experimental  $\% \Delta R_a$ . The closeness amid the predicted and experimental values gets authenticated from the model as the R-squared and Adj R-squared values are 90.24 % and 83.14 % respectively. These higher values reveal that experimental data is closely fitted with the predicted data. Further, each significant parameter's effect on the output response ( $\% \Delta R_a$ ) in the terms of the percentage contribution ( $PC$ ) has been analyzed using Eq. (5.6) (*chapter 5*). Using Eq. (5.6), the  $PC$  of process parameters is determined and displayed in Table 6.8. Further, after the regression analysis, the outcomes of the various significant parameters have been discussed.

#### 6.2.3.1 Effect of the significant parameter on $\% \Delta R_a$

The simultaneous effect of the working gap ( $S$ ) and BGF tool rotation ( $T$ ) on the  $\% \Delta R_a$  at a constant magnetizing current of 2 A is depicted in Fig. 6.11(a). As initially working gap ( $S$ ) and tool rotation ( $T$ ) upsurge concurrently, the trend line of the  $\% \Delta R_a$  increases. The main reason for the rise in the  $\% \Delta R_a$  is a simultaneous upsurge in the finishing pressure ( $P$ ) (Eq. 5.7) (*Chapter 5*) and tangential shear force ( $F_{tan}$ ) in the working gap (*Chapter 4, section 4.2*). Owing to the increase in  $P$  and  $F_{tan}$ , the AAPs which are firmly held in the chains of EIPs clip off the surface asperities from the polymer BG surface. Hence there is an increase in material removal leading to a rise in the  $\% \Delta R_a$  trend line. However, as the working gap increases further along with the tool rotation

beyond the optimum value, the trend of  $\% \Delta R_a$  decreases. This is due to the decrease in the magnetic flux density (MFD) over the BGF tool surface owing to which the MRP becomes less stiffened over the BGF tool surface. This further decreases the MRP fluid's shear strength. Hence, the clipping off the asperities from the polymer BG surface less effective and decreasing the trend of the  $\% \Delta R_a$ .

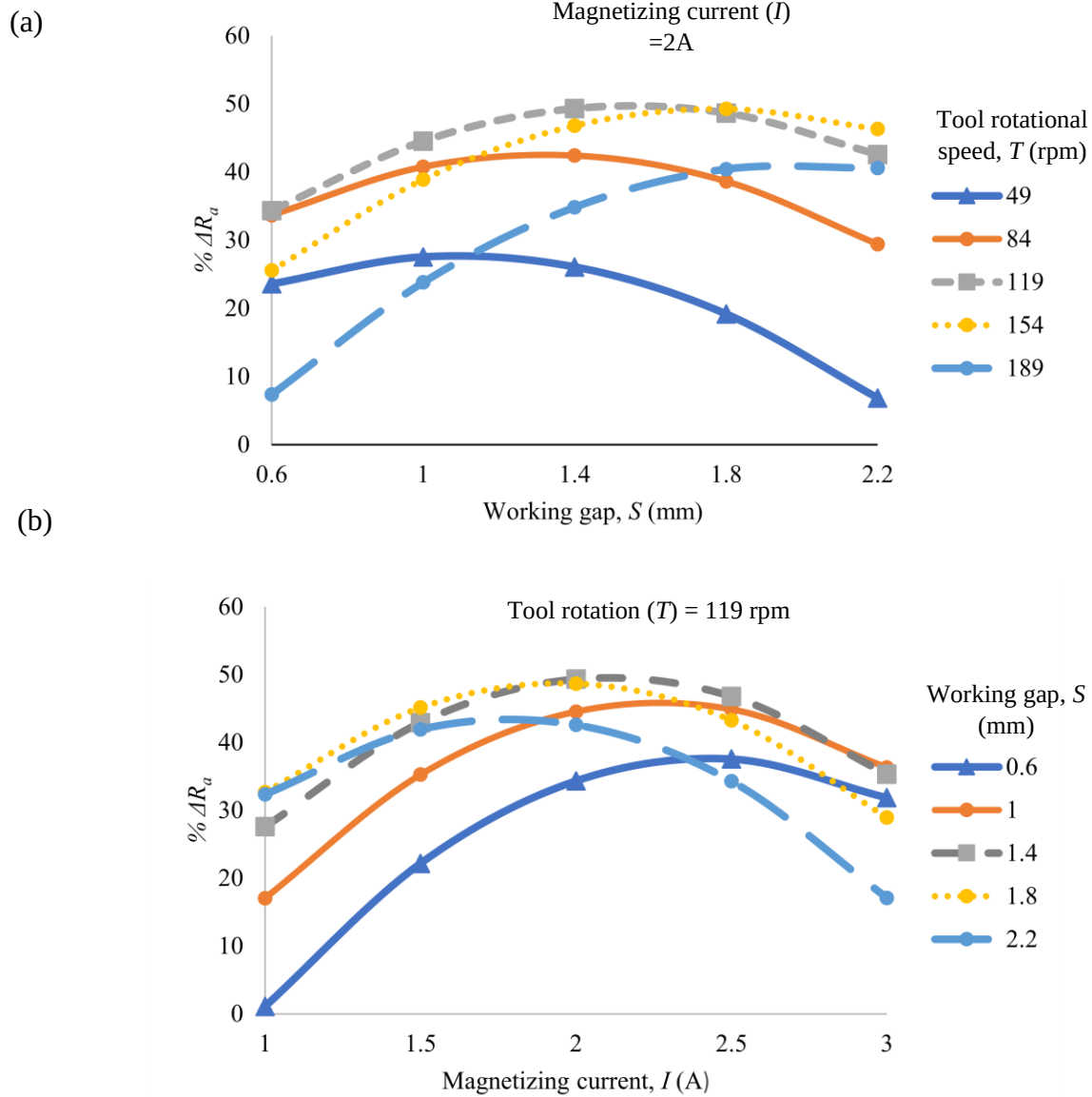


**Fig. 6.11.** Effect of (a) working gap ( $S$ ) at different tool rotation ( $T$ ) and (b) magnetizing current ( $I$ ) at different working gap ( $S$ ) on percentage improvement in the surface finish ( $\% \Delta R_a$ ).

The simultaneous effect of the working gap ( $S$ ) and magnetizing current ( $I$ ) on the  $\% \Delta R_a$  at constant BGF tool rotation of 119 rpm is espied in Fig. 6.11(b). As the magnetizing current ( $I$ )

upsurges along with the working gap ( $S$ ) initially, the trend of the  $\% \Delta R_a$  rises. This is because initially the simultaneous rise in the working gap ( $S$ ) and magnetizing current ( $I$ ) leads to the higher strength of the MFD. Due to this, the chains of EIPs firmly gripped the AAPs, and the finishing pressure increases. Thus, there is a rise in clipping off surface asperities from the polymer BG surface. Owing to this the material removal rate increases and there is a rise in the trend of the  $\% \Delta R_a$ . However, when the magnetizing current ( $I$ ) and working gap ( $S$ ) are increased further beyond the optimum value, the trend of the  $\% \Delta R_a$  decreases. This is because the MFD decreases over the BGF tool surface. Also, the finishing pressure ( $P$ ) reduces with the increase in the working gap. Due to this, the MRP fluid becomes less stiffened over the BGF tool surface which further decreases the MRP fluid's strength. Hence, with an increase in the working space ( $S$ ), the normal force acting over EIPs decreases. This further lowers the material removal rate and hence the trend of  $\% \Delta R_a$  decreases.

For effective fine finishing of the polymer BGs using the MRBGF process, the  $\% \Delta R_a$  is to be maximized and minimum the  $R_a$  value. Following the regression analysis, the best possible result for the  $\% \Delta R_a$  was obtained by predicting the optimal process parameters. The model developed by regression analysis is used to determine the surface asperities' minimal value ( $R_a$ ). To maximize the output response ( $\% \Delta R_a$ ), process parameters are subjected to

$$49 \text{ rpm} \leq T \leq 189 \text{ rpm}$$

$$0.6 \text{ mm} \leq S \leq 2.2 \text{ mm}$$

$$1 \text{ A} \leq I \leq 3 \text{ A}$$

The effects of various process parameters on  $\% \Delta R_a$  are evaluated in order to predict the optimal parameters. To maximize the  $\% \Delta R_a$ , the quadratic model equation (Eq. 6.5) is used after the regression analysis. After experimentations, from the complete analysis of the RSM study, the optimum MRBGF process parameters are obtained as  $T= 119$  rpm,  $S= 1.4$  mm, and  $I= 2$  A for effectively MR finishing of the overall polymer BGs.

#### 6.2.3.2 Observation of reduction in surface roughness of the polymer bevel gear surface

Further, experiments on the polymer bevel gear (BG) are done utilizing the optimal parameters to assess the capability of the present MRBGF process. The finishing is performed on the overall surface polymer BG of 36 teeth (7.06 mm involute length and 42.3 mm pitch circle diameter) until the substantial enhancement over the polymer BG surface is noticed. The average surface roughness ( $R_a$ ) value was reduced from the initial ground value of 380 nm to 100 nm in 150 min

of MR finishing using the MRBGF process on the overall polymer BG surface (36 teeth). After 150 min, no noticeable change on the overall polymer BG surface with 36 teeth was observed. The roughness profiles after the initial gear grinding process and then again after the MRBGF process are shown in Figs. 6.12(a) and (b) respectively. The initial ground roughness profile parameters roughness is measured as  $R_a = 380$  nm,  $R_z = 37000$  nm, and  $R_q = 540$  nm while the final finished polymer BG surface after 150 min of MRF with optimal process parameters over BG with 36 teeth are measured as  $R_a = 100$  nm,  $R_z = 800$  nm,  $R_q = 150$  nm. The %age improvement in roughness parameters  $R_a$ ,  $R_z$ , and  $R_q$  is achieved as 73.68 %, 78.37 %, and 72.22 % respectively using the optimum parameters. On comparing the final MR finished roughness profiles with the initial ground surface roughness profile, the substantial upsurge in the surface finish of the polymer BG tooth can be confirmed after the MRBGF process. This substantial surface finish after the MRBGF process may enhance the functional performance of polymer bevel gears with improved service life and minimal wear.

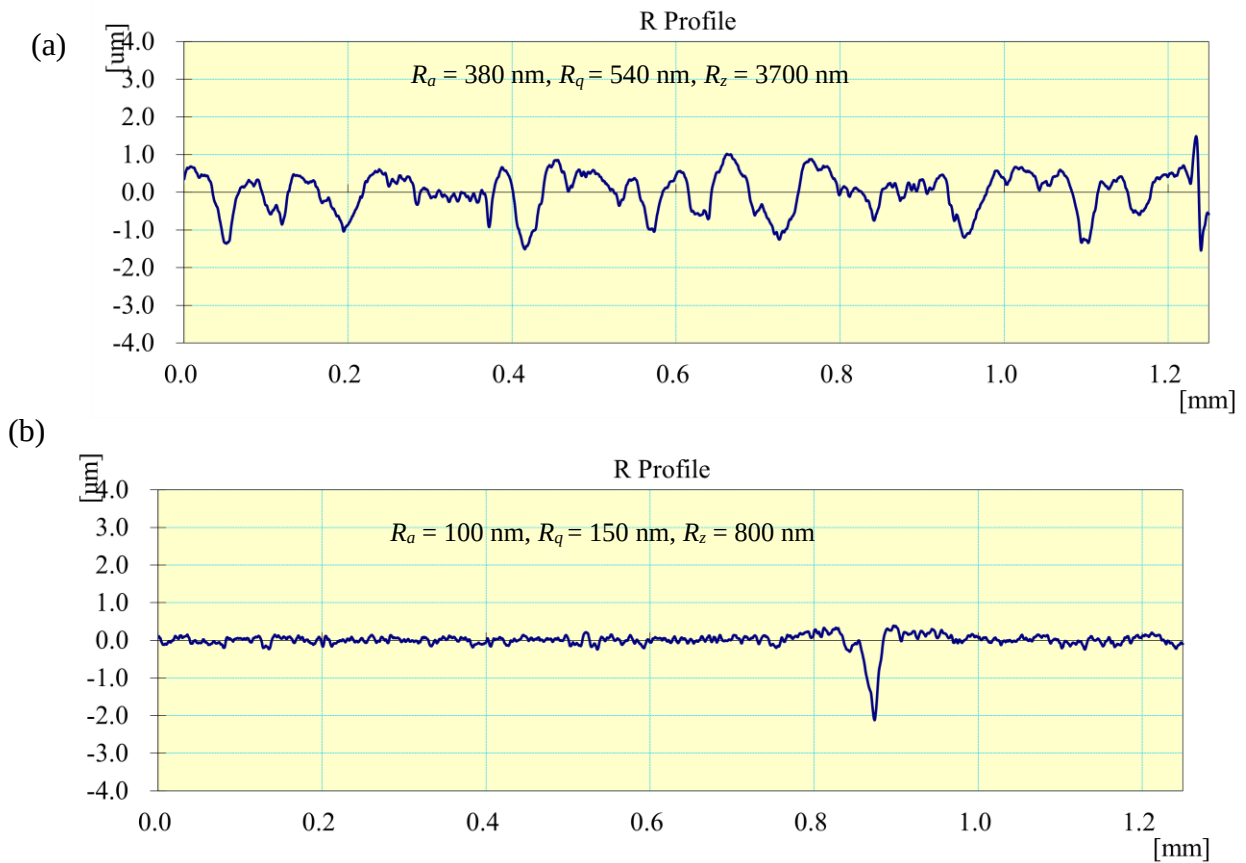


**Fig. 6.12.** Surface roughness profiles for (a) initial surface and (b) after 150 min of MR finishing on final polymer bevel gear surface with 36 teeth at  $T= 119$  rpm,  $S= 1.4$  mm, and  $I= 2$  A.

Next, to confirm the legitimacy of the present regression model obtained from the implementation of the response methodology (RSM) technique, further nine experiments were performed. For the confirmatory experimentation, the finishing time of 60 min is taken. The parameters used for the experimentations were kept within the range of the designed experiments. The confirmatory experimentation data and along with their predicted values are stated in Table 6.9. From their comparative study, it can be said that this developed regression model is well suited for the repeatability as the error amid the theoretical and experimental  $\% \Delta R_a$  lies within the -5.75 % to 9.97 %. This confirms that the present MRBGF process is repeatable.

**Table 6.9.** Confirmation tests and their comparison with the results.

| S. No. | Tool rotation, $T$ (rpm) | Working gap, $S$ (mm) | Magnetizing current, $I$ (A) | Experimental $\% \Delta R_a$ Eq. (5.2) | Predicted $\% \Delta R_a$ Eq. (6.5) | % error Eq. (6.3) |
|--------|--------------------------|-----------------------|------------------------------|----------------------------------------|-------------------------------------|-------------------|
| 1      | 119                      | 0.6                   | 2                            | 34.21                                  | 34.32                               | -0.32             |
| 2      | 84                       | 1.4                   | 3                            | 31.57                                  | 28.42                               | 9.97              |
| 3      | 154                      | 2.2                   | 1.5                          | 44.73                                  | 45.64                               | -2.03             |
| 4      | 84                       | 1.8                   | 1                            | 23.68                                  | 22.64                               | 4.39              |
| 5      | 154                      | 1                     | 2.5                          | 40.54                                  | 39.23                               | 3.23              |
| 6      | 119                      | 1.4                   | 2                            | 53.84                                  | 49.31                               | 8.41              |
| 7      | 49                       | 1.4                   | 2                            | 27.77                                  | 26.07                               | 6.12              |
| 8      | 154                      | 1.8                   | 1.5                          | 43.24                                  | 45.73                               | -5.75             |
| 9      | 189                      | 1.4                   | 2                            | 36.84                                  | 34.82                               | 5.48              |

### 6.2.3.3 Observation of surface characteristics of the polymer bevel gear workpiece

Next, the analysis of the surface morphology is done to study the initial and final finished surface characteristics of polymer BGs using scanning electron microscopy (SEM). Figure 6.13 depicts the SEM images of the initial ground surface and after 150 min of MRF over polymer BG surface using the MRBGF process. The initial ground polymer BG tooth surface with the uneven finishing is espied in Fig. 6.13(a). On the polymer BG tooth's initial surface, surface irregularities like microcracks, deep feed marks, and grinding marks can be observed. These defects reveal the material displacement at different locations forming clusters owing to which wear tends to upsurge over the tooth initial surface. This results in the accumulation of worn debris and pitting which may lower the service life of the polymer BGs while functioning. However, on comparing the final finished with the ground surface, significant improvement is seen after 150 min over the polymer BG surface with 36 teeth using the MRBGF process as espied in Fig. 6.13(b). After the MRF, the initial surface irregularities are removed substantially from the BG tooth surface as compared to the ground surface. This is because, in the MRF process, the AAPs gripped in the EIPs chain clip off the asperities from the polymer BG surface in a controlled way under the magnetic field's

influence. Furthermore, in the MRF process, the normal force is comparatively low, and material removal occurs in the microchip form. Thus, the present MRF process, the significantly reduces the material wear from the MR finished polymer BG surface. Owing to this the crack formation chances reduce over the polymer BG tooth surface while meshing, leading to a reduction in vibration while functioning.

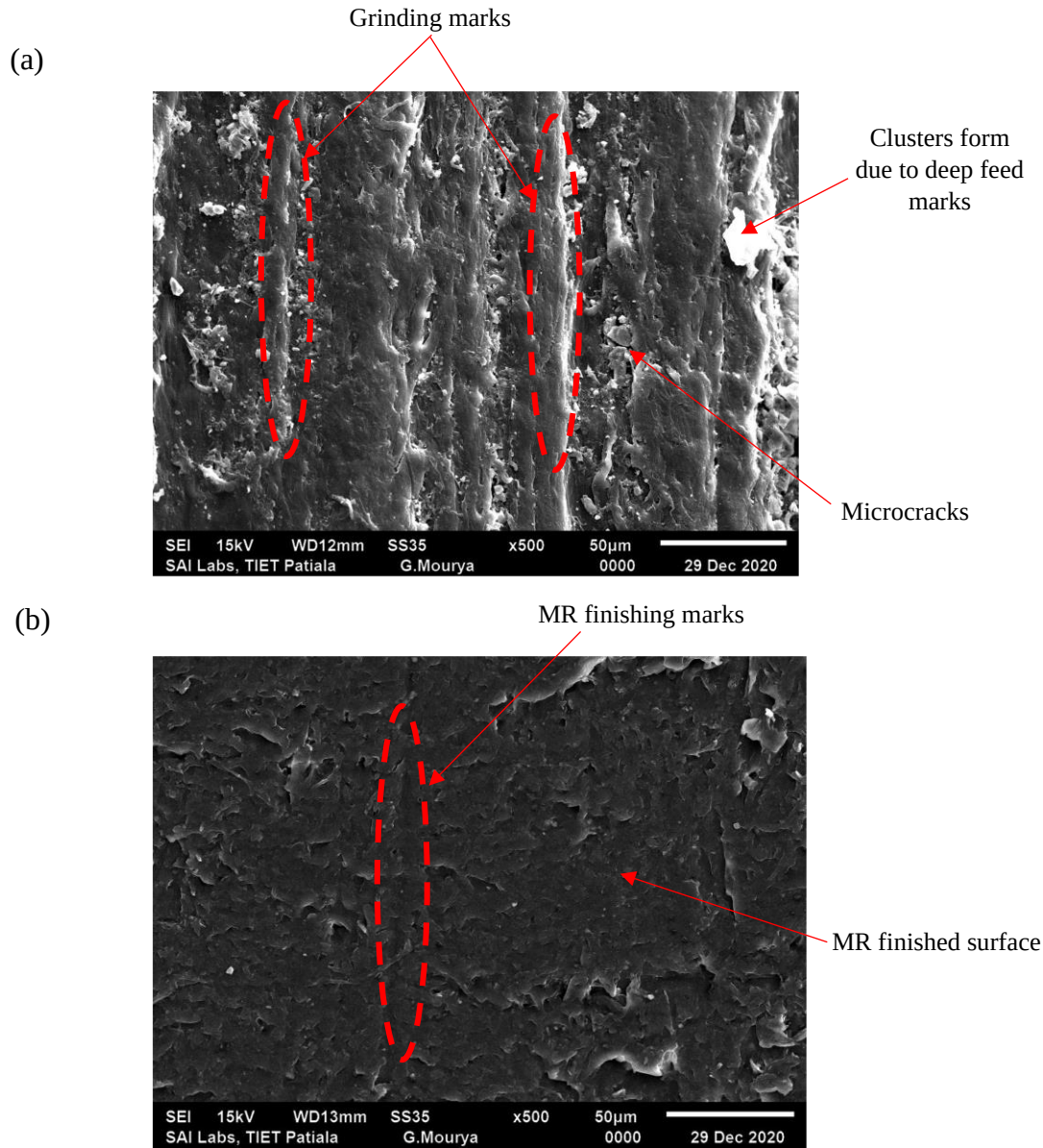


**Fig. 6.13.** Scanning electron microscopy for (a) initial surface and (b) final surface after 150 min of MR finishing on final polymer bevel gear surface with 36 teeth at  $T= 119$  rpm,  $S= 1.4$  mm, and  $I= 2$  A.



The present MRBGF process improves the surface quality of the BG teeth profile by reducing surface roughness. This may also further lead to improving the gear form precision and tooth accuracy. During the bevel gear (BG) transmission, one of the most critical elements that affect gear accuracy is gear runout. The gear runout is frequently induced in gears when they are manufactured using the traditional method. The gear runout occurs mainly due to the higher material removal rate and the pressures required to cut the bevel gear teeth are high. Finishing processes, however, can help to decrease gear runout ( $F_r$ ). In the present work, run out is measured on the initial polymer ground BG surface and then again after the MRBGF process as shown in Figs. 6.14(a) and (b) respectively. The gear run-out parameters are measured in DIN 3965 standard. DIN value describes the gear tooth surface accuracy. Further, the measurement for the gear runout ( $F_r$ ) of the initial ground polymer BG tooth surface following the typical grinding is included in the DIN 8 standard (Fig. 6.14a). However, after finishing over the polymer BG surface with the best parameters using the MRBGF process, the measurements of gear run out ( $F_r$ ) were included in DIN 6 standard (Fig. 6.14b).

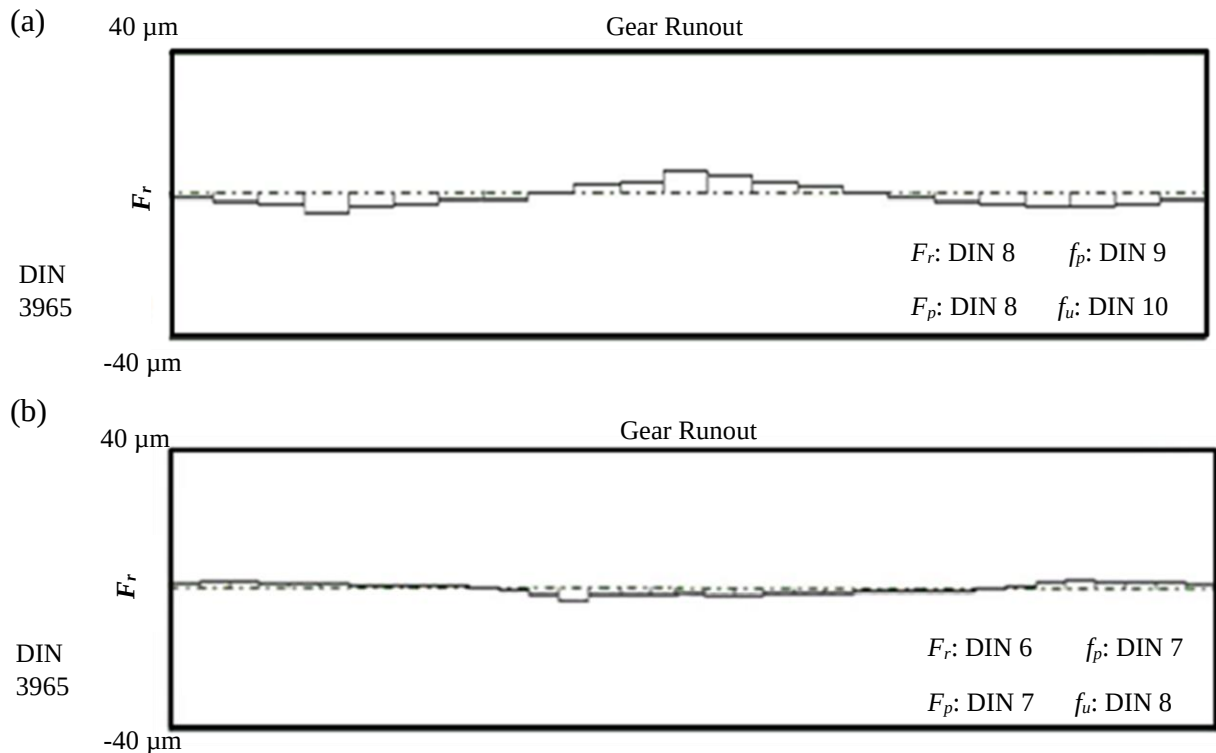


**Fig. 6.14.** Gear runout of (a) initial ground polymer bevel gear surface and (b) after 150 min of MR finishing on final polymer bevel gear surface with 36 teeth at  $T= 119$  rpm,  $S= 1.4$  mm, and  $I= 2$  A.

Further, as compared to the initial ground polymer BG surface, the total index error ( $F_p$ ) reduces to DIN 7 from DIN 8, single pitch deviation ( $f_p$ ) reduces to DIN 7 from DIN 9, and the tooth-to-tooth spacing error ( $f_u$ ) reduces to DIN 8 from DIN 10 after finishing using the MRBGF process (Fig. 6.14). The reduced runout value of polymer BG after MR finishing implies less noise and vibration and better transmission efficiency and accuracy in polymer BGs gears over their working life, which improves gear overall performance. As a result, the present MRBGF process may be utilized to improve the performance and efficacy of gears after the grinding in industries.

#### 6.2.3.4 Functional testing of the polymer bevel gear after magnetorheological finishing

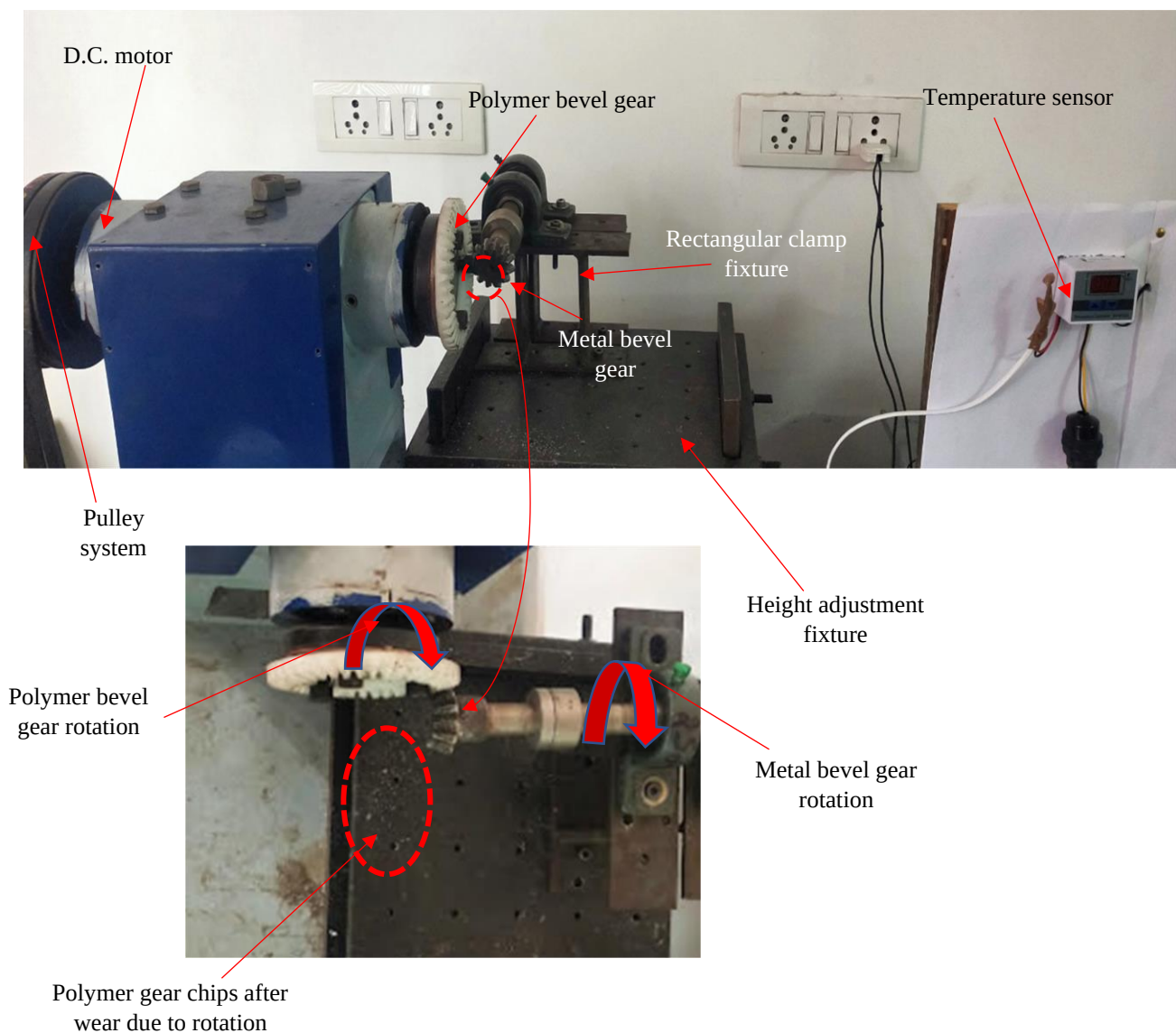


**Fig. 6.15.** Photograph of the developed gear testing setup.

The gear functional testing machine is depicted in Fig. 6.15 in which the polymer BG to be tested is connected to the DC motor (1 HP) and meshes with the metal gear. The metal gear properly meshes with the polymer gear. As the polymer BG rotates by the DC motor, the properly meshed rotates with it. The polymer gear is rotated at a speed of 120 rpm at three different loads i.e., 50 g, 100 g, and 150 g respectively for both MR finished and unfinished BG surface. The initial and final MR finished polymer test gears are run up to  $0.72 \times 10^5$  cycles for the comparative analysis.

#### *6.2.3.5 Observation of thermal and wear behavior of the before and after MR finished polymer gear*

Figure 6.16 illustrate the thermal behavior of initial and final finished polymer BG at various loads (50 g, 100 g, and 150 g) and a rotational speed of 120 rpm, respectively. At each load, three readings were taken, and further, the average was taken. As depicted in Fig. 6.16, the temperature rise in polymer gear is found higher for the initial ground polymer gear surface (Fig. 6.16a) as compared to the final finished surface (Fig. 6.16b). It happens because the surface roughness is higher for the initial surface (380 nm) as compared to the final finished gear surface (100 nm). Owing to this the surface asperities are higher on the initial surface as compared to the final finished surface. This leads to the higher wear on the initial surface leading to a rise in temperature. Furthermore, when the load increases, the temperature at the surface of the polymer gear rises in both cases. The surface temperature rises rapidly at first, then stabilizes after a specific number of cycles. The reason behind this is that friction causes the temperature to rise at first. After a certain period of time, the surface temperature of polymer gears rises significantly above the ambient temperature, and conduction phenomena occur with the assistance of metal gear. The metal gear starts to dissipate heat, and finally reaches a point where almost all of the heat generated at the polymer gear surface is dissipated to the environment at the same time. As a consequence, the heat generated and the heat lost is in balance.

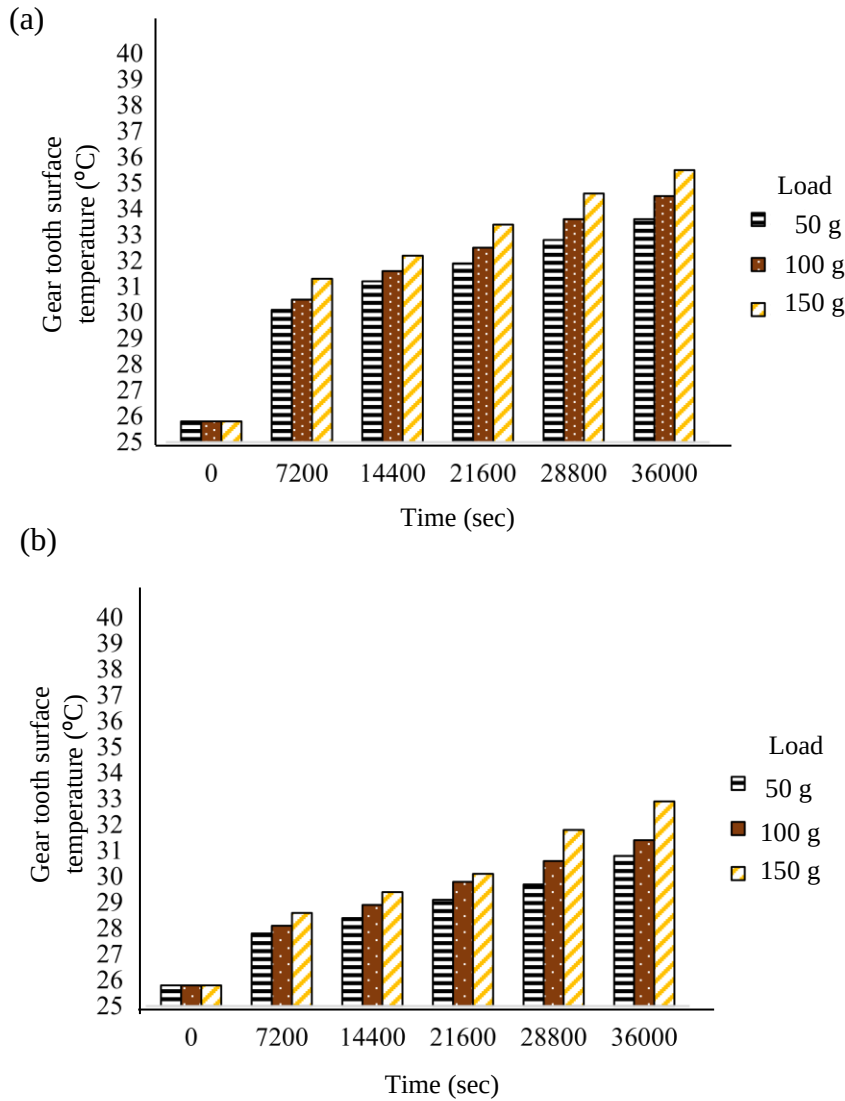


**Fig. 6.16.** Thermal behavior of (a) initial ground and (b) final MR finished teeth surface at different loads.

Figure 6.17 demonstrate the wear behavior of polymer gears under constant speed of 120 rpm and various loads (50 g, 100 g, and 150 g) for initial and final MR finished surface respectively. Wear is also a dynamic process that involves the continuous loss of material from surfaces that are moving relative to one another. Wear is the gradual loss of material in polyamide gears that cannot be avoided but may be significantly reduced by using fine finishing techniques. In the present work, a weighing machine is used to determine the weight of the polyamide gear before and after it has been subjected to various loads. The specific wear rates ( $W_{sw}$ ) on the polymer gear are calculated using Eq. (6.6) (Kim, 2006).

$$W_{sw} = \frac{W_{vol}}{2zmf_wN} \quad (6.6)$$

where  $z$  is the BG teeth which is 36,  $W_{vol}$  is the volumetric wear,  $f_w$  is the tooth face width which is 14.54 mm,  $m$  is the module 2 mm, and  $N$  is the number of rotations which is 120.  $W_{vol}$  is obtained when the weight loss of the gear is divided by the density of the polymer material (polyamide in present study). The density of polyamide is  $1.06 \text{ g/cm}^3$  (Vasanthan and Salem, 2000).

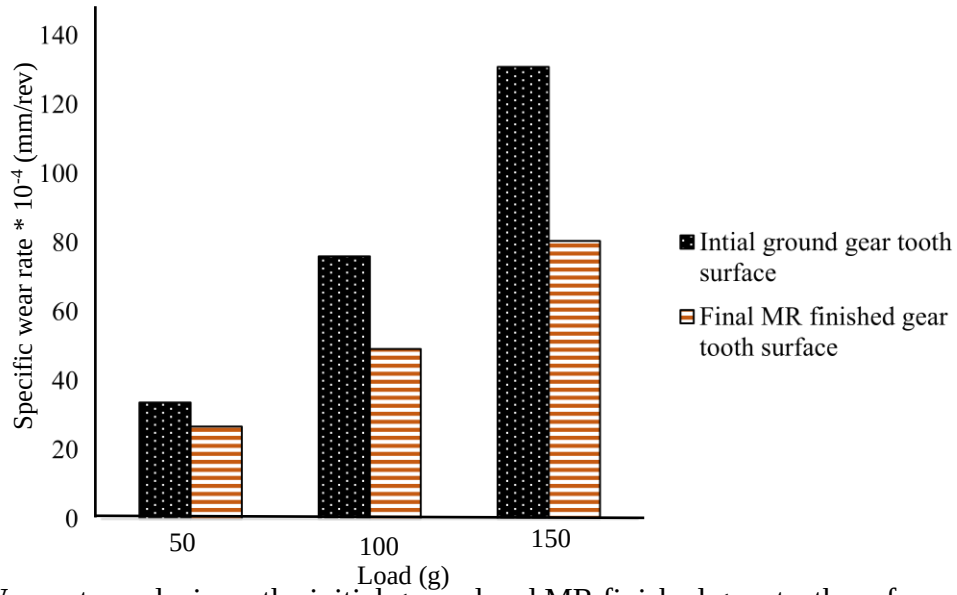


**Fig. 6.17.** Wear rate analysis on the initial ground and MR finished gear teeth surfaces at different loads.

Using Eq. (6.6), the specific wear rate is calculated at different loads for initial and final MR finished gear surface. The effect of applied load on wear rate for the initial and MR finished workpiece surfaces is shown in Fig. 6.17. For both the polymer test gears (initial and final MR finished), the specific wear rate rises as the load rises (Fig. 6.17). The reason for this is, with increasing loads, the temperature rises quickly, causing the material to loosen due to the heat accumulated on the gear surface. As a result, higher loads cause polymer gears to wear out more quickly. In addition, as compared to the final gear surface, the initial ground surface has a greater wear rate, as seen in Fig. 6.17. The higher wear rate on the initial gear surface may occur because of the lower hardness of the surface due to the higher surface roughness. However, after the MR finishing over the polymer gear, there is a substantial decrease in the surface roughness owing to which the hardness of the finishing surface increases. Hence, the wear rate decreases which may enhance the reliability and durability of the polymer gears. At a constant rotary speed of 120 rpm and weights of 50 g to 150 g, Fig. 6.26 provides a quantitative comparison of wear behavior for

the initial and final MR finished polymer bevel test gears. The initial ground surface wears 20.47 % more than the final MR finished gear teeth surface with a weight of 50 g at a rotational speed of 120 rpm. Further, the initial ground gear has a wear rate of 35.28 % at 100 g at 120 rpm, when compared to the final MR finished gear tooth surface. Further, at 150 g at 120 rpm, the initial ground surface wears 38.53 % as compared to the final MR finished surface. hence after the MR finishing, the wear rate of the polymer BG teeth tends to decrease which may enhance its functional performance in industries.

#### 6.2.3.6 Experimental validation of the theoretical analysis reduction in surface finishing of the polymer bevel gear using electromagnet bevel gear finishing tool

Experiments are carried out to validate the theoretical model (*Chapter 4, section 4.2*) for a reduction in surface roughness of the polymer bevel gear workpiece utilizing the MR finishing process. The experimentation is done in five cycles and each finishing cycle is 30 min. The experimentally obtained surface roughness values are compared with theoretically calculated surface roughness values as reported in Table 6.10. The range of error amid the experimentally obtained and theoretically calculated surface roughness is reported in Table 6.10 and is evaluated using Eq. (6.3). The range of the error between the experimentally obtained and theoretically calculated surface roughness value lies within 2.30 % to 10 % (Table 6.10). This reveals that the developed regression model is decently accurate.

**Table 6.10** Validation of the theoretical value and the experimental value of surface roughness with different number of finishing cycles.

| Number of the finishing cycle (i) | Finishing cycle time (min) | Experimental obtained $R_a$ value (nm) | Theoretical calculated $R_a$ value (nm) (Eq. 4.57) | % error (Eq. 6.3) |
|-----------------------------------|----------------------------|----------------------------------------|----------------------------------------------------|-------------------|
| 0                                 | 0                          | 380                                    | 380                                                | 0                 |
| 1                                 | 30                         | 310                                    | 323                                                | 4.19 %            |
| 2                                 | 60                         | 260                                    | 266                                                | 2.30 %            |
| 3                                 | 90                         | 190                                    | 209                                                | 10 %              |
| 4                                 | 120                        | 140                                    | 152                                                | 8.57 %            |
| 5                                 | 150                        | 100                                    | 95                                                 | 5 %               |

Hence, the reduction in the surface roughness value of the polymer BG teeth achieved by the present MRBGF process increases the surface quality, hardness, and lowers the COF. This further results in lower operating temperature, wear rate, and strain rate of the polymer BGs which tends to improve their service life, tooth accuracy, and mechanical efficiency while functioning in various industrial applications.

#### 6.2.4 Conclusions

The present MRBGF process with the electromagnetic tool is capable of providing the fine finishing of the polyamide bevel gears (BGs). Fine finished polymer BGs are useful in the marine, textile, and automobile industries. The surface roughness reduction of the polymer BGs after the MRBGF process tends to increase surface morphology and decrease the surface coefficient of friction. This may reduce the wear rate, temperature, and strain rate of the BGs which may further lead to the enhancement in the service life and functional performance of the polymer BGs. The following are the conclusions that illustrate the efficacy and usefulness of the MRBGF process for the fine finishing of polymer BGs.

- The optimum process parameters obtained from the parametric study as tool rotation of 119 rpm, a working gap of 1.4 mm, and magnetizing current of 2 A reveal the effective finishing of the polymer bevel gear (BG) tooth surface for maximum % reduction in surface roughness.
- The significant %age reduction in surface roughness parameters  $R_a$ ,  $R_z$ , and  $R_q$  by 73.68 %, 78.37 %, and 72.22 %, respectively over polymer bevel gear surface of 36 teeth in 150 min of finishing cycle with predicted optimized process parameters shows the efficacy of the present MRBGF process.
- The error obtained amid the experimental and the predicted %  $\Delta R_a$  is – 5.75 % to 9.97 % which reveals that the developed regression model is decently accurate. Therefore, the predicted optimized process parameters for MR finishing the polymer bevel gears are found in good order.
- The improvement in surface morphology of the polymer BG tooth surface after MR finishing confirms the removal of surface defects such as micro cracks, grinding lays, and accumulation of the worn debris using the present MRBGF process with the best-obtained parameters that help in the smooth functioning of BGs during their applications.
- After the fine finishing of the polymer BG using the MRBGF process with the best parameters, the gear runout of the polymer BG tooth gets reduced to DIN 6 from its initial ground surface of DIN 8. The results signify the better transmission efficiency and accuracy in polymer bevel gears (BGs) over their working life.

- The range of the error between the experimentally obtained and theoretically calculated surface roughness (2.30 % to 10 %) are in close agreement. This validates the repeatability and effectiveness of the developed model.
- The thermal behavior of the initial and final MR finished under various loads and constant rotational speed reveals that as the load increases, the surface temperature of the gear rises. Furthermore, the temperature rise is found to be lower for MR finished gears as compared to the initial ground gear.
- Polymer gears' specific wear rate rises as the load increases for both initial ground and final MR finished surface. However, the specific wear rate is found to be lower for MR finished gear tooth surface which may tend to upsurge the service life of gears.
- The developed MRBGF process is found beneficial in the effective finishing of the polymer gears with enhanced surface characteristics, and gear quality in the minimum finishing time as each polymer BG's tooth profile gets meshed properly in the working gap with MRP fluid after every rotation of the magnetic tool tooth surface.

### **6.3 Parametric investigation of typical polymer bearing's internal surface for improving their functional performance in hydropower industries**

Journal bearings are extensively utilized in rotating machines in hydropower industries owing to their low wear and good damping characteristics. Pump shafts, water turbines, and marine propeller are a few machines used in hydropower industries where bearing play a key role while practical working. From a designer's perspective, a journal bearing must support the required load by occupying minimal space with minimum energy loss and slow wear out (Hirani *et al.*, 1997). For the past few decades, polymer bearings (PBs) are recommended over metal bearings in various industries where oil or grease are not tolerable as lubricants (Panda *et al.*, 2020). Since metal or alloy bearings tend to corrode under the influence of the water as a lubricant, therefore, the importance of PBs in these machine upsurges significantly. The polymers commonly used for manufacturing the bearings are polytetrafluoroethylene (PTFE), polyamide (PA66), and polyether ether ketone (PEEK) (Golchin *et al.*, 2014). The limiting factor in the PBs, however, is the lower service life which decreases the functional efficacy and load-bearing capability in hydropower machines. These limitations in PBs occur owing to the non-uniform surface finish and wear (Blanchet *et al.*, 1998). One of the main reasons for the failure of the PBs is overheating which occurs due to friction. In PBs, overheating due to friction normally leads to rapid adhesive wear



and malfunctions while practical applications (Ünlü *et al.*, 2009). The upsurge in friction primarily occurs due to the non-uniform surface finish or the inaccuracy of the dimensional constraints of the bearing. Therefore, uniform internal bearing surface finishing is required to enhance the service life of the PBs with improved dimensional accuracy and high load-bearing capability.

Therefore, a permanent magnet-based rotational magnetorheological (R-MR) honing tool (*Chapter 3, section 3.1.4*) is used for the fine finishing of the PBs with minimal errors and high dimensional precision. Further, the optimum process parameters of the present process are predicted for the fine finishing of the PTFE bearing. The surface morphology, waviness, hardness, and circularity of the bearing workpiece are investigated further to check the efficacy of the present process.

### **6.3.1 Material selection and workpiece preparation**

Polytetrafluoroethylene (PTFE) is one of the most widely utilized polymers in industries (Tzanakis *et al.*, 2013). Further, PTFE PBs are also used in industries where oil or grease is not tolerable as lubricants. The uniform and fine surface finish contribute to a decrease in friction due to which the rapid adhesive wear of the polymer is decreased. This further increases the PTFE bearing's service life and functional efficacy. A typical PTFE bearing is utilized with an inner diameter of 38 mm, an outer diameter of 48 mm, and a length of 40 mm as depicted in Fig. 6.18. Initially, machining is done on the bearing surface to remove the uneven marks. Further, workpieces are cleaned with the help of acetone and maintained properly before the magnetorheological finishing process.



**Fig. 6.18.** PTFE bearing workpiece along with the dimensions.

### 6.3.2 Experimentation for fine finishing of the PTFE bearing using R-MR honing process

The experimental setup for the fine finishing of the PTFE bearing using the present rotational magnetorheological (R-MR) honing process is depicted in Fig. 6. 19. For the fine finishing of the PTFE bearing internal surface, a magnetorheological honing tool is used. The design of the hemispherical tool used has been discussed in *Chapter 3 (section 3.1.4)*. Three types of motion are used naming the rotary motion of the magnetorheological honing (MRH) tool, the rotary motion of the PBs workpiece, and the reciprocation motion of the MRH tool. It can be seen that initially the eccentricity is maintained amid the MRH tool and the PTFE bearing surface. This is done so that there is proper alignment amid the MRH tool and PTFE bearing internal surface while finishing owing to which there is smooth functioning with minimal errors. Next, the constant gap is maintained for the MRP fluid amid the MRH tool and bearing workpiece. Owing to the proper alignment the working space remains constant during finishing.

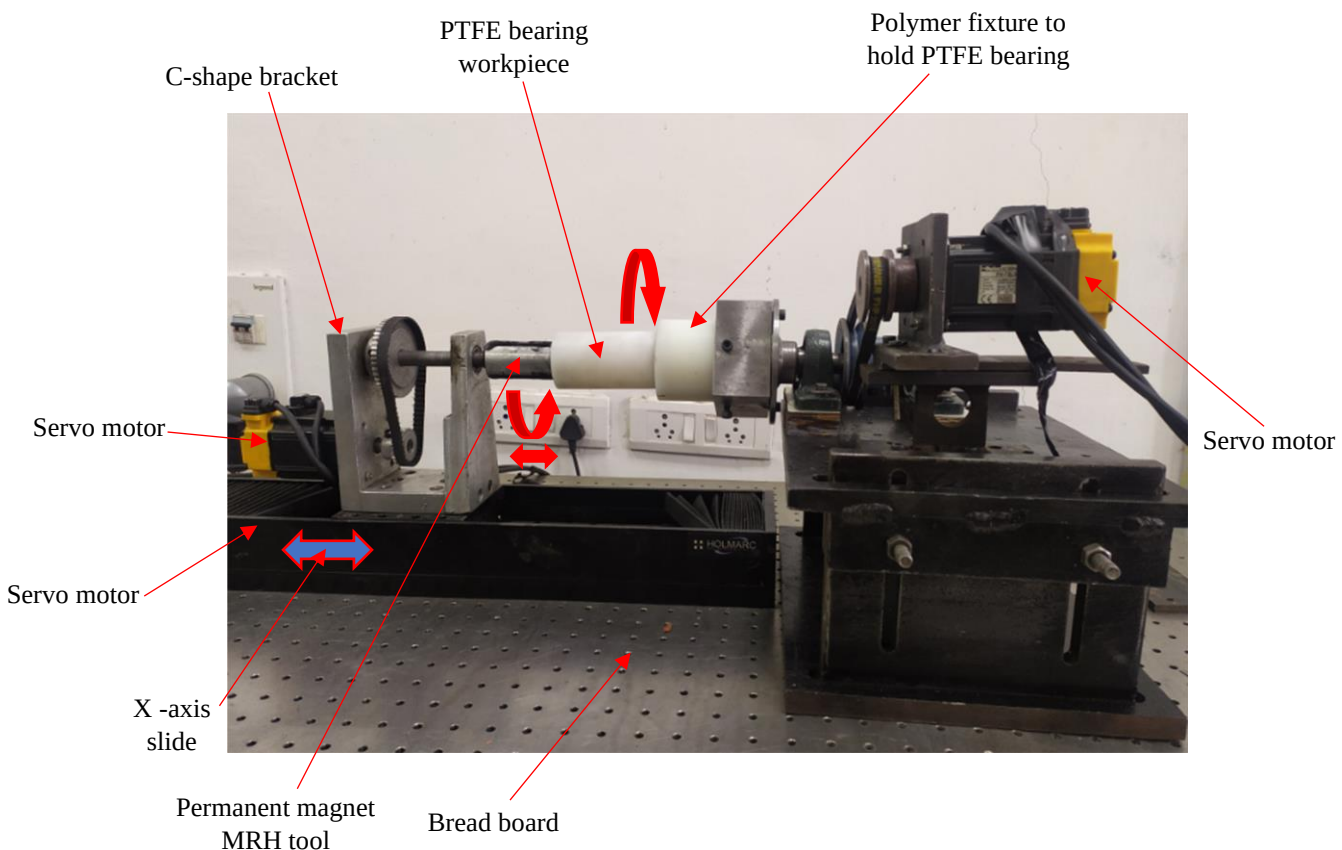


**Fig. 6.19.** Experimental setup of presently used MRH tool-based finishing setup.

Further, the MRP fluid is applied manually over the MRH tool which gets stiffened once comes into the contact with the permanent magnets. Finally, the finishing process takes place over the PTFE bearing surface owing to the simultaneous MRH tool rotation and reciprocation along with the PTFE bearing workpiece rotation till the fine finishing is achieved.

#### *6.3.2.1 Selection of process parameters*

In the present work, for the effective fine finishing of the internal surface of the PTFE bearings, a detailed study of the various process parameters has been done using the R-MR honing process with the permanent magnetic tool. In the present research, five parameters naming MRH tool rotational speed ( $T$ ), the rotational speed of the PTFE bearing ( $W$ ), reciprocating speed of the MRH tool ( $F$ ), % volume concentration of the  $Al_2O_3$  abrasives ( $C$ ), and % volume concentration of the EIPs ( $E$ ) are used. Each of the parameters has its influence on the present process. The tangential shear force acting on the AAPs is governed by the workpiece rotational speed ( $W$ ) and tool rotational speed ( $T$ ). The  $T$  and  $W$  also guide the relative motion that takes place amid the AAPs and the workpiece surface. The reciprocating tool speed controls the axial force acting on the AAPs. It controls the collision between the AAPs and the asperities on the workpiece surface. Further, the concentration of EIPs and  $Al_2O_3$  abrasives present in MRP fluid also plays an important role as the stiffness of the MRP fluid is dependent on the EIPs concentration and the shearing off the surface asperities from the bearing relies on the concentration of the AAPs (*Chapter 5, section 5.3*).

#### *6.3.3 Design of experiments*

For the analysis of the various parameters on the bearing surface, the design of experiments (DOE) with response surface methodology (RSM) is used. In the present work, RSM is used to attain the optimized process parameters for the fine finishing of the internal surface of the PTFE bearings. Further, the % volume of the base fluid in MRP fluid varies from 55 %-65 % depending on the % volume concentration of  $Al_2O_3$  abrasives and % volume concentration of EIPs selected for experimentation. The range of process parameters used for the experimentation is selected based on the preliminary experimentations and reported in Table 6.11. In the present study, DOE is utilized to study the effects of various process parameters on the % change in the surface roughness ( $\% \Delta R_a$ ). The measurement of the average surface roughness ( $R_a$ ) value was done with the help of the Mitutoyo SJ-400 surfest profilometer with a cut-off length of 0.25 mm. The  $\% \Delta R_a$  is taken as the output parameter because the initial average  $R_a$  value varies from 380-420 nm. The foremost

objective of the present regression model is to provide the analysis of the reduction in the process variability in  $\% \Delta R_a$  and to enhance the efficiency of the present R-MR honing process. In the present model, the relation amid the output ( $\% \Delta R_a$ ) and the input independent parameters is given by Eq. (6.7).

$$\% \Delta R_a = f(T, W, F, E, C) \quad (6.7)$$

where  $f$  is the response function,  $T$  is MRH tool rotation in rpm,  $W$  is PTFE bearing rotation in rpm,  $F$  is the reciprocation motion of the MRH tool in mm/min,  $E$  is % volume concentration of electrolytic iron particles (EIPs) and  $C$  is % volume concentration of  $Al_2O_3$  abrasives.

**Table 6.11.** Process parameters and their ranges.

| S. No. | Parameters                                         | Range |      |     |      |     |
|--------|----------------------------------------------------|-------|------|-----|------|-----|
| 1.     | Tool rotation, $T$ (rpm)                           | 100   | 200  | 300 | 400  | 500 |
| 2.     | PTFE bearing workpiece rotation, $W$ (rpm)         | 5     | 10   | 15  | 20   | 25  |
| 3.     | Tool reciprocation, $F$ (mm/min)                   | 10    | 30   | 50  | 70   | 90  |
| 4.     | % volume concentration of $Al_2O_3$ abrasives, $C$ | 10    | 12.5 | 15  | 17.5 | 20  |
| 5.     | % volume concentration of EIPs, $E$                | 15    | 20   | 25  | 30   | 35  |

In RSM, the composite planning adds some precise samples based on the regression design. This reduces the number of experiments and also adjusts the orthogonality of the design experiments accordingly. In the present study, a total of 50 experiments are designed by the central composite design (CCD) as reported in Table 6.12. Each experimentation is performed for 60 min over the PTFE internal surface with 38 mm internal diameter and 20 mm length. After every 20 min of the finishing cycle, the MRP fluid is changed so that the abrasive cutting edges remain fresh during the surface finishing of the PTFE bearing. Further, the confidence level of the regression model is 95 % to verify the efficacy of the model. The F-level test from analysis of variance (ANOVA) is performed for the identification of the implied regression equation to strengthen the relationship between the  $\% \Delta R_a$  and the process parameters. The % change in surface roughness ( $\% \Delta R_a$ ) can be calculated using Eq. (5.2).

In the present work, the second-order mathematical regression model Eq. (6.8) is utilized for analyzing the effect of the process parameter and the  $\% \Delta R_a$ .

$$\begin{aligned} \% \Delta R_a = & -242.56 + 0.077T + 8.328W + 0.457F + 23.157C + 3.477E - 1.6 \times 10^{-4}T^2 - \\ & 0.2W^2 - 1.128 \times 10^{-2}F^2 - 1.002C^2 - 0.185E^2 - 6.25 \times 10^{-3}TW - 8.8 \times 10^{-4}TF + \\ & 5.375 \times 10^{-3}TE - 0.019WR + 0.041FC + 0.027FE + 0.22CE \end{aligned} \quad (6.8)$$

Further, to demonstrate the efficacy of the R-MR honing process for the fine finishing of the PTFE bearing internal surface, the dimensional accuracy, and the surface characteristics are observed utilizing the co-ordinate measuring machine, and scanning electron microscopy. Also, the PTFE bearings hardness is measured using the microhardness tester Mitutoyo HM-210 model.

**Table 6.12.** Experimentation plans and results.

| S.no. | Process Parameters |           |                 |       |       | Initial<br>$R_{ai}$<br>(nm) | Final $R_a$ (nm) |      |      | Final<br>average<br>$R_{af}$ (nm) | $\% \Delta R_a$<br>(Eq. 5.2) |
|-------|--------------------|-----------|-----------------|-------|-------|-----------------------------|------------------|------|------|-----------------------------------|------------------------------|
|       | $T$ (rpm)          | $W$ (rpm) | $F$<br>(mm/min) | $C$   | $E$   |                             | $X1$             | $X2$ | $X3$ |                                   |                              |
| 1     | 300.00             | 15.00     | 50.00           | 10.00 | 25.00 | 390                         | 210              | 210  | 200  | 207                               | 46.92                        |
| 2     | 100.00             | 15.00     | 50.00           | 15.00 | 25.00 | 380                         | 130              | 130  | 140  | 134                               | 64.73                        |
| 3     | 400.00             | 10.00     | 70.00           | 12.50 | 20.00 | 410                         | 260              | 260  | 250  | 256                               | 37.56                        |
| 4     | 400.00             | 20.00     | 70.00           | 17.50 | 20.00 | 390                         | 290              | 300  | 300  | 297                               | 23.93                        |
| 5     | 300.00             | 15.00     | 50.00           | 15.00 | 25.00 | 410                         | 120              | 140  | 120  | 127                               | 69.02                        |
| 6     | 400.00             | 10.00     | 30.00           | 17.50 | 20.00 | 390                         | 240              | 230  | 230  | 234                               | 40.00                        |
| 7     | 400.00             | 10.00     | 70.00           | 17.50 | 20.00 | 380                         | 240              | 230  | 220  | 230                               | 39.47                        |
| 8     | 500.00             | 15.00     | 50.00           | 15.00 | 25.00 | 390                         | 140              | 140  | 130  | 137                               | 64.87                        |
| 9     | 200.00             | 10.00     | 70.00           | 12.50 | 30.00 | 420                         | 210              | 220  | 210  | 214                               | 49.04                        |
| 10    | 200.00             | 10.00     | 70.00           | 17.50 | 20.00 | 410                         | 220              | 210  | 220  | 184                               | 47.07                        |
| 11    | 200.00             | 20.00     | 30.00           | 17.50 | 20.00 | 400                         | 190              | 180  | 190  | 187                               | 53.25                        |
| 12    | 300.00             | 15.00     | 50.00           | 15.00 | 15.00 | 400                         | 210              | 200  | 210  | 207                               | 48.25                        |
| 13    | 300.00             | 15.00     | 50.00           | 20.00 | 25.00 | 410                         | 220              | 210  | 210  | 214                               | 47.80                        |
| 14    | 200.00             | 20.00     | 30.00           | 17.50 | 30.00 | 380                         | 200              | 200  | 210  | 204                               | 46.31                        |
| 15    | 300.00             | 15.00     | 50.00           | 15.00 | 25.00 | 420                         | 190              | 180  | 190  | 187                               | 55.41                        |
| 16    | 400.00             | 20.00     | 30.00           | 17.50 | 30.00 | 400                         | 240              | 250  | 250  | 247                               | 38.25                        |
| 17    | 300.00             | 15.00     | 50.00           | 15.00 | 25.00 | 380                         | 140              | 150  | 140  | 144                               | 62.10                        |
| 18    | 200.00             | 20.00     | 30.00           | 12.50 | 30.00 | 390                         | 240              | 240  | 230  | 237                               | 39.23                        |
| 19    | 300.00             | 15.00     | 50.00           | 15.00 | 25.00 | 390                         | 120              | 130  | 120  | 124                               | 68.20                        |
| 20    | 200.00             | 20.00     | 70.00           | 12.50 | 30.00 | 410                         | 250              | 250  | 260  | 254                               | 38.04                        |
| 21    | 200.00             | 10.00     | 30.00           | 12.50 | 30.00 | 400                         | 270              | 260  | 270  | 267                               | 33.25                        |
| 22    | 200.00             | 10.00     | 30.00           | 17.50 | 20.00 | 420                         | 250              | 260  | 260  | 257                               | 38.80                        |
| 23    | 400.00             | 20.00     | 30.00           | 12.50 | 30.00 | 420                         | 250              | 240  | 250  | 247                               | 41.19                        |
| 24    | 200.00             | 20.00     | 70.00           | 17.50 | 20.00 | 400                         | 210              | 200  | 210  | 203                               | 48.25                        |
| 25    | 400.00             | 20.00     | 30.00           | 12.50 | 20.00 | 400                         | 230              | 230  | 240  | 233                               | 41.75                        |
| 26    | 300.00             | 25.00     | 50.00           | 15.00 | 25.00 | 380                         | 210              | 220  | 220  | 217                               | 42.89                        |
| 27    | 300.00             | 15.00     | 50.00           | 15.00 | 25.00 | 410                         | 140              | 140  | 150  | 144                               | 64.87                        |

|    |        |       |       |       |       |     |     |     |     |     |       |
|----|--------|-------|-------|-------|-------|-----|-----|-----|-----|-----|-------|
| 28 | 300.00 | 15.00 | 50.00 | 15.00 | 25.00 | 410 | 130 | 120 | 120 | 124 | 69.75 |
| 29 | 300.00 | 15.00 | 50.00 | 15.00 | 25.00 | 400 | 120 | 130 | 130 | 127 | 68.25 |
| 30 | 200.00 | 10.00 | 30.00 | 17.50 | 30.00 | 390 | 260 | 250 | 250 | 253 | 38.05 |
| 31 | 300.00 | 15.00 | 50.00 | 15.00 | 25.00 | 420 | 120 | 140 | 130 | 130 | 69.04 |
| 32 | 200.00 | 20.00 | 70.00 | 12.50 | 20.00 | 410 | 220 | 240 | 240 | 234 | 42.92 |
| 33 | 400.00 | 20.00 | 70.00 | 12.50 | 20.00 | 390 | 290 | 280 | 290 | 287 | 26.41 |
| 34 | 200.00 | 10.00 | 70.00 | 17.50 | 30.00 | 390 | 140 | 150 | 140 | 144 | 63.07 |
| 35 | 400.00 | 20.00 | 30.00 | 17.50 | 20.00 | 400 | 300 | 300 | 290 | 297 | 25.75 |
| 36 | 200.00 | 20.00 | 70.00 | 17.50 | 30.00 | 380 | 170 | 170 | 160 | 167 | 56.05 |
| 37 | 200.00 | 10.00 | 30.00 | 12.50 | 20.00 | 420 | 230 | 240 | 240 | 237 | 43.57 |
| 38 | 400.00 | 20.00 | 70.00 | 12.50 | 30.00 | 390 | 260 | 260 | 240 | 254 | 34.87 |
| 39 | 400.00 | 10.00 | 70.00 | 17.50 | 30.00 | 420 | 150 | 160 | 160 | 157 | 62.61 |
| 40 | 400.00 | 10.00 | 30.00 | 12.50 | 20.00 | 390 | 250 | 230 | 250 | 244 | 37.43 |
| 41 | 300.00 | 5.00  | 50.00 | 15.00 | 25.00 | 410 | 170 | 180 | 170 | 173 | 57.80 |
| 42 | 200.00 | 20.00 | 30.00 | 12.50 | 20.00 | 400 | 220 | 210 | 220 | 217 | 45.75 |
| 43 | 400.00 | 10.00 | 30.00 | 17.50 | 30.00 | 390 | 200 | 190 | 190 | 194 | 50.25 |
| 44 | 300.00 | 15.00 | 50.00 | 15.00 | 35.00 | 380 | 150 | 170 | 160 | 160 | 57.89 |
| 45 | 300.00 | 15.00 | 90.00 | 15.00 | 25.00 | 390 | 180 | 190 | 190 | 187 | 52.05 |
| 46 | 300.00 | 15.00 | 10.00 | 15.00 | 25.00 | 420 | 220 | 210 | 220 | 217 | 48.33 |
| 47 | 200.00 | 10.00 | 70.00 | 12.50 | 20.00 | 410 | 210 | 220 | 220 | 217 | 47.07 |
| 48 | 400.00 | 20.00 | 70.00 | 17.50 | 30.00 | 400 | 210 | 220 | 210 | 213 | 46.75 |
| 49 | 400.00 | 10.00 | 30.00 | 12.50 | 30.00 | 390 | 200 | 200 | 210 | 204 | 47.69 |
| 50 | 400.00 | 10.00 | 70.00 | 12.50 | 30.00 | 410 | 220 | 210 | 220 | 217 | 47.07 |

#### 6.3.4 Results and discussion

The data obtained after experimentations are done over the internal surface of the PTFE bearing surface is reported in Table 6.12. After performing experimentations, three experimental surface roughness values ( $X_1$ ,  $X_2$ , and  $X_3$ ) are obtained at three different points on the internal polymer bearing surface using the roughness profilometer. To get the final surface roughness ( $R_a$ ) value, the average roughness value is calculated as reported in Table 6.12. Further, the average  $R_a$  value is used in Eq. (5.2) to obtain the  $\% \Delta R_a$ . After the analysis of the regression model is done using ANOVA, the p-value of the model is found less than 0.001 as reported in Table 6.13. This shows the significance of the present regression model. This can also be validated from the developed model as R square value 88.24 %, and Adj R- square value 81.99 % is obtained which shows the accuracy of the present developed model. Further, to know the effect of the significant process parameters, the percentage contribution of each factor and its interaction has been calculated using Eq. (5.6).

**Table 6.13.** ANOVA analysis for % change in surface roughness ( $\% \Delta R_a$ ).

| Source                | Sum of squares | Degree of freedom (DOF) | Mean square | F value | Prob>F   | Percentage Contribution (Eq. 5.6) |
|-----------------------|----------------|-------------------------|-------------|---------|----------|-----------------------------------|
| Model                 | 5826.2         | 17                      | 342.72      | 14.12   | < 0.0001 |                                   |
| <i>T</i>              | 220.9          | 1                       | 220.9       | 9.1     | 0.005    | 3.70                              |
| <i>W</i>              | 280.9          | 1                       | 280.9       | 11.58   | 0.0018   | 4.71                              |
| <i>F</i>              | 108.9          | 1                       | 108.9       | 4.49    | 0.042    | 1.83                              |
| <i>C</i>              | 108.9          | 1                       | 108.9       | 4.49    | 0.042    | 1.83                              |
| <i>E</i>              | 240.1          | 1                       | 240.1       | 9.89    | 0.0036   | 4.02                              |
| <i>T</i> <sup>2</sup> | 85.81          | 1                       | 85.81       | 3.54    | 0.0692   | 1.44                              |
| <i>W</i> <sup>2</sup> | 804.01         | 1                       | 804.01      | 33.13   | < 0.0001 | 13.48                             |
| <i>F</i> <sup>2</sup> | 651.6          | 1                       | 651.6       | 26.85   | < 0.0001 | 10.92                             |
| <i>C</i> <sup>2</sup> | 1255.01        | 1                       | 1255.01     | 51.72   | < 0.0001 | 21.04                             |
| <i>E</i> <sup>2</sup> | 688.2          | 1                       | 688.2       | 28.36   | < 0.0001 | 11.54                             |
| <i>TW</i>             | 312.5          | 1                       | 312.5       | 12.88   | 0.0011   | 5.24                              |
| <i>TF</i>             | 98             | 1                       | 98          | 4.04    | 0.053    | 1.64                              |
| <i>TE</i>             | 231.12         | 1                       | 231.12      | 9.52    | 0.0042   | 3.87                              |
| <i>WF</i>             | 120.13         | 1                       | 120.13      | 4.95    | 0.0333   | 2.01                              |
| <i>FC</i>             | 136.12         | 1                       | 136.12      | 5.61    | 0.0241   | 2.28                              |
| <i>FE</i>             | 242            | 1                       | 242         | 9.97    | 0.0035   | 4.06                              |
| <i>CE</i>             | 242            | 1                       | 242         | 9.97    | 0.0035   | 4.06                              |
| Residual              | 776.52         | 32                      | 24.27       |         |          |                                   |
| Lack of fit           | 636.65         | 25                      | 25.47       | 1.27    | 0.3936   |                                   |
| Pure error            | 139.88         | 7                       | 19.98       |         |          | 2.34                              |
| Cor total             | 6602.72        | 49                      |             |         |          |                                   |

Using Eq. (5.6), percentage contribution of each significant parameter is calculated and reported in Table 6.13. After the analysis of the significant parameters on the output response, the individual and interactional effect of the highly significant parameters has been conferred in this section.

#### 6.3.4.1 Effect of significant parameters on $\% \Delta R_a$

The effect of tool rotational speed (*T*) and workpiece rotational speed (*W*) on  $\% \Delta R_a$  is depicted in Fig. 6.20(a). The *F*, *C*, and *E* are kept constant at 70 mm/min, 17.5 %, and 30 % respectively. From Fig. 6.19(a), it can be observed that as the *T* and *W* are upsurged initially, there is an increase in the trendline of the  $\% \Delta R_a$ . However, beyond the optimal value of *T* and *W* simultaneously, the trendline of  $\% \Delta R_a$  starts decreasing. As the MRH tool and workpiece are rotated simultaneously in opposite directions, there is an increase in the net relative motion of AAPs owing to which the

net tangential shearing force upsurges. This leads to the higher shearing off asperities from the bearing's internal surface. Also, with an increase in the  $T$  and  $W$ , there is an increment in the length of the helical path which is followed by the AAP leading a higher finishing rate. This leads to the increase in the trendline of the  $\% \Delta R_a$ . However, beyond the optimal values, at a simultaneous higher tool and workpiece rotation, the relative motion of AAPs becomes very high which leads to less interaction time for AAP to shear off the asperities from the bearing surface. This leads to the lower removal of material. Also, at higher speeds, the net tangential shear force becomes very high that the EIPs present in the columnar structure of MR polishing fluid becomes unstable which reduces the finishing performance. This leads to a decrease in the trendline of the  $\% \Delta R_a$ .

The effect of tool reciprocation speed ( $F$ ) and % volume concentration of EIPs ( $E$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.20(b). The  $T$ ,  $W$ , and  $C$  are kept constant at 300 rpm, 15 rpm, and 17.5 % respectively. It can be seen from Figure 6.19(b) that as the  $F$  and  $\% E$  upsurge, there is an increment in the trendline of the  $\% \Delta R_a$ . However, after the optimal value of  $F$  and  $\% E$ , the trendline of the  $\% \Delta R_a$  decreases. This trend occurs because initially with the simultaneous upsurge in  $F$  and  $\% E$ , there is an upsurge in the normal magnetic force along with the relative speed of the AAP along a helical path over the work part surface. This leads to the higher shear strength of the EIPs columnar structure which tightly the AAPs present in the MRP fluid and also the increase in the helical path, the interaction time of the AAPs with the bearing surface upsurges. Owing to this the removal rate of the material from the bearing surface upsurges leading to the increase in the trendline of  $\% \Delta R_a$ . However, beyond the optimal values of  $F$  and  $\% E$  the overall magnetic force and relative speed of the AAP becomes too high which leads to the loosening in the gripping of the EIPs columnar structure during surface finishing. Also, there is a decrement in the overall cutting edges of AAPs which are accountable for surface finishing as the accumulation of the EIPs increases outside the already existing EIPs chains. This leads to the reduction in the chipping off the surface roughness peaks from the work part. Further, the duration of time for which AAPs interact with the bearing surface also decreases. All these reasons collectively reduce the material removal rate leading to the decrease in the trendline of the  $\% \Delta R_a$ .

The effect of % volume concentration of abrasives and % volume concentration of EIPs on  $\% \Delta R_a$  is depicted in Figure 6.20(c). The tool rotational speed, workpiece rotational speed, and tool reciprocation speed are kept constant at 300 rpm, 15 rpm, and 70 mm/min, respectively.



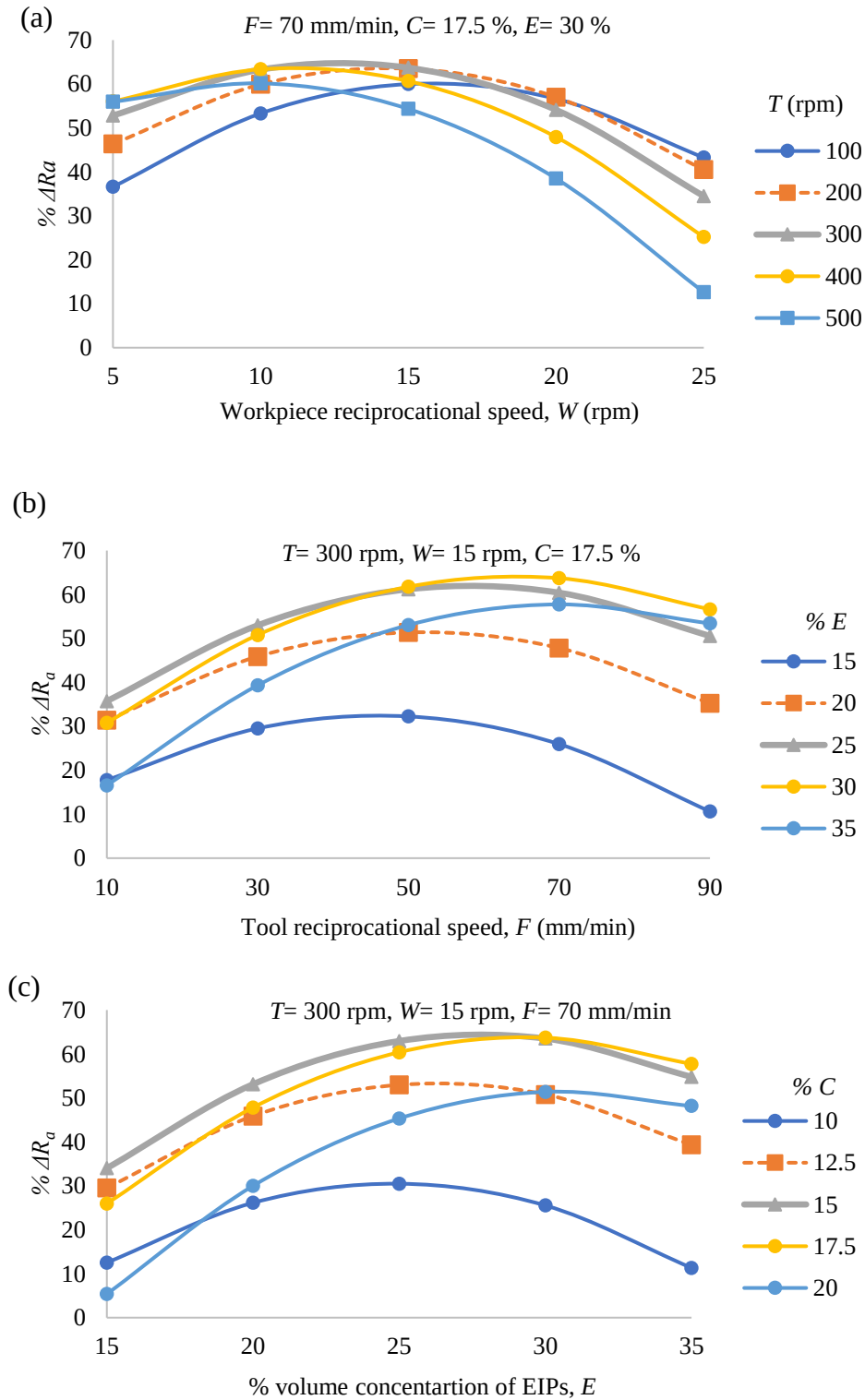


**Fig. 6.20.** Simultaneous effect of (a)  $W$  and  $T$ , (b)  $F$  and %  $E$  and (c)  $E$  and  $C$  on %age improvement in the surface finish (%  $\Delta R_a$ ).

It can be observed that as the  $C$  and  $E$  increase simultaneously, there is an upsurge in the trendline of the  $\% \Delta R_a$ . However, after the optimum values of  $C$  and  $E$ , there is a decrease in the trend of the  $\% \Delta R_a$ . Initially, upsurging both the parameters simultaneously leads to enhancing the shear strength of the MRP fluid as the magnetic normal force acting on the AAPs increases. This leads to the clipping of the surface asperities from the bearing at a higher speed owing to which the trend of the  $\% \Delta R_a$  increases. However, beyond the optimal value of the  $\% C$  and  $\% E$ , the shear strength of the MRP fluid starts decreasing. This is due to the increase in the distance between the EIPs as the  $C$  increases excessively. This led to a decrease in the magnetic interaction force as given in Eq. (5.7). Also, at higher  $E$ , more EIPs accumulate outside the already existing EIPs chain leading to a decrease in the cutting edges of the AAPs which are accountable for the surface finishing.

The main objective of the present study is to provide minimum surface roughness and maximum  $\% \Delta R_a$  for fine finishing of the PTFE bearings using the rotational magnetorheological (R-MR) honing process. In order to get the best possible outcomes for the  $\% \Delta R_a$ , the optimum significant parameters are predicted after the regression analysis. Next, to maximize the  $\% \Delta R_a$ , the process parameters were subjected to

$$100 \text{ rpm} \leq T \leq 500 \text{ rpm}$$

$$5 \text{ rpm} \leq W \leq 25 \text{ rpm}$$

$$10 \text{ mm/min} \leq F \leq 90 \text{ mm/min}$$

$$10\% \leq C \leq 20\%$$

$$15\% \leq E \leq 35\%$$

Further, the outcomes of different process parameters on the output response ( $\% \Delta R_a$ ) are evaluated to predict the optimum parameters. To maximize the  $\% \Delta R_a$ , Eq. (6.8) obtained from the quadratic model after regression analysis is used. The values of predicted optimum process parameters were found as  $T= 300 \text{ rpm}$ ,  $W= 15 \text{ rpm}$ ,  $F= 70 \text{ mm/min}$ ,  $C=17.5\%$  and  $E= 30\%$ . Hence, the predicted optimum concentration of the MRP fluid for the fine finishing of the PTFE bearing surface is predicted as  $C= 17.5\%$  and  $E = 30\%$ , and  $\%$  volume concentration of water-based fluid (WBC) fluid  $52.5\%$ . Next, in order to validate the repeatability of the present regression model obtained for the fine finishing of the PTFE bearing, further five experimentations were performed. For the confirmatory experimentation, the finishing time of 60 min is taken over the internal surface of the PTFE bearing surface with an inner diameter of 38 mm and a length of 20 mm. The parameters used for the experiments were kept within the range of the designed experiments. The confirmatory

experimentation data and their comparison with the predicted values are stated in Table 6.14. From their comparative study, it can be said that this developed regression model is well suited for the repeatability as the error amid the theoretical and experimental  $\% \Delta R_a$  lies within the -6.52 % to 7.71 %, which concludes that the developed regression model is decently accurate.

**Table 6.14.** Confirmation tests and their comparison with the results.

| S. No. | Tool rotation, $T$ (rpm) | Workpiece rotation, $W$ (rpm) | Tool reciprocation, $F$ (mm/min) | % concentration of abrasive, $C$ | % concentration of EIPs, $E$ | Experimental $\% \Delta R_a$ Eq. (5.2) | Predicted $\% \Delta R_a$ Eq. (6.8) | % Error Eq. (6.3) |
|--------|--------------------------|-------------------------------|----------------------------------|----------------------------------|------------------------------|----------------------------------------|-------------------------------------|-------------------|
| 1      | 100                      | 10                            | 10                               | 12.5                             | 25                           | 17.5                                   | 16.15                               | 7.71              |
| 2      | 300                      | 15                            | 30                               | 17.5                             | 30                           | 52.5                                   | 51.61                               | 1.69              |
| 3      | 300                      | 25                            | 90                               | 17.5                             | 30                           | 25                                     | 26.63                               | -6.52             |
| 4      | 200                      | 5                             | 50                               | 20                               | 25                           | 30                                     | 29.89                               | 0.36              |
| 5      | 400                      | 10                            | 10                               | 17.5                             | 30                           | 31.57                                  | 32.34                               | -2.38             |

#### 6.3.4.2 Observation of reduction in surface roughness of the PTFE bearing internal surface

Further, the experimentations were performed on the internal surface of the PTFE bearing with a surface area of 4772.80 mm<sup>2</sup> (internal diameter of 38 mm and length of 40 mm) using the predicted optimum parameters of the R-MR honing process. The  $R_a$  value of the PTFE bearing is reduced from 400 nm to 70 nm in 120 min of the MR finishing. The  $R_a$  value was taken at three different points on the internal bearing surface every 20 min of the finishing cycle. The average  $R_a$  values obtained after every finishing cycle of 20 min are recorded as 310 nm, 250 nm, 190 nm, 140 nm, 100 nm, and 70 nm respectively. Further, after 120 min of finishing, no significant improvement was observed on the internal PTFE bearing surface. The roughness parameters ( $R_a$ ,  $R_q$ , and  $R_z$ ) of the initial and final MR finished PTFE bearing's internal surface is depicted in Fig. 6.21(a) and (b) respectively. The total surface improvement ( $\% \Delta R_a$ ,  $\% \Delta R_q$ , and  $\% \Delta R_z$ ) on the internal PTFE bearings surface area of 4772.80 mm<sup>2</sup> after 120 min was found as 82.5%, 84.37%, and 89.47% respectively which reveals the effective finishing over bearing surface using the present R-MR honing process.

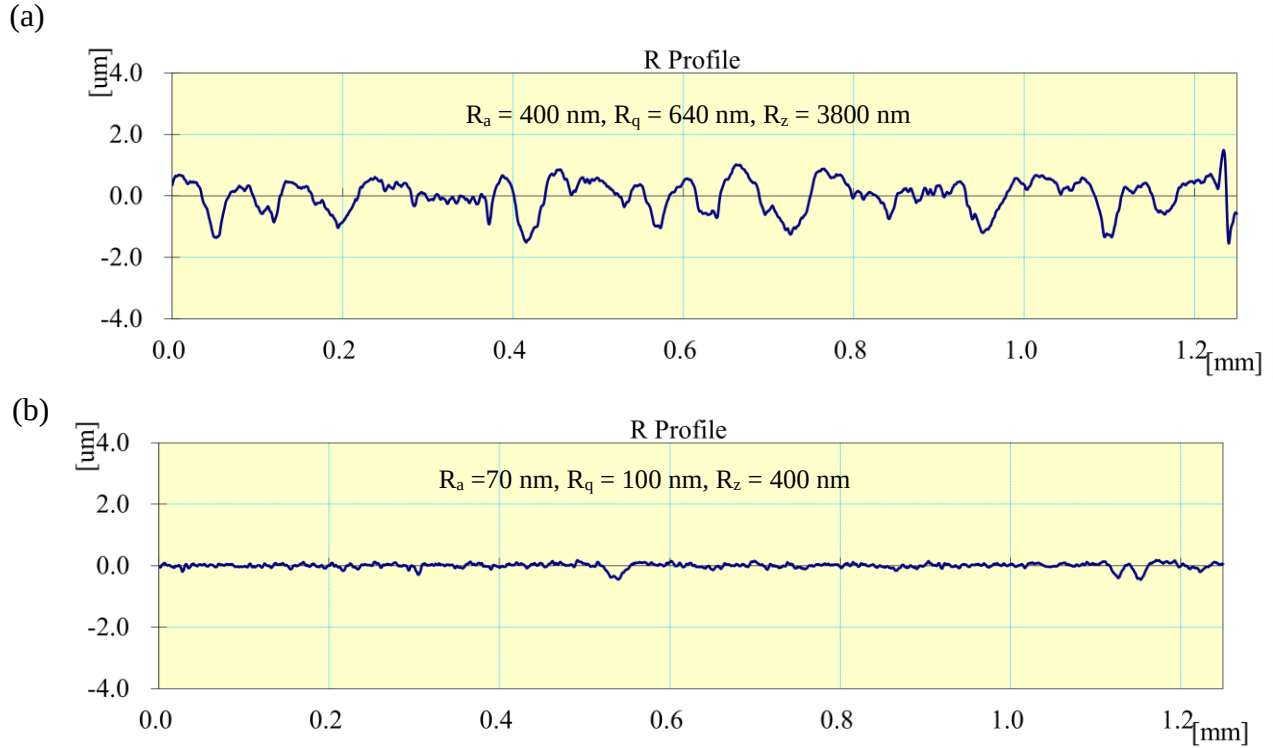


**Fig. 6.21.** Surface roughness profiles of the PTFE internal bearing with 4772.80 mm<sup>2</sup> surface area for (a) initial ground surface and (b) after 120 min of MR finishing of final surface at  $T=300$  rpm,  $W=15$  rpm,  $F=70$  mm/min, %  $C=17.5\%$  and %  $E=30\%$ .

#### 6.3.4.3 Observation of surface characteristics of the PTFE bearing internal surface

Further, to analyze the surface characteristics of the internal surface of the bearing, scanning electron microscopy (SEM) is utilized in the present work. The initial ground surface and MR finished PTFE bearing surface images are depicted in Fig. 6.22. From Fig. 6.22(a) it can be observed that there are various defects on the initial internal surface of the PTFE bearing such as material deformation, cracks, debris, and scratches. These defects are due to the no control over finishing forces during the grinding process which leads to the non-uniform material removal. Owing to these defects, the dimensional accuracy of the bearing surface decreases, and the wear rate upsurges. This may lead to higher friction owing to which overheating occurs and decreases the service life and functional efficacy of bearing. However, after the R-MR honing process, there is a significant enhancement over the final finished bearing surface as shown in Fig. 6.22(b). This is because, in the present process, normal forces acting over the internal bearing surface are comparatively low. Further, the material removal by the AAPs due to the tangential and axial forces occurs in the form of microchips which leads to the fine finished internal surface. Also, in the present process, the external forces can be controlled magnetically which also improves its surface characteristics. Owing to this improvement in surface characteristics, the wear rate may

decrease which further tends to enhance the service life and functional efficacy of the PTFE bearings.

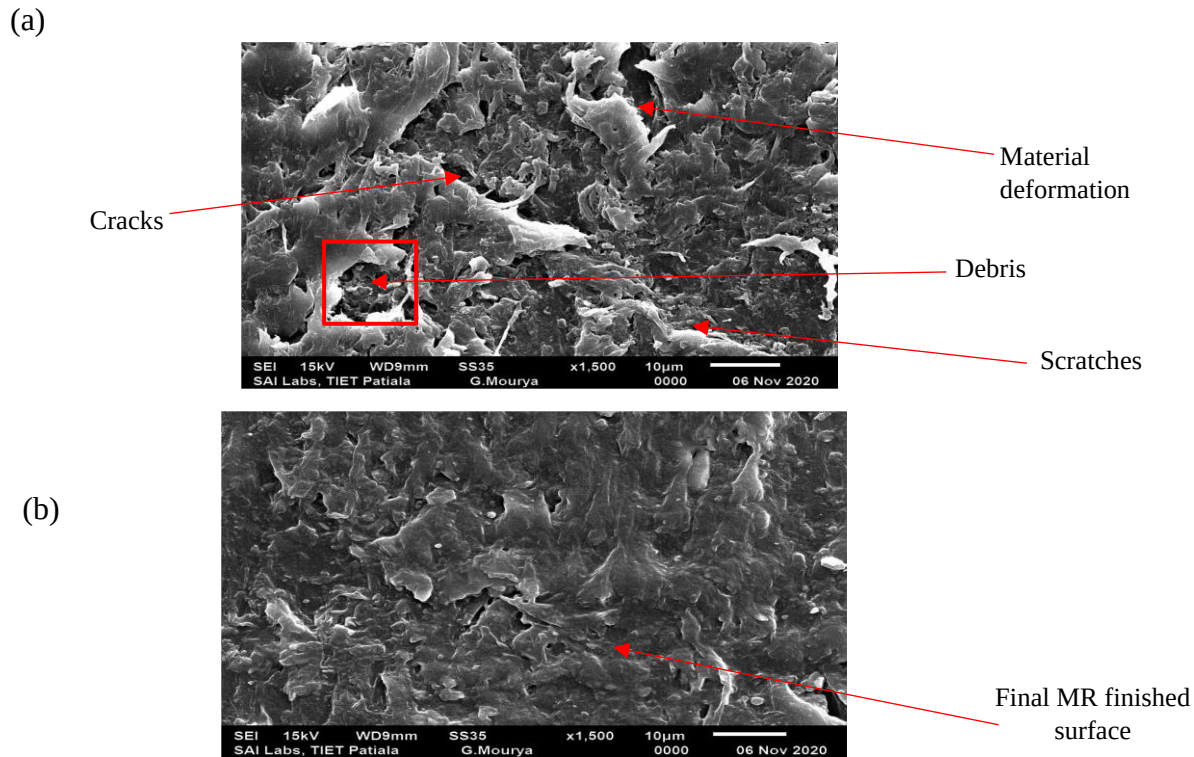


**Fig. 6.22.** Scanning electron microscopy for (a) initial ground surface and (b) final surface after 120 min of MR finishing over 4772.80 mm<sup>2</sup> surface area of PTFE bearing  $T= 300$  rpm,  $W= 15$  rpm,  $F= 70$  mm/min,  $C=17.5$  % and  $E= 30$  %.

#### 6.3.4.4 Observation of dimensional characteristics of the PTFE bearing internal surface

Pump shafts, water turbines, and marine propellers are few machines where PBs are of great use. The fine finishing of these PBs plays a significant role in these rotating machines in hydropower industries. This is because non-uniform finished bearing may lead to overheating due to the friction there are chances of rapid adhesive wear and malfunctions while practical applications which may have an adverse effect on the machining components. Therefore, uniform internal bearing surface finishing is required to enhance the service life of the polymer bearing with improved dimensional accuracy and high load-bearing capability. The dimensional accuracy of the PTFE bearings plays an important role in the enhancement of the service life and load-bearing capability.

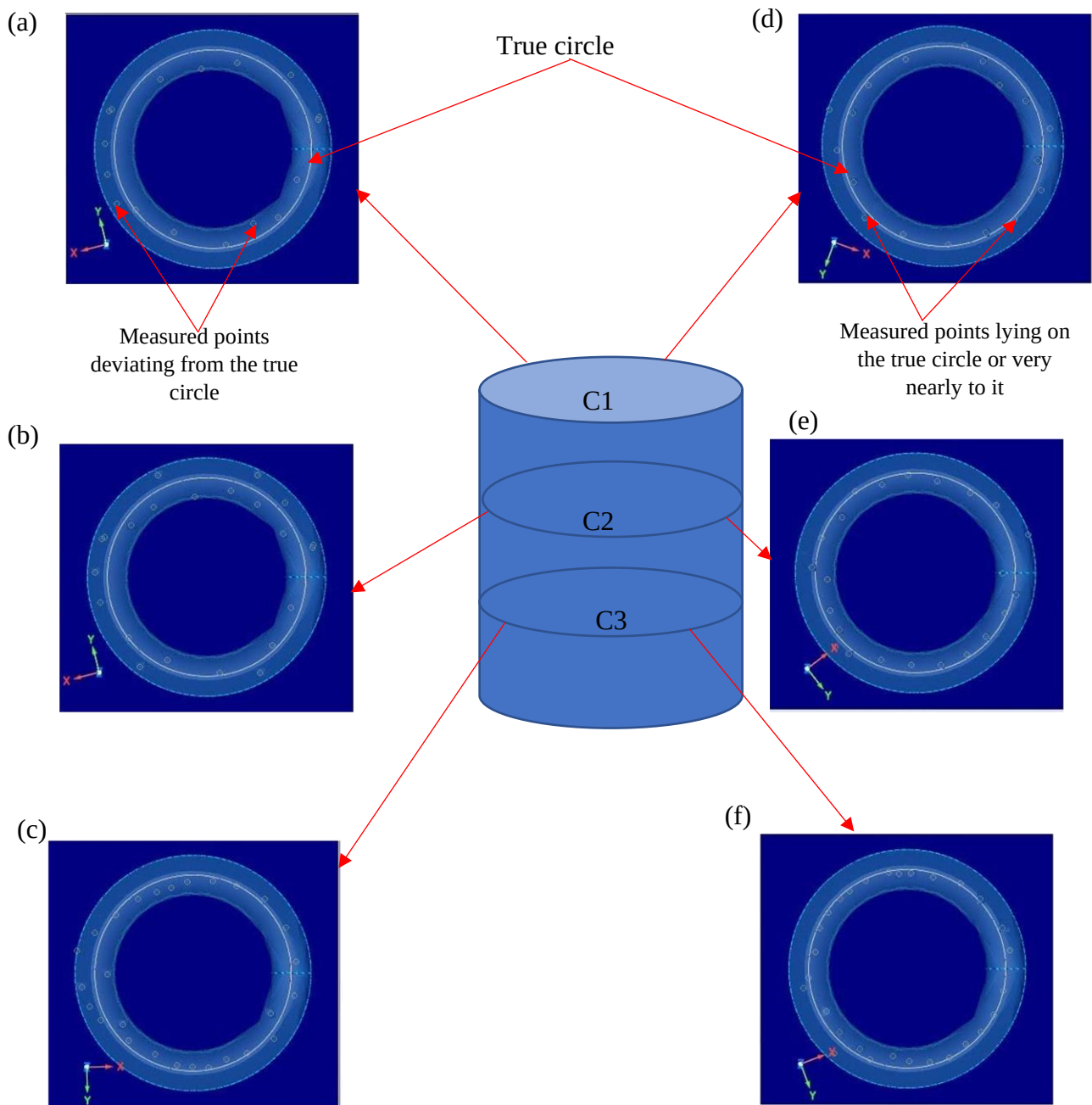
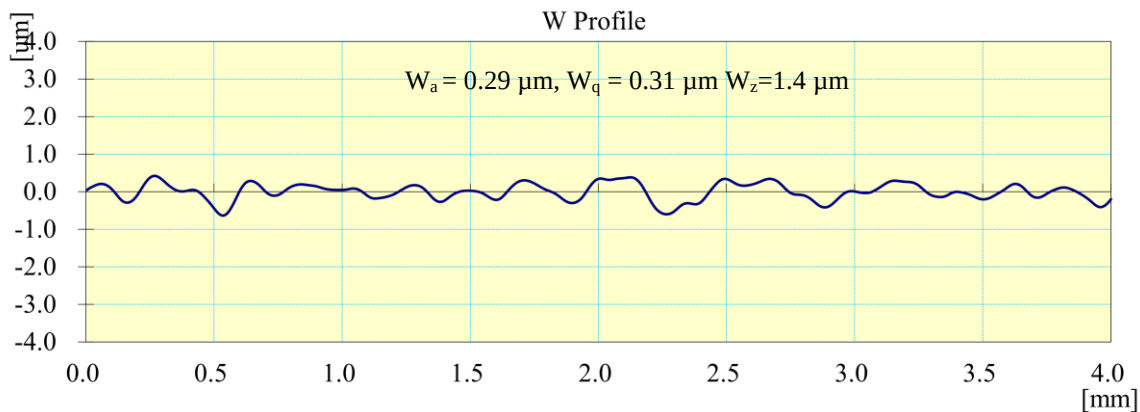


**Fig. 6.23.** Circularity image of initial surface at circular sections (a) C1, (b) C2 and (c) C3 and final surface at circular sections (d) C1, (e) C2 and (f) C3 after 120 min of MR finishing of PTFE bearing over  $4772.80 \text{ mm}^2$  surface area at  $T= 300 \text{ rpm}$ ,  $W= 15 \text{ rpm}$ ,  $F= 70 \text{ mm/min}$ ,  $C=17.5 \%$  and  $E= 30 \%$ .

This is due to the fact that the low dimensional accuracy of the bearing surface may lead to wear owing to which friction occurs leading to the component failure. Hence, to confirm the precision in dimensional constraints of the PTFE bearing, a circularity test, and waviness test is performed. The circularity was measured using the co-ordinate measuring machine (CMM) at three different sections C1, C2, and C3 at the initial and final surface of the PTFE bearing surface as shown in Fig. 6.23. The probe of CMM moves over a circular surface at different sections of the bearing's internal surface. The true circle as depicted in Fig. 6.23, is an ideal circle with zero circularity

error. The closeness amid the measuring points and the true circle defines the circular accuracy of the PTFE bearing work part (Singh and Singh, 2020). Fig. 6.23(a), (b), and (c) shows the initial bearing surface circularity at three different sections C1, C2, and C3 respectively with the average circularity measured as 0.0913 mm. Most of the measuring points at different sections deviate from the true circle in the initial surface. This describes that the initial dimensional accuracy of the PTFE bearing is poor. After the fine finishing of 120 min on the PTFE bearing with the surface area of 4772.80 mm<sup>2</sup> using the R-MR honing process, the circularity at the three different sections C1, C2, and C3 is depicted in Fig. 6.23(d), (e) and (f) with average circularity value is measured as 0.0398 mm. It can be observed that most of the measuring points on the final finished surface are close to the true circle as compared to the initial surface.

(a)



(b)

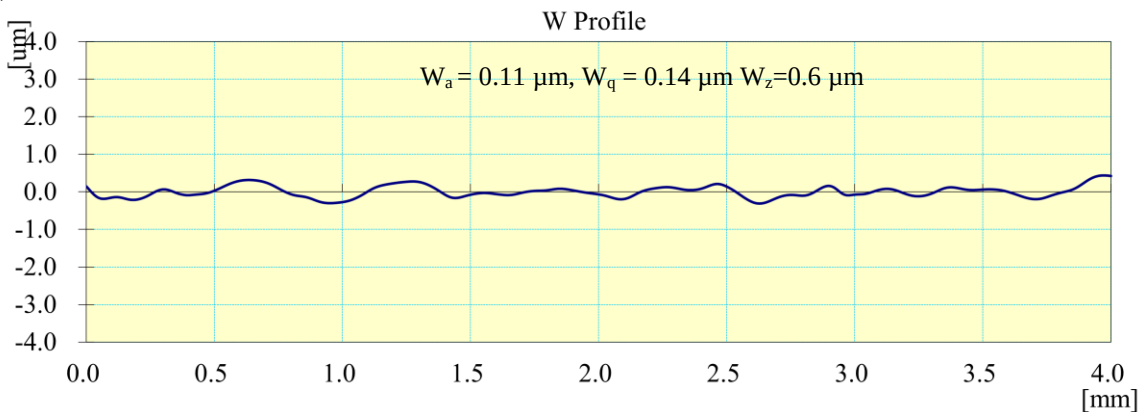


**Fig. 6.24.** Surface waviness for (a) initial surface and (b) final surface after 120 min of MR finishing over 4772.80 mm<sup>2</sup> surface area of PTFE bearing.

Further, in order to avoid wear and have close fits and tolerance, a uniform linear surface (straightness) is necessary for polymer bearing. Therefore, in-depth detailing of the linear surface

waviness is performed on the bearing surface. The waviness has a long sample length as compared to the surface roughness profile which helps in providing insight into the linear surface. The initial ground waviness profile and MR finished surface profile with predicted optimized parametric conditions are depicted in Fig. 6.24(a) and (b), respectively. The arithmetic mean waviness ( $W_a$ ) value of the initial ground PTFE bearing surface is  $0.29\text{ }\mu\text{m}$  and  $W_a$  value of the final PTFE bearing surface with  $4772.80\text{ mm}^2$  area is  $0.11\text{ }\mu\text{m}$  as measured with the assistance of Tylor Hobson profilometer. The improvement in the circularity and straightness of the PTFE bearing surface after the R-MR honing process reveals the enhancement in the dimensional accuracy which tends to upsurge the bearing's service life.

Further, to study the load-bearing capability of the PTFE bearing, the micro-hardness of the bearing is tested before and after the MR finishing. Total of five indentations were done on the initial and final surface at 100 g load. Further, the average value of the hardness of the initial and final surface was taken for analysis. At the initial surface, the average hardness of the PTFE bearing is found as 6.8 HV. However, after 120 min of finishing, the average hardness was found as 9.1 HV. The surface hardness test reveals that after finishing, there is an increase in the bearing surface hardness. This is because in initial surface asperities peaks have more height (Fig. 6.21a) and low concentration area. Owing to this the load-bearing capability of the bearing work part reduces and results in lower hardness. However, after the MR finishing, the peaks of the surface asperities get more flattened (Fig. 6.21b) due to which the area of concentration and load-bearing capability increases. This upsurges the hardness of the PTFE bearing surface owing to which the load-bearing capability tends to increase over the bearing surface (Singh and Singh 2020). Clinically, the above study reveals that the present R-MR honing process leads to an upsurge in hardness, enhancement in circularity, and waviness (straightness) after a decrease in the surface roughness of the internal PTFE bearing surface. This tends to enhance the service life, dimensional accuracy, and efficacy of the bearing component used in various machines such as water turbines, marine propellers, and pump shafts.

### **6.3.5 Conclusions**

The present rotational magnetorheological (R-MR) honing process with the permanent magnet tool is capable to provide the fine internal finishing of the PTFE bearing surface. The finely finished bearing can be used in the marine, textile, and food processing industries. The reduction in the wear, surface roughness and upsurge in hardness, and load-bearing capability of the surface



further validate the efficacy of the present process. The following conclusions have been made from the R-MR honing of the internal surface of the bearing.

- The regression analysis with response surface methodology reveals that the effectively finishing over the PTFE bearing internal surface is achieved with optimized parameters such as tool rotation at 300 rpm, workpiece rotation speed 15 rpm, tool reciprocation speed 70 mm/min, % volume concentration of  $\text{Al}_2\text{O}_3$  abrasives 17.5 % and % volume concentration of EIPs of 30 %.
- The %age reduction in roughness parameters as 82.5 %, 84.37 %, and 89.47 % respectively over PTFE bearing surface with 4772.80 mm<sup>2</sup> surface area for 120 min of finish time using the best process parameters shows the efficiency of the present finishing process for improving the internal surface finish of the bearings.
- In the present work, the error obtained between the experimental and the predicted %  $\Delta Ra$  is found within – 6.52 to 7.71%, which concludes that the developed regression model is decently accurate. Therefore, the predicted optimized process parameters for finishing the PTFE bearings are found in good order.
- The enhancement in the hardness, circularity, waviness, and surface characteristics of the MR finished surface reveals the upsurge in functional efficacy of the polymer bearing's internal surface in the various rotating machines in hydropower industries.

#### **6.4 Parametric investigation of typical polymer valve seat/seal for improving their functional performance in ball valves**

Transport of mediums such as oil or gas using pipelines is a way to continuous delivery which can help to produce goods amid two cities or even two countries. Pipeline valves are one of the integral parts for transporting the medium from one place to another. Ball valves are used in pipeline areas where the steam flow has to be switched on or off. In recent times, many industries tend to have fuel pipelines, high-pressure air pipelines, and systems for protecting gas distributions (Rogula, 2012). However, in the gas and oil pipeline sectors, the imminent incidents of a gas pipeline valve leakage during the transportation process of gas or oil cause significant problems for pipeline reliability, supply, and economy (Li *et al.*, 2017). The majority of issues encountered when working with pipeline valves, especially ball valves, are due to the valve seats' poor performance (Jemaa *et al.*, 2012). This problem has been the subject of a lot of research work and the types of service valve failure have been identified for the common types of the valve (Salan, 2007; Wang

*et al.*, 1996). The ball valve seat, which has a wide variety of specifications, is typically made from polymeric materials. Due to their superior properties, such as high-temperature stability, low friction coefficient, and high chemical resistance, polymers such as polytetrafluorethylene (PTFE) and polyetheretherketone (PEEK) are seeing growing use in high-performance mechanical seats in recent years (Mnif *et al.*, 2013). Since the valve leakage has a high impact on the system efficiency, therefore, in the ideal case for the smooth functioning of the oil or gas transportation, the valve seats should possess a zero-leakage rate at the higher or lower differential pressure (Briscoe and Tweedale, 1989). Further, the valves should operate at lower torques when they turn on/off as well as should have high wear resistance and high dimensional accuracy. However, the design and engineering specification of the valve seats inevitably gives rise to the compromise in the operating parameters such as leakage and operating friction torque during practical applications. Also, PEEK and PTFE show poor abrasion and wear resistance, leading to early leakage and failure problems in the seats (Unal and Mimaroglu, 2003). Hence, to enhance the performance of the valves during working, the fine finish polymer seats are important. This is due to the fact that the finely finished polymer valve seat reduces wear and friction when in operation, potentially lowering leakage and working friction torque. Hence, improving the functional performance of the valve in pipelines.

The hemispherical tip-based magnetorheological finishing (MRF) process is used for the fine finishing of the polymer valve seats with minimal errors and high dimensional precision. Since the polymer seat surface is not flat but circular truncated in shape, therefore, for fine finishing of the polymer valve seats with a constant working gap, initially, a proper arrangement of the experimental setup is done. The optimum process parameters are predicted for the effective finishing of the polymer valve seats. In addition, the dimensional precision and the surface characteristics are observed using the coordinate measurement machine and field emission scanning electron microscopy (FESEM) to show the effectiveness of the present finishing process for the fine finishing of the polymer valve seat. Further, the hardness of the polymer valve seat is also tested using the model Mitutoyo HM-210 microhardness tester. The present hemispherical tip-based magnetorheological finishing (MRF) process tends to enhance the service life of the polymer valve seats by providing fine finishing with improved functional efficacy.

#### 6.4.1 Material selection and workpiece preparation

In the ball valves, a polymer material such as polyetheretherketone (PEEK) are finding upsurge utility in high-performance mechanical valve seat owing to the properties such as high-temperature stability, low friction coefficient, and high chemical resistance, and ability to work in either presence or absence of external lubrication make them beneficial for various industrial components. The front view of the ball valve used in the present study is depicted in Fig. 6.25(a). The ball valve consists of a spherical ball, sleeves, valve seat, and stem as depicted in Fig. 6.25(b).

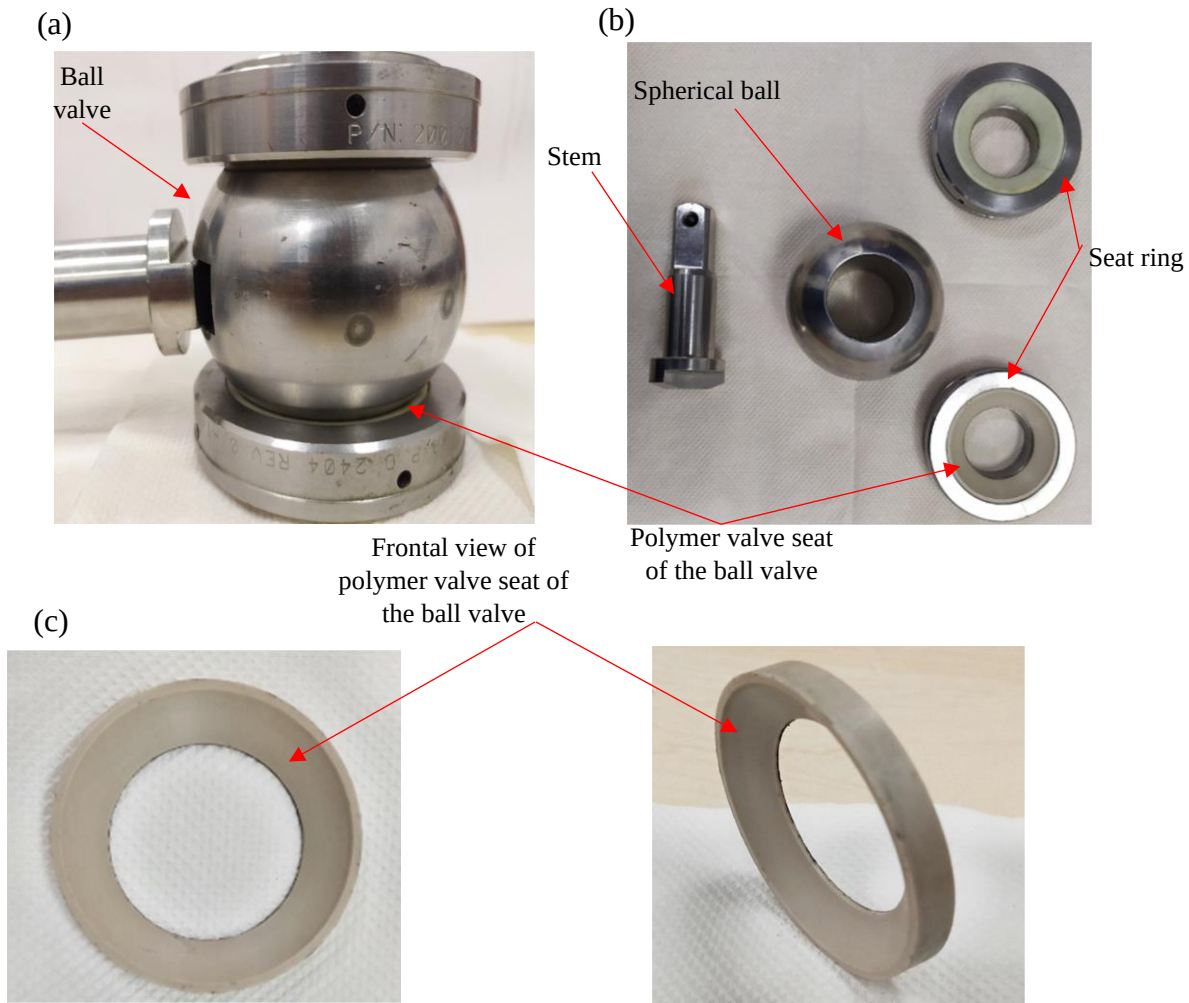


**Fig. 6.25.** (a) Front view of ball valve, (b) different components of ball valve and (c) polymer valve seat workpiece.

The ball valve seat consists essentially of a brass sleeve that encloses a pierced brass sphere rubbing against valve seats. The sliding contact between the ball and seat is ensured by clamping the sleeve against the seat and the cyclic rotation of the ball. In the present study, the ball valve

and circular truncated polymer valve seats are manufactured by MERLA, LLC industry. The polymer valve seat of the ball valve is cleaned using acetone and adequately handled before the magnetorheological (MR) fluid-based finishing. The initial and final finished surface roughness values of the polymer valve seat surface are evaluated using the Mitutoyo profilometer (SJ-400) at 5 numbers of sampling lengths and with a 0.25 mm cut-off length. Further, a workpiece holder is made to hold the polymer valve seat surface over the workpiece fixture as depicted in Fig. 6.25(c). The polymer valve seat is tightly fitted in the workpiece fixture which is further used for experimentations. As the MRP fluid is employed over the external bulged magnetic tool surface, the electrolytic iron particles (EIPs) of the fluid get magnetized and start attracted to the external bulged surface of the present tool. To confirm the improvement obtained in surface roughness, circularity, and scanning electron microscopy tests are performed respectively before and after the MR finishing process.

#### **6.4.2 Experimentation**

In the present study, the experimental setup used for the fine finishing of the polymer valve seats is depicted in Fig. 3.37 (chapter 3). In the present work, two types of motion are used naming the rotary motion of the magnetic hemispherical tip-based tool and the rotary motion of the workpiece surface as depicted in Fig. 6.26. Further, to have precise motions with minimal errors, two servo motors and drivers are used with the assistance of the programming logic controller (PLC). The simultaneous motion is given to the tool core and the work part surface in the opposite direction (Fig. 6.26) so that the relative speed of the abrasive particles present over the valve seat surface increases. This leads to the overall fine finishing of the polymer valve seat. Three process parameters naming tool rotational speed ( $T$ ), magnetizing current ( $I$ ), and workpiece rotational speed ( $W$ ) are used. Each of the parameters has its own influence on the fine finishing of the polymer valve seat with the present MRF process. The tangential shear force acting on the AAPs is governed by the work part rotational speed ( $W$ ) and tool rotational speed ( $T$ ). The tool rotational speed and work part rotational speed also guides the relative motion that takes place amid the AAPs and the workpiece surface. Similarly, the magnetizing current ( $I$ ) controls the MFD which governs the indentation of the AAPs over the polymer BG surface. Hence, magnetizing current ( $I$ ) also plays an important role in the present MRF process.

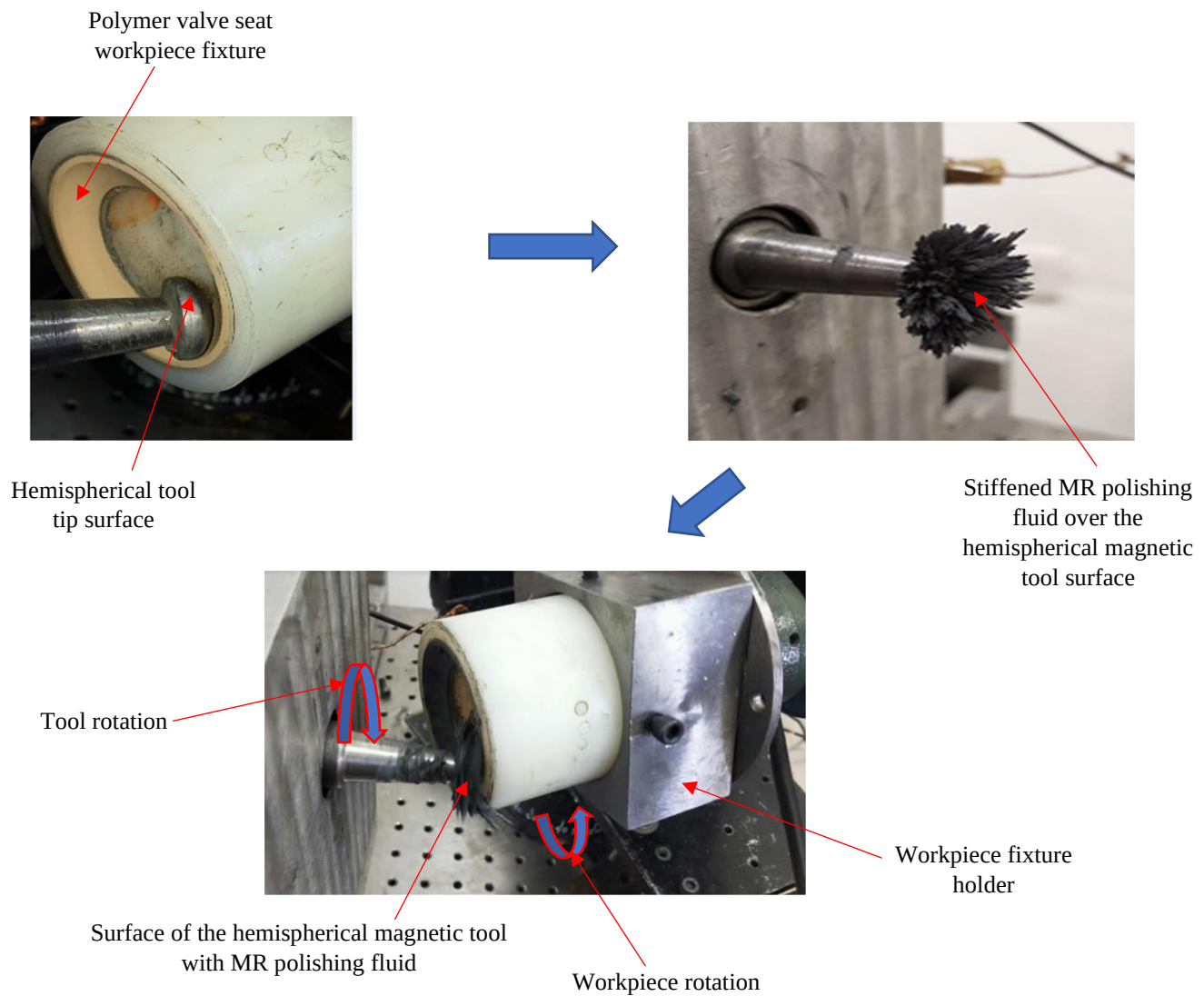


**Fig. 6.26.** Photograph of the MR finishing of the polymer valve seal surface using hemispherical tip-based electromagnetic tool.

For the analysis of the various parameters on the polymer valve seat surface, design of experiments (DOE) with response surface methodology (RSM) is used. In the present work, RSM is used to attain the optimized process parameters of the present process for fine finishing of the polymer valve seat. Further, the % volume concentration of the MR polishing (MRP) fluid is taken as 10 % volume concentration of the  $\text{CeO}_2$  abrasives, 30 % volume concentration of the EIPs and 60 % volume concentration of base fluid (80 % deionized water and 20 % glycerol). The range of process parameters used for the experimentation is selected on the basis of the preliminary experimentations and reported in Table 6.15.

**Table 6.15.** Process parameters and their range.

| S. No. | Parameters                               | Range |     |     |     |     |
|--------|------------------------------------------|-------|-----|-----|-----|-----|
| 1.     | Tool rotational speed,<br>$T$ (rpm)      | 125   | 250 | 375 | 500 | 625 |
| 2.     | Magnetizing current,<br>$I$ (A)          | 1     | 2   | 3   | 4   | 5   |
| 3.     | Workpiece rotational<br>speed, $W$ (rpm) | 48    | 78  | 108 | 138 | 168 |

For the analysis of the various parameters on the percent improvement in surface finishing ( $\% \Delta R_a$ ) of the polymer valve seat surface, the design of experiments (DOE) with response surface methodology (RSM) is used. The average surface roughness ( $R_a$ ) value was determined with the help of the Mitutoyo SJ-400 surface profilometer with a 0.25 mm cut-off range. The  $\% \Delta R_a$  is taken as the output parameter because the initial average  $R_a$  value varies from 540-570 nm. The foremost objective of the present regression model is to provide the analysis of the reduction in the process variability in  $\% \Delta R_a$  and to enhance the efficiency of the present magnetorheological finishing process. In the present model, the relation amid the output ( $\% \Delta R_a$ ) and the input independent parameters is given by Eq. (6.9).

$$\% \Delta R_a = f(T, I, W) \quad (6.9)$$

where  $f$  is the response function,  $T$  is tool rotational speed in rpm,  $I$  is the magnetizing current in A and  $W$  is polymer valve seat rotation in rpm.

The composite planning in RSM adds several detailed samples depending on the nature of the regression. RSM method of parameter optimization is based on statistics and mathematics which is used for the analysis and developing of a mathematical model for engineering-based issues. The relation between the independent input parameters (say  $X_i$ ) and dependent output variable i.e., surface response (say  $Y$ ) is established through the RSM technique to analyze the problem (Hazir and Ozcan, 2019). To comply with the motive of the RSM for the present study i.e., finding out the correlation between the response ( $Y$ ) and affecting variables ( $X_i$ ) an appropriate estimation for the true functional relationship is determined as follows in Eq. (6.10).

$$Y = \alpha_0 + \sum_{i=1}^n \alpha_i X_i + \sum_{i=1}^n \alpha_{ii} X_i^2 + \sum \sum_{i < j} \alpha_{ij} X_i X_j + \varepsilon \quad (6.10)$$

where  $\alpha$  are the coefficients and  $\varepsilon$  is the error in the model. In the present study, design expert 6.0.8 is utilized to analyze the experimentations and central composite design (CCD) is used with three parameters and five levels.

### 6.4.3 Results and discussion

A total of 20 experiments are designed by the CCD as reported in Table 6.16. Every experiment is carried out on the polymer valve seat for 60 min. The MR polishing fluid is changed over the hemispherical tip-based tool surface every 20 min of the finishing cycle. This is done so that the abrasive cutting edges remain fresh during the surface finishing of the polymer valve seat.

**Table 6.16.** Experimentation plans and results.

| Std | Run | Tool rotational speed, $T$ (rpm) | Magnetizing current, $I$ (A) | Workpiece rotational speed, $W$ (rpm) | Initial average surface roughness (nm) $R_{ai}$ |      |      |      | Final average surface roughness (nm) $R_{af}$ | % surface finishing improvement (% $\Delta R_a$ ) Eq. (5.2) |
|-----|-----|----------------------------------|------------------------------|---------------------------------------|-------------------------------------------------|------|------|------|-----------------------------------------------|-------------------------------------------------------------|
|     |     |                                  |                              |                                       |                                                 | $X1$ | $X2$ | $X3$ |                                               |                                                             |
| 15  | 1   | 375                              | 3                            | 108                                   | 550                                             | 160  | 170  | 170  | 167                                           | 69.63                                                       |
| 14  | 2   | 375                              | 3                            | 168                                   | 570                                             | 220  | 210  | 210  | 217                                           | 61.92                                                       |
| 17  | 3   | 375                              | 3                            | 108                                   | 540                                             | 150  | 160  | 160  | 157                                           | 70.92                                                       |
| 16  | 4   | 375                              | 3                            | 108                                   | 550                                             | 180  | 170  | 180  | 177                                           | 67.81                                                       |
| 4   | 5   | 500                              | 4                            | 78                                    | 560                                             | 220  | 210  | 220  | 217                                           | 61.25                                                       |
| 5   | 6   | 250                              | 2                            | 138                                   | 570                                             | 260  | 270  | 260  | 263                                           | 53.85                                                       |
| 9   | 7   | 125                              | 3                            | 108                                   | 550                                             | 350  | 340  | 340  | 343                                           | 37.63                                                       |
| 10  | 8   | 625                              | 3                            | 108                                   | 570                                             | 270  | 260  | 270  | 267                                           | 53.15                                                       |
| 1   | 9   | 250                              | 2                            | 78                                    | 540                                             | 290  | 290  | 280  | 287                                           | 46.85                                                       |
| 12  | 10  | 375                              | 5                            | 108                                   | 560                                             | 240  | 230  | 240  | 237                                           | 57.67                                                       |
| 18  | 11  | 375                              | 3                            | 108                                   | 550                                             | 210  | 210  | 220  | 213                                           | 61.27                                                       |
| 6   | 12  | 500                              | 2                            | 138                                   | 560                                             | 270  | 260  | 260  | 263                                           | 53.03                                                       |
| 13  | 13  | 375                              | 3                            | 48                                    | 570                                             | 290  | 280  | 290  | 287                                           | 48.75                                                       |
| 8   | 14  | 500                              | 4                            | 138                                   | 540                                             | 200  | 190  | 200  | 197                                           | 63.51                                                       |
| 3   | 15  | 250                              | 4                            | 78                                    | 550                                             | 230  | 230  | 220  | 227                                           | 58.72                                                       |
| 19  | 16  | 375                              | 3                            | 108                                   | 540                                             | 170  | 160  | 170  | 167                                           | 69.07                                                       |
| 20  | 17  | 375                              | 3                            | 108                                   | 560                                             | 160  | 160  | 170  | 163                                           | 70.89                                                       |
| 2   | 18  | 500                              | 2                            | 78                                    | 560                                             | 340  | 350  | 340  | 343                                           | 38.75                                                       |
| 7   | 19  | 250                              | 4                            | 138                                   | 570                                             | 310  | 320  | 320  | 317                                           | 44.38                                                       |
| 11  | 20  | 375                              | 1                            | 108                                   | 540                                             | 310  | 310  | 320  | 307                                           | 43.14                                                       |

Further, the confidence level of the regression model is 95 % to verify the efficacy of the model. The F-level test from analysis of variance (ANOVA) is performed for the identification of the implied regression equation to strengthen the relationship between the %  $\Delta R_a$  and the process parameters. The % improvement in surface finish (%  $\Delta R_a$ ) can be calculated using Eq. (5.2). In the present work, the second order mathematical regression model (Eq. 6.11) is utilized for analyzing the effect of the process parameter and the %  $\Delta R_a$ .

$$\% \Delta R_a = -71.89 + 0.129T + 34.29I + 0.94W - 3.8 \times 10^{-4}T^2 - 4.56I^2 - 3.69 \times 10^{-3}W^2 - 0.029TI - 8.33 \times 10^{-4}TW + 0.12IW \quad (6.11)$$

where  $T$  is the tool rotation in rpm,  $I$  is the magnetizing current in A and  $W$  is the workpiece rotation in rpm.

The  $\% \Delta R_a$  predicted is calculated for each experimentation trial using Eq. (5.2), and is further compared with the experimental values. The closeness amid the predicted and experimental values gets authenticated from the model as the R-squared value is 94.07 % and Adj R-squared is 88.74 % value showing the accuracy of the model. Further each significant parameter's effect on the output response ( $\% \Delta R_a$ ) in the terms of the percentage contribution (PC) has been analyzed using Eq. (5.6) and reported in Table 6.17. Further, after the regression analysis, the outcomes of the various significant parameters have been discussed further.

**Table 6.17.** ANOVA analysis for % change in surface roughness ( $\% \Delta R_a$ ).

| Source      | Sum of Squares | DF | Mean Square | F value | Prob>F   | PC (Eq. 5.6)    |
|-------------|----------------|----|-------------|---------|----------|-----------------|
| Model       | 1951.93        | 9  | 216.88      | 17.63   | < 0.0001 | significant     |
| $T$         | 115.56         | 1  | 115.56      | 9.39    | 0.0119   | 4.68            |
| $I$         | 232.56         | 1  | 232.56      | 18.90   | 0.0014   | 9.42            |
| $W$         | 68.06          | 1  | 68.06       | 5.53    | 0.0405   | 2.75            |
| $T^2$       | 888.08         | 1  | 888.08      | 72.19   | < 0.0001 | 35.97           |
| $I^2$       | 524.69         | 1  | 524.69      | 42.65   | < 0.0001 | 21.25           |
| $W^2$       | 276.83         | 1  | 276.83      | 22.50   | 0.0008   | 11.21           |
| $TI$        | 105.12         | 1  | 105.12      | 8.55    | 0.0152   | 4.25            |
| $TW$        | 78.12          | 1  | 78.12       | 6.35    | 0.0304   | 3.16            |
| $WI$        | 120.13         | 1  | 120.13      | 9.76    | 0.0108   | 4.86            |
| Residual    | 123.02         | 10 | 12.30       |         |          |                 |
| Lack of fit | 63.52          | 5  | 12.70       | 1.07    | 0.4723   | not significant |
| Pure error  | 59.50          | 5  | 11.90       |         |          | 2.46            |
| Cor total   | 2074.95        | 19 |             |         |          |                 |

All the significant factors involved in Eq. (6.18) influence the response model developed from the RSM analysis in this work. To evaluate the value of the effect of significant factors on the response model, the substitution of values of process parameters is done in Eq. (6.11) and values are pictorially represented as in Fig. 6.27. In this section, the combined effect of the significant interacting factors on the  $\% \Delta R_a$  is discussed.

#### 6.4.3.1 Effect of significant parameters on $\% \Delta R_a$

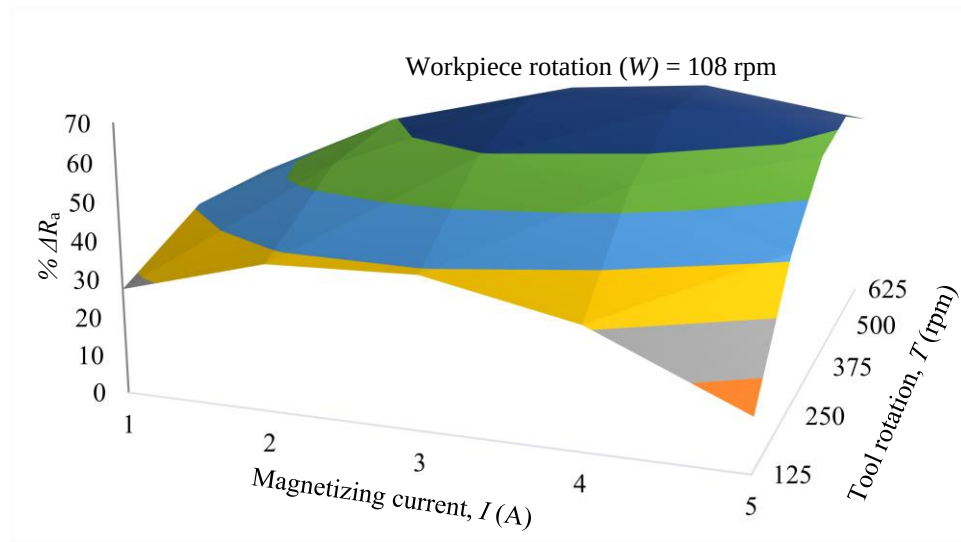
The effect of hemispherical tool rotational speed ( $T$ ) and magnetizing current ( $I$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.27(a). The workpiece rotational speed ( $W$ ) is kept constant at 108 rpm. It can be observed that as the  $T$  and  $I$  are upsurged initially, there is an increase in the trendline of the  $\% \Delta R_a$ . However, beyond the optimal value of  $T$  and  $W$  simultaneously, the trendline of  $\% \Delta R_a$  starts decreasing. As the tool rotation and magnetizing current increase simultaneously, there is an



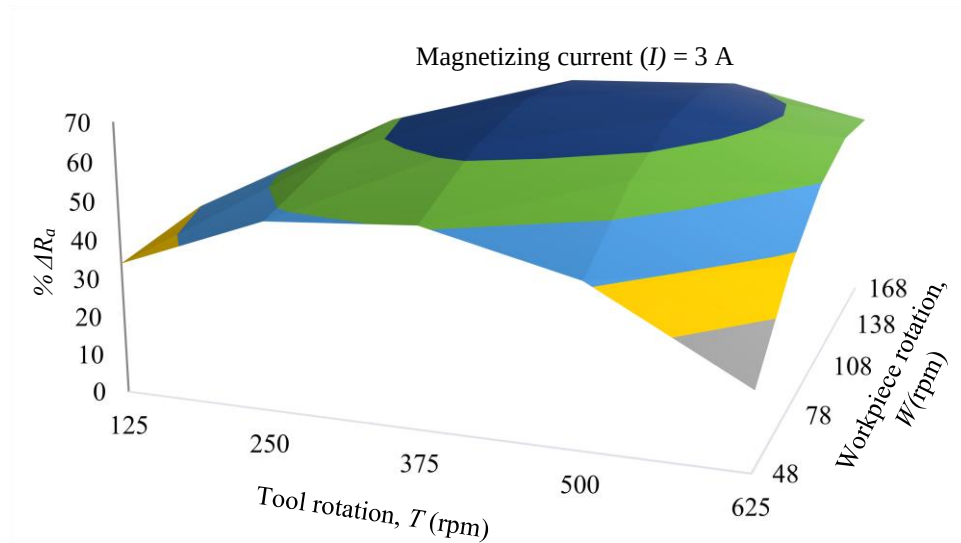
upsurge in the resultant force acting on the AAPs present over the valve seat work part surface. Owing to this, the tightly gripped AAPs in the EIPs chains tend to move outwards leading to the upsurge in the shearing off the asperities from the workpiece surface leading to the fine finish. However, beyond the optimum values, the further increase in the  $I$  along with  $T$  leads to higher resultant force. As a result, AAPs which are gripped in the EIPs chain during finishing not only shear off the asperities but also deteriorate the polymer valve seat surface leading to the formation of pits. This reduces the quality of the surface and reduces the surface finish.

The simultaneous effect of hemispherical tool rotational speed ( $T$ ) and workpiece rotational speed ( $W$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.27(b). The magnetizing current ( $I$ ) is kept constant at 3 A. It can be observed that as the  $T$  and  $W$  are upsurged initially, there is an increase in the trendline of the  $\% \Delta R_a$ . However, beyond the optimal value of  $T$  and  $W$  simultaneously, the trendline of  $\% \Delta R_a$  starts decreasing. As the hemispherical surface based-tool and polymer valve seat workpiece are rotated simultaneously in opposite directions, the net relative speed of the AAPs rises owing to which the tangential shearing force upsurges. Owing to this there is a rapid upsurge in the clipping off asperities from the polymer valve seat surface. Also, with the simultaneous increase in the  $T$  and  $W$ , there is an increment in the spiral length of AAP over the workpiece surface, leading to a higher finishing rate. However, beyond the optimal values at a simultaneous higher tool and workpiece rotation, the relative motion of AAPs becomes very high owing to which there is very less time for AAP to interact with the polymer valve seat surface. Due to this, there is a rapid decrease in the shearing off the asperities from the workpiece surface. Also, at a higher net relative speed of the AAPs, the net tangential shear force becomes so high that the EIPs present in the columnar structure of MR polishing fluid becomes unstable which reduces the finishing performance. Hence there is a reduction in material removal rate which decreases the surface finish.

(a)



(b)



(c)

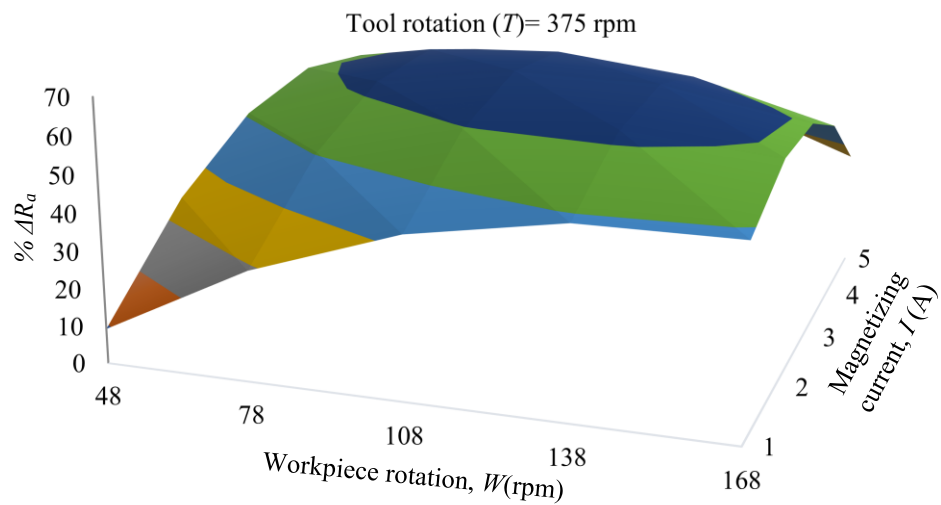


**Fig. 6.27.** Simultaneous effect of (a) magnetizing current and tool rotation, (b) tool rotation and workpiece rotation and (c) workpiece rotation and magnetizing current on %age improvement in the surface finish ( $\% \Delta R_a$ ).

The simultaneous effect of magnetizing current ( $I$ ) and workpiece rotational speed ( $W$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.27(c). The tool rotational speed ( $T$ ) is kept constant at 375 rpm. It can be observed that as the  $I$  and  $W$  are upsurged initially, there is an increase in the trendline of the  $\% \Delta R_a$ . However, beyond the optimal value of  $I$  and  $W$  simultaneously, the trendline of  $\% \Delta R_a$  starts decreasing. This is because as the  $I$  and  $W$  increase initially, there is a rise in the shear and magnetic normal force acting over the AAPs present over the valve seat surface. This leads to a higher resultant force. Owing to this there is a higher rate of collision amid the asperities of polymer valve seat surface and AAPs leading to the enhancement in the clipping off the asperities. Hence there is a rise in material removal rate leading to the fine surface finish. However, beyond the optimum value as the  $I$  and  $W$  are further increased simultaneously, there is a reduction in the  $\% \Delta R_a$ . This is because, with the further upsurge in the  $W$  along with  $I$ , there is a decrease in the interaction time for which tightly gripped AAPs shear off the roughness asperities present over the valve seat surface. This decreases the removal of material from the workpieces which reduces the surface finish.

The primary objective of the current work is the fine finishing of the polymer valve seat surface using the present magnetorheological finishing process. Further, from the complete analysis of the RSM study, the optimum process parameters obtained for fine finishing of the polymer valve seat are as  $T= 375$  rpm,  $W= 108$  rpm and  $I= 3$  A. Next, five further experimentations were conducted to validate the repeatability of the present regression model obtained by the implementation of the RSM technique.

**Table 6.18.** Confirmation tests and their comparison with the results.

| S. No. | Tool rotation, $T$ (rpm) | Magnetizing current, $I$ (A) | Workpiece rotation, $W$ (rpm) | Experimental $\% \Delta R_a$ Eq. (5.2) | Predicted $\% \Delta R_a$ Eq. (6.11) | $\% Error$ Eq. (6.3) |
|--------|--------------------------|------------------------------|-------------------------------|----------------------------------------|--------------------------------------|----------------------|
| 1      | 250                      | 2                            | 78                            | 47.36                                  | 48.59                                | -2.59                |
| 2      | 250                      | 3                            | 48                            | 45.61                                  | 48.33                                | -5.96                |
| 3      | 375                      | 4                            | 108                           | 64.91                                  | 67.35                                | -3.75                |
| 4      | 500                      | 2                            | 138                           | 59.64                                  | 58.59                                | 1.76                 |
| 5      | 125                      | 5                            | 108                           | 14.03                                  | 13.81                                | 1.01                 |

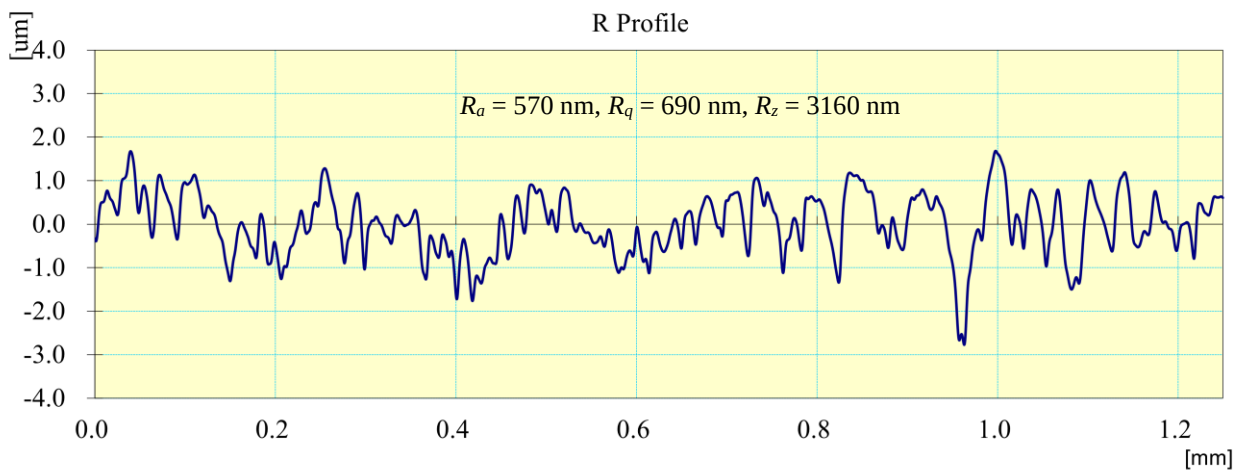
For the confirmatory experimentation, the finishing time of 60 min is taken. The parameters used for the experimentations were kept within the range of the designed experiments. The confirmatory experimentation data and their comparison with the predicted values are stated in Table 6.18. The

% error amid the predicted values and the experimental values are calculated. From their comparative study it can be said that this developed regression model is well suited for the repeatability as the error amid the predicted and experimental %  $\Delta R_a$  lies within the -5.96 % to 1.76 % which concludes that the developed regression model is decently accurate,

#### 6.4.3.2 Observation on the reduction in surface roughness of the polymer valve seat surface

Next, the finishing is performed over the polymer valve seat's total surface area of 4878 mm<sup>2</sup> until the substantial enhancement is noticed.

(a)



(b)

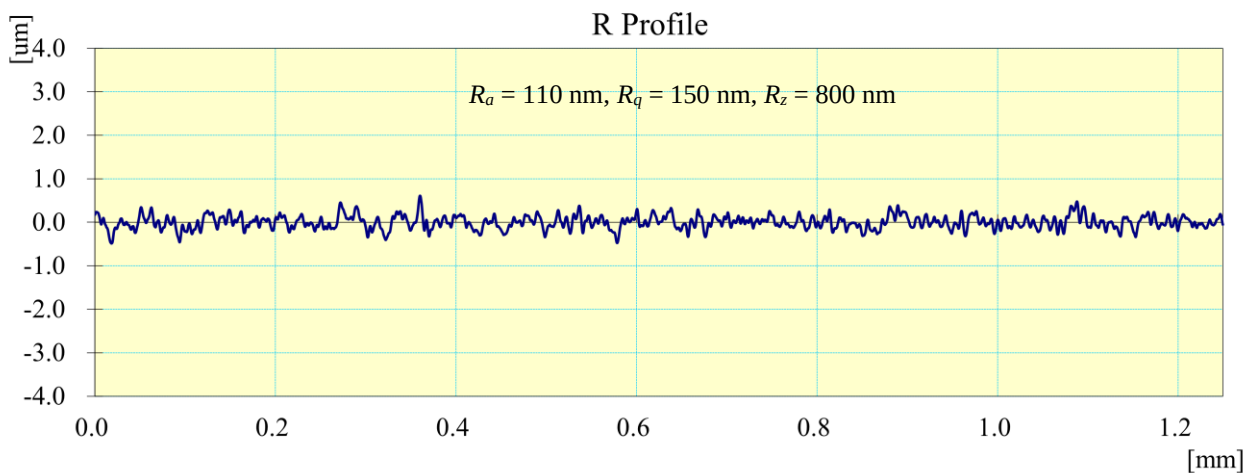


**Fig. 6.28.** Surface roughness profiles of the polymer valve seat surface with 4878 mm<sup>2</sup> surface area for (a) initial ground surface and (b) after 140 min of MR finishing of final surface at  $T=375$  rpm,  $W=108$  rpm and  $I=3$  A.

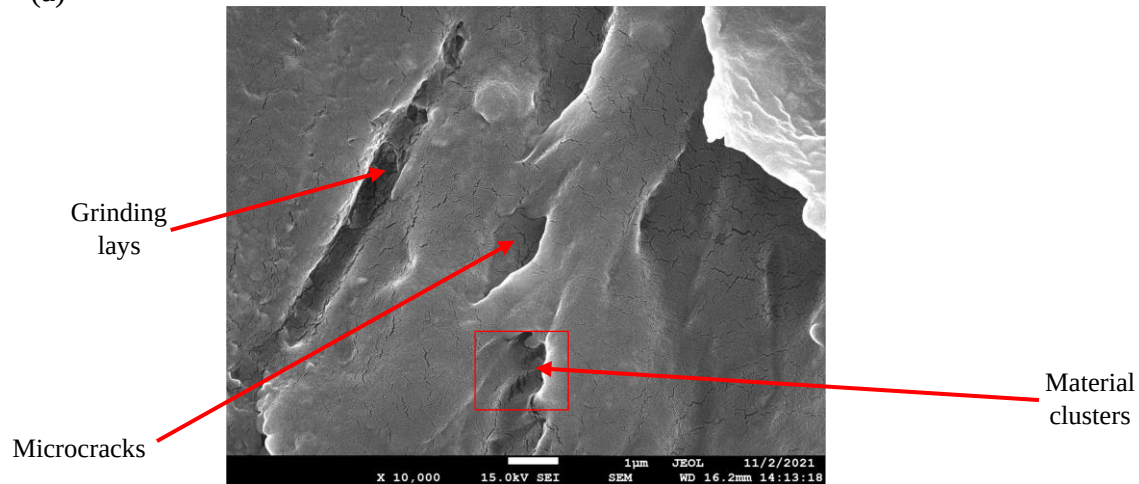
The average surface roughness value ( $R_a$ ) is reduced from 570 nm to 110 nm on the overall polymer valve seat surface in 140 min of the finishing cycle (FC) time. The FC time is taken as 20 min for each fine finishing set over the polymer valve seat. After each FC, the MR polishing fluid is changed over the hemispherical surface-based electromagnetic tool so that the polymer valve seat surface remains in contact with the freshly cut AAPs edges throughout finishing. After the completion of each finishing cycle, the  $R_a$  value is measured. Furthermore, no significant improvement was observed after 140 min of MR finishing on the polymer valve seat surface. The surface roughness (SR) profiles for the initial ground surface and the final surface of the MR finished polymer valve seat are shown in Fig. 6.28. The initial SR profile parameters measured as  $R_a = 570$  nm,  $R_q = 690$  nm, and  $R_z = 3160$  nm are shown in Fig. 6.28(a). Further, Fig. 6.28(b) depicts the SR profile of the final MR finished after 140 min of FC with optimized process parameters over the polymer valve seat's total surface of 4878 mm<sup>2</sup>. With the MRF finishing process, the final finished SR parameters on the polymer valve seat surface are measured as  $R_a = 110$  nm,  $R_q = 150$  nm, and  $R_z = 800$  nm. Thus, after 140 min of MRF on the overall polymer valve seat's total surface of 4878 mm<sup>2</sup>, the %age reduction in  $R_a$ ,  $R_q$ , and  $R_z$  is achieved as 80.70 %, 78.26 %, and 74.68 % respectively using the optimum parameters. Hence, the substantial upsurge in the surface finish can be confirmed by the degree of variation in roughness profile parameters from before and after MR finished polymer valve seat.

#### 6.4.3.3 Observation of the surface characteristics of the polymer valve seat surface

Further, to analyze the surface characteristics, the study of surface morphology is carried out using field emission scanning electron microscopy (FESEM). The FESEM micrographs at 10,000x of the initial grinding surface and after 140 min of the final MR finished polymer valve seat are depicted in Fig 6.29. Figure 6.29(a) depicts the initial polymer valve seat surface which is unevenly finished after the grinding process. There are several surface defects such as grinding lays and microcracks on the initial surface. The grinding lays and microcracks on the valve seat surface reveal the displacement of the material at different locations forming clusters. In addition, the grinding lays formed during the grinding process are non-uniform, contributing to the accumulation of worn debris. This reduces the service life of the valve seats which may lead to leakage. However, after the MR finishing is performed on the overall polymer valve seat surface area of 4878 mm<sup>2</sup> with 140 min of finishing cycle, there is a significant improvement. Figure 6.29(b) indicates that the grinding and microcracks are substantially eliminated from the polymer

valve seat surface after the MR finishing (MRF). This is because, in the MRF process, under the effect of the magnetic field, the AAPs which are closely clenched in the EIPs chain shear off the asperities from the valve seat surface in a controlled manner. Also, the normal force is comparatively very low in MRF process and material is removed in the microchip form. This reduces the chances of the leakage on the valve seat surface which leads to the reduction in component failure while functioning.

(a)



(b)

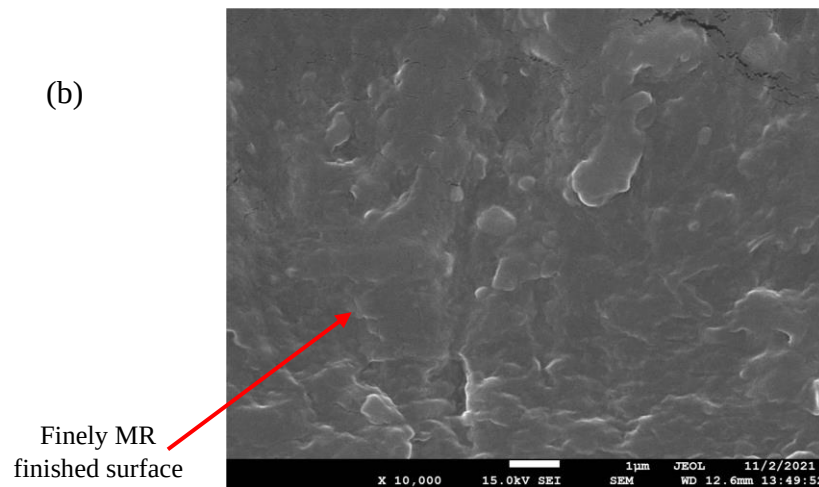


**Fig. 6.29.** Surface morphology of the polymer valve seat surface with 4878 mm<sup>2</sup> surface area for (a) initial ground surface and (b) after 140 min of MR finishing of final surface at  $T= 375$  rpm,  $W= 108$  rpm and  $I= 3$  A.

#### 6.4.3.4 Observation on the dimensional accuracy and microhardness of the polymer valve seat surface

Further, in order to avoid the leakages, the polymer valve seat should have dimensional accuracy. Hence to confirm the dimensional accuracy of the polymer valve seat, the circularity test is performed on the initial and final MR finished surface. The circularity test foresees the real circle's closeness to the polymer valve seat surface's true circle. Hence to confirm the dimensional accuracy of the polymer valve seat, the circularity test is performed on the initial and final MR finished surface. The circularity test foresees the real circle's closeness to the polymer valve seat surface's true circle. The circularity of the initial and final MR finished valve seat surface is measured using the coordinate measuring machine and results are depicted in Figs. 6.30(a) and (b) respectively.

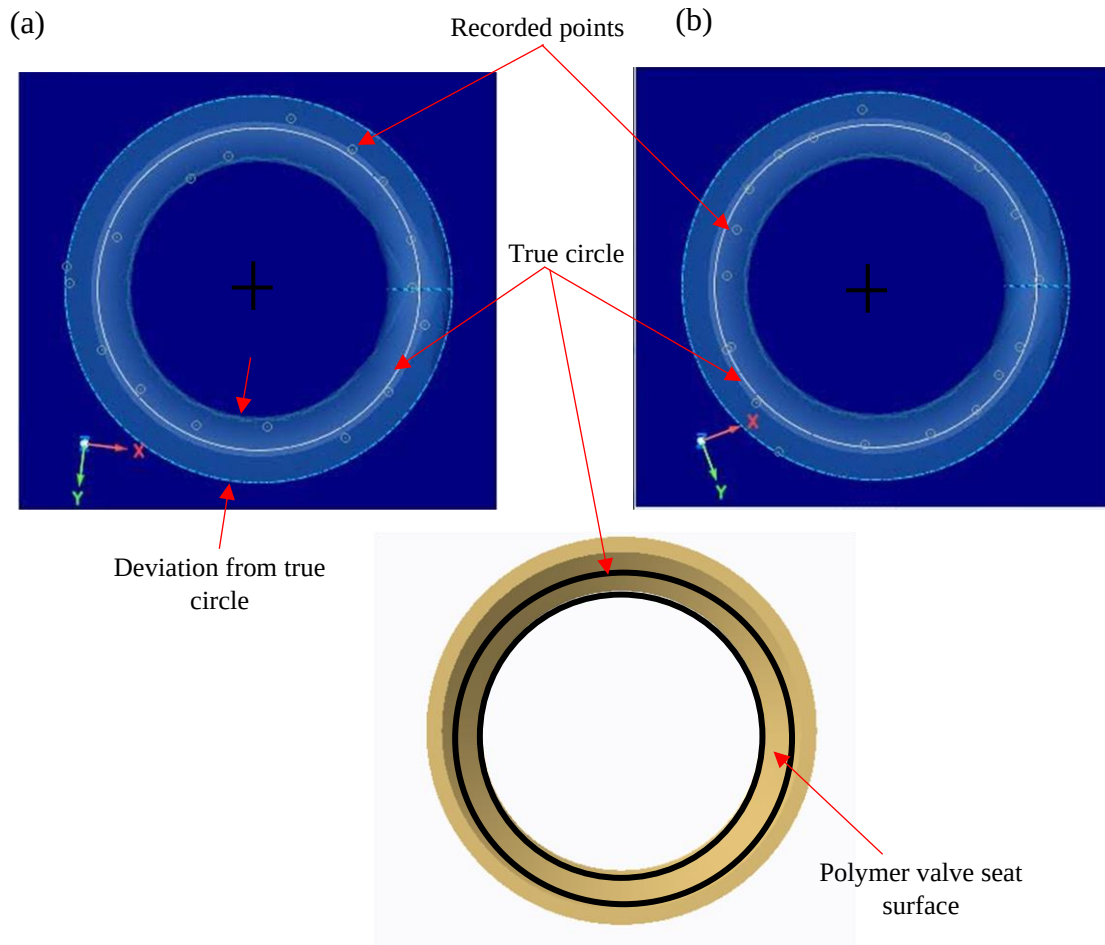


**Fig. 6.30.** Circularity images of the polymer valve seat surface with 4878 mm<sup>2</sup> surface area for (a) initial ground surface and (b) after 140 min of MR finishing of final surface at  $T= 375$  rpm,  $W= 108$  rpm and  $I= 3$  A.

From Fig. 6.30(a) it can be observed that most of the recorded points have deviated away from the true circle. Also, the circularity value is found to be 0.1045 mm. However, after the MR finishing over the polymer valve seat surface, there is a significant improvement in circularity as most of the recorded points are close to the true circle. Further, the circularity value after the MR finishing is found as 0.0560 mm as depicted in Fig. 6.30(b). The circularity results reveal the enhancement in the dimensional accuracy of the polymer valve seat surface after MR finishing which tends to reduce the chance of leakages while working. Hence improving the service life of the ball valves. Further, in the polymer valve seat higher wear rate may lead to friction which is evident in the form of loss in accuracy, and efficiency of ball valves and may eventually lead to its premature failures.

The wear rate can be calculated using Eq. (5.8). From Eq. (5.8), it is evident that as the hardness of the surface increases, the wear rate decreases. To measure the surface hardness in the present work, the Mitutoyo HM-210 model microhardness tester is used. The hardness test is performed for a dwell time of 20 seconds over the polymer valve seat surface with a 100 g load. Three indentations were done at 100 g load for initial and final MR finished polymer valve seat surfaces. Further, the average value was taken for analysis. At the initial ground surface, the hardness of the polymer valve seat surface is found as 17.32 HV. However, after the 140 min of MR finishing on the polymer valve seat with the surface area of 4878 mm<sup>2</sup> the hardness was found to be 22.31 HV. The surface hardness test reveals that the hardness of the polymer valve seat surface upsurges after the MR finishing. This is due to the fact that peaks in the initial workpiece surface have a higher peak (Fig. 6.28a) and a low concentration range. As a result, the load-bearing capability of the polymer valve seat workpiece decreases, resulting in reduced stiffness. However, after the MRF, the asperities present on the polymer valve seat surface get flattened significantly (Fig. 6.28b) resulting in an upsurge in the concentration area. As a result, the polymer valve seat surface's load bearing capability upsurges and the hardness increases. Further, as given in Eq. (5.8), when the hardness of the surface increases, the wear rate decreases. Hence, as the results show, after the MR finishing over the polymer valve seat surface, the hardness tends to upsurge. This may tend to decrease the wear rate and improves the dimensional accuracy of the ball valves.

Clinically, the above study reveals that the present MRF process with the hemispherical surface-based tool leads to the upsurge in hardness, and enhancement in circularity after a decrease in the surface roughness of the PEEK valve seat. This tends to enhance the service life, dimensional



accuracy, and efficacy of the valve seats used in ball valves for the transportation of oil and gases in different industries.

#### **6.4.4 Conclusions**

The present magnetorheological finishing (MRF) process with the hemispherical surface-based tool is capable of providing the fine finishing of the polymer valve seat surface. The ball valves with finely finished polymer valve seats can be used in industries that tend to have fuel pipelines, high-pressure air pipelines, and systems for protecting gas distributions. The enhancement in surface characteristics, microhardness, and dimensional accuracy after the reduction in the polymer valve seat surface roughness further validate the efficacy of the present MRF process. The following conclusions have been made from the MR finishing of the polymer valve seats. The optimum process parameters obtained from the parametric study such as magnetic tool rotational speed 375 rpm, workpiece rotation speed 108 rpm, and magnetizing current 3 A reveal the effective fine finishing of the polymer valve seat surface for maximum reduction in surface roughness value with the suitable magnetorheological polishing fluid.

- The optimum process parameters obtained from the parametric study such as magnetic tool rotational speed 375 rpm, workpiece rotation speed 108 rpm, and magnetizing current 3 A reveal the effective fine finishing of the polymer valve seat surface for maximum reduction in surface roughness value with the suitable magnetorheological polishing fluid.
- The significant %age reduction in roughness parameters as 80.70 %, 78.26 % and 74.68 % respectively on the overall polymer valve seat surface area of 4878 mm<sup>2</sup> with 140 min of finishing cycle with the predicted best process parameters shows the efficiency of the present MR finishing process with the hemispherical surface based tool.
- In the present work, the error obtained between the experimental and the predicted %  $\Delta R_a$  is found within – 5.96 % to 1.76 %, which concludes that the developed regression model is decently accurate, therefore, the predicted optimized process parameters for finishing the PEEK valve seats are found in good order.
- The improvement in surface morphology of the MR finished polymer valve seat surface confirms the removal of surface defects such as micro cracks, grinding lays, and accumulation of the worn debris using the present MRF process with optimized parameters that further help in the smooth operation of valve seats during their practical applications.

- The enhancement in the hardness and circularity of the MR finished valve seat surface reveals the reduction in leakage and upsurge in dimensional accuracy of the valve seat surface. This helps in the improvement of the functional efficacy of the ball valves in fuel pipelines, high-pressure air pipelines, and systems for protecting gas distributions.

## **6.5 Parametric investigation of typical additive manufactured turbine blade surface for improving its functional performance**

In today's era, with fossil fuel reserves decreasing, there is an urgent need to tap into alternative energy sources. Wind Stream (WS) energy is a viable alternative resource since it is renewable and reliable. WS is a renewable energy source that replenishes itself, making it a long-term source of energy for future generations (Herbert *et al.*, 2007). A wind turbine may be used to capture wind energy and transform it from kinetic to mechanical energy. There are two types of conventional wind turbines: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) (Balat. 2009; Islam *et al.*, 2013). HAWT has high efficacy and has a fairly straightforward operating principle (Bahaj *et al.*, 2007). However, VAWT is a popular alternative to HAWT due to its omnidirectionality, which is beneficial in wind streams where the flow direction changes every six hours (Priegue and Stoesser, 2017). Despite their benefits, VAWT has gotten less attention owing to certain drawbacks such as non-uniform surface roughness and wear which leads to a significant upsurge in erosion and a decrease in the service life of blades under high pressure and temperature condition while functioning. Studies have shown that the higher blade surface roughness can effectively reduce the efficacy of wind turbines (Bai *et al.*, 2014). Hence fine surface finishing plays an important role to enhance the service life of the wind turbine blades with improved dimensional accuracy and an upsurge in efficacy.

Therefore, an attempt has been made to fine finish the additive manufactured typical wind turbine blade workpiece surface with improved dimensional accuracy using the MRF process with the novel hexagonal tip-based magnetic finishing tool *Chapter 3 (section 3.1.3)*. The prediction of the functional efficacy of the present MRF finishing process is done on the basis of the theoretical analysis and the mechanism of material removal during AM typical wind turbine blade workpiece finishing. Finally, the optimum process parameters of the present MRF process are predicted for the fine finishing of the additive manufactured typical wind turbine blade. Also, the theoretical model for fine finishing of AM typical wind turbine blade workpiece developed in *Chapter 4 (section 4.3)* is experimentally validated. The surface roughness reduction, and surface

characteristics, are investigated after final MR finishing over the blade surface. The present MRF process with the novel hexagonal tip-based magnetic finishing tool tends to enhance the additive manufactured typical wind turbine blade life by providing fine finishing with improved functional efficacy.

#### **6.5.1 Material and methods**

In the present study, the typical wind turbine blades are manufactured using the additive manufacturing (AM) process named fused deposition modeling (FDM). The acrylonitrile butadiene styrene (ABS) rods are used in this study. The specification of the AM typical wind turbine blades is a length of 200 mm, a width of 20 mm, a building time 10 hrs, a layer height of 100 microns, and a printing speed of 100 mm/s. The properties of ABS such as high strength, durability, low heat, and electrical conductivity, corrosion-resistant, and low cost make them beneficial for various industrial polymer components. Nowadays, the AM process is significantly used in various industries such as automobile, medical, aerospace, textile, marine, etc. for manufacturing the various complex shapes of polymer components in minimum time. To fabricate the FDM cylindrical workpieces, initially, a 3-D CAD model is made using Creo Parametric 5.0. Further, the workpieces are cleaned using acetone and maintained properly before the magnetorheological (MR) fluid-based finishing. The AM fabricated typical wind turbine blades along with dimensions are depicted in Fig. 6.31.

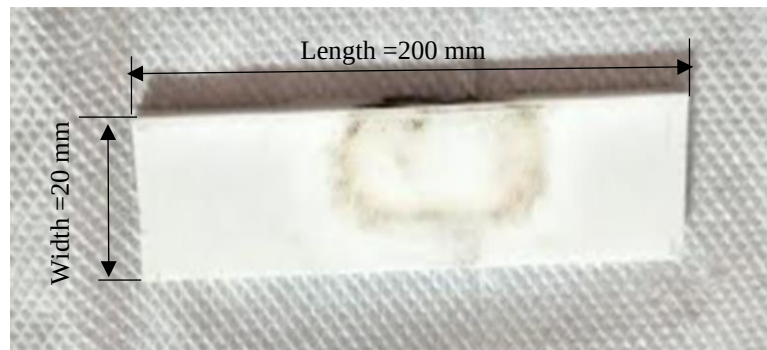
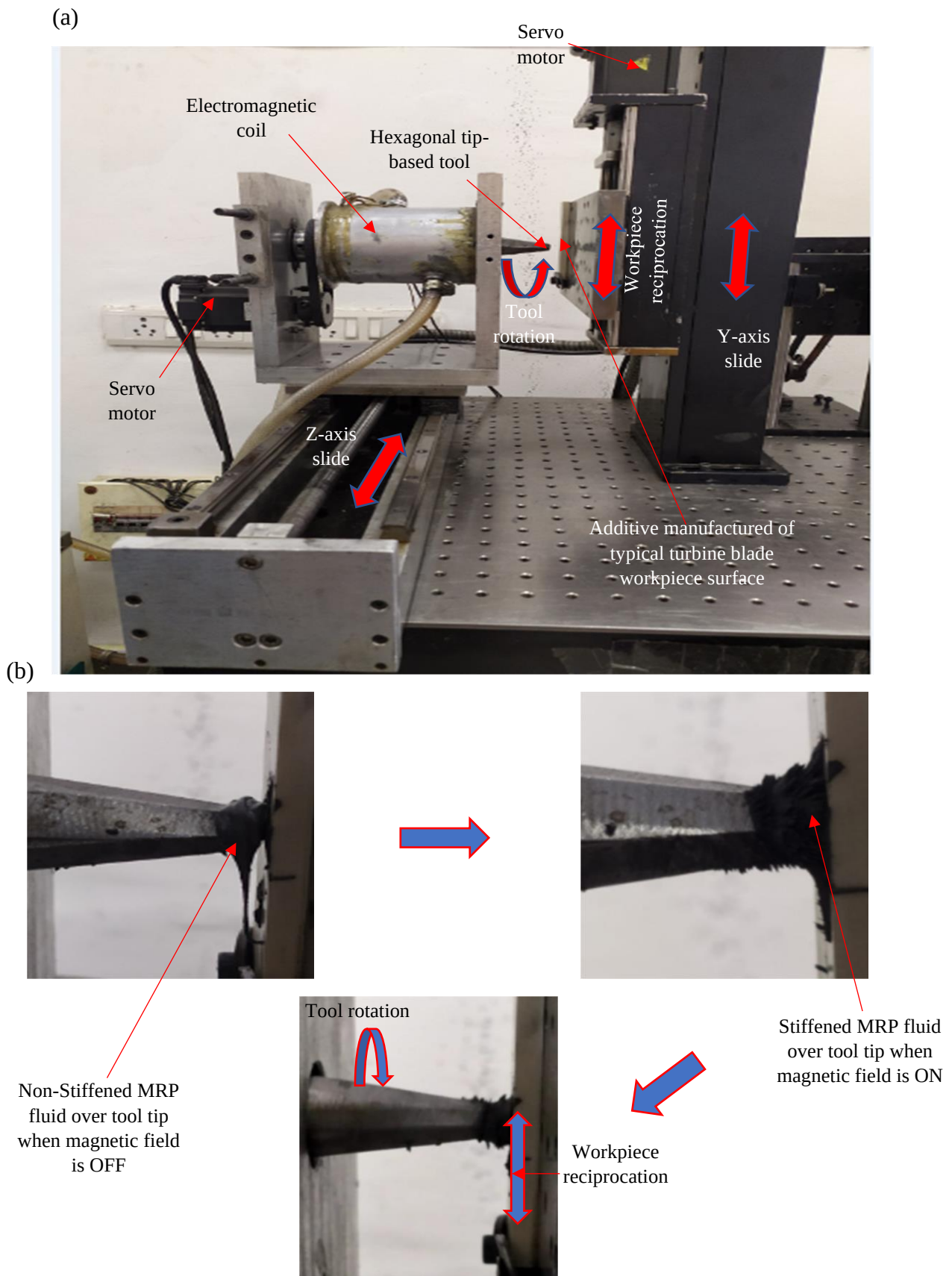


**Fig. 6.31.** Photographic image of the AM typical polymer turbine blade work part.

#### **6.5.2 Experimentation**

The present experimental set-up for fine finishing of the AM typical wind turbine blade workpiece surface is demonstrated in Fig. 6.32(a). For the fine finishing of the AM fabricated typical wind turbine blades surface, a hexagonal tip based electromagnetic tool is used. The design of hexagonal tip-based tool has been discussed in *Chapter 3 (section 3.1.3)*.



Two types of motion are utilized for fine finishing of the AM typical wind turbine blades workpiece naming rotary motion of the tool and reciprocatory motion of the workpiece. Under the magnetic field, the MRP fluid's resistance tends to increase the viscosity, causing the MRP fluid to become semi-solid as depicted in Fig. 6.32(b). Hence, upsurging the MRP fluid's yield stress. The AAPs are tightly held in the EIPs chain structure at the same time, and when these AAPs are rotated along with the reciprocate workpiece (Fig. 6.32b), the surface asperities are chipped off. As a result, the current experimental setup improves the overall surface finish of the AM typical wind turbine blades workpiece

### 6.5.3 Design of experiments

The thorough investigation in this work uses a magnetorheological finishing (MRF) process with a newly magnetic hexagonal tip-based tool to finish the AM typical wind turbine blade workpiece surface efficiently. Four parameters are utilized in the current study: magnetic tool rotational speed ( $T$ ), workpiece reciprocating speed ( $R$ ), magnetizing current ( $I$ ), and % volume concentration of graphene in the MRP fluid ( $G$ ) (*Chapter 5, section 5.4*). Further, the initial trials were also carried out to determine the different process parameter ranges for the effective finishing of the AM typical turbine blade workpiece surface with the MRF process. The Taylor Hobson Surtonic instrument is used to measure the  $R_a$  on the work part surface. Table 6.19 reports the process parameters' range that was chosen.

**Table 6.19.** Process parameters and their range.

| S. No. | Parameters                                  | Range |     |     |     |      |
|--------|---------------------------------------------|-------|-----|-----|-----|------|
| 1      | Tool rotational speed, $T$ (rpm)            | 300   | 500 | 700 | 900 | 1100 |
| 2      | Workpiece reciprocating speed, $R$ (cm/min) | 5     | 10  | 15  | 20  | 25   |
| 3      | Magnetizing current, $I$ (A)                | 1     | 2   | 3   | 4   | 5    |
| 4      | % Volume of graphene in MRP fluid, $G$      | 1     | 1.5 | 2   | 2.5 | 3    |

For the experimentation the composition of MRP fluid was taken as % volume concentration of abrasive 15 %, % volume of base fluid 60 %, % volume concentration of EIPs varies from 22 % - 24 % as per the variation of graphene (1 % - 3 %). Design of experiments (DOE) with response surface methodology (RSM) is used to analyze process parameters on the AM typical wind turbine blade workpiece surface. In the present work, five level and four parameter, central composite

design (CCD) is utilized to analyze experiments. CCD has planned 30 experiments in total, and each experiment is conducted for 60 min and the MRP fluid is changed over the hexagonal tip-based tool surface after every 20 min of the finishing. This is done in order to keep the abrasives cutting edges fresh while finishing the AM typical wind turbine blade workpiece surface. On the basis of the analysis of variance (ANOVA), the second-order mathematical regression model equation in terms of actual factors which is utilized for analyzing the effect of the process parameter on % improvement in surface finish ( $\% \Delta R_a$ ) is given by Eq. (6.12).

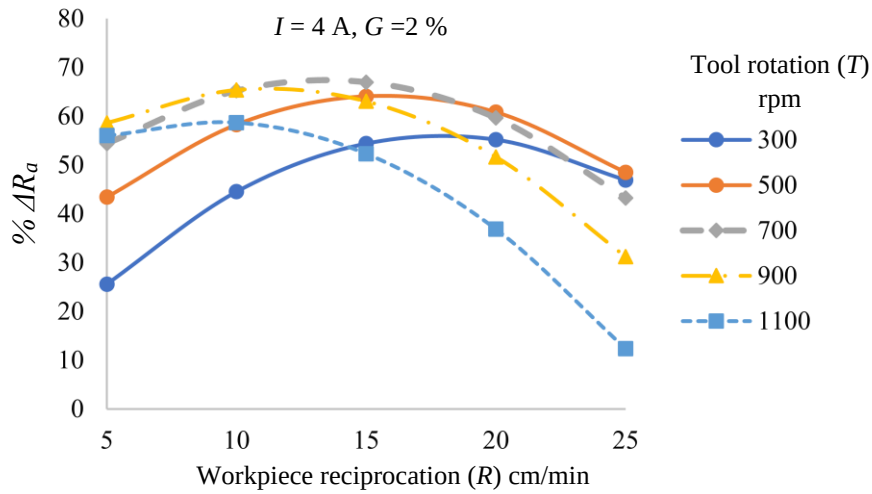
$$\% \Delta R_a = -167.539 + 0.1188 T + 7.7229 R + 26.5312 I + 91.708 G - 8.5 \times 10^{-5} T^2 - 0.1812 R^2 - 3.156 I^2 - 17.125 G^2 + 4.06 \times 10^{-3} TR + 4.1 \times 10^{-3} TI - 6.375 IG \quad (6.12)$$

where actual factors are presented as  $T$  is the tool rotation (rpm),  $R$  is the workpiece reciprocation (cm/min),  $I$  is the magnetizing current (A) and  $G$  is the % volume concentration of graphene.

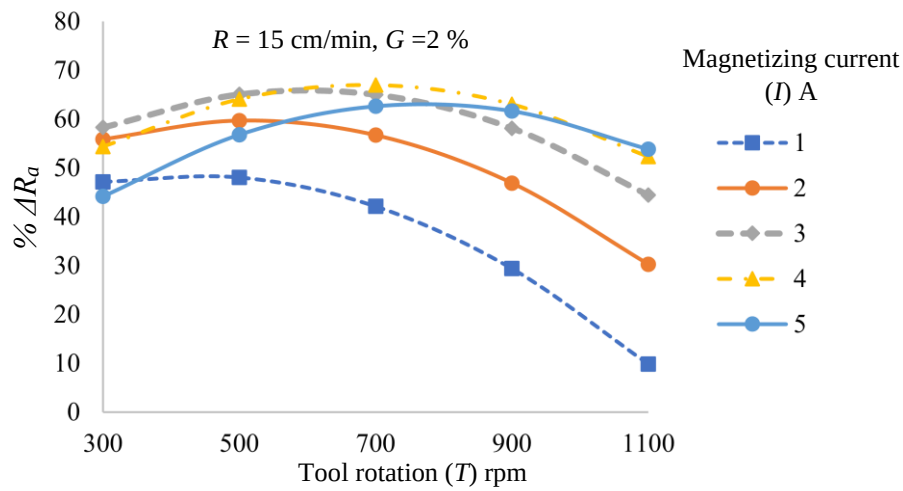
#### 6.5.4 Results and discussion

The effect of the hexagonal tip-based electromagnetic tool's rotational ( $T$ ) and workpiece reciprocatory speeds ( $R$ ) on the  $\% \Delta R_a$  are shown in Fig. 6.33(a). The  $G$  and  $I$  is kept constant at 2 %, and 4 A respectively. It is observed that initially, with the increase in the  $T$  along with the  $R$ , the trend-line of  $\% \Delta R_a$  enhances. However, with the simultaneous further increment in the  $T$  and  $R$  beyond their optimum values (700 rpm and 15 cm/min), the trend-line of  $\% \Delta R_a$  starts decreasing. When both the parameters are increased at the same time, the net relative combined motion of the AAPs increases. This further upsurges the resultant finishing force which enhances the surface finishing performance as the workpiece abrasion rate upsurges. Further, the finishing tool's rotational and along with the workpiece reciprocatory motion causes the AAPs to travel along the path, forming a spiral raster on the finishing workpiece surface. The AAPs cover a longer spiral raster path as the tool rotation and workpiece reciprocatory speeds increases during finishing. Traveling off the AAPs and along the spiral raster leads in a longer path length, which increases the material removal rate even. Owing to which the trend line of the  $\% \Delta R_a$  increases. However, on further increase in the tool rotation along with the workpiece reciprocation, the trend line of  $\% \Delta R_a$  decreases. This is because, with the further upsurge in  $T$  and  $R$ , the spiral raster path length followed by an AAP reduces. As a result, the AAP's interaction with the finishing surface has a short duration, resulting in less material removal. Hence the trend line of  $\% \Delta R_a$  decreases.

(a)



(b)



(c)

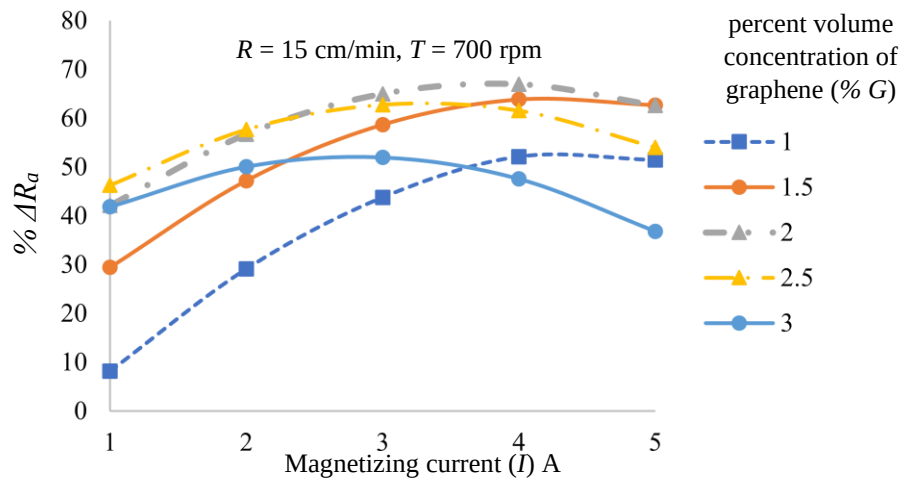


**Fig. 6.33.** Combined effect of (a) Tool rotation and workpiece reciprocation, (b) tool rotation and magnetizing current and (c) magnetizing current and  $\%$  graphene volume on  $\% \Delta R_a$ .

The finishing process is based on the material's abrasion from finishing the workpiece surface by the AAPs. As a result, while abrading materials, the time duration of the AAPs interaction with the workpiece's finishing surface plays a significant role. Hence as the interaction time decreases with the further upsurge in  $T$  and  $R$ , the material removal rate decreases.

The effect of hexagonal tool rotational speed ( $T$ ) and magnetizing current ( $I$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.33(b). The  $G$  and  $R$  are kept constant at 2 %, and 15 cm/min, respectively. It can be seen that when the  $T$  and  $I$  are upsurged initially, the  $\% \Delta R_a$  trendline increases. However, beyond the optimal value (700 rpm and 4 A) of  $T$  and  $I$  simultaneously, the trendline of  $\% \Delta R_a$  starts decreasing. As the tool rotation and magnetizing current increase simultaneously, there is an upsurge in the net tangential force and magnetic force acting on the AAPs present over the work part surface. Owing to this, the tightly gripped AAPs move outwards leading to the upsurge in the clipping off the roughness peaks present on the workpiece surface leading to the fine finish. However, beyond the optimum values, the further increase in the  $I$  along with  $T$  leads to higher resultant force. As a result, AAPs entrenched in the EIPs chain during finishing shear off the asperities while simultaneously deteriorating the workpiece surface, resulting in pit formation. This reduces the quality of the surface and reduces the surface finish. Hence, the trend of the  $\% \Delta R_a$  starts decreasing.

The effect of the percent volume concentration of graphene in MRP fluid ( $G$ ) and magnetizing current ( $I$ ) on the  $\% \Delta R_a$  is depicted in Fig. 6.33(c). The  $T$  and  $R$  is kept constant at 700 rpm and 15 cm/min respectively. It can be seen that as the parameters  $\% G$  and  $I$  upsurge at the same time, the trend of the  $\% \Delta R_a$  increases. However, the trend of the  $\% \Delta R_a$  decreases after 2 % vol concentration of graphene particles and 4 A magnetizing current. Increasing both the parameters simultaneously upsurgs the MRP fluid shear strength. This results the strong gripping of the AAPs in the EIPs chain which results in enhancement in shearing off the roughness asperities from the work part surface. hence, the material removal rate increases leading in the trendline of the  $\% \Delta R_a$ . However, as the  $\% G$  and  $I$  are further increases, the number of graphene particles that become tangled between the EIPs and abrasive increases. As a result, the EIPs lattice structure became weaker, lowering the shear strength of the MR fluid. This leads to a decrease in the MRP fluid's strength. Owing to this there is a reduction in material removal rate which decreases the trend of  $\% \Delta R_a$ . The effects of various process factors on  $\% \Delta R_a$  are studied to determine the optimal values. To maximize the  $\% \Delta R_a$ , the quadratic model equation (Eq. 6.12) is utilized following the



regression analysis. The optimized parameters for AM typical turbine blade workpiece surface finishing were found as  $T = 700$  rpm,  $R = 15$  cm/min,  $I = 4$  A, and  $G = 2$  % .

#### 6.5.4.1 Observation of the reduction in surface roughness of the additive manufactured (AM) typical turbine blade workpiece

Next, the finishing is performed over the AM typical turbine blade workpiece until a substantial enhancement is noticed. The average surface roughness value ( $R_a$ ) is reduced from 751 nm to 101 nm on the overall AM typical turbine blade workpiece in 120 min of finishing cycle (FC) time. The FC time is taken as 20 min for each fine finishing set over AM typical turbine blade workpiece.

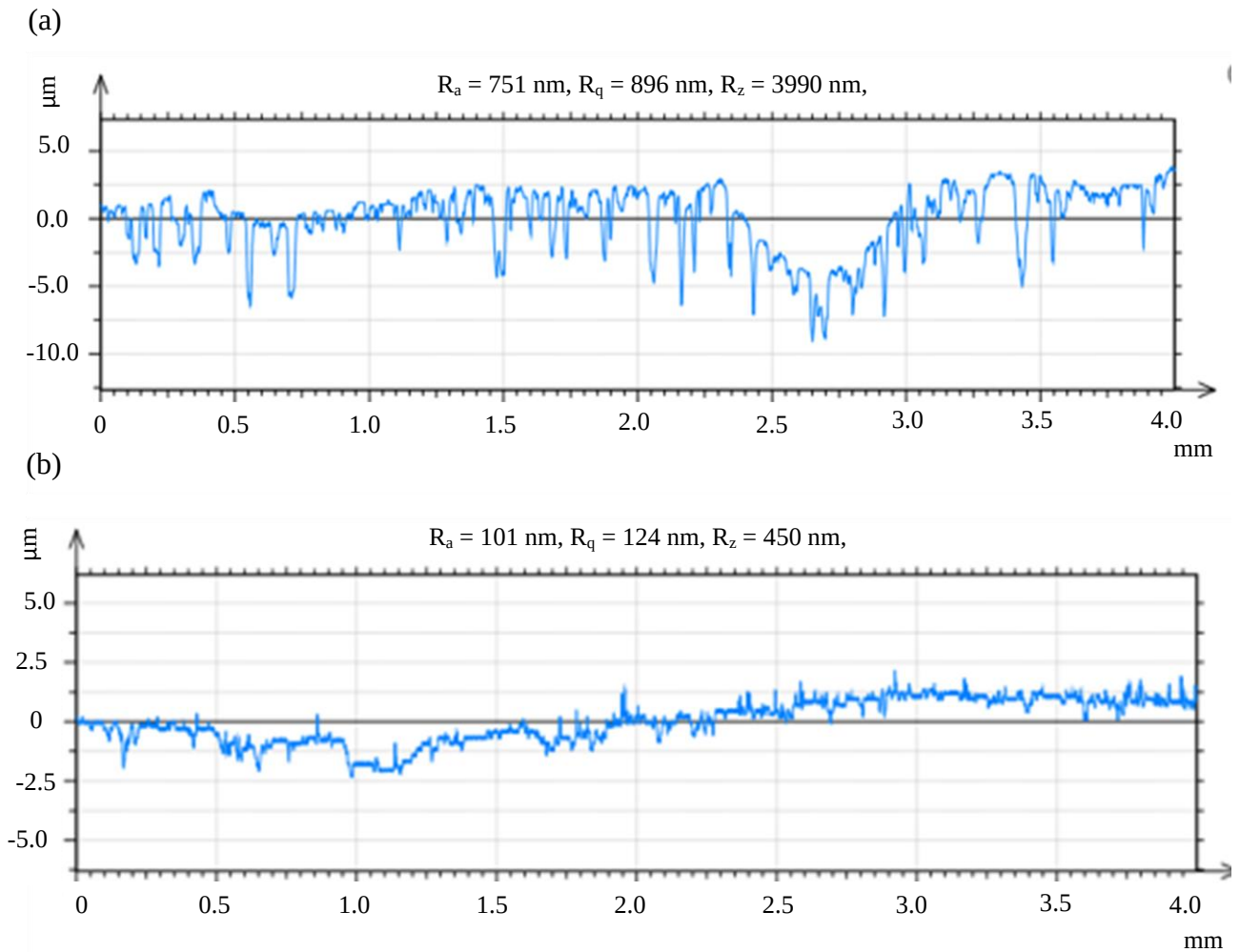


**Fig. 6.34.** Surface roughness profile of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the AM typical blade surface (width of 20 mm and length of 200 mm) with 120 min of finishing with the parameters at  $T = 700$  rpm,  $R = 15$  cm/min,  $I = 4$  A, and  $G = 2$  %.

After each FC, the MR polishing fluid is changed over the hexagonal tip surface-based electromagnetic tool so that the AM typical turbine blade workpiece remains in contact with the freshly cut AAPs edges throughout finishing. After the completion of each finishing cycle, the  $R_a$  value is measured. Furthermore, no significant improvement was observed after 120 min of MR finishing on the workpiece surface. The surface roughness (SR) profiles for the initial ground surface and the final surface of the MR finished polymer valve seat are shown in Fig. 6.34. The initial SR profile parameters measured as  $R_a = 751$  nm,  $R_q = 896$  nm, and  $R_z = 3990$  nm are shown in Fig. 6.34(a). Further, Fig. 6.34(b) depicts the SR profile of the final MR finished after 120 min of FC with optimised process parameters over the polymer AM typical turbine blade workpiece. With the MR finishing process, the final finished SR parameters on AM typical turbine blade workpiece are measured as  $R_a = 101$  nm,  $R_q = 124$  nm, and  $R_z = 450$  nm. Thus, after 120 min of MRF on the overall AM typical turbine blade workpiece, the %age reduction in  $R_a$ ,  $R_q$ , and  $R_z$  is achieved as 86.55 %, 86.16 % and 88.72 % respectively using the optimum parameters. Hence, the substantial upsurge in the surface finish can be confirmed by the degree of variation in SR profile parameters from before and after MR finished polymer valve seat.

#### *6.5.4.2 Observation on the surface characteristics of the additive manufactured (AM) typical turbine blade workpiece*

Further, the surface morphology of AM typical wind turbine blade surface is studied using scanning micrographs of the original ground surface and final finished after min of MRF as shown in Fig. 6.35. Figure 6.35(a) illustrates the AM typical wind turbine blade surface after grinding which is unevenly finished. There are different surface flaws on the original surface, such as grinding layers and scratch marks. The material displacement reveals that these markings on the original surface form clusters. Furthermore, the non-uniform grinding lays generated during the grinding process contribute to the buildup of worn debris. However, the subsequent ABS material's fused layer has been entirely flattened, with visible scratch marks. Further, after the MRF process is performed on the AM typical wind turbine blade in 120 min of the finishing cycle, the substantial enhancement in the surface characteristics can be observed. Figure 6.35(b) indicates that the grinding and scratch marks are substantially eliminated from the after the MRF. This is because, the AAPs that are tightly gripped in the EIPs chain shear off the asperities from the workpiece surface in a controlled way under the influence of the magnetic field in the MRF

process. Furthermore, the normal force is relatively low, and material removal occurs in the microchip form. The significant improvement in the surface characteristics of AM typical wind turbine blade surface tends to enhance the service life of the components in comparison to the ground workpiece surface during working conditions.

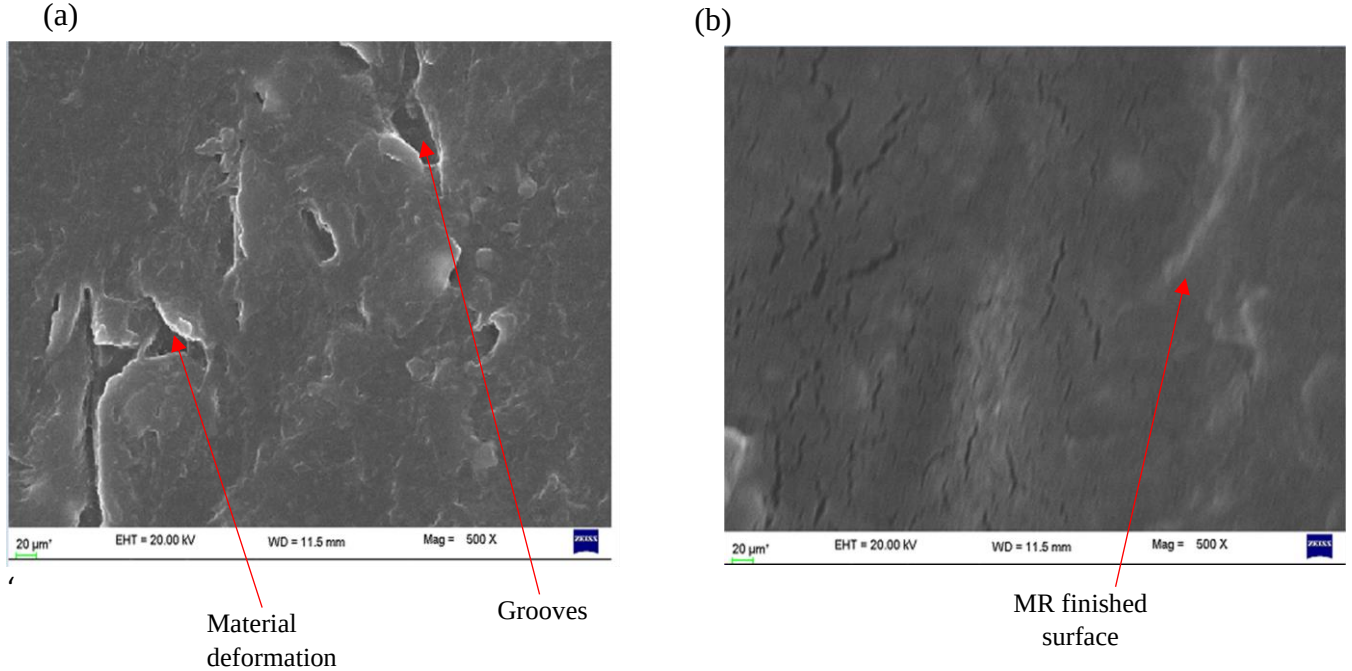


**Fig. 6.35.** Surface morphology of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the AM typical blade surface (width of 20 mm and length of 200 mm) with 120 min of finishing with the parameters at  $T = 700$  rpm,  $R = 15$  cm/min,  $I = 4$  A, and  $G = 2$  %.

#### 6.5.4.4 Experimental validation of the theoretical analysis of the reduction in surface roughness of the additive manufactured typical turbine blade using hexagonal tip based electromagnetic tool

Experiments are carried out to validate the theoretical model (Chapter 4, section 4.3) for reduction in surface roughness of the additive manufactured typical turbine blade workpiece utilizing the MR finishing process. The experiment is carried out in six cycles, each of which lasts 20 min. For the calculation of the theoretical change in roughness value, the same initial average surface roughness value was considered. The surface roughness profile of the final finished hemispherical cup work part surface was found as 101 nm after 120 min of finishing cycle as depicted in Fig 6.30(b). The work part surface is finely-finished in two phases in the present work. The indentation of the AAPs on the workpiece surface, caused by the net normal force is the initial stage. The material from the location of the work part is clipped off by the indented AAPs in the second step,

which is caused by the rotation of the electromagnetic tool and work part reciprocation. The net tangential force and the axial shear force are responsible for these motions. The range of error amid the experimentally obtained and theoretically calculated surface roughness are reported in Table 6.20. The % error is evaluated using Eq. (6.3). The % error range lies amid 9.09 % to 0.55 %, which confirms the closeness amid the experimental and theoretical value.

**Table 6.20.** Validation of the theoretical value and the experimental value of surface roughness with different number of finishing cycles.

| Number of the finishing cycle (i) | Finishing cycle time (min) | Experimental obtained $Ra$ value (nm) | Theoretical calculated $Ra$ value (nm) (Eq. 4.71) | % error (Eq. 6.3) |
|-----------------------------------|----------------------------|---------------------------------------|---------------------------------------------------|-------------------|
| 0                                 | 0                          | 751                                   | 751                                               | 0                 |
| 1                                 | 20                         | 630                                   | 644                                               | 2.22              |
| 2                                 | 40                         | 540                                   | 537                                               | 0.55              |
| 3                                 | 60                         | 410                                   | 430                                               | 4.87              |
| 4                                 | 80                         | 332                                   | 323                                               | 2.71              |
| 5                                 | 100                        | 203                                   | 216                                               | 9.09              |
| 6                                 | 120                        | 101                                   | 109                                               | 7.92              |

### 6.5.5 Conclusions

In the present study, for the fine finishing of the additive manufacturing (AM) based typical turbine blade a novel graphene based magnetorheological finishing process is used. Further, from the experimental analysis, the following conclusions have been made.

- The optimum process parameters obtained from the parametric study such as tool rotary speed as 700 rpm, workpiece reciprocatory speed as 15 cm/min, magnetizing current = 4 A, and % volume composition of graphene = 2 % reveal the effective finishing of the AM fabricated typical turbine blade surface for maximum reduction in surface roughness value.
- The reduction in surface roughness from 751 nm to 101 nm and improvement in the surface morphology images after 120 min of the finishing cycle reveals the fine finishing of the AM work part. It also reveals the significant improvement in the surface as it is free from the initial grinding marks and scratch marks after MR finishing.
- The error range between the experimentally obtained and theoretically calculated surface roughness (9.09 % to 2.71 %) is in close agreement. This validates the repeatability and effectiveness of the developed model.
- The developed experimental and theoretical analysis is found to be beneficial for the prediction of the reduction in the surface roughness value while performing MR finishing

on the AM typical turbine blade surface with improved surface finish and surface characteristics which may be beneficial for the marine industry.

### **6.6 Parametric investigation of typical Fused Deposition Modelling (FDM) manufactured external cylindric surface for improving their functional performance**

Additive manufacturing (AM) is one of the key technologies which play an important role in the third industrial revolution. AM is also highly demanded within the Industry 4.0 framework owing to its superior technology for manufacturing polymer components (Garret, 2014). The evolution of unique AM technologies has played a vital role in the production of cost-effective and difficult-to-manufacture components in industries (Vyavahare *et al.*, 2020). Nowadays, the AM process is most significantly used in industries such as medical, aerospace, textile, automobile, etc. for manufacturing the various complex shapes of polymer components in minimum time (Nagalingam *et al.*, 2020; Horáček *et al.*, 2011). The main advantage of AM over traditional manufacturing is that it gives designers and engineers more freedom in designing as only a single tool is used in AM to design an infinite number of polymer components with different shapes. Also, no specific die or tool is required for manufacturing in AM making it more suitable in different industries (Chua *et al.*, 2014). Also, there are numerous advantages offered by the AM such as easy implementation, easy support removal, and minimum usage of the product material (Singh *et al.*, 2017; Taufik and Jain, 2016). However, the usage of the AM parts in the different applications is still quite questionable due to the rough geometrical texture (poor surface finish) and poor dimension precision of the final manufactured components. The surface finish of manufactured FDM parts is poor because to residual stress and uneven shrinkage (Singh *et al.*, 2017). Also, layer-by-layer deposition in the FDM process leads to the staircase effect on the part's surface which is also one of the reasons for the poor surface finish (Pandey *et al.*, 2003). Owing to the poor surface finish and low dimensional accuracy, the functional efficacy and service life of FDM manufactured components tend to decrease which can affect the overall productivity of machines. Hence, to upsurge the efficacy of the FDM manufactured components in various industries, fine finishing plays an important role.

Therefore, to fine-finish the exterior surface of FDM-fabricated cylindrical polymer components with improved dimensional accuracy magnetorheological finishing process is used. The optimum process parameters of the current MRF process are predicted for the effective finishing of the polymer FDM parts. The surface roughness reduction, surface characteristics, and dimensional

accuracy, are investigated after final MR finishing over the FDM work part's external surface. The present MRF process with the novel hexagonal tip-based tool tends to enhance the FDM fabricated cylindric polymer workpiece surface characteristics by providing fine finishing.

#### **6.6.1. Material selection and workpiece preparation**

In the present study, the cylindrical shape acrylonitrile butadiene styrene (ABS) rods are manufactured using the FDM process. The properties of ABS such as high strength, durability, low heat, and electrical conductivity, corrosion-resistant, and low cost make them beneficial for various industrial polymer cylindrical components such as printer rollers, conveyor roller, shafts, winding drums, and rapid prototyping tools, etc. (Kerremans *et al.*, 2011; Bagalkot *et al.*, 2019). The FDM parts are fabricated in a closed system. To fabricate the FDM cylindrical workpieces, initially, a 3-D CAD model is made using Creo Parametric 5.0. Next, the primary finishing is done over the FDM fabricated cylindrical components which is beneficial for various industrial components with processes namely turning and precision external grinding process to remove the uneven marks. Before the MR finishing, the work components are also cleaned with acetone and carefully maintained. The FDM fabricated cylindrical rod along with dimensions is depicted in Fig. 6.36.

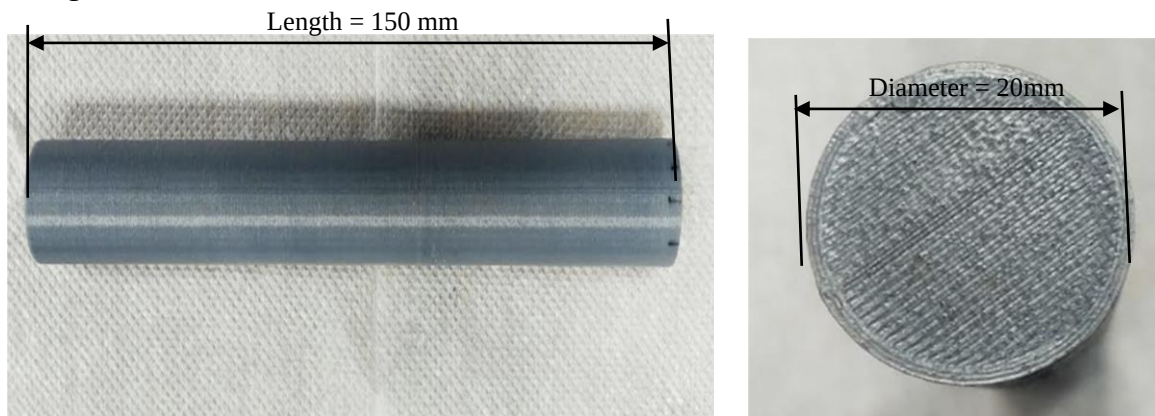


**Fig. 6.36.** FDM fabricated cylindrical rod with dimensions.

#### **6.6.2. Experimentation**

Fig. 6.37 shows the front view of the current experimental set-up for fine finishing the exterior cylindric FDM workpiece surface. Three types of motions are employed in finishing operations naming tool rotary motion (*T*), rotary motion of workpiece (*W*), and reciprocatory motion of tool (*F*). as depicted in Fig. 6.37.



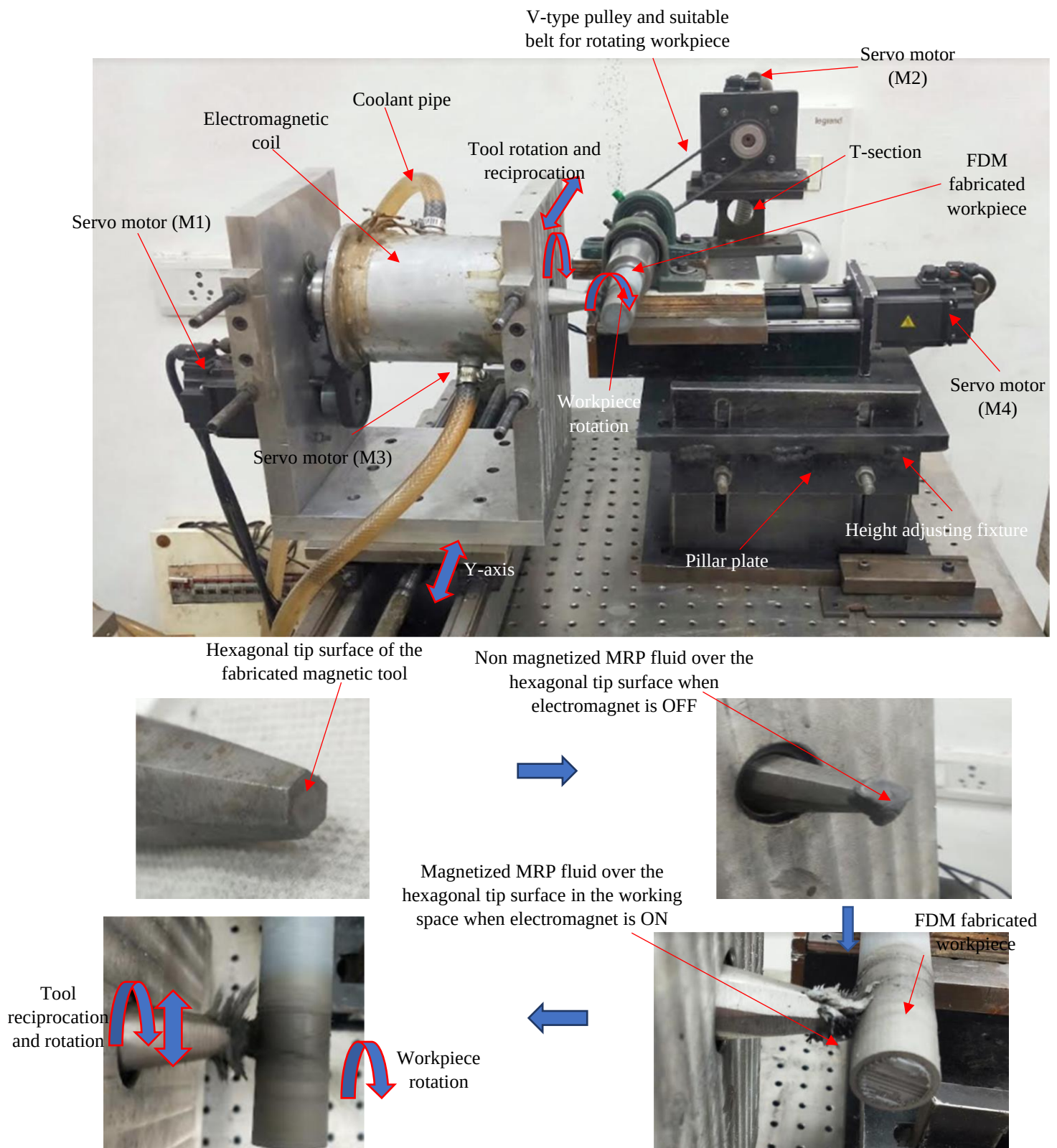


**Fig. 6.37.** Experimental setup for surface finishing of the FDM fabricated external cylindric surface using novel hexagonal tip surface -based electromagnetic tool.

Further, the abrasives, EIPs, and base fluid are mixed in the mixture for preparing the magnetorheological polishing (MRP) fluid. The MRP fluid on the tooltip surface stiffens as the magnetic current is applied, as seen in Fig. 6.37. As the magnetic field is applied during the experimentations, the EIPs get allied along the magnetic field's path, which resist the fluid stream. Under the magnetic field, the MRP fluid's resistance tends to increase the viscosity, causing the MRP fluid to become semi-solid. Hence, upsurging the MRP fluid's yield stress. The AAPs are tightly held in the EIPs chain structure at the same time, and when these AAPs are rotated and reciprocated across the rotating external cylindrical surface of the FDM workpiece (Fig. 6.37), the surface asperities are chipped off. As a result, the current experimental setup improves the surface finish.

#### 6.6.2.1 Selection of process parameters

To determine the different process parameter ranges for the effective finishing of the exterior FDM fabricated cylindrical surface with the MRF process, the initial trials were also carried out. The value of average surface roughness ( $R_a$ ) of the external cylindrical FDM ground surface is measured between 590-630 nm. The  $R_a$  is measured on the external cylindrical workpiece surface with the Mitutoyo SJ-410 instrument. The instrument's cut-off length is kept as 0.25 mm. The process parameters selected range is reported in Table 6.21.

**Table 6.21.** Process parameters and their range.

| S. No. | Parameters                             | Range |     |     |     |     |
|--------|----------------------------------------|-------|-----|-----|-----|-----|
| 1      | Tool rotational speed, $T$ (rpm)       | 100   | 200 | 300 | 400 | 500 |
| 2      | Workpiece rotational speed, $W$ (rpm)  | 10    | 20  | 30  | 40  | 50  |
| 3      | Tool reciprocating speed, $F$ (cm/min) | 5     | 10  | 15  | 20  | 25  |
| 4      | Magnetizing current, $I$ (A)           | 1     | 2   | 3   | 4   | 5   |

For the process parameters analysis on the external surface of the FDM fabricated polymer cylindric external surface, design of experiments (DOE) with response surface methodology (RSM) is used. The RSM is a set of graphical, statistical, and mathematical techniques for determining the relationship between process parameters and output response. The primary aim of the present predicted model is to analyze variance in  $\% \Delta R_a$  reduction and to increase the efficiency of the current MRF method using a novel hexagonal tip-based tool core.



**Table 6.22.** Experimentation plans and results.

| Std | Run | Tool<br>rotation<br>speed, $T$<br>(rpm) | Workpiece<br>rotation<br>speed, $W$<br>(rpm) | Tool<br>reciproca<br>tion<br>speed, $F$<br>(cm/min) | Magne<br>tizing<br>current<br>, $I$ (A) | Initial<br>average<br>surface<br>roughness<br>$R_{ai}$ (nm) | Final measured<br>average surface<br>roughness (nm) |               |               | Final<br>average<br>surface<br>roughness<br>$R_{af}$ (nm) | % $\Delta R_a$<br>(Eq. 5.2) |
|-----|-----|-----------------------------------------|----------------------------------------------|-----------------------------------------------------|-----------------------------------------|-------------------------------------------------------------|-----------------------------------------------------|---------------|---------------|-----------------------------------------------------------|-----------------------------|
|     |     |                                         |                                              |                                                     |                                         |                                                             | $X_1$<br>(nm)                                       | $X_2$<br>(nm) | $X_3$<br>(nm) |                                                           |                             |
| 17  | 1   | 100.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 590                                                         | 360                                                 | 350           | 360           | 356                                                       | 39.66                       |
| 22  | 2   | 300.00                                  | 30.00                                        | 25.00                                               | 3.00                                    | 590                                                         | 270                                                 | 260           | 270           | 267                                                       | 54.74                       |
| 30  | 3   | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 630                                                         | 240                                                 | 240           | 250           | 243                                                       | 61.42                       |
| 26  | 4   | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 620                                                         | 240                                                 | 230           | 230           | 233                                                       | 62.41                       |
| 28  | 5   | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 610                                                         | 240                                                 | 230           | 240           | 237                                                       | 61.14                       |
| 24  | 6   | 300.00                                  | 30.00                                        | 15.00                                               | 5.00                                    | 600                                                         | 400                                                 | 390           | 400           | 397                                                       | 33.83                       |
| 20  | 7   | 300.00                                  | 50.00                                        | 15.00                                               | 3.00                                    | 590                                                         | 370                                                 | 380           | 370           | 373                                                       | 36.77                       |
| 9   | 8   | 200.00                                  | 20.00                                        | 10.00                                               | 4.00                                    | 610                                                         | 330                                                 | 340           | 340           | 336                                                       | 44.91                       |
| 19  | 9   | 300.00                                  | 10.00                                        | 15.00                                               | 3.00                                    | 630                                                         | 340                                                 | 350           | 340           | 343                                                       | 45.55                       |
| 13  | 10  | 200.00                                  | 20.00                                        | 20.00                                               | 4.00                                    | 620                                                         | 330                                                 | 340           | 340           | 336                                                       | 45.80                       |
| 3   | 11  | 200.00                                  | 40.00                                        | 10.00                                               | 2.00                                    | 610                                                         | 390                                                 | 390           | 400           | 393                                                       | 35.57                       |
| 23  | 12  | 300.00                                  | 30.00                                        | 15.00                                               | 1.00                                    | 590                                                         | 300                                                 | 310           | 310           | 306                                                       | 48.13                       |
| 10  | 13  | 400.00                                  | 20.00                                        | 10.00                                               | 4.00                                    | 610                                                         | 340                                                 | 330           | 340           | 336                                                       | 44.91                       |
| 14  | 14  | 400.00                                  | 20.00                                        | 20.00                                               | 4.00                                    | 590                                                         | 310                                                 | 310           | 320           | 316                                                       | 46.44                       |
| 8   | 15  | 400.00                                  | 40.00                                        | 20.00                                               | 2.00                                    | 620                                                         | 280                                                 | 280           | 290           | 286                                                       | 53.87                       |
| 2   | 16  | 400.00                                  | 20.00                                        | 10.00                                               | 2.00                                    | 610                                                         | 400                                                 | 390           | 390           | 393                                                       | 35.57                       |
| 6   | 17  | 400.00                                  | 20.00                                        | 20.00                                               | 2.00                                    | 630                                                         | 320                                                 | 330           | 320           | 323                                                       | 48.73                       |
| 4   | 18  | 400.00                                  | 40.00                                        | 10.00                                               | 2.00                                    | 620                                                         | 370                                                 | 360           | 360           | 363                                                       | 41.45                       |
| 27  | 19  | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 600                                                         | 310                                                 | 300           | 310           | 307                                                       | 48.83                       |
| 21  | 20  | 300.00                                  | 30.00                                        | 5.00                                                | 3.00                                    | 590                                                         | 370                                                 | 370           | 360           | 367                                                       | 37.79                       |
| 5   | 21  | 200.00                                  | 20.00                                        | 20.00                                               | 2.00                                    | 630                                                         | 340                                                 | 330           | 330           | 333                                                       | 47.14                       |
| 18  | 22  | 500.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 630                                                         | 350                                                 | 340           | 340           | 343                                                       | 45.55                       |
| 25  | 23  | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 620                                                         | 250                                                 | 250           | 260           | 253                                                       | 59.19                       |
| 16  | 24  | 400.00                                  | 40.00                                        | 20.00                                               | 4.00                                    | 630                                                         | 280                                                 | 290           | 290           | 287                                                       | 54.44                       |
| 29  | 25  | 300.00                                  | 30.00                                        | 15.00                                               | 3.00                                    | 610                                                         | 240                                                 | 250           | 250           | 246                                                       | 59.67                       |
| 11  | 26  | 200.00                                  | 40.00                                        | 10.00                                               | 4.00                                    | 590                                                         | 430                                                 | 440           | 430           | 433                                                       | 26.61                       |
| 1   | 27  | 200.00                                  | 20.00                                        | 10.00                                               | 2.00                                    | 630                                                         | 300                                                 | 290           | 300           | 296                                                       | 53.01                       |
| 7   | 28  | 200.00                                  | 40.00                                        | 20.00                                               | 2.00                                    | 620                                                         | 330                                                 | 340           | 340           | 336                                                       | 45.80                       |
| 12  | 29  | 400.00                                  | 40.00                                        | 10.00                                               | 4.00                                    | 600                                                         | 390                                                 | 380           | 380           | 383                                                       | 36.16                       |
| 15  | 30  | 200.00                                  | 40.00                                        | 20.00                                               | 4.00                                    | 630                                                         | 440                                                 | 430           | 430           | 433                                                       | 31.26                       |

The relation amid the output (%  $\Delta R_a$ ) and the input independent parameters is given by Eq. (6.13).

$$\% \Delta R_a = f(T, W, F, I) \quad (6.13)$$

where  $f$  is the response function  $I$  is the magnetizing current,  $T$  is the tool rotation,  $W$  is the workpiece rotational speed and  $F$  is the tool reciprocation speed.

The composite planning in RSM adds some reliable samples based on the regression design. As a result, the number of trials is reduced, and the design experiments' orthogonality is adjusted accordingly. In the current research, with five levels and four parameters, central composite design (CCD) is utilized to analyze experiments. CCD has planned 30 experiments in total, as stated in Table 6.22. Each experiment is conducted for 60 min and the MRP fluid is changed over the hexagonal tip-based tool surface after every 20 min of the finishing. This is done in order to keep the abrasives cutting edges fresh while completing the exterior surface of the FDM produced polymer component. Further, the analysis of variance's (ANOVA) F-test is performed for identification of the implied predicted equation to strengthen the relation amid the process parameters the  $\% \Delta R_a$ . The  $\% \Delta R_a$  can be calculated using Eq. (5.2). Further, to analyse the efficacy of the present MRF process, the study of the surface roughness and waviness using Mitutoyo SJ-410 instrument, surface characteristics using scanning electron microscopy (SEM), and circularity using co-ordinate measuring machine Spectra 5.6.4 (Accurate).

### **6.6.3 Results and discussion**

A total of 30 experimentations are conducted in the present work to evaluate the effect on the outcome response ( $\% \Delta R_a$ ) of the process parameters. Since the initial  $R_a$  ( $R_{ai}$ ) values of the external surface of the FDM fabricated polymer workpiece varies from 630-590 nm, therefore the outcome is taken as percentage improvement in the surface finish ( $\% \Delta R_a$ ) for experimentations. The data of the experimentation is reported in Table 6.22. After the experimentations, three values of the average surface roughness ( $X_1$ ,  $X_2$ , and  $X_3$ ) are analyzed at three different points over the FDM fabricated external surface and reported in Table 6.22. Further, the final  $R_{af}$  value is obtained by taking the average of  $X_1$ ,  $X_2$ , and  $X_3$  which is further utilized in Eq. (5.2) for obtaining the  $\% \Delta R_a$ . Next, for developing the statistical model, ANOVA is used and reported in Table 6.23. Based on the sequential model upon performing ANOVA, the predicted model's p-value is found less than 0.05. It verifies the significance of the present predicted model. Furthermore, the p-value of the lack of fit is larger than 0.05 (0.9567), indicating that it is non-significant. Parameters with a p-value less than 0.05 are considered significant, while those with a p-value more than 0.05 are considered non-significant.

**Table 6.23.** ANOVA analysis for % improvement in surface finish (%  $\Delta R_a$ ).

| Source                | Sum of squares | Degree of freedom (DOF) | Mean square | F value | Prob>F   | Remark          | Percentage contribution (Eq. 5.6) |
|-----------------------|----------------|-------------------------|-------------|---------|----------|-----------------|-----------------------------------|
| Model                 | 2351.67        | 12                      | 195.97      | 12.63   | < 0.0001 | Significant     |                                   |
| <i>T</i>              | 80.67          | 1                       | 80.67       | 5.20    | 0.0358   |                 | 2.44                              |
| <i>W</i>              | 140.17         | 1                       | 140.17      | 9.03    | 0.0080   |                 | 4.66                              |
| <i>F</i>              | 322.67         | 1                       | 322.67      | 20.79   | 0.0003   |                 | 10.74                             |
| <i>I</i>              | 140.17         | 1                       | 140.17      | 9.03    | 0.0080   |                 | 4.66                              |
| <i>T</i> <sup>2</sup> | 411.86         | 1                       | 411.86      | 26.54   | < 0.0001 |                 | 14.46                             |
| <i>W</i> <sup>2</sup> | 495.43         | 1                       | 495.43      | 31.92   | < 0.0001 |                 | 16.33                             |
| <i>F</i> <sup>2</sup> | 267.86         | 1                       | 267.86      | 17.26   | 0.0007   |                 | 8.79                              |
| <i>I</i> <sup>2</sup> | 525.00         | 1                       | 525.00      | 33.83   | < 0.0001 |                 | 17.31                             |
| <i>TW</i>             | 240.25         | 1                       | 240.25      | 15.48   | 0.0011   |                 | 7.99                              |
| <i>TF</i>             | 72.25          | 1                       | 72.25       | 4.66    | 0.0456   |                 | 2.40                              |
| <i>TI</i>             | 81.00          | 1                       | 81.00       | 5.22    | 0.0355   |                 | 2.69                              |
| <i>WF</i>             | 72.25          | 1                       | 72.25       | 4.66    | 0.0456   |                 | 2.40                              |
| Residual              | 263.83         | 17                      | 15.52       |         |          |                 |                                   |
| Lack of fit           | 111.83         | 12                      | 9.32        | 0.31    | 0.9567   | not significant |                                   |
| Pure error            | 152.00         | 5                       | 30.40       |         |          |                 | 5.06                              |
| Cor total             | 2615.50        | 29                      |             |         |          |                 |                                   |

In the mathematical regression model, the non-significant parameters are not included and the significant parameters in actual forms are given as namely tool rotational speed (*T*), workpiece rotation (*W*), tool reciprocation speed (*F*), magnetizing current (*I*), square of tool rotational speed (*T*<sup>2</sup>), square of workpiece rotational speed (*W*<sup>2</sup>), square of tool reciprocation speed (*F*<sup>2</sup>), square of magnetizing current (*I*<sup>2</sup>), combined effect of tool and workpiece rotational speed (*TW*), combined effect of tool rotation and reciprocation speed (*TF*), combined effect of tool rotational and magnetizing current (*TI*) and combine effect of workpiece rotation and tool reciprocation (*WF*). Further, Table 6.23 states the p-value and study of ANOVA for each of the significant parameters on the output response (%  $\Delta R_a$ ). The predicted quadratic model's F-value is 12.63 (Table 6.23), which is higher than the actual F-value of 2.948, as shown by ANOVA. This confirms the significance of the present predicted model. The second-order mathematical regression model equation in terms of actual factors which is utilized for analyzing the effect of the process parameter on %  $\Delta R_a$  is given by Eq. (6.14).

$$\begin{aligned} \% \Delta R_a = & 9.75 + 3.33 \times 10^{-3} T + 0.508W + 1.933F + 17.08I - 3.875 \times 10^{-4} T^2 - \\ & 0.0425W^2 - 0.125F^2 - 4.375I^2 + 3.875 \times 10^{-3} TW + 4.25 \times 10^{-3} TF + 0.0225TI + \\ & 0.0425WF \end{aligned} \quad (6.14)$$

where actual factors are presented as  $W$  is the workpiece rotation (rpm),  $T$  is the hexagonal tip-based tool rotation (rpm),  $F$  is the reciprocation of the tool (cm/min) and  $I$  is the magnetizing current (A).

Further, the closeness amid the predicted and experimental values also gets authenticated from the model as the R-squared value is 89.91 % and Adj R-squared is 82.79 % value showing the accuracy of the model. Further each significant parameter's effect on the output response ( $\% \Delta R_a$ ) in the terms of the percentage contribution (PC) has been analyzed using Eq. (5.6). Using Eq. (5.6), the PC of process parameters is determined and reported in Table 6.23. It can be observed that PC of square of magnetizing current ( $I^2$ ) contributes majorly as 17.31 %, followed by square of workpiece rotation ( $W^2$ ) as 16.33 %, square of tool rotation ( $T^2$ ) as 14.46 %, and square of tool reciprocation ( $F^2$ ) as 8.79 %. Further, after the regression analysis, the outcomes of the various significant parameters have been discussed further.

#### 6.6.3.1 Effect of significant parameters on $\% \Delta R_a$

The effect of the finishing tool's ( $T$ ) and workpiece's ( $W$ ) rotary speeds on the percent improvement in surface finish ( $\% \Delta R_a$ ) is shown in Fig. 6.38(a). The  $F$  and  $I$  are retained at 20 cm/min and 3 A, respectively. It is observed that the trend-line of  $\% \Delta R_a$  improves initially as the tool's rotational speed ( $T$ ) and workpiece rotation ( $W$ ) increase. However, with the simultaneous further increment in the  $T$  and  $W$  beyond their optimum values, the trend-line of  $\% \Delta R_a$  starts decreasing. When  $T$  and  $W$  are increased at the same time the AAPs' net relative rotational speed rises. This results in increases the tangential shear force across the external surface of the FDM produced cylindrical surface. Due to the enhanced AAPs relative rotary speed, there is a rapid upsurge in the clipping off asperities from the workpiece surface. However, after the parameters go beyond their optimal values ( $T=300$  rpm and  $W=30$  rpm), the relative motion of AAPs becomes very high owing to which there is very little time for AAP to interact with the workpiece surface. As a result, there is a rapid decrease in the shearing off the asperities from the workpiece surface. Also, at the higher net relative speed of the AAPs, the net tangential shear force becomes so high that the EIPs present in the columnar structure of MR polishing fluid becomes unstable which reduces the finishing performance. As a result, the rate of material removal decreases, lowering the surface quality.

The effects of the hexagonal tip-based electromagnetic tool's rotational ( $T$ ) and reciprocatory speeds ( $F$ ) on the  $\% \Delta R_a$  are shown in Fig. 6.38(b). The  $W$  and  $I$  is kept constant at 30 rpm, and 3 A respectively. It is observed that initially, with the increase in the  $T$  along with the  $F$ , the trend-

line of  $\% \Delta R_a$  enhances. However, with the simultaneous further increment in the  $T$  and  $F$  beyond their optimum values, the trend-line of  $\% \Delta R_a$  starts decreasing. When both the parameters are increased at the same time, the net relative combined motion of the AAPs increases, resulting in increased shear force against the workpiece's finishing surface. This enhances the surface finishing performance as the workpiece abrasion rate upsurges. In the current work, the finishing tool's simultaneous rotational and reciprocatory action causes the AAPs to travel along the path, forming a helical shape on the finishing workpiece surface. The AAPs cover a longer helical-shaped path as the rotational and reciprocatory speeds of the tool increase throughout the finishing operation *Chapter 4 (section 4.7)*. Traveling off the AAPs and along the helical-shaped route leads in a longer path length, which increases the material removal rate even further. Owing to which the trend line of the  $\% \Delta R_a$  increases. However, on further simultaneous increase in the tool rotation and reciprocation, the trend line of  $\% \Delta R_a$  decreases. This is because, with the further upsurge in  $T$  and  $F$ , the helical-shaped path length crossed by an AAP reduces. As a result, the AAP's interaction with the finishing surface has a shorter duration, resulting in less material removal. Hence the trend line of  $\% \Delta R_a$  decreases. The finishing process is based on the material's abrasion from finishing the workpiece surface by the AAPs. As a result, while abrading materials, the time duration of the AAPs interaction with the workpiece's finishing surface plays a significant role. The effect of tool rotational speed ( $T$ ) and magnetizing current ( $I$ ) on  $\% \Delta R_a$  is depicted in Fig. 6.38(c). The  $W$  and  $F$  are constant at 30 rpm and 20 cm/min, respectively. As the  $T$  and  $I$  upsurge, there is an increment in the trendline of the  $\% \Delta R_a$ . However, after the optimal value of  $T$  and  $I$ , the trendline of the  $\% \Delta R_a$  decreases. This trend occurs because initially with the simultaneous upsurge in  $T$  and  $I$  there is an upsurge in the normal magnetic force along with the relative speed of the AAP on the helical path over the external surface of workpiece. This leads to the higher shear strength of the EIPs columnar structure in which the AAPs are tightly entrenched. Owing to this, the removal rate of the material from the workpiece surface upsurges leading to the increase in the trendline of  $\% \Delta R_a$ . However, beyond the optimal values of  $T$  and  $I$  the relative speed of the AAP overcomes overall magnetic force which leads to the loosening in the gripping of the EIPs columnar structure during surface finishing.

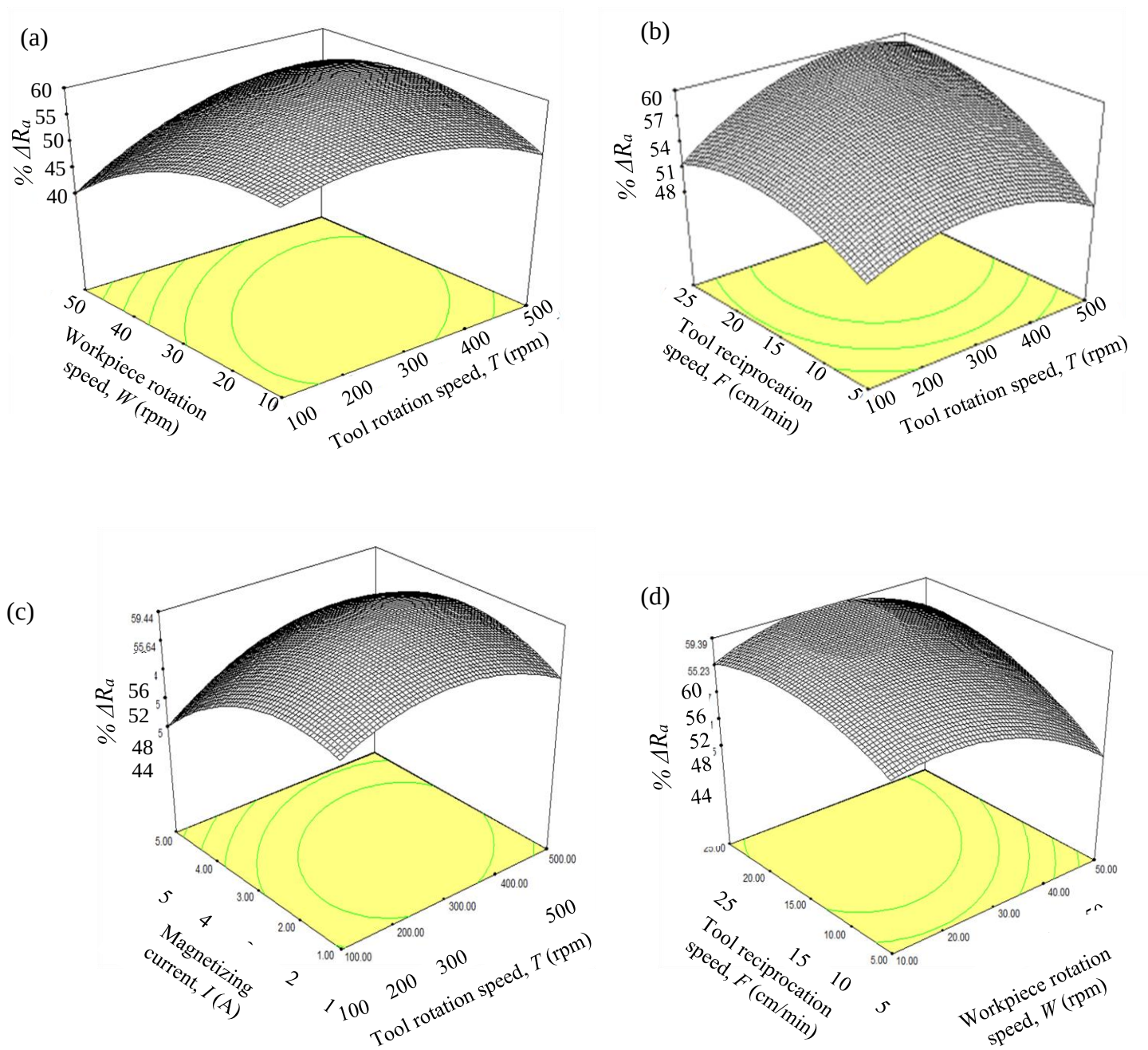


**Fig. 6.38.** Combined effect of (a) tool rotation and workpiece rotation, (b) tool rotation and tool reciprocation, (c) tool rotation and magnetizing current and (d) tool reciprocation speed and workpiece rotational speed on  $\% \Delta R_a$ .

Fig. 6.38(d) illustrates the effect of the  $W$  and  $F$  on the  $\%$  improvement in surface finish. The  $T$  and  $I$  are kept constant at 300 rpm, and 3 A respectively. It is found that initially, with the increase

in the tool's reciprocation speed ( $R$ ) along with the workpiece rotation ( $W$ ), the trend-line of  $\% \Delta R_a$  increases. However, with the simultaneous further upsurge in  $W$  and  $F$  beyond their optimum values, the trend-line of  $\% \Delta R_a$  starts decreasing. When both  $W$  and  $F$  are increased at the same time, the shear force and axial force acting on the AAPs increases. Owing to this, the interaction time of the tightly entrenched AAPs in the EIPs chain with the external from workpiece surface upsursges. As a result, the shearing off the roughness asperities from the cylindric external surface rises which leads to a higher removal rate. Hence the trend line of the  $\% \Delta R_a$  rises. However, on a further simultaneous increase in the tool rotation and reciprocation, the trend line of  $\% \Delta R_a$  decreases. The reason for the sudden decrease in the trend is that the columnar chains of the EIPs in the MRP fluid get disturbed due to the very fast to and fro motion of the tool over the workpiece surface. This leads to the deformation in the EIPs chain owing to which the EIPs may not hold the AAPs tightly. Also, at a higher speed of  $W$  along with  $R$ , the MRP fluid interacts quickly with the surface due to which AAPs get very less time for shearing the asperities from the surface of the external cylindric component. As a result, the AAPs are unable to finish the workpiece surface properly, resulting in a reduction in  $\% \Delta R_a$ . As a result, the shearing off of roughness asperities from the finishing surface is reduced, lowering the rate of material removal. Thus, the  $\% \Delta R_a$  trend line is decreasing.

In present work, initially, a novel hexagonal tip-based electromagnetic tool is developed to finish effectively the exterior FDM fabricated polymer workpiece surface. Experiments were carried out on the workpiece surface to predict the optimum process parameters for the present process by achieveing maximum  $\% \Delta R_a$  for the MRF of the external FDM fabricated polymer workpiece surface. The predicted optimum process parameters were determined using regression analysis to get the best possible outcome for the  $\% \Delta R_a$ . In order to maximize the  $\% \Delta R_a$ , the parameters were subjected to

$$100 \text{ rpm} \leq T \leq 500 \text{ rpm}$$

$$10 \text{ rpm} \leq W \leq 50 \text{ rpm}$$

$$5 \text{ cm/min} \leq R \leq 25 \text{ cm/min}$$

$$1 \text{ A} \leq I \leq 5 \text{ A}$$

The effects of various process factors on  $\% \Delta R_a$  are studied to determine the optimal values. To maximize the  $\% \Delta R_a$ , the quadratic model equation (Eq. 6.14) is utilized following the regression analysis. The best process parameters for fine finishing of the FDM fabricated external cylindrical

surface were found as  $T= 300$  rpm,  $W= 30$  rpm,  $F= 20$  cm/min, and  $I= 3$  A. Furthermore, the best parameters are utilized to fine finish the surface of an external FDM-fabricated cylindrical workpiece with a diameter of 20 mm and a length of 150 mm.

#### 6.6.3.2 Observation of reduction in surface roughness of FDM-fabricated cylindrical workpiece

The finishing is performed using the best process parameters over the  $18,840 \text{ mm}^2$  external surface area (diameter 20 mm and length 150 mm) of the FDM fabricated cylindrical component until substantial enhancement is noticed.

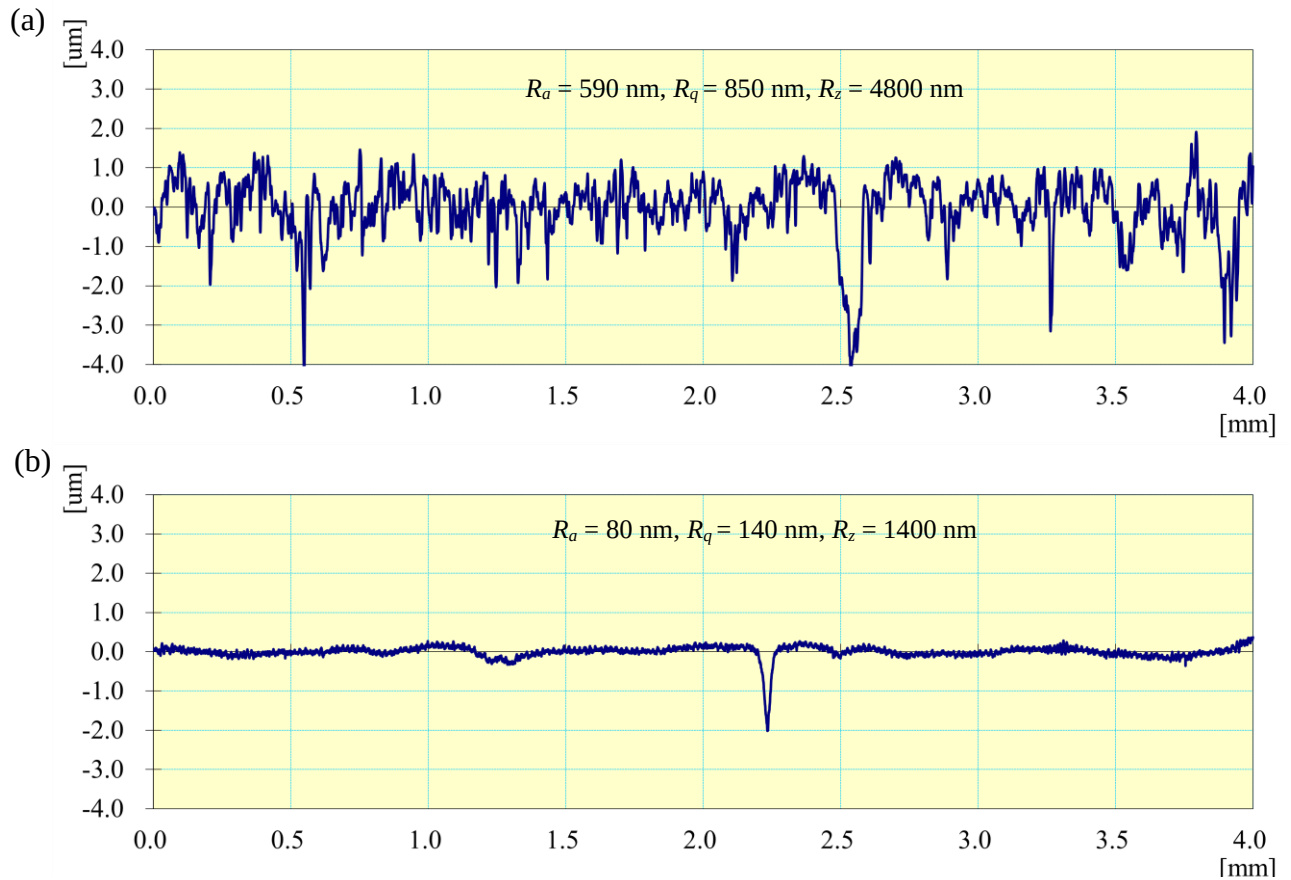


**Fig. 6.39.** Surface roughness profile of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the external FDM fabricated cylindric surface (diameter of 20 mm and length of 150 mm) with 120 min of finishing.

The  $R_a$  value is reduced from 590 nm to 80 nm on the overall external surface of the polymer workpiece in 120 min of finishing cycle (FC) time as shown in Fig. 6.39. The FC time is taken as 20 minutes for each fine finishing set over the workpiece surface. After each FC, the MRP fluid is changed over the hexagonal tip-based electromagnetic tool so that the workpiece surface remains in contact with the freshly cut AAPs edges throughout finishing. After the completion of each



finishing cycle, the  $R_a$  value is measured. Furthermore, no significant improvement was observed after 120 min of MRF on the FDM fabricated cylindric external surface. Fig. 6.39 shows the surface roughness (SR) profiles for the before and after MR finished surface. Figure 6.39(a) depicts the initial ground SR profile parameters as  $R_a = 590$  nm,  $R_q = 850$  nm,  $R_z = 4800$  nm. Further, Fig. 6.39(b) depicts the SR profile of the final MR finished after 120 min of FC with the best process parameters over the workpiece total external surface of  $18,840 \text{ mm}^2$ . With the MRF process, the final finished SR parameters on the FDM fabricated workpiece surface is measured as  $R_a = 80$  nm,  $R_q = 140$  nm,  $R_z = 1400$  nm. Thus, after 120 min of MRF on the FDM fabricated workpiece surface, the %age reduction in  $R_a$ ,  $R_q$ , and  $R_z$  is achieved as 86.44 %, 83.52 %, and 70.83 % respectively using the optimum parameters. This confirms the substantial upsurge in the surface finish by the degree of variation in SR profile parameters from before and after MR-finished FDM fabricated polymer cylindrical external surface.

#### 6.6.3.3 Observation of surface characteristics of FDM-fabricated cylindrical workpiece

Further, the optical microscopy is utilized to examine surface morphology in order to assess surface properties. On the initial surface, there are various surface defects such as grinding lays and scratch marks. These marks on the Figure 6.40 shows micrographs of the initial ground surface at 100x and the final MR finished FDM fabricated external cylindric polymer surface after 120 min. Figure 6.40(a) shows the initial workpiece's exterior cylindric surface after grinding which is unevenly finished. On the initial surface clusters are formed as revealed by the material displacement. Furthermore, the non-uniform grinding lays are generated during the grinding process contribute to the buildup of worn debris. However, the subsequent ABS material's fused layer has been entirely flattened, with visible scratch marks. Further, after the MRF process is performed on the overall external FDM cylindrical surface area of  $18,840 \text{ mm}^2$  with 120 min of the finishing cycle, the substantial enhancement in the surface characteristics can be observed. Figure 6.40(b) indicates that the grinding and scratch marks are substantially eliminated from the external cylindric FDM workpiece surface after the MRF.

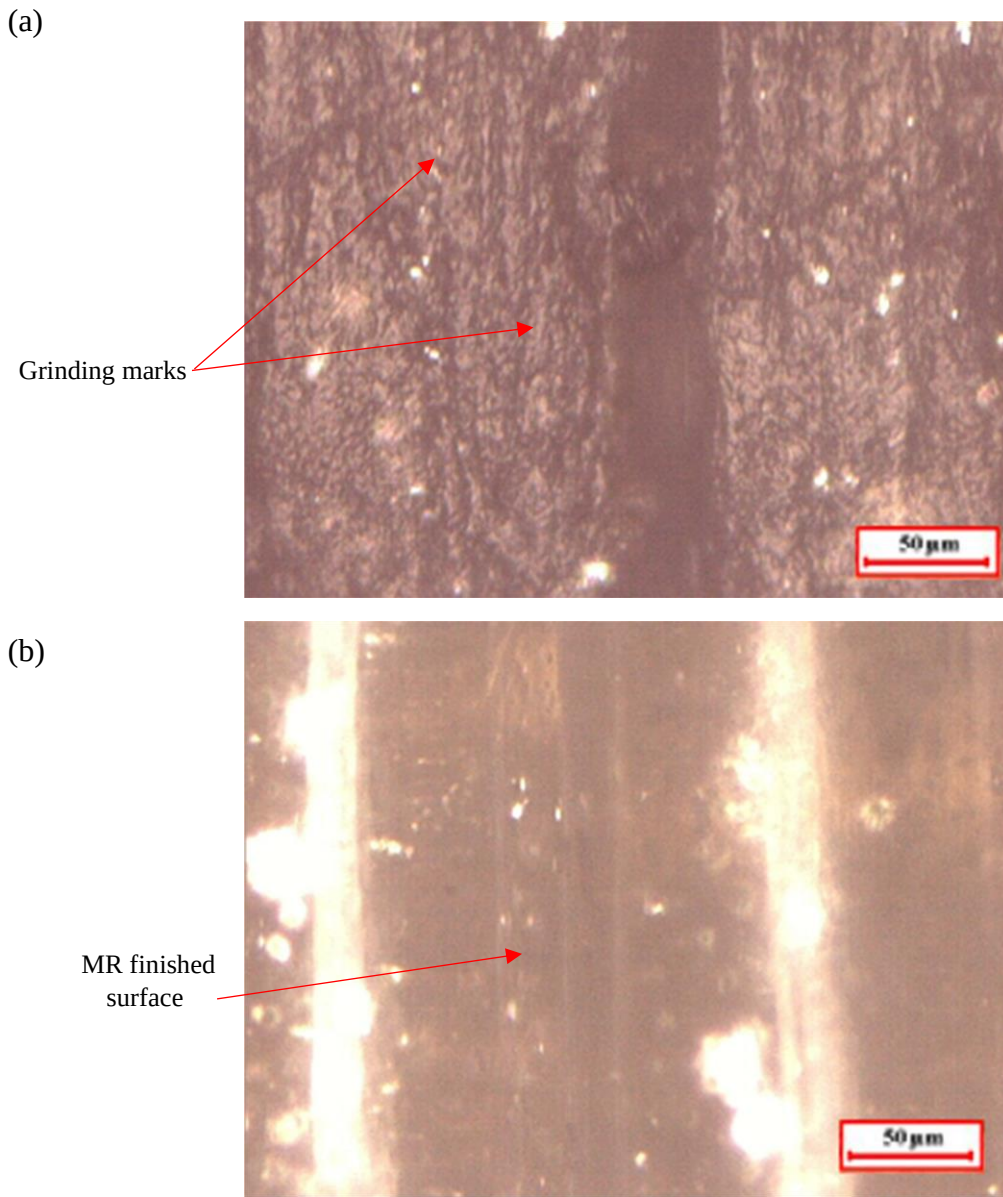


**Fig. 6.40.** Optical microscopic surface images at 100x of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the FDM fabricated external cylindric surface (diameter of 20 mm and length of 150 mm) with 120 min of finishing.

This is because, the AAPs that are tightly gripped in the EIPs chain shear off the asperities from the workpiece surface in a controlled way under the influence of the magnetic field in the MRF process. Furthermore, the normal force is relatively low, and material removal occurs in the microchip form. The significant improvement in the surface characteristics of the external surface of the FDM fabricated surface tends to enhance the service life of the components in comparison to the ground FDM surface during working conditions.

#### 6.6.3.4 Observation of improvement in dimensional accuracy of FDM-fabricated cylindrical workpiece

Further, to enhance the service life of FDM fabricated polymer cylindrical components in industries, the components must have high dimensional accuracy. Hence, to confirm the dimensional accuracy of the FDM fabricated polymer cylindrical components, the circularity test and waviness test are performed on the before and after MR finished surface. The circularity test foresees the actual circle's closeness to the workpiece surface's true circle. The accuracy of the external cylindric FDM fabricated workpiece is defined by the closeness amid the true and actual circle (Martorelli *et al.*, 2017). The circularity was measured using the co-ordinate measuring machine (CMM) at two different sections C1, and C2 at the initial and final surface of the FDM fabricated external cylindric surface as espied in Figs. 6.41(a) and (b), respectively. The majority of the recorded locations deviated from the actual circle, as seen in Fig. 6.41(a). Also, the average circularity deviation value is found to be 0.1128 mm. However, after the MRF process over the workpiece surface, there is a substantial circularity improvement since most of the recorded points are closer to the true circle (Fig. 6.41b). Further, the average circularity deviation value after the MR finishing is found as 0.0780 mm. The circularity test results reveal the enhancement in the dimensional accuracy of the polymer workpiece external cylindric surface after MRF which tends to enhance the component efficacy while working. The accuracy of the external cylindric FDM fabricated workpiece is defined by the closeness amid the true and actual circle (Martorelli *et al.*, 2017). The circularity was measured using the co-ordinate measuring machine (CMM) at two different sections C1, and C2 at the initial and final surface of the FDM fabricated external cylindric surface as espied in Figs. 6.41(a) and (b) respectively. The majority of the recorded locations deviated from the actual circle, as seen in Fig. 6.41(a). Also, the average circularity deviation value is found to be 0.1128 mm. However, after the MRF process over the workpiece surface, there is a substantial circularity improvement since most of the recorded points are closer to the true circle (Fig. 6.41b). Further, the average circularity deviation value after the MR finishing is found as 0.0780 mm. The circularity test results reveal the enhancement in the dimensional accuracy of the polymer workpiece external cylindric surface after MRF which tends to enhance the component efficacy while working.

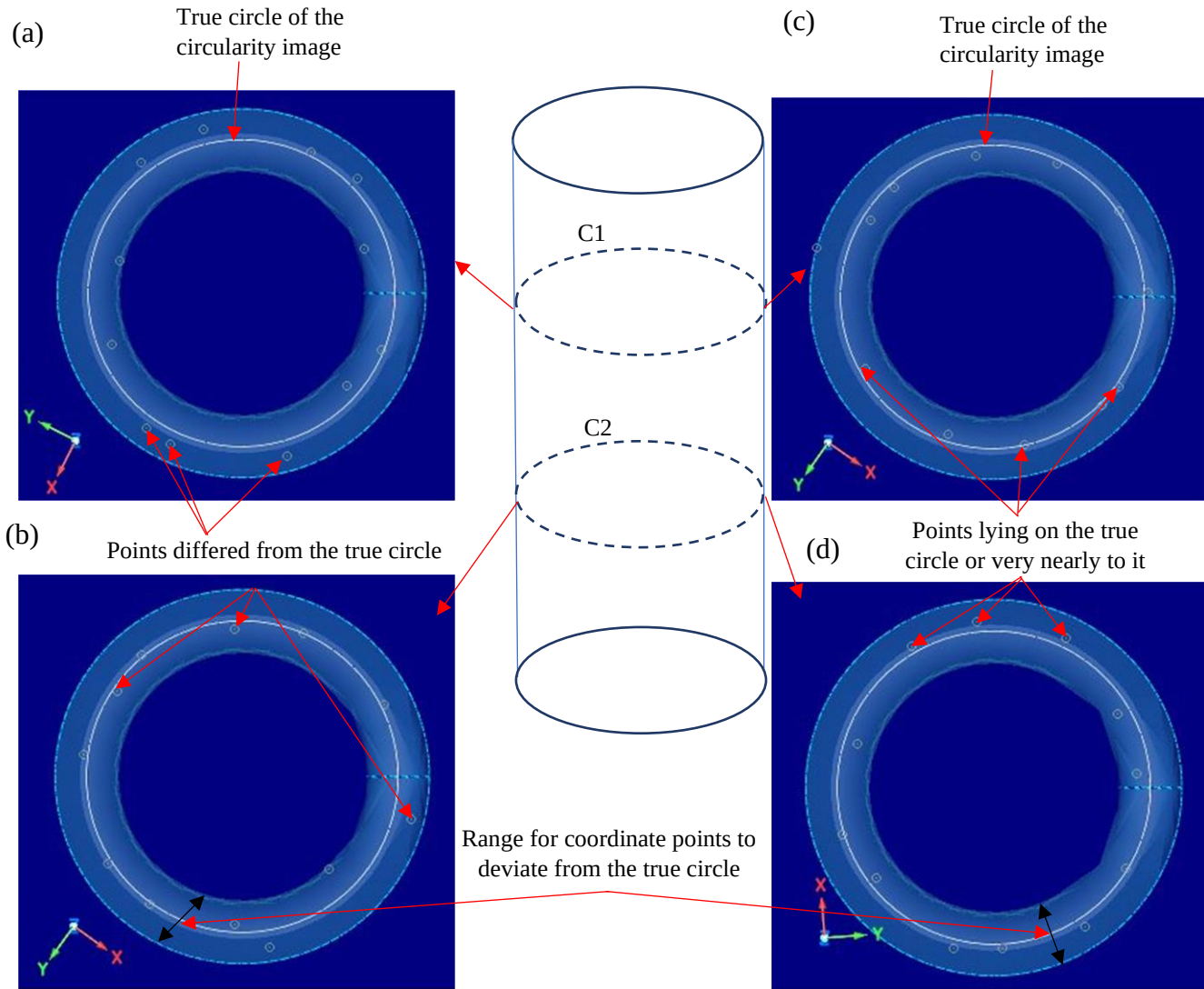


**Fig. 6.41.** Circularity images of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the external FDM fabricated cylindric surface (diameter of 20 mm and length of 150 mm) with 120 min of finishing.

Further, in order to have close fits and tolerance, a uniform linear surface (straightness) is necessary for the workpiece. Therefore, for in-depth detailing of the linear surface waviness is performed on the workpiece external cylindric surface. On comparing the surface roughness profiles, the waviness has a longer sample length, which aids in offering insight into the linear surface. Figs. 6.42(a) and (b) show the initial ground and the MR finished waviness profile with predicted optimum parametric conditions. The waviness parameters ( $W_a$ ,  $W_q$ , and  $W_z$ ) of the initial surface is found as 440 nm, 560 nm, and 2100 nm respectively and the on the final MR finished external cylindric surface with 18,840 mm<sup>2</sup> area is 180 nm, 230 nm, and 800 nm respectively as

measured with the assistance of Tylor Hobson profilometer. Thus, after 120 min of MRF on the FDM fabricated workpiece surface, the %age reduction in  $W_a$ ,  $W_z$  and  $W_q$  is achieved as 59.09 %, 61.90 %, and 58.92 %, respectively using the optimum parameters. The improvement in the circularity and straightness of the FDM fabricated polymer cylindrical external surface after the MRF process reveals the enhancement in the dimensional accuracy which tends to upsurge the service life of polymer cylindrical components such as printer rollers, conveyor roller, shafts, winding drums, and rapid prototyping tools.

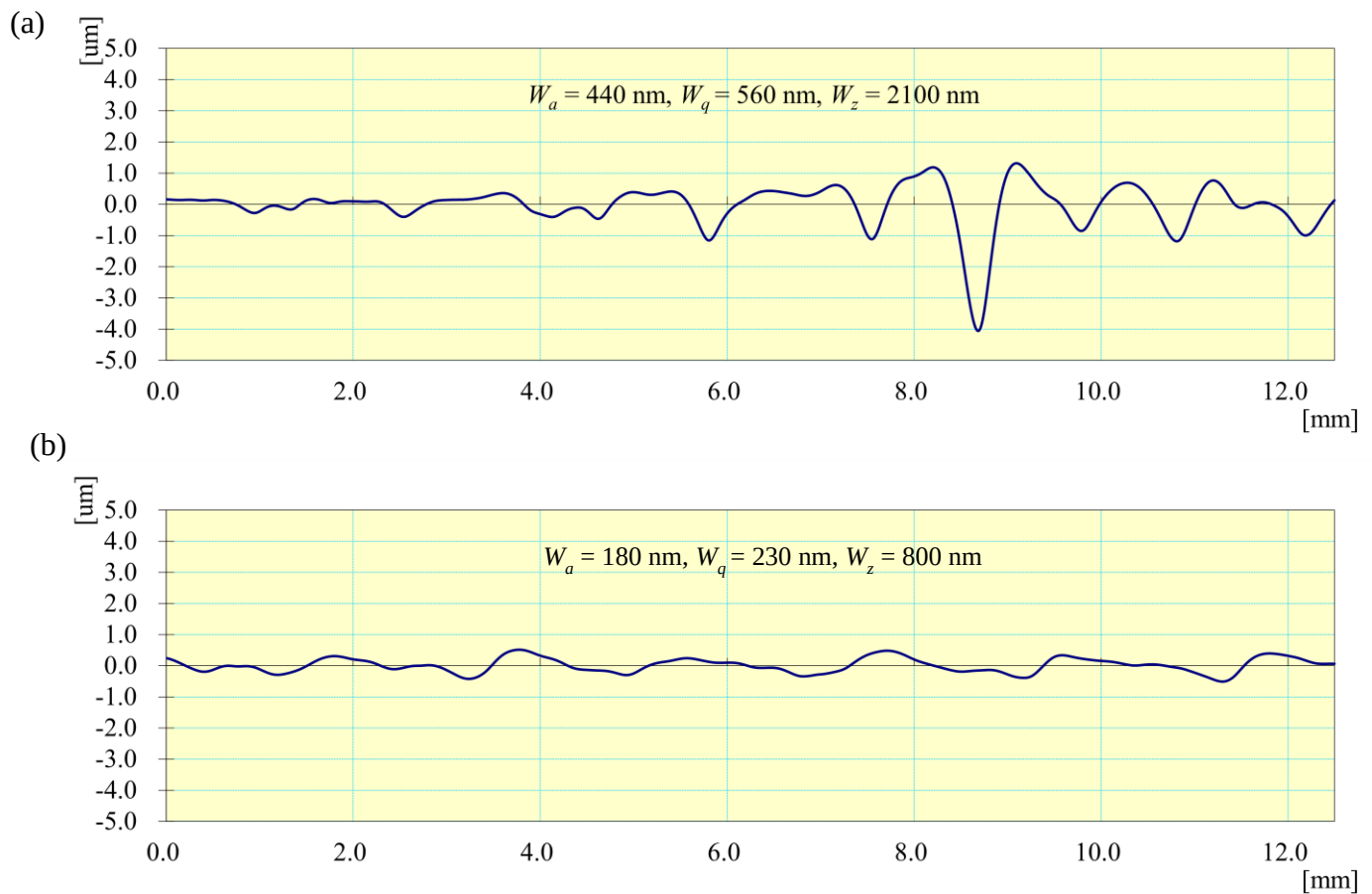


**Fig. 6.42.** Surface waviness profile of the (a) initial ground surface, and (b) final finished surface using MR-finishing on the external FDM fabricated cylindric surface (diameter of 20 mm and length of 150 mm) with 120 min of finishing.

Clinically, from the above studies it can be revealed that the present MRF process with the novel hexagonal tip-based electromagnetic tool leads to the enhancement in surface morphology, circularity, and waviness, after a substantial reduction in the surface roughness of the FDM

fabricated polymer cylindric workpiece. This tends to enhance the service life, dimensional accuracy, and efficacy of the polymer cylindric components such as printer rollers, conveyor rollers, shafts, winding drums, and rapid prototyping tools, etc. in different industries.

#### **6.6.4 Conclusions**

The present magnetorheological finishing (MRF) process with the novel hexagonal tip-based rotary electromagnetic tool is capable of providing the fine finishing of the FDM-fabricated external cylindric surface. The enhancement in surface characteristics, dimensional accuracy and wear properties after the reduction in the FDM fabricated cylindric external surface roughness further validates the present MRF process efficacy. The MRF process of the FDM fabricated workpiece exterior surface led to the following conclusions.

- The optimum process parameters obtained from the parametric study such as tool rotational speed 300 rpm, workpiece rotation speed 30 rpm, tool reciprocation speed 20 cm/min and magnetizing current 3 A reveal the effective finishing of the FDM fabricated cylindric external surface for maximum reduction in surface roughness value.
- The significant %age reduction in roughness parameters  $R_a$ ,  $R_q$ , and  $R_z$  as 86.44 %, 83.52 % and 70.83 % respectively on the FDM fabricated cylindric external surface with an overall area of 18,840 mm<sup>2</sup> in 140 min of finishing with the predicted best process parameters shows the efficiency of the present MRF process with the novel hexagonal tip based electromagnetic tool.
- The improvement in surface morphology of the MR finished FDM fabricated cylindric external surface confirms the removal of surface defects such as grinding lays and accumulation of the worn debris using the present MRF process with the best process parameters that further help to enhance the service life of the components.
- The enhancement in the circularity and waviness of the FDM fabricated cylindric external surface upsurge in dimensional accuracy of the workpiece surface. This improvement in the functional efficacy of the polymer cylindric components such as printer rollers, conveyor rollers, shafts, winding drums, and rapid prototyping tools, etc. in different industries.

## CHAPTER 7

### CONCLUSIONS AND SCOPE OF FUTURE WORK

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#### 7.1 Conclusions

The designed and fabricated magnetorheological (MR) finishing tools have been found to be effective for fine finishing a variety of polymer components of various shapes (flat, hemispherical, external cylindrical workpiece, internal, external curve surface like valve seal, gear profile). The magnetostatic finite element analysis (MFEA) is utilized to design the different tools' core tip surface for providing uniform and higher magnitude of magnetic flux density in fine finishing the different polymer workpieces. For fine finishing of the various shapes of polymer workpieces, different fixtures and holders are fabricated. Further, the in-sight mechanism of material removal during fine finishing of the different shaped polymer workpieces is analyzed. Also, the developed different magnetorheological polishing fluids and their performance in the finishing of the different polymer materials are found effective. The capability of the designed and fabricated different magnetorheological finishing tools has been successfully demonstrated for the fine finishing of the various polymer components such as polymer gears, bearing, acetabular cups, valve seals, and additive manufacture components. Results obtained in the present work are evident that the developed different magnetorheological (MR) finishing tools are competent to fine finish the various polymer components for different industrial applications. Following specific conclusions have been drawn on the basis of results obtained from the present research work.

- The ability to retain the magnetorheological polishing (MRP) fluid on the tool surface for fine finishing the various types of polymer workpieces is revealed by the magnetostatic finite element analysis result (0.515 T-0.331T) for the different finishing tools as per the polymer workpiece shape. The decreasing magnetic flux density value from the tool-tip surface to the workpiece surface ensures that electrolytic iron particles of the MRP fluid hold over the tool surface and apply force to the abrasive particles towards the polymer workpiece surface. As a result, the currently developed finishing tools are capable of providing fine finishing with the proper relative motion of the abrasive particles over a variety of polymer workpiece surfaces of various shapes.
- The uniform distribution of the magnetic flux density over the surface of the magnetic tool core tip surface is revealed by an experimentally determined magnetic field over

various tool tip surfaces. This is a necessity in order to get uniform and effective fine finishing over the polymer workpiece surface.

- The fabricated height adjustment fixtures and workpiece holders offer a constant working space between the tool and various polymer workpiece surfaces, allowing the present fabricated tools to finish the workpiece surface effectively.
- Based on the process mechanism, the magnetic normal force along with the forces produced while the rotational as well as reciprocation motion of the tool, and the rotating workpiece helps to shear off material from the polymer workpiece surfaces. The material removed by shearing off the asperities provides fine finishing over the workpiece surface which tends to enhance the functional efficacy of the polymer components.
- The rotational motion of the gear work part is caused by the rotary motion of the tool core and proper meshing between the tool teeth and bevel gear work part teeth with MR polishing fluid in the designated working space. As a result, the MR polishing fluid on the magnetic tool teeth surface comes into contact with each tooth of the bevel gear which provides overall finishing in the shortest amount of time possible.
- The water-based magnetorheological polishing fluid shows significantly effective finishing over polyamide surface with 15 % by volume of EIPs (500 mesh size), 15 % by volume of CeO<sub>2</sub> abrasive (800 mesh size), and 70 % by volume of base fluid (the base fluid further consists of 80 % by volume deionized water and 20 % by volume of glycerol).
- Graphene-based magnetorheological polishing fluid results in the increased bonding strength of the magnetic iron particles over the abrasive particles, and higher shear stress is delivered to the workpiece surface. This leads to the enhancement in the surface finishing of the polymer workpiece surface.
- The reduction of surface asperities of polyamide surface from 560 nm to 100 nm and waviness from 0.19  $\mu\text{m}$  to 0.09  $\mu\text{m}$  in 100 min of finishing time for the surface area of 706.5 mm<sup>2</sup> using optimum parameters confirms the functional improvement in the polyamide components used in industries.
- The reduction in roughness value from 240 nm to 80 nm after MR finishing with the optimized parameters on the 1140 mm<sup>2</sup> hemispherical surface area of the UHMWPE acetabular cup workpiece reveals the effectiveness of the present MR finishing process



with the newly fabricated hemispherical tool tip surface for the UHMWPE acetabular cup workpieces.

- The significant %age reduction in surface roughness parameters  $R_a$ ,  $R_z$ , and  $R_q$  by 73.68 %, 78.37 %, and 72.22 % respectively over polymer bevel gear surface of 36 teeth in 150 min of finishing cycle with predicted optimized process parameters confirms the enhanced surface characteristics, and gear quality.
- The reduction in surface roughness from 751 nm to 101 nm and improvement in the surface morphology images after 120 min of the finishing cycle reveals the fine finishing of the additive manufactured (AM) work part. It also reveals the significant improvement in the surface as it is free from the initial grinding marks and scratch marks after MR finishing.
- The %age reduction in roughness parameters of 82.5 %, 84.37 %, and 89.47 % respectively over PTFE bearing surface with 4772.80 mm<sup>2</sup> surface area for 120 min of finishing time using the best process parameters shows the efficiency of the present MR honing process for improving the internal surface finish of the polymer bearings.
- Overall results show that the presently developed magnetorheological finishing tools are found to be effective for fine finishing of the various polymer workpieces with different shapes which are beneficial for various industrial components such as gears, bearings, acetabular cups, and additive manufacturing components.

## 7.2 Future work

The recently designed magnetorheological tools have proved their capability to finely finish the various polymer surface with different shapes (flat, hemispherical, external cylindrical workpiece, internal cylindric surface, external curve surfaces like valve seal, gear profile). Some of the scopes of future work by which efforts can be made to further enhance the finishing performance of the present magnetorheological finishing tools are listed as follows.

- In order to finish various industrial components with the free form surface, a flexible fixture may be developed which can lead to their fine finishing.
- To find out more feasibility of the developed magnetorheological fluid-based finishing tools and to validate the real-time performance, further various industrial applications can be used for fine finishing.

- The properties of the polymers named polyamide, PTFE, ABS, and PEEK can be studied in detail.
- The workpiece surface with some parts having high non-uniform surface roughness as compared to the other part can be finished by using the different process parameters till the uniform surface is obtained.

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## LIST OF PUBLICATIONS

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### SCI Journals:

1. **Arora, K.**, Singh, A. K. Magnetorheological finishing of UHMWPE acetabular cup surface and its performance analysis. *Materials and Manufacturing Processes* 2020, 35(14): 1631-1649.  
*Status: Published online*  
*Publisher: Taylor and Francis*  
*Impact factor: 4.616*
2. **Arora, K.**, Singh, A. K. Magnetorheological finishing process for improved performance of polymer gears. *Materials and Manufacturing Processes* 2021 1-18. DOI: 10.1080/10426914.2021.1967975.  
*Status: Published online*  
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*Impact factor: 4.616*
3. **Arora, K.**, Singh, A. K. Magnetorheological finishing of polyamides for improving their functional performance. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 2021, **43**(12),1-23.  
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4. **Arora, K.**, Paswan, S. K., Singh, A. K. Investigation of surface roughness in novel magnetorheological finishing of the internal hemispherical shaped workpieces. *Journal of Manufacturing Science and Engineering*. DOI: 10.1115/1.4054682.  
*Status: Accepted*  
*Publisher: ASME*  
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5. **Arora, K.**, Singh, A. K. Magnetorheological finishing of internal polymer bearing surface for hydropower machines. *Materials and Manufacturing Processes*.  
*Status: Under review*  
*Publisher: Taylor and Francis*  
*Impact factor: 4.616*



6. **Arora, K.,** Singh, A. K. An investigation of magnetorheological finishing on the tribological and functional performance of polymer gears. *Proceedings of Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*  
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7. **Arora, K.,** Singh, A. K. Theoretical and experimental investigation of additive manufactured typical turbine blade using novel graphene based magnetorheological finishing process. *Journal of Manufacturing Processes*  
*Status: Submitted*  
*Publisher: Elsevier*  
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8. **Arora, K.,** Singh A.K. Magnetorheological finishing of FDM fabricated external polymer cylindrical workpiece for improving mechanical and surface properties. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*  
*Status: Submitted*  
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9. **Arora, K.,** Uppal, A. S., Singh, A. K. Improving the performance of polymer valve-seal surface of ball valves using magnetorheological finishing process. *Surface review and letters*.  
*Status: Submitted*  
*Publisher: World Scientific*  
*Impact factor: 1.152*

#### **International Conferences:**

1. **Arora, K.,** Singh A.K. Theoretical and Experimental investigation on surface roughness of straight bevel gears using a novel magnetorheological finishing process, 23rd International Conference on Wear of Materials, April 26-29, 2021.