

Design and Development of A Rotating Core Based Magnetorheological Finishing Process for Different External Cylindrical Surfaces

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MANPREET SINGH

Roll No. 901508010

Under the supervision of

Dr. ANANT KUMAR SINGH

Associate Professor, MED



**Department of Mechanical Engineering,
Thapar Institute of Engineering and Technology, Patiala-147004, India
(Deemed to be University)
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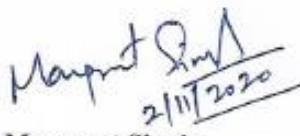
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CERTIFICATE

I, Manpreet Singh, Roll No. 901508010, hereby declared that the thesis entitled “**Design and Development of A Rotating Core Based Magnetorheological Finishing Process for Different External Cylindrical Surfaces**” 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.

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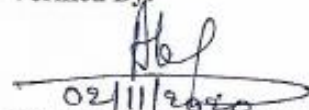

2/11/2020
Manpreet Singh

Dated: 02-11-2020

Roll No. 901508010

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

Verified By:


02/11/2020

Dr. Anant Kumar Singh

(Supervisor)

Associate Professor

Department of Mechanical Engineering

Thapar Institute of Engineering and Technology, Patiala- 147001 (Punjab)

India

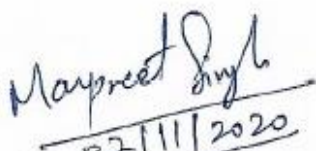
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ABSTRACT

The external surface finishing of cylindrical components at the nano-meter level with good surface characteristics is highly demanded in today's industries for improving their operative functionalities. In industries, mostly traditional finishing process like grinding is used to finish the external surface of the various cylindrical components because of their easy accessibility and low making cost. Grinding makes use of a rigid bonded abrasive wheel. This rigid bonded abrasive wheel gives non-controllable finishing forces over the external surface of the cylindrical workpiece. Owing to this, sometimes the defects get produced like heat affected zone, micro-cracks, microstructural changes, folded metals, etc. on the final finished surface. Control over finishing forces is of great concern for achieving productive and defect-free components. Therefore, there is a mandatory requirement of the advanced finishing processes with controlled forces to finish the external surface of the cylindrical components for enhancing their operational life in real time applications. The finished surface using the advanced finishing processes has several benefits like close tolerance design, reduction in wear, friction losses and increase in product service life, etc. From the literature review, it has been found that very less work is done in fine finishing of the external cylindrical surfaces with the advanced finishing processes. Magnetic abrasive finishing (MAF) is the process that has been used to finish the cylindrical external surfaces. But MAF is used more effectively only to finish the hard material cylindrical surfaces. MAF process makes use of mostly a mixture of magnetic iron and abrasive particles as the magnetic abrasive brush. This may generate a lack of flowability and friction on the surface of ductile workpieces.

As compared to the magnetic abrasive finishing, the magnetorheological (MR) finishing process has been found more flexible with its finishing medium as MR polishing fluid. In the MR finishing process, the carrier fluid facilitates more flexibility to move the active abrasives on the different shapes of the different workpiece materials. The flexibility and controllability of the MR polishing fluid make the process more effective for finishing the hard as well as soft material workpieces. The performance in the MR finishing processes majorly depends upon the relative motion between the stiffened MR polishing fluid and workpiece surface which is provided either by the motion of the workpiece surface or the tool. Recently, a turning type magnetorheological finishing process with the stationary magnetic curved tool tip surface was developed to finish the external surface of the cylindrical workpieces. In this process, the standard lathe machine is utilized to provide the rotational motion of the cylindrical workpiece against the stationary curved tool core tip surface. As the magnetized curved tool core tip

surface was kept stationary, the active abrasive particles of the MR polishing fluid which perform finishing on the external surface of the rotating cylindrical workpiece may get less relative motion. Therefore, to improve the further process performance with an increase in relative motion, a rotating core-based magnetorheological finishing process has been developed in the present work where the magnetic tool core tip surface also gets rotational motion over the rotating external surface of the cylindrical workpiece. Also, the automatic feed arrangement is provided to the magnetic tool for finishing the external cylindrical workpiece longitudinally. The iron particles (IPs) chains are rotated along with the rotation of the tool core. This results in an increase in kinetic energy of the gripped active abrasive particles with the IPs chains which causes a better finishing performance. Finishing is performed on the external surface of the cylindrical workpieces by both the processes and their corresponding results are compared. The overall results revealed that the present developed process using a rotating flat tool core tip surface is more useful in finishing of external cylindrical surfaces as compared to the stationary curved tool core tip surface.

Fine finishing of the tapered cylindrical components is the utmost need of the advanced manufacturing industries. The tapered coloured glass making industries require highly finished punches and cavity. To achieve this requirement, the developed magnetorheological (MR) finishing process with the rotating circular flat tip surface is utilized through its advancement for enhancing the surface characteristics of the tapered cylindrical workpiece. Also, the variation in linear velocity, helix angle, and the helical path made by the active abrasives on the tapered cylindrical surface has been analyzed in estimating the time taken for uniform finishing on the tapered cylindrical surface. The surface roughness parameters (R_a , R_q , and R_z) values get reduced to 97.28%, 95.82%, and 95.42% in 120 minutes of MR finishing with optimized parametric conditions. The surface waviness value gets reduced from the initial value of $0.841\text{ }\mu\text{m}$ to the final value of $0.205\text{ }\mu\text{m}$.

After the development of a rotating core-based MR finishing process, the best-required shape of the tool core tip surface in the magnetorheological finishing process is designed for improving the efficiency of the process on external cylindrical surfaces. The design of a rectangular shaped tool core tip surface is found more effective for uniform and higher flux density. The preliminary experiments are conducted on the cylindrical external surface using the rectangular shaped tool core tip surface and the circular-shaped tool core tip surface. After the magnetorheological finishing with the rectangular and circular shaped tool core tip surfaces, the final surface roughness values of the external surface of the cylindrical workpieces get reduced to 18 nm with the rectangular-shaped tool core tip surface and 45 nm with the circular-

shaped tool core tip surface from the initial value of 310 nm in 60 minutes. Hence, the rectangular-shaped design of the tool core tip surface is found more useful to improve the efficiency of the present process. Further to achieve the fine finishing of the real-time industrial applications such as cold rolling rolls, micro-punches, winding grooved drum, spline shaft, and copper cylindrical rollers, the improved magnetorheological (MR) finishing process with the rotary rectangular tool core tip surface is employed. Cold rolling is one of the most vital manufacturing operations in the sheet metal industries. In cold rolling operation, the rolls are the most important component. If the surface of the rolls gets fine finished at a greater level, a smooth surface on the final products can be achieved. For effectively performing the MR finishing operation, the optimum process parameters are predicted by using the response surface methodology. The surface roughness gets reduced to 18 nm from the initial ground roughness value of 200 nm with the optimized parameters. After the MR finishing operation, the cold rolling rolls are tested their functional performance in the industry. The performance of the MR finished rolls surface is investigated and found better as compared with the ground rolls surface.

The modern trend towards miniaturization has provided an innovative push towards the creation of micro-fabrication parts. Micro-extrusion is one such emerging process. Micro-punches are the main part of the micro-extrusion process. In the extrusion process, high contact forces are generated due to the sliding between the punch and billet. These high contact forces are governed by the surface topography of the punch. When the punches are finely finished, lesser contact forces are generated. On the basis of the applications, four industrial micro-punches are used in the present MR finishing investigation. After MR finishing, surface roughness values of the micro-punches of the initial ground surface 210, 230, 250, and 200 nm are reduced to 20, 20, 30, and 10 nm.

Further, the fine level finishing of grooved drum surfaces is an essential requirement for enhancing the performance of the winding machines in today's textile industries. The fine level of surface finishing is required as less as possible on the grooved surface of the textile winding drum. With the least possible roughness value over the external grooved surface of the winding drum, the breakage of the yarn and hairiness of the yarn can be reduced. After the 60 minutes of MR finishing, the average surface roughness value of the grooved drum surface gets reduced from 200 nm to 10 nm. The functional performance of the MR finished grooved drum is found better than the ground grooved winding drum due to the fine level of finishing.

Also, fine and uniform finished spline shaft teeth surface tend to enhance the pressure distribution uniformly over the teeth surface and increase the life span of the spline shaft.

Uniformly and fine finished teeth surface requirement has been accomplished by using the presently developed rotary rectangular tool core-based magnetorheological (MR) finishing process. The surface response methodology is utilized to optimize the process parameters for better finishing of the spline shaft. The Ra value gets decreased to 20 nm from the initial value of 270 nm with the optimum process parameters. The significant decrease in Ra value also improves the mechanical property as micro-hardness gets increased from 649 HV to 746 HV after the MR finishing of the teeth surface of the spline shaft.

As in the printing industries, the copper cylindrical rollers play an important role in the printing operation. In the printing, the copper rollers are required fine and uniform finishing to uniformly distribute the colours and ingot material. Also, it provides the uniform distribution of the pressure. Fine and uniform finishing of copper cylindrical rollers are difficult due to its ductility and less hardness during the traditional finishing. Therefore, obtain fine finishing, initially, the MR polishing composition (%age concentration of electrolyte iron particles and aluminium oxide abrasives with base fluid) is analyzed for better performance. Furthermore, the central composite design is used to optimize the finishing parameters. The surface roughness value is reduced from the initial value of 190 nm to 25 nm after 60 minutes of MR finishing on 30 mm length and 25 mm diameter of the copper cylindrical roller.

Finally, in the present work, a theoretical model is developed to predict the reduction in the surface asperities during the magnetorheological finishing of the external cylindrical surfaces. The rotational speed of the rectangular tool core on the rotating cylindrical work-part enhances the relative speed of active abrasives which decreases the pitch, helix angle, and increases the helical path length. This result enhances the uniform precise finishing on the cylindrical work-parts and also enhances the process performance. The %age error between the experimentally obtained Ra value and theoretical Ra value is found to be -2.08% to 4.76%, which is good agreement between the theoretical model and experimental results.

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LIST OF ABBREVIATIONS

AAPs	Active abrasive particles
Al ₂ O ₃	Aluminium oxide
ANOVA	Analysis of variance
BEMRF	Ball end magnetorheological finishing
CBN	Carbon boron nitride
CCD	Central composite design
CIPs	Carbonyl iron particles
CMM	Coordinate measuring machine
DOE	Design of experiments
EIPs	Electrolytic iron particles
FEA	Finite element analysis
HMI	Human-machine interface
I-CNT	Iron-carbonyl nano-tubes
MAF	Magnetic abrasive finishing
MR	Magnetorheological
MRF	Magnetorheological finishing
MRR	Material removal rate
PLC	Programable logic controller
RSM	Response surface methodology
S/N	Signal-to-noise ratio
SEM	Scanning electron microscopy
S-FMAB	Static flexible magnetic abrasive brush
SiC	Silicon carbide

LIST OF NOMENCLATURES

A_1	evaluated finish surface area of the cylindrical roll, mm^2
A_2	surface area of the entire surface length of the industrial roll, mm^2
A_{ab}	projected area of the single active abrasive particle, m^2
A_f	final cross-sectional area of the billet, mm^2
A_h	indentation cross-sectional area of helical path, m^2
A_i	initial cross-sectional area of the billet, mm^2
A_{sg}	area of cylindrical segment, m^2
A_{sic}	area of the single abrasive particle, m^2
A_w	external surface area of the tapered cylindrical workpiece, m^2
$B_{MR}(x)$	variation of magnetic flux density along the working gap, m
$B_{t(z)}$	total magnetic flux density at any point in the working gap (space), A/m
B_z	magnetic flux density on any point P in a working space produced by the electromagnet coil, A/m
C	static load rating for slide blocks, kN
C_l	centre distance between two pulleys, m
D	diameter of the cold rolling roll workpiece, mm
d	bearing diameter, m
d_1	pitch circle diameter of the driven pulley, m
d_2	pitch circle diameter of the driver pulley, m
D_{bf}	final billet bigger diameter, mm
d_{bf}	final billet smaller diameter, mm
D_{bi}	initial billet bigger diameter, mm
d_{bi}	initial billet smaller diameter, mm
d_d	diameter of the grooved drum, m
d_{driven}	diameter of the driven pulley, mm
d_{driver}	diameter of the driver pulley, mm
d_i	indentation diameter of active abrasive particle, m
D_l	unit length of the current segment on electromagnetic circular coil, m
d_p	depth of indentation from the single active abrasive on the external tapered surface of the cylindrical workpiece, μm
dr_m	variable strip radius of the external tapered surface of the cylindrical workpiece, m

dr_t	variable radial distance of the active abrasive on the projected curve area of the rotary rectangular tool core tip surface on the cylindrical work part, m
d_{SiC}	single abrasive diameter, m
dV	variation in linear velocity of the external tapered surface of the cylindrical workpiece, m/s
e_x	extrusion ratio
F	resultant processing force in magnetic abrasive finishing, N
F'	extrusion load or force on a micro-punch, N
F_a	axial shear force acting on the active abrasive due to the reciprocation motion of the tool core, N
F_{AB}	magnetic interaction per SiC abrasive reduces due to the consecutive space between the two iron particles
F_{af}	net cutting axial finishing force, N
F_{ax}	axial force for timing belt drive system, N
F_c	resultant cutting shear force acting on the active abrasive, N
F_{cf}	centrifugal force due to tool core rotation, N
F_f	frictional force act on the external surface of the cold rolling surface, N
F_{in}	indentation force on the abrasive particle to indent on the work-part surface, N
F_n	magnetic normal force exerted by an iron particle on active abrasive, N
F_N	normal to the rotating grinding wheel to the workpiece's external surface, N
F_{Rt}	net tangential force acting on the active abrasive due to rotary motion of rectangular tool core and cylindrical work-part, N
F_{S1}	resultant cutting shear force when the tool core rotates in the anticlockwise direction, and the cylindrical workpiece rotates in the anticlockwise direction, N
F_{S2}	resultant cutting shear force when the tool core rotates in the anticlockwise direction, and the cylindrical workpiece rotates in the clockwise direction, N
F_T	tangent to the rotating grinding wheel to the workpiece's external surface, N
F_t	net tangential finishing force, N
F_{ta}	total axial force for timing belt drive system, N
F_{ta}	net cutting tangential finishing force, N

F_{tt}	tangential shear force acting on the active abrasive due to the rotary motion of rectangular tool core, N
F_{tw}	tangential shear force acting on the active abrasive due to the rotary motion of the cylindrical work-part, N
F_x	magnetic processing force component act on the direction of magnetic field lines, N
F_y	component act on the direction of magnetic equipotential lines, N
g	acceleration due to gravity, m/s^2
H	dimensional tolerances of height of slides, μm
H_r	normal reaction, N
H'_z	total magnetic field intensity on any point P in a working space produced by the electromagnet, A/m
h_{bf}	final billet height, mm
H_{BHN}	brinell hardness number, kgf/mm^2
h_{bi}	initial billet height, mm
H_z	magnetic field intensity on any point P in a working space produced by the single electromagnet coil, A/m
I	current pass through the electromagnetic circular coil, A
J_t	total inertia of the timing belt drive system, kgm^2
K	random point on the helical path
k	factor of friction
L	length of timing belt used for transmission, m
L_1	evaluated finish length of cold rolling roll during experimentation with the optimized parameters, mm
L_2	entire external surface length of the cold rolling rolls, mm
l_a	total helical length of the external tapered surface of the cylindrical workpiece, m
L_h	length of helical path of the active abrasive on the cylindrical work-part surface, m
L_c	contact length of rolls, m
L_w	length of cylindrical work-part, m
L_{wt}	length of the tapered workpiece to be finished, m
M	static permissible moment of slide blocks, kN-m

M_a	torque per unit width act on the external surface of the cold rolling surface, Nm
m_b	mass of timing belt in drive system, kg
M_{ip}	magnetization of the magnetic iron particle, A-m ² /kg
m_{ip}	single iron particle mass, kg
m_l	mass of moved load (both the tool core and drive pulley), kg
M_p	static moment in the X-axis direction of slide blocks, kN-m
M_R	static moment in the Z-axis direction of slide blocks, kN-m
m_{sic}	single abrasive mass, kg
M_t	magnetization of the tool core, A-m ² /kg
M_w	magnetization of the cylindrical work-part, A-m ² /kg
M_Y	static moment in the Y-axis direction of slide blocks, kN-m
N	number of circular copper coil turns in the electromagnet
N_a	numbers of active abrasives on per unit area (1mm×1mm) of the external surface of the tapered cylindrical workpiece
N_{ab}	total number of active abrasive particles on the external surface of the tapered cylindrical workpiece
n_d	revolution of the grooved drum, rpm
N_{driven}	rotational speed of the driven pulley, rpm
N_{driver}	rotational speed of the driver pulley, rpm
N_{net}	net rotating speed of the active abrasive because of the rotational speed of tool core and cylindrical tapered workpiece, rpm
N_{max}	maximum angular velocity which is required during experimentation, rpm
N_r	rotational speed of cold rolling roll, rpm
N_s	number of active abrasives on the curved area of the cylindrical work-part which is projection of rectangular tool tip surface
N_t	rotary speed of the rectangular tool core, rpm
N_w	rotary speed of the cylindrical work-part, rpm
$N_{\emptyset}$	rolls angular rotation, rpm
P	essential power required for plastic deformation of the flat strip, kW
P_d	the micro-punch diameter, mm
p_h	pitch of helix path, m
P_i	individual surface roughness value, nm

P_n	power loss due to the friction in the two rolls neck bearings and evaluated for both ground and MR finished surfaces, kW
P_r	roll force, N
P_{total}	total power consumption to operate the rolls, kW
q	axial distance in z axis direction of electromagnetic coil, m
Q	consecutive space between the two iron particles, μm
Q_p	pressure intensification factor
R	distance of hypotenuse of electromagnetic coil, m
r	variable radius of the circular electromagnet coil, m
r_1	minor radius of the tapered cylindrical workpiece, m
r_2	major radius of the tapered cylindrical workpiece, m
R_a	arithmetic mean of surface roughness values, μm
r_a	radius of the active abrasive particle from the tool core rotational axis, m
r_{ab}	radius of single abrasive particle, m
R_a^i	the surface roughness in i^{th} stroke, μm
R_a^{i-1}	the surface roughness in $(i-1)^{\text{th}}$ stroke, μm
r_d	radius of driven pulley, m
R_f	theoretical final average surface roughness value, nm
r_i	inner radius of the circular electromagnet coil, m
R_i	highest roughness peak at the initial level on the external tapered surface of the cylindrical workpiece, μm
r_o	outer radius of the circular electromagnet coil, m
R_q	root mean square of surface roughness values, μm
r_t	radial distance of the active abrasive on the curved projected area of the rotary rectangular tool core tip surface on the cylindrical work-part, m
R_w	radius of cylindrical work-part, m
R_z	average maximum peak to valley of five consecutive sampling lengths within the measuring length, μm
S	number of revolutions required for the drum for double traverse, m
SS	sum of squares
S_m	shear flow stress of the deformed material, Nm
t	depth of the indentation, m

T	total finishing time required to finish the entire surface area of the roll surface, sec
T_a	elapsed time by active abrasive to trace one helical path on the external rotating cylindrical surface, sec
t_{ac}	time for acceleration, sec
t_a	time consumed by the active abrasive to complete single stroke of reciprocation motion along the tapered surface of the workpiece, sec
T_{acc}	torque required to accelerate the load, N-mm
T_c	required motor torque during constant velocity, N-mm
t_c	time for constant velocity, sec
T_d	motor drive torque required for deceleration, N-mm
t_d	time for deceleration, sec
T_{driven}	number of teeth of the driven pulley
T_{driver}	number of teeth of the driver pulley
T_{RMS}	root mean square of the motor drive torques required during acceleration, constant velocity, and deceleration, N-mm
T_{ta}	total torque required during acceleration, N-mm
t_t	total time duration utilized for uniform finishing the whole external tapered surface of the cylindrical workpiece, sec
t_{total}	time for movement (including any idle time between movements), sec
V	MR polishing fluid volume in the working space, m^3
v_a	axial velocity of rectangular tool core, m/sec
V^i	volume removed by the active abrasives in i^{th} finishing stroke, m^3
V_s	surface velocity of the grooved drum, m/min
V_{sic}	single abrasive particle volume, m^3
V_t	transverse velocity of the yarn, m/min
W	dimensional tolerances of width of slides, μm
w'	width of the flat strip, m
W_a	arithmetic mean of waviness values, μm
W_q	root mean square of waviness values, μm
W_t	total height of profile of waviness values, μm
X	distance from the measuring point along x-axis on cylindrical workpiece, m
Y	distance from the measuring point along y-axis on cylindrical workpiece, m

Y_a	collect coefficient
Z	distance from the measuring point along z-axis, m
Z_a	intensity of magnetization, A/m
%C	percentage contribution of the individual process parameter
% ΔR_a	%age improvement in the surface finish
χ_m	mass of magnetic susceptibility, m ³ /kg
α	regression coefficient
μ	coefficient of friction
μ_{MRP}	magnetic permeability of the magnetorheological polishing fluid, H/m
μ_n	coefficient of friction factor which induced in the bearings roll
μ_o	free space magnetic permeability, H/m
μ_{rMRP}	relative permeability of the MR polishing fluid, H/m
μ_{rt}	relative permeability of the tool core, H/m
μ_{rw}	relative permeability of the cylindrical work-part, H/m
μ_t	the magnetic permeability of the tool core, H/m
μ_w	magnetic permeability of the cylindrical work-part, H/m
ε_x	actual true stain of strip
η	efficiency of the belt drive system
$\emptyset$	angle of wind, radian
α	the angle between the radius of the cylindrical work-part (R_w) and horizontal component of the cylindrical work-part, rad
α_c	coil angle, radian
β	helix angle, radian
ε_0	strain during the rolling pass
η_m	driving motor efficiency
η_t	transmission efficiency
σ	standard deviation
σ_f	shear friction between billet material and micro-punch, N
σ_{fm}	average flow strength of strip material, Pa
σ_r	stress during the rolling pass, N/m ²
τ_{driven}	torque of the driven pulley, Nm
τ_{driver}	torque of the driver pulley, Nm
τ_f	forward torque for the forward movement of the rack, Nm

τ_r	reverse torque for the reverse movement of the rack, Nm
τ_s	shear strength of the cylindrical work-part, N/m ²
Φ	the angle between the resultant component of the magnetic flux density and horizontal component of the magnetic flux density, radian
φ	angle between electric current segment length (Idl) and the resultant component of the magnetic flux density (R), radian
ω_R	resultant relative angular velocity of the active abrasive because of the rotation of the rectangular tool core and cylindrical work-part, radian/s
ω_t	angular velocity of the active abrasive because of the rotary motion of the rectangular tool core, radian/s
ω_w	angular velocity of the active abrasive due to the rotary motion of the cylindrical work-part, radian/s
ε	residual measurement from the experimental error

CHAPTER 1

INTRODUCTION

1.1 Introduction

Nowadays, the surface finishing of components is required in industries for their precise operative functionality (Al-samaria *et al.*, 2012). This is because fine finished surface of industrial components tends to decrease power losses, friction losses and also enhances the machine working performance. Finishing is also a value-added operation which results in an increase in cost as well as processing time (Chen *et al.*, 2008). Due to this reason, there is a need for continuous improvement in the performance of the finishing processes to reduce time and cost. The problems related to friction such as wear-resistance and power loss are greatly influenced by the surface roughness (Jain, 2008). Finishing processes not only need to overcome these problems but also be able to achieve accuracy as well as minimize the surface defects (Bedi and Singh, 2016).

The fine finished external cylindrical components are the soul of the industrial machines. The uniform fine finishing is in huge demand for external cylindrical components in various industries such as automotive, machine tool manufacturing, aerospace and die manufacturing, etc. The fine finished external surface of cylindrical components has various advantages like minimum friction, lesser noise, reduces wear and tear, long lifespan, improves load bearing capacity, good appearance and improves the overall efficiency of the machine. Finishing processes for external surfaces are mainly divided into two categories namely traditional and advanced finishing processes. In the industries, the external surface of the components is mainly finished with the traditional finishing processes such as grinding and lapping. Micro-cracks, microstructural changes, heat affected zone, etc. are few of the surface or subsurface defects which are generated during the traditional finishing processes (Singh *et al.*, 2016). The finishing forces are not controlled during the traditional finishing operation is also responsible for the low grade of finishing (Jain, 2009).

To fulfill the necessities like enhancement in surface characteristics and reduction in roughness profile after the traditional finishing process, various advanced finishing processes are developed (Hashimoto *et al.*, 2016). Among the developed advanced finishing processes, magnetic assisted finishing processes are most preferred because these processes provide better deterministic control over the finishing forces. This results in improved surface characteristics of the workpiece with minimum surface defects (Jain, 2009). Magnetic assisted finishing

processes (Sadiq *et al.*, 2009) are utilized for precisely finishing the flat and 3D surfaces. The ball end magnetorheological finishing process is more preferred to finish the three-dimensional external surfaces than the other processes (Singh *et al.*, 2011). The magnetorheological (MR) finishing processes used MR polishing fluid in which the carbonyl iron particles (CIPs) and the abrasive particles are suspended in the carrier fluid (Harris, 2011). Carrier fluid is a combination of oil or water, various surfactants, and additives. Various compositions are used with the different sizes of the CIPs and abrasive particles into the base fluid as per the requirement of the type of workpiece materials surface to be finished (Chen *et al.*, 2008). The flexibility and controllability of the MR polishing fluid under the influence of magnetic field which makes it effective for finishing hard as well as soft materials (Niranjan *et al.*, 2014). In the presence of a magnetic field, CIPs forms stiffened chains of CIPs in MR polishing fluid. These chains hold the abrasive particles strongly which help to remove the material from the surface of the metals or non-metals for achieving the desired surface finish (Shorey *et al.*, 2004). MR polishing fluid has rheological characteristics which make the process useful for nano-level surface finishing of complex and three-dimensional surfaces (Sidpara and Jain, 2014).

1.2 Traditional finishing processes

The grinding and lapping are commonly used in the industries as commercial finishing processes for attaining the surface finish over the various components. These processes utilize a rigid tool that applies substantial normal stress on the workpiece surface. So, finishing operations may sometime provide the finished surface with some defects like micro-cracks, heat affected zone, stressed area, etc. (Benardos and Vosniakos, 2003). Also, abrasives used in these traditional finishing processes are either in loose or bonded form. These geometries continuously vary in an unpredictable manner during the finishing operation. The various traditional finishing processes are explained as under.

1.2.1 Grinding

The grinding process is the oldest finishing process which is commonly used in industries. The grinding process divided into various types like surface grinding, cylindrical grinding, centreless grinding, belt grinding, and internal grinding. Each grinding technique has advantages and limitations. In grinding, the shape and size of the components to be finished is the basic limitation for this process. The surface grinder and cylindrical grinder are the commonly used grinding techniques for flat and cylindrical surfaces, respectively. 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 the abrasive particles (Linke *et al.*, 2013). The

abrasive particles bonded on the grinding wheel removes the material in the form of microchips. The important parameter in the grinding process is a uniform distribution of the grinding abrasive particles (Linke and Dornfeld., 2012). 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 (Shinichi *et al.*, 1987).

In the cylindrical grinding, both grinding wheel and cylindrical workpiece are kept in rotational motion in the opposite direction to each other and also reciprocation motion is provided to the grinding wheel as depicted in Fig. 1.1. The feed rate mechanism is provided for giving the depth of cut to the cylindrical workpiece by the grinding wheel. Two forces are acting during the grinding operation namely normal force (F_N) and tangential force (F_T). F_N acts normal to the rotating grinding wheel on the external surface of the workpiece. As the surface contact area of the abrasive particles and workpiece is increase, the normal force (F_N) increases faster than tangential force (F_T) (Grisbrook *et al.*, 1962). The normal force (F_N) indent the rigid abrasive particles into the cylindrical workpiece surface and tangential force (F_T) help to remove the material from the external surface of the cylindrical workpiece in the form of microchips. The normal force and tangential force both depend on each other for better finishing in lesser time (Hoang *et al.*, 2019). The normal force depends on the depth of cut and tangential force depends on the rotational speed of the grinding wheel. The best combination of depth of cut and rotational speed gives a better finishing (Sarma *et al.*, 2017).

During the grinding operation, the abrasive particles get blunt due to which removed chips get trapped between the abrasive grains. Grinding wheel needed to be glazed, which remove the fractured abrasives. The main drawback of grinding is high heat generation. This results in thermal cracks, residual stresses, etc.

Centreless grinding is a variant of the cylindrical grinding, involves to finish the rotating cylindrical workpiece against a high-speed grinding wheel. Centreless grinding is best suited for high-precision applications with very low margins of error (Takeuchi and Ge, 1993). The centreless grinding setup with twin grinding head is shown in Fig. 1.2. In this process, the cylindrical workpiece is supported by the angular blade which helps to pass the workpiece through the grinding wheel and the feed wheel. The feed wheel gives the depth of cut to the cylindrical workpiece. The belt grinding is also a traditional grinding process. In belt grinding, a coated abrasive material belt is used to finish the various industrial applications such as crank shafts etc.



Fig. 1.1 Mechanism of material removal in cylindrical grinding (Hoang *et al.*, 2019).

This process is more flexible to finish the different shapes and sizes of the workpiece than the standard cylindrical grinding process (Jourani *et al.*, 2005).

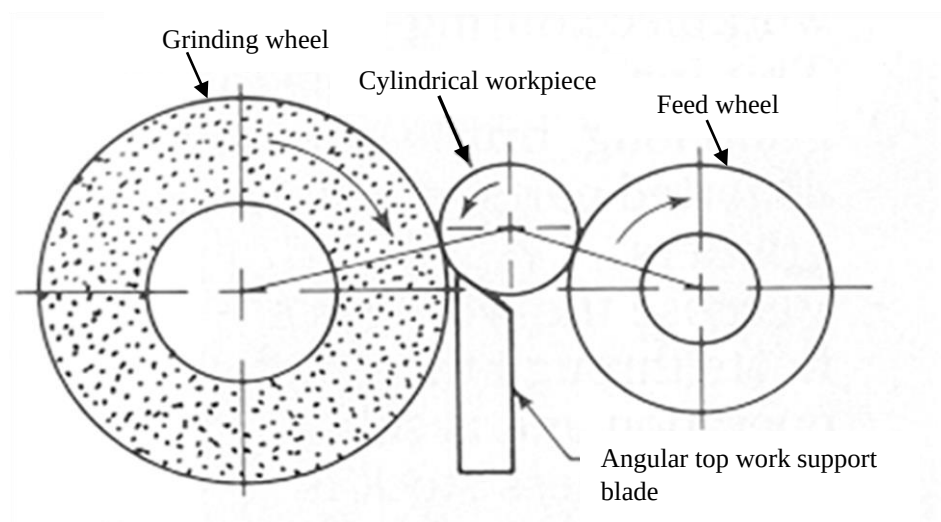


Fig. 1.2 Centreless grinding for finishing the cylindrical workpieces (Bednarski, 2017).

This is because the abrasive bonded belt has flexibility to reach out to the complex geometries as compared to the rigid grinding wheel. This is the main advantage of the belt grinding over the standard cylindrical grinding. The principle of belt grinding process is depicted in Fig. 1.3. The CNC abrasive belt grinding technology is utilized for finishing the complex shapes like turbine blades which is the important part of the steam turbines and aero-engines (Zhi *et al.*, 2005). The bonded abrasive belt runs on the workpiece surface and provide fine finished surface. In these processes, the main disadvantage is lesser control over the finishing forces (Gupte *et al.*, 2008).

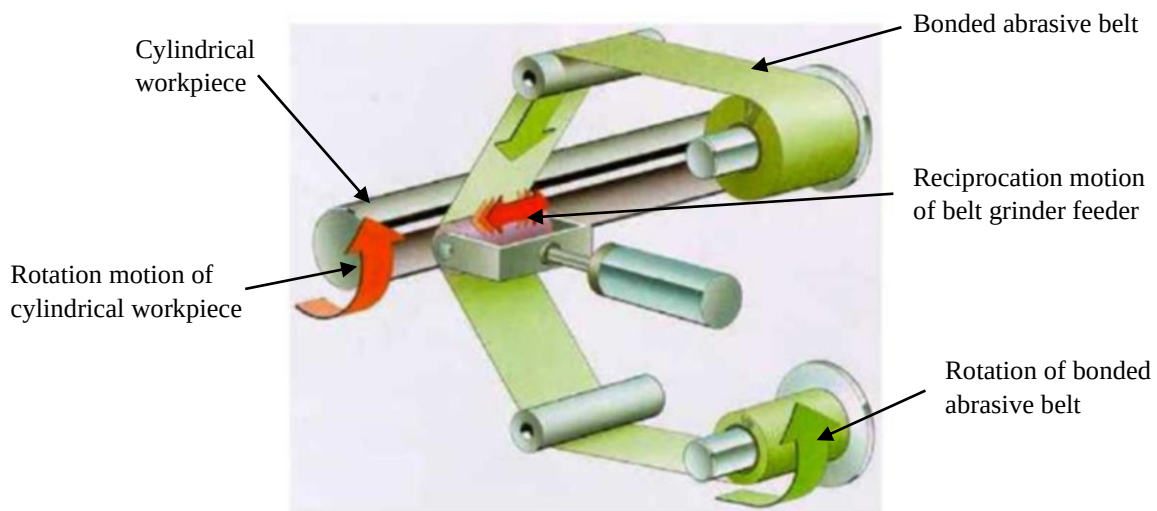


Fig. 1.3 Principle of belt grinding (Jourani *et al.*, 2005).

In addition, computer numerical control (CNC) grinding is stood for reliable, efficient and automatic machinery even with the most complicated system geometrics such as crankshafts, camshafts, cylinders, ball bearings, and transmission shafts (Wei and Zhang, 2016). Today, CNC crankshaft grinding machines are available which work dynamically with different crankshaft variants. This method of CNC grinding is a specific form of grinding which is called CNC crankshaft pin grinding (Wei and Zhang, 2016). It can be classified broadly into two categories based on the tool path. The first form is based on the central axis rotation of the crankshaft matching the X-axis radial feed (two-axes). The second type is based on the central axis of crankshaft rotation, the X-axis of radial feed, and the additional Y-axis of vertical feed (three axes) (Wei and Zhang, 2016).

1.2.2 Lapping

Lapping is performed to achieve the close fit tolerance, better accuracy, remove minor imperfection in shape. It generally works on the principle of three body abrasive wear (Deaconescu and Tudor, 2014) (Kumar *et al.*, 2103). It makes use of loose abrasive slurry-like

silicon carbide and aluminium oxide etc. The lapping is done by placing the loose abrasives between the lap and workpiece as shown in Fig. 1.4. Lapping process is done both manual 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. On the lapping plate, the abrasive particles are provided with a carrier fluid. The abrasion between the abrasives and workpiece surface shear off the material in the form of tiny chips and provides surface finishing. The performance of free loose abrasives depends on the pressure which applies by the lapping plate. The non-uniformity of pressure and non-uniform distribution of the abrasive is the main limitation in the lapping process (Zhang *et al.*, 2011). This results in a lesser uniform surface finishing on the workpiece.

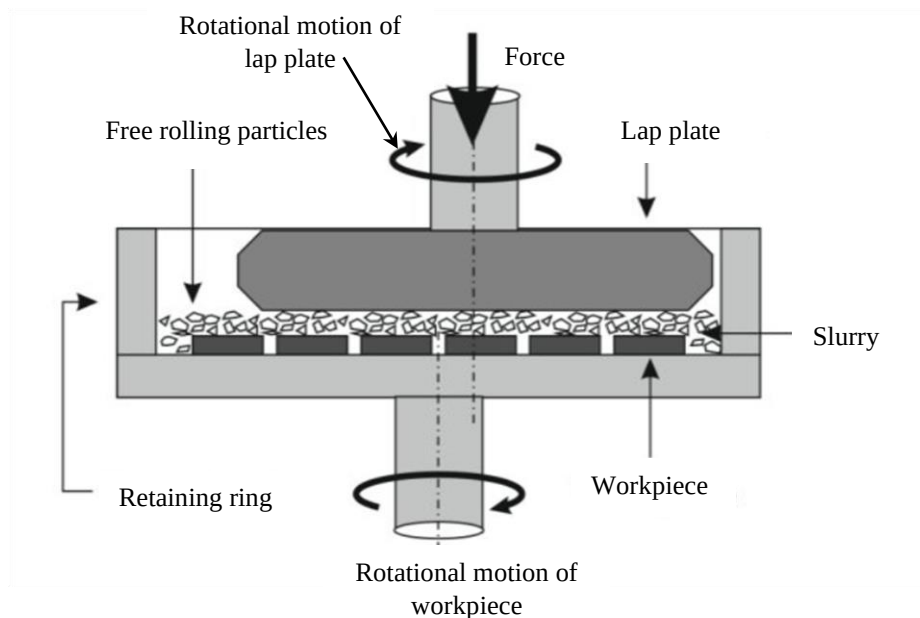


Fig. 1.4 Mechanism of material removal in lapping process (Deaconescu and Tudor, 2014).

The fine finishing with minimum surface defects is highly demanded in today's modern industries. For some of the conventional finishing techniques, this is not feasible to do. Because the traditional abrasive finishing methods use a rigid type of tool without control of finishing forces. By removing unwanted superfluous material from the workpiece surface, small multiple cutting edges of rigid abrasives are typically used to achieve surface characteristics and all traditional finishing processes (grinding, lapping, honing, etc.) work on this mechanism of finishing (Jha and Jain, 2004, Khurana *et al.* 2017). Due to this, the traditional finishing processes can perform finishing on the workpiece surface upto a certain level and after that, it

cannot be performed finishing effectively because of the use of a rigid type of tool (Jha and Jain, 2004). Due to this, the workpiece gets substantial normal stress which causes many surfaces and subsurface defects such as heat-affected zone, micro-cracks, etc. (Jain, 2008, Jain, 2009). This results in reduced strength and functional operation of the workpiece finished surface (Das *et al.*, 2012). Therefore, the objectives like fine finishing with minimum surface defects can be achieved with the help of the different advanced finishing processes.

To achieve fine finishing with minimized surface or subsurface defects, it is important to finish the workpiece surface with the application of low forces (Jha and Jain, 2004). Thus, precise control of finishing forces become important criteria for fine finishing of the workpiece surface with close tolerances and with minimum surface defects. These requirements had led to the development of several advanced finishing processes. The advanced finishing processes with the controlled forces used for finishing the external surface of the workpieces are discussed below.

1.3 Advanced finishing processes

The development of materials results in high strength, high-temperature resistant materials which make it difficult to machine by traditional methods (Kumar *et al.*, 2014). To use these materials and machining to desire shape and size, the non-traditional processes have been used (Jain, 2008). High precision on the surface of the workpieces is needed in the manufacturing world, which is attained by the advanced finishing methods (Jain, 2009). In traditional finishing processes, the limitation of shape and size has been overcome by the use of the flexible controlled finishing medium which can be assessable on the different shapes and sizes of the workpiece surfaces. The influence of the magnetic field controls the finishing forces that are acting on the workpiece surface during the finishing process. The strength of the gripped abrasives by the magnetic iron particles in the finishing medium changes under the influence of the magnetic field.

1.3.1 Magnetic abrasive finishing (MAF)

Magnetic abrasive finishing (MAF) is advanced finishing process which is utilized for fine finishing of the external and internal surface finishing of the cylindrical workpieces. In this process, either bonded or non-bonded abrasive particles are used to finish the workpiece surface (Misra *et al.*, 2017). When the cylindrical workpiece is rotated at high speed, the abrasive particles in the non-bonded powder tend to separate from the iron particles due to the effect of centrifugal force. Thus, to overcome this problem, bonded abrasive particles are used. Bonded abrasive particles are nothing but the sintered ferromagnetic and abrasive particles (Jain, 2009).

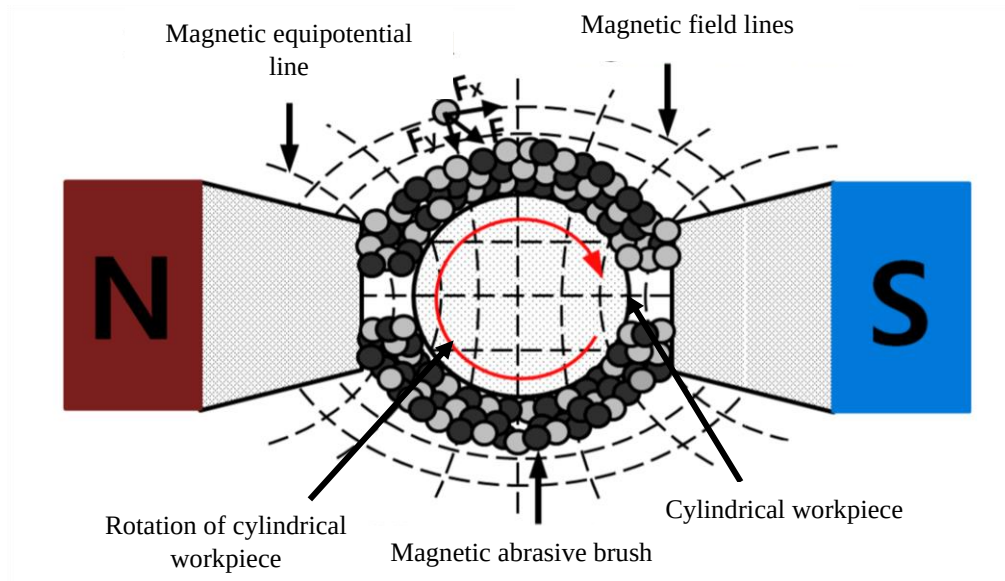


Fig. 1.5 Mechanism of magnetic abrasive finishing (Wang *et al.*, 2017).

In this process, the dry brush of the sintered ferromagnetic iron particles and abrasive particles is used as a finishing medium (Chaurasia *et al.*, 2018). The magnetic field control the strength of dry brush of finishing medium which holds the abrasive particles towards the external surface of the cylindrical workpiece (Wang *et al.*, 2017) (Misra *et al.*, 2017). These abrasives shear off the surface asperities from the rotating cylindrical workpiece as depicted in Fig.1.5. The 2-dimensional magnetic forces act on the abrasive particles. The F_x component of magnetic processing force (F) act on the direction of magnetic field lines and F_y component act on the direction of magnetic equipotential lines depicted in Fig. 1.5. The F_x and F_y act on the cylindrical workpiece and result in the resultant processing force (F). This process has been more effective and gives a good surface finish as compare to the traditional finishing processes (cylindrical grinding, belt grinding, and lapping) (Singh *et al.*, 2010).

MAF process is found appropriate for various applications because of the micro-chip size material removal and self-refine the cutting edges of the abrasive's capability (Sihag *et al.*, 2015). Due to these advantages, this process helps to produce a fine level surface finish. This is very difficult to achieve with the help of traditional finishing processes. The advantage of this MAF process is that the materials which are difficult to machine and high hardness is possible to finish. This process achieves the fine surface finishing and close tolerances for the workpieces made with hard materials.

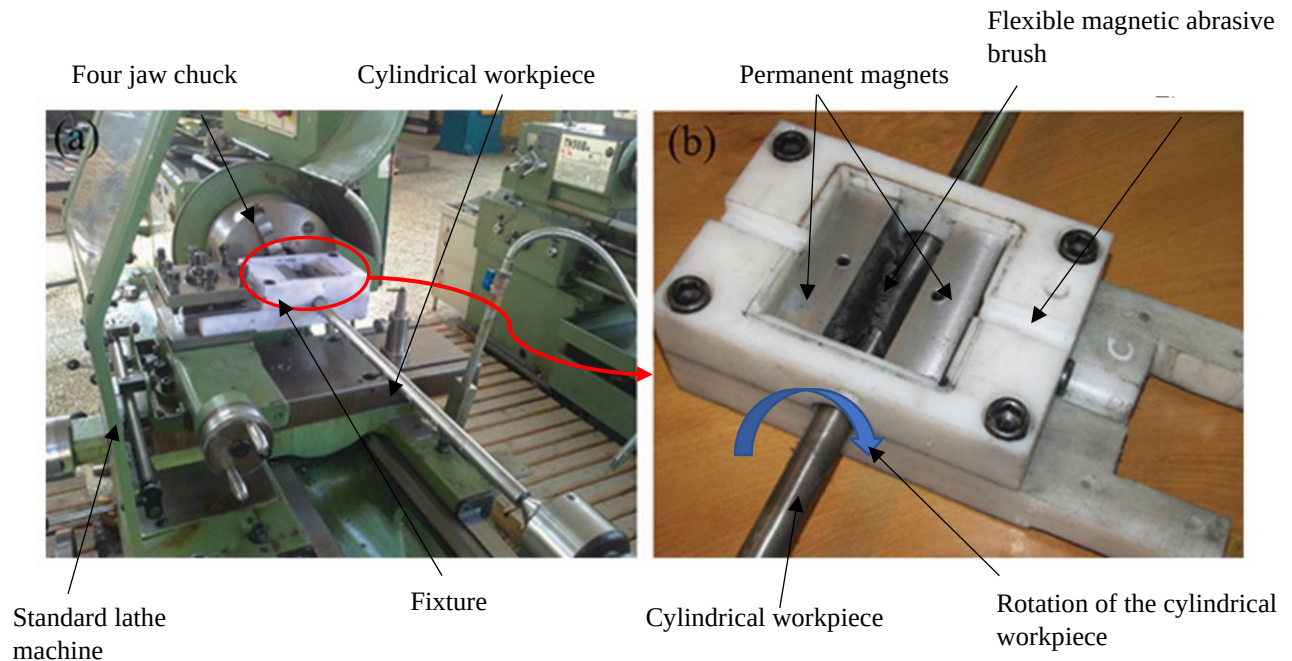


Fig. 1.6 (a) Magnetic abrasive finishing (MAF) setup for finishing the cylindrical workpiece (AISI321 stainless steel) and (b) holding fixture of the cylindrical workpiece and permanent magnets during the finishing operation (Saraeian *et al.*, 2016).

In the MAF process, various types of magnetic abrasives are used for finishing the different types of workpiece materials (Kremen *et al.*, 1996). MAF process is utilized for finishing the flat, cylindrical external as well as internal surfaces of the workpieces and balls, etc (Verma *et al.*, 2017).

In Fig. 1.6, the MAF process is utilized for finishing the external surface of the AISI321 stainless steel cylindrical workpiece. In this MAF setup, the standard lathe is used with the holding fixture for the permanent magnets and cylindrical workpiece. The rotational motion is given to the cylindrical workpiece with the help of standard lathe machine and reciprocation is given to the workpiece fixture to finish the whole cylindrical workpiece. MAF also used for the internal surface finishing of tubes that are used in critical applications including clean gas or liquid piping systems (Yamaguchi and Shinmura, 1999). Finishing of the internal surfaces of aluminium ceramic components was aided with MAF (Yamaguchi and Shinmura, 2004). A highly polished internal surfaces were suggested for workpieces which were used for critical applications with the help of a pole rotation system in MAF (Yamaguchi and Shinmura, 2000). The multiple poles tip system was applied using a tool with alternating magnetic and nonmagnetic properties. This unique magnetic property facilitates the simultaneous finishing of multiple sections with a short pole stroke (Yamaguchi *et al.*, 2011). The internal surface of the capillary tubes was finished using a multiple poles tip system (Kang and Yamaguchi, 2012).

Flat selective laser melting (SLM)-processed stainless steel workpieces were finished using the MAF (Wu and Yamaguchi, 2018). Thus, MAF is used on both internal and external surfaces for various industrial applications.

1.3.2 Vibration assisted cylindrical magnetic abrasive finishing

This process is also developed to finish the cylindrical workpiece of high hardness. The cylindrical workpiece is placed between the two electromagnetic poles in this process (Judal *et al.*, 2014). The electromagnetic poles are excited by supplying the current through the coil of the electromagnet. In the working gap between the tool and workpiece, the magnetic flux gradient is created. The abrasives are supplied in the working gap which takes the form of the brush to perform the finishing operation and also vibration is supplied to the electromagnetic poles to enhance the process performance (Judal *et al.*, 2014). In this process, the normal force acting on magnetic abrasive brush tends to indent the abrasive into the surface roughness peaks and rotational and vibration motion of the cylindrical workpiece shear off the roughness peaks from the workpiece surface. The vibration system attached to the lathe carriage with the help of the 25 mm diameters shafts as depicted in Fig. 1.7. In magnetic abrasive finishing, the dry brush of magnetic iron particles and abrasive particles is used which generates the greater frictional forces between the abrasive and workpiece surface. This results in a high temperature in the working gap (Wu *et al.*, 2015). This may lower the finishing process performance.

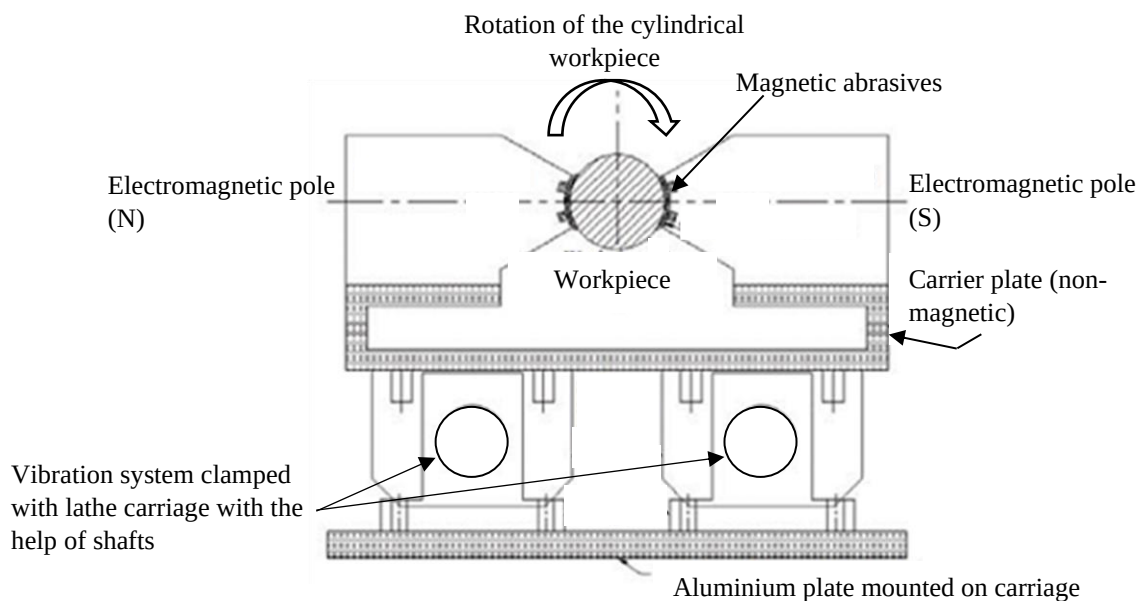


Fig. 1.7 Experimental setup for vibration assisted cylindrical finishing process (Judal *et al.*, 2014).

This limitation can be further minimized by using the magnetorheological fluid-based finishing processes.

1.4 Magnetorheological polishing fluid

Magnetorheological (MR) polishing fluid is a smart fluid. MR polishing fluid is the mixer of magnetic iron particles and non-magnetic abrasives in the carrier medium like oil, mineral oil, etc.

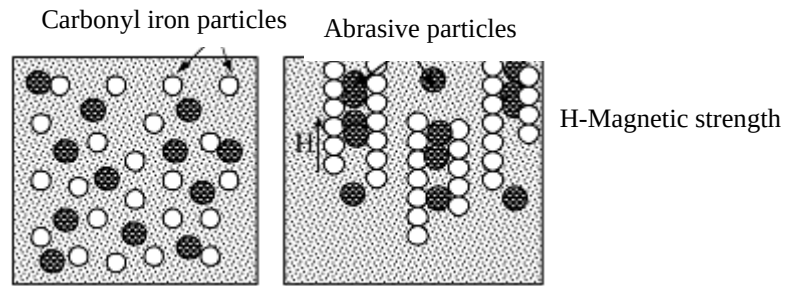


Fig. 1.8 Effect of magnetic field on magnetorheological polishing fluid (Jain,2008).

MR polishing fluid acts as Newtonian fluid when there is no magnetic field. Under the influence of the magnetic field, MR polishing fluid acts as non-Newtonian fluid (Jain, 2009) shown in Fig. 1.8. Magnetorheological (MR) polishing fluid exhibits the Bingham plastic Model (Weiss *et al.*, 1993). This model states that the fluid behaves as a semi-solidified body at low stresses but flows as a viscous fluid at high stress. Dipoles are created when the external magnetic field is applied to the fluid. Fig. 1.9 shows that the dipoles are attracted to each other to form chains of magnetic iron particles. The MR polishing fluid has a very good response time with the effect of the externally applied magnetic field, its responses in milliseconds (Sidpara *et al.*, 2009).

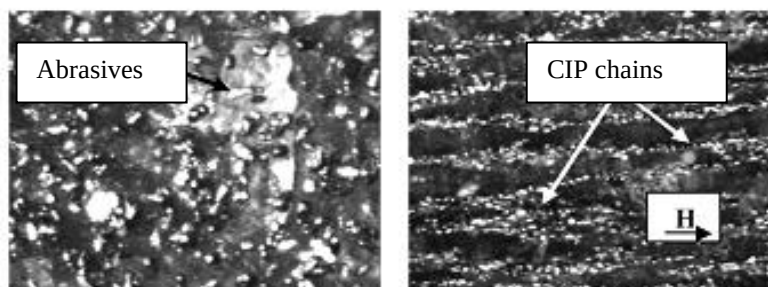


Fig. 1.9 Generation of chain like structure in MR polishing fluid (Jain,2008).

magnetic lines of forces move from region of higher flux gradient to region of lower flux gradient. The magnetic iron particles move toward the region of higher magnetic flux gradient and non-magnetic abrasives move toward the lower magnetic flux gradient (Jain, 2008).

1.4.1 Features of the magnetorheological (MR) polishing fluid

- The concentration of magnetic and abrasive particles can be altered at an optimum level. Due to the base fluid with stabilizers which uniformly distributes the iron particles and abrasive particles.
- MR fluid has low viscosity when no magnetic field is applied to the fluid. Because this fluid has contained 50 to 60% concentration of non-magnetic carrier fluid.
- Under the effect of the magnetic field, MR polishing fluid show high yield strength. Because in MR fluid iron particles generates a chain-like structure which gives the high yield strength to the abrasive particles for removing the roughness peaks.
- Because the fluid has non-corrosion base fluid (paraffin oil, AP3 grease), stabilizers, and additives that provide resistance to the corrosion.
- MR fluid has good re-dispersibility. Because of the stabilizers in the MR fluid that help to provide the stability to the particles which use in the various applications like dumper, clutches, and MR finishing, etc. This also reduces the lumps of particles in the MR fluid.

1.4.2 Components of magnetorheological (MR) polishing fluid

Magnetorheological (MR) polishing fluid plays a major role in the finishing process under the effect of the magnetic field. MR polishing fluid is the suspension of micron-sized abrasive and iron particles in a carrier medium with some additives (Jain, 2009). Carrier fluid is a combination of oil or water, various surfactants, and additives. Various compositions are used with the different sizes of the CIPs and abrasive particles into the base fluid as per the requirement of the different types of workpiece material surface to be finished (Chen *et al.*, 2008). The rheological behaviour of MR polishing fluid is influenced by the magnetic flux density (Sidpara *et al.*, 2009). The rheological properties of MR polishing fluid include viscosity and shear strength. Rheological behaviour of MR polishing fluid is affected with the change in temperature and chemical configuration of the magnetorheological (MR) polishing fluid (Sidpara *et al.*, 2009) (Sujith *et al.*, 2019). The rheological characteristics vary with variation in different compositions of CIPs, abrasive particles and base fluid under the different magnitude of magnetic field (Sidpara and Jain, 2014).

The main elements of MR polishing fluid are:

- Abrasive particles
- Magnetic particles

- Carrier medium
- Stabilizer / Additive

1.4.2.1 Abrasive particles

The roughness asperities on the workpiece surface are removed by the abrasives gripped in the iron particles chains. These gripped abrasive particles that remove surface asperities are known as active abrasives. During the finishing, these active abrasives face the surface asperities. The removal of material depends on the properties of abrasive particles used for finishing. The most important characteristics of the abrasive particle affecting wear rate are size, hardness, and geometry (Pintaude, 2018).

Commonly used abrasive particles are:

- Silicon carbide (SiC)
- Cubic boron nitride (CBN)
- Alumina (Al_2O_3)

1.4.2.2 Magnetic particles

The magnetic particles are the key element of the magnetorheological (MR) polishing fluid. These iron particles form the chain like structure in the working gap under the effect of magnetic field. In these chains, the abrasive particles get gripped and perform the finishing operation. The rheological characteristics of the MR polishing fluid play a vital role in finishing. Because in the presence of the magnetic field, the iron particles make dipoles and form the chain like structure. This structure gives the shear strength to the active abrasive particles for shearing off the surface asperities from the external surface of the cylindrical workpiece. Magnetic particles must have high magnetic saturation and low coercivity for good rheological properties of MR polishing fluid (Sidpara *et al.*, 2009). Commonly used magnetic particles are:

- Carbonyl iron particles (CIPs)
- Electrolytic iron particles (EIPs)

Carbonyl iron particles (CIPs) are highly pure iron and prepared by chemical decomposition of the purified iron pentacarbonyl. Electrolytic iron particles (EIPs) are produced by an electrolytic process. In this process, the electrolytic deposition of the metal from an aqueous solution of an appropriate iron electrolyte occurs. Further, this metal is deposited onto a cathode (-ve) and can be subsequently chipped off from the cathode and ground into a fine powder.

1.4.2.3 Carrier medium

The suspension of abrasives and magnetic iron particles take place in a carrier medium. The desirable properties of the carrier medium are the low freezing point, high boiling point and resistance to corrosion. Carrier medium is generally used as oil-based or water-based. Oil based carrier medium has high viscosity which results in a good performance against sedimentation (Sidpara *et al.*, 2009).

1.4.2.4 Stabilizer/additives

For the proper dispersion of abrasive particles and magnetic iron particles in MR polishing fluid, the stabilizers are added. Grease or other thixotropic additives are added to the MR polishing fluid for improving the stability of the particles. Some additives are necessary to be added to prevent oxidation of suspended magnetic particles. Stabilizer such as glycerol are added to improve the suspension of particles in MR polishing fluid (Sidpara *et al.*, 2009).

1.5 Magnetorheological (MR) fluid-based finishing processes

The magnetorheological polishing fluid-based finishing processes are advanced finishing processes which are used the MR polishing fluid as a finishing medium. The MR polishing has the advantage that the rheological properties of this fluid can be controlled by varying the magnetic flux density. Due to this, MR fluid-based finishing processes are used for finishing the hard and soft material workpieces. This fluid also gives the flexibility to the processes to finish the different shapes and sizes of workpieces. This happens because the carrier fluid gives the space to the magnetic iron particles and abrasive particles to reform as per the shape of the components. This is beneficial for finishing the complex shaped workpiece surface. These processes finish the ferromagnetic as well as non-ferromagnetic workpiece surfaces.

1.5.1 Advantages of magnetorheological (MR) polishing fluid-based processes

- Capable to finish the workpiece upto the nano-level. Because of flexible finishing medium that meets to the almost every shape of the industrial components and produces controllable finishing forces which helps to achieve the nano-level finishing.
- Low normal forces act on the workpiece surface which reduces the surface and sub-surface defects (scratch, micro-cracks).
- Closer tolerance design can be achieved on the MR finished surfaces.
- Decreases the wear and friction losses. Because after removal of roughness peaks with the MR finishing, the surface hardness of the components gets improved which helps to decreases the wear and friction losses of the industrial components. This leads to increases in the life span of the work materials.

- Finishing forces exerted on the workpiece's surface can be controlled by controlling the magnetizing current as per the shear strength required for finishing the workpiece surfaces. This helps to finish the soft as well as hard material workpieces.

1.5.2 Magnetorheological finishing (MRF)

The finishing of precise lenses is very difficult because they are made of brittle material. Commonly the grinding and lapping is used in the lens manufacturing industries. 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).

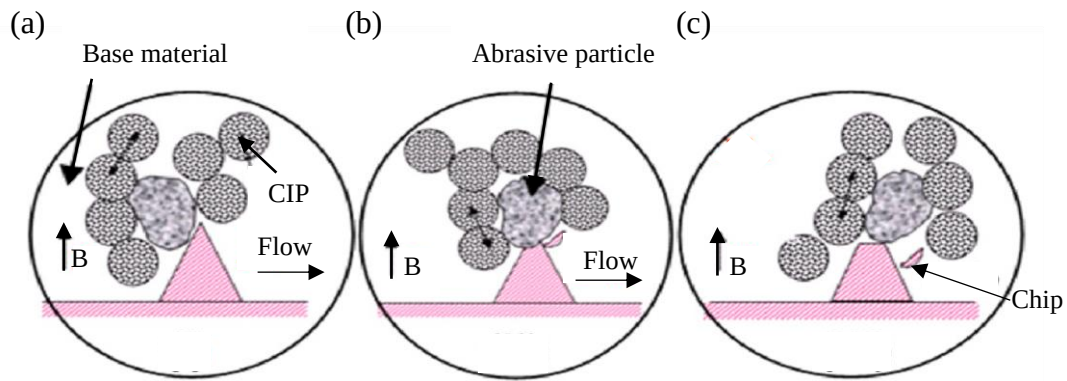


Fig. 1.10 Three stages of material elimination from the roughness peaks in MRF process (Jain, 2009).

In the lapping, the non-uniformity of pressure and non-uniform distribution of the abrasive is the main limitation. Due to this, the lesser uniform surface finishing is achieved on the surface of the cylindrical or flat workpiece. To achieve the fine surface finishing the magnetorheological finishing (MRF) process was developed in 1996 at the centre of optics manufacturing at Rochester (Kordonski, 1996). This process uses the magnetorheological (MR) fluid which is known as smart fluid. MR polishing fluid consists of magnetic iron particles and abrasive particles mixed in a fluid such as silicone oil and paraffin oil (Kordonski *et al.*, 1996). The rheological properties of MR polishing fluid get changed with changing the magnitude of the magnetic flux density. When there is no magnetic field, the carbonyl iron particles (CIPs) of MR fluid are unevenly distributed. Under the influence of the magnetic field, the iron particles align along the line of the magnetic field forming columnar structure. The CIP chains grip abrasive particles on the surface of the workpiece and remove the peaks from the workpiece surface as depicted in Fig. 1.10. In the magnetorheological finishing process, MR polishing fluid is supplied by the nozzle over the rotating wheel rim as

depicted in Fig. 1.11. It demonstrates that the abrasives particles are in contact with the surface of the workpiece while MR polishing fluid is closer to the rotating wheel rim. Indentation force transfers to the work material through the active abrasives and penetrates the surface of the workpiece. When the wheel rotates over the workpiece surface, then due to relative motion between the gripped active abrasive and workpiece surface, the material gets eroded out from the workpiece surface and produce fine finishing.

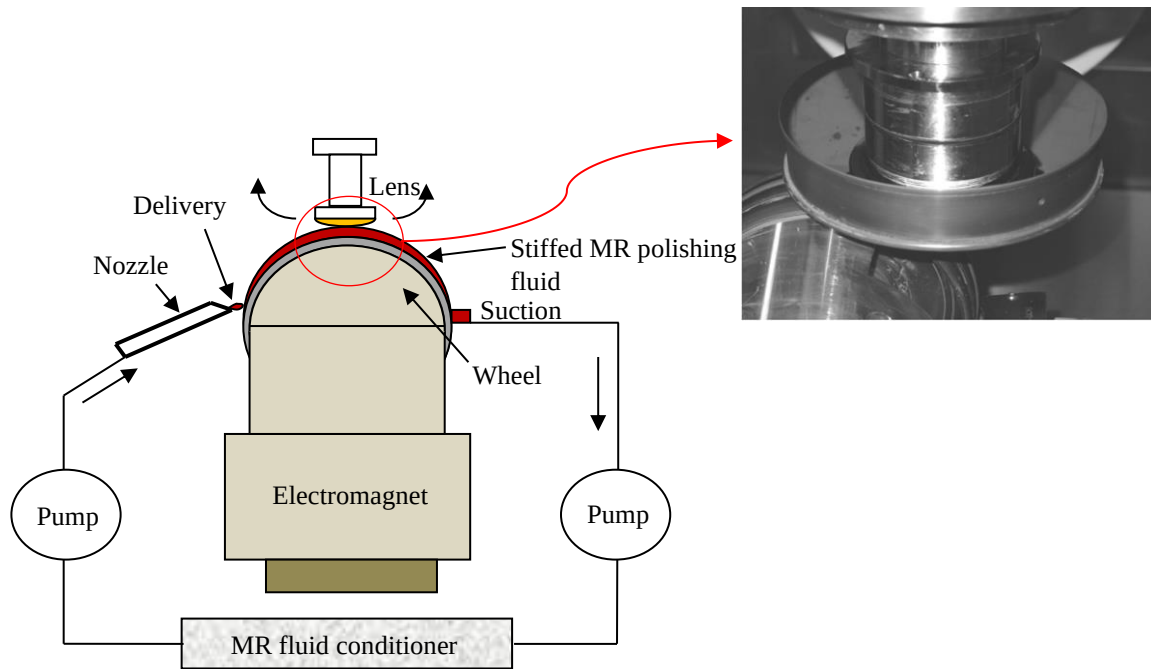


Fig. 1.11 Schematic diagram of MRF (Shorey *et al.*, 2004).

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 magnetorheological polishing fluid brings heat and debris away from finishing region and doesn't lose its shape as it is self-deformable (Wu *et al.*, 2016).

1.5.3 Ball end magnetorheological finishing (BEMRF) process

The wheel type magnetorheological finishing (MRF) process can finish only the specific shapes of surfaces such as concave, convex, etc. This limitation has been overcome by the development of the BEMRF. In BEMRF (Singh *et al.*, 2013), the ball end like magnetized MR polishing fluid at the tool tip was used for finishing the flat as well as 3D surfaces. In the working gap, the tool tip gets magnetized with the help of the electromagnet coil. The MR polishing fluid forms like a ball shape spot at the magnetized tool tip. The relative motion between the ball end formed MR polishing fluid and workpiece surface perform finishing on the workpiece surface.

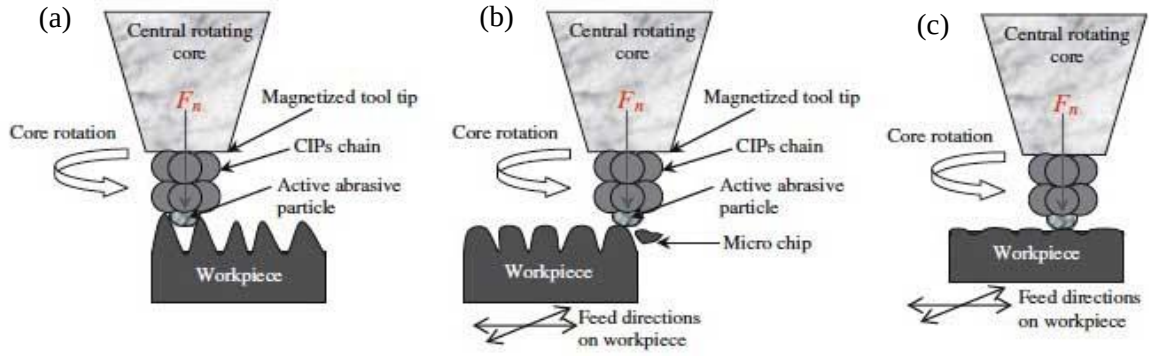


Fig. 1.12 Material removal during the MR finishing of the workpiece (Singh *et al.*, 2013).

Figs. 1.13(b) represents the finishing operation performed by ball end MR finishing process and Fig. 1.13(c) shows the MR fluid formed ball end like shape at the magnetized tool tip surface. In the existence of magnetic flux density, carbonyl iron particles (CIPs) form chains like structure and grip the abrasive particles on the workpiece surface.

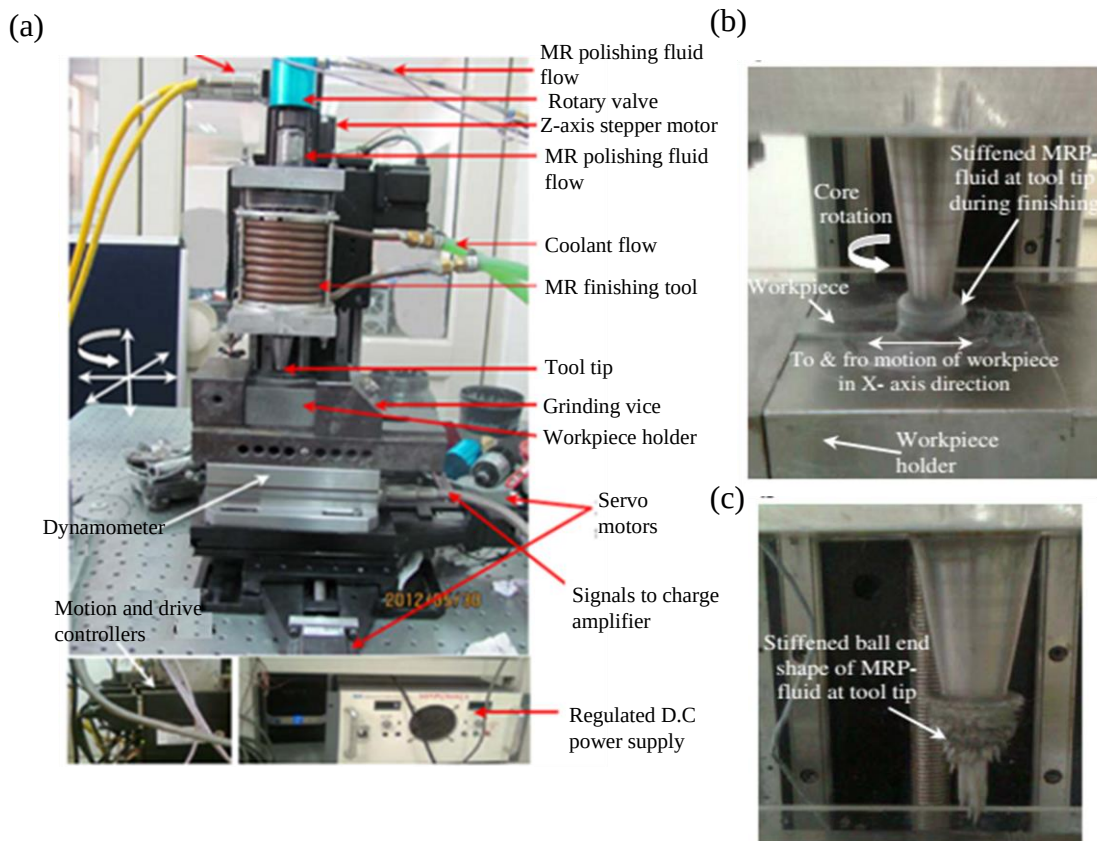


Fig. 1.13 (a) Experimental setup, (b) stiffened MR polishing fluid during finishing, and (c) stiffened MR polishing fluid at the magnetized tool tip surface (Singh *et al.*, 2013).

The abrasives get indent inside workpiece roughness peaks because of the magnetic normal force (F_n) as depicted in Fig. 1.12(a). Due to the rotation of central rotating core and relative motion between abrasives and workpiece surface, the indented abrasives shear the roughness

peaks in the form of micro-chips as depicted in Fig. 1.12(b). Due to the constant feed of workpiece, all the peaks get removed from the surface of the workpiece and fine finishing is achieved as shown in Fig. 1.12(c). 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., 2013). This process can finish the surface of ferromagnetic and non-ferromagnetic materials. Fig. 1.13(a) shows the experimental set-up developed for this process.

1.5.4 Turning type magnetorheological (MR) finishing process

This process was developed to finish the external surface of the ferromagnetic as well as non-ferromagnetic cylindrical components (Singh et al., 2016). This process overcomes the problems of in-process controlling of forces which give rise to surface defects associated with traditional finishing processes for cylindrical surfaces (Jain, 2008). Fig. 1.14 shows the material removal mechanism of the magnetorheological finishing of the cylindrical workpiece surface. The solid tool core is magnetized with the help of an electromagnetic coil and holds the active abrasives which approach the cylindrical workpiece as depicted in Fig. 1.14(a). These active abrasives indent into the roughness asperities and due to the rotation of the cylindrical workpiece and feed given to the tool core, the surface asperities get sheared off in micro-chips as depicted in Fig. 1.14(b). Further, the performance of the solid core tip surface with a flat and the curved surface is compared with each other on the same operational conditions.

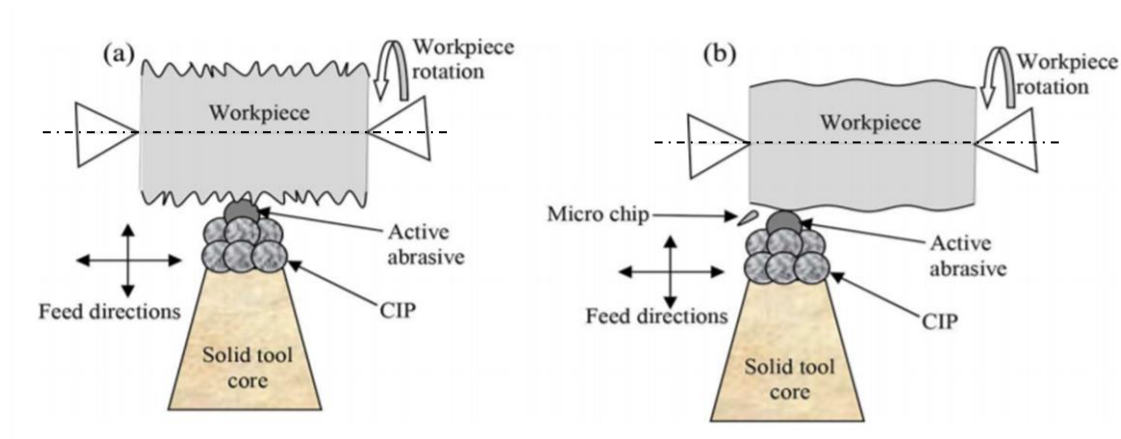


Fig. 1.14 Material removal mechanism of MR finishing of the cylindrical workpiece surface (Singh et al., 2016).

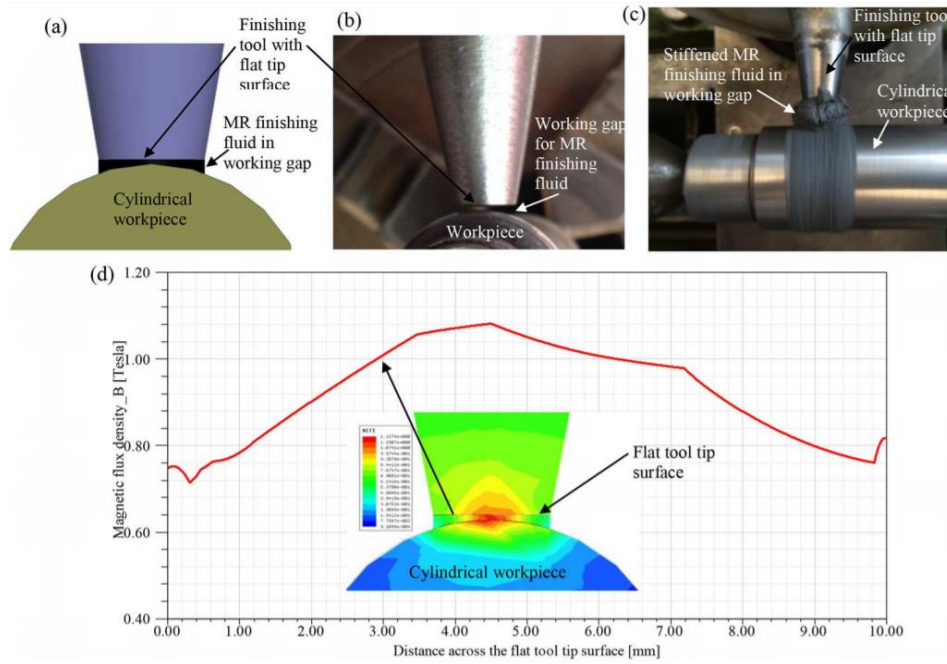


Fig. 1.15 Flat solid stationary tool core tip surface (a) finite element analysis (FEA) model, (b) enlarge view with cylindrical workpiece, (c) finishing operation (top view) and (d) plot of flux density distribution along tip surface (Singh *et al.*, 2016).

The finite element analysis (FEA) is performed on both tool core tip as depicted in Figs. 1.15 and 1.16, respectively.

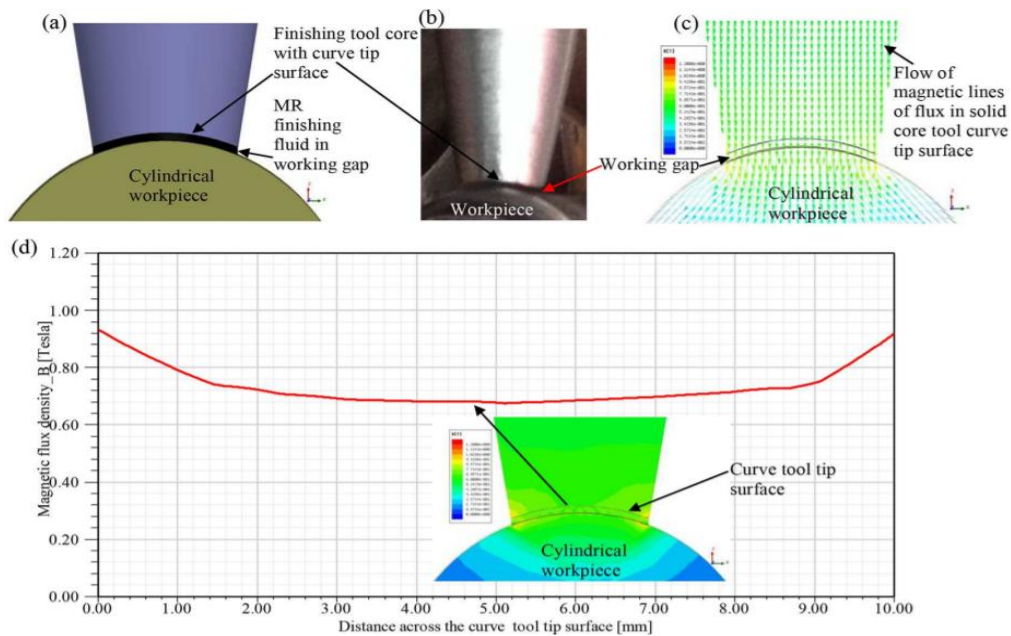


Fig. 1.16 Curved solid stationary tool core tip surface (a) finite element analysis (FEA) model, (b) enlarge view with cylindrical workpiece, (c) distribution magnetic field lines in working gap and (d) plot of flux density distribution along the tip surface (Singh *et al.*, 2016).

FEA result concluded that the uniform distribution of the flux density is provided by the curved shaped tool tip surface as compared to the flat shaped tool tip surface as depicted in Fig. 1.16. This concludes that the MR finishing tool with a curved tip surface can perform better surface finish than the flat tip surface for finishing of the external cylindrical surfaces. The head stock of the lathe machine was utilised to rotate the cylindrical workpiece and the tool remained stationary. The U-shaped aluminium clamp is used to hold the electromagnetic tool with a base plate which is fixed on the tool post of the lathe machine. The electromagnetic tool is fix on the tool post with the help of nut bolt assembly. This turning type MR finishing process can make its way in automobile, aerospace, and machine tool industries for utilizing the fine finished cylindrical workpieces.

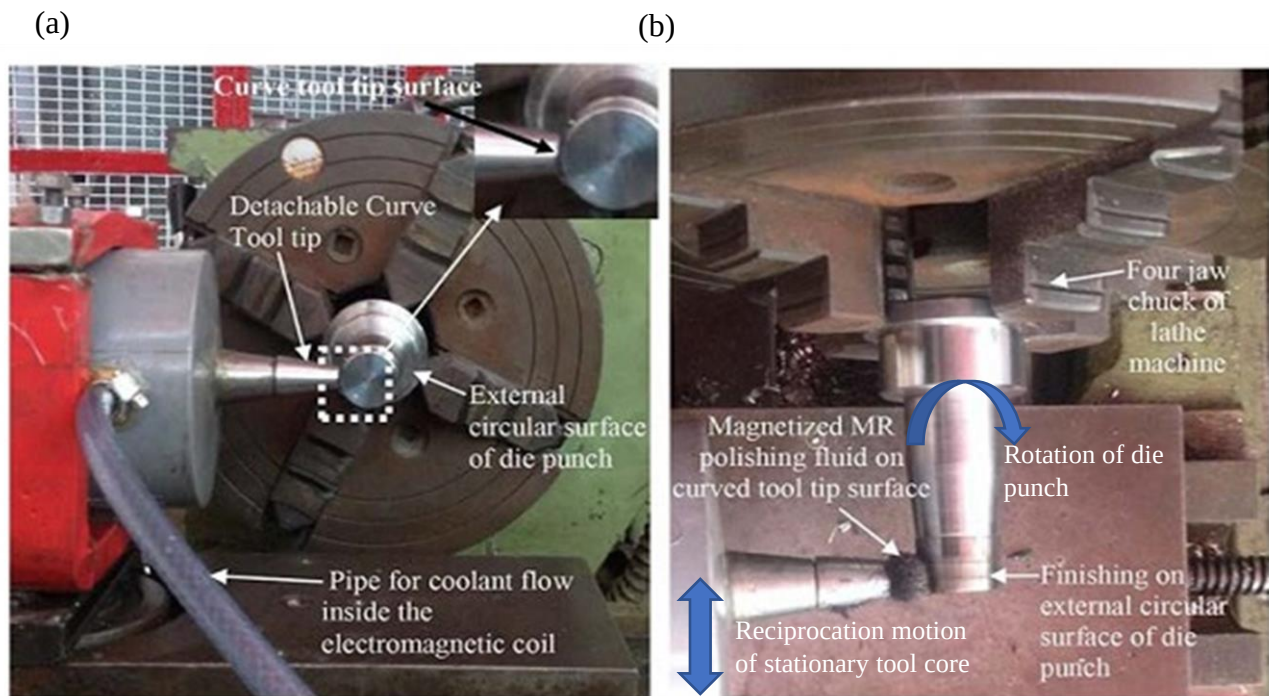


Fig. 1.17 Magnetorheological finishing (a) experimental setup for the external cylindrical surface workpiece and (b) during finishing with magnetized MR polishing fluid (Maan *et al.*, 2017).

The turning type MR experimental setup designed for finishing the external surface of cylindrical workpieces as depicted in Fig. 1.17(a). In the working gap, MR polishing fluid is applied as depicted in Fig. 1.17(b). The performance of this process was checked for flat tool tip and curved tool tip, and found better with the curved tool tip surface because of the uniform higher magnitude flux density as compared to the flat tool tip surface (Singh *et al.*, 2016). The limitation of this process is that there was no precise and controlled arrangement for the feed either to the workpiece or the tool rotation. This happens because in the standard lathe, the feed

rate was not precise and a fixed ratio of feed was provided in the standard lathe which was also a drawback for this process. Also, the tool core tip was made stationary with only feed rate while finishing performed on the rotating cylindrical workpiece surface. Due to this arrangement, the lesser relative motion can be provided to the active abrasives which may lower the process performance. Also, this process has no such arrangement for finishing the taper cylindrical surfaces because the electromagnetic tool is fixed on the tool post of the lathe machine. Also, the curved tool tip surface has fixed curvature to finish a fixed diameter workpiece. This curved tool tip has not finished the tapered and stepped cylindrical workpieces because the curvature is not constant at every point. Due to this, only straight cylindrical surfaces can be finished using the curved tool tip MR finishing process.

1.5.5 Applications of various external cylindrical parts in different industries

The application of fine finishing with the defect-free cylindrical external surface is extremely necessary to improve mechanical properties and work performance. The cylindrical external surface components are used in various industrial applications and machines. The fine finishing with lesser surface defects cylindrical components can improve its functionality. There are various industrial applications as given below.

- In the automobile industry various applications which require a fine finish to improve the efficiency of the engine by reduces the noise, friction and wear and tear of the components. These components are spline shafts, armature shafts, stepped shaft, camshaft, and valve stems.
- In the hydraulic and pneumatic industries, the hydraulic and pneumatic cylinders are required fine finishing for responding effectively at loading conditions. Also, hydraulic pump applications like gear pump shafts, pump pistons are required the fine finishing to improve the process performance.
- In the automobile steering system, the steering rack bar requires the nano-finishing to improve the response time and reduces the steering effort. The nano-finishing of the automobile steering rack bar can improves its functional operation.
- In air bearing, the uniform and fine finishing of the air bearing components is playing an important role. Because, as much as the surface finish is uniform and fine, the friction between air and the cylinder of the air bearing reduces and also uniform distribution of the air around the cylindrical part improves its functionality and efficiency. The air bearing has cylindrical surface which require uniform and fine finishing for its smooth operation at higher speeds.

- In metal forging industries, the rolling rolls are used to roll the material into the desired shape. As the surface of the roll is fine finished, the rolling force can be reduced and the surface texture of the end product can be improved.
- The textile industrial is also needed the fine finished surface components to perform the operation smoothly and with lesser noise. The component like the grooved winding drum requires fine finished to reduce the yarn breakage. This can also enhance the quality of the yarn winding.
- The micro extrusion industries have used to produce the micro-sized parts like micro dies, micro punches. The external surface of the micro extrusion punches requires fine finished surface to uniformly distribute the billet material and reduce the punching forces.
- In the printing industries, the distribution of the colours and ingot material is very important to the printing of PVC sheets. The uniform distribution of pressure is also an important factor for better printing. This needs a uniform and fine finishing of the printing roller. The fine and uniform finishing of the copper cylindrical rollers is required to fulfill these needs.
- The tapered cylindrical punches require fine and uniform finishing to provide the close tolerances, improves the end product quality, reduces the friction and to enhance the punch life span.

CHAPTER 2

LITERATURE REVIEW

The precise surface finishing of cylindrical components with good surface integrity is a very important requirement in industries for improving the operative functionality (Singh and Singh, 2016). Presently, there are many applications in an industry where nano-finishing of the external cylindrical components is of great concern. The benefits of nano-finishing are better dimensional accuracy, close tolerance fit or design, enhancement in life span and reduced wear and frictional losses, etc. Grinding is a finishing process that is commonly used to finish the various external cylindrical surfaces. It consists of a circular wheel having abrasives, strongly bonded to its outer surface. The circular grinding wheel is made to rotate over the surface of the workpiece and the strongly bonded abrasives shear out the roughness peaks present over the surface. The traditional finishing processes use a rigid type of tool for finishing the surface of the workpieces due to which the finishing forces cannot be controlled in these processes. Due to uncontrollable finishing forces, several surfaces or subsurface defects like micro-cracks, heat affected zone, thermal residual stress, and ploughed materials are observed over the finished surface (Gupte *et al.*, 2008). To attain the surface finish with good surface characteristics on the cylindrical external surfaces, various advanced finishing processes with control of the finishing forces externally by controlling the magnetic field are developed. While performing finishing with these processes, finishing forces can easily be controlled by controlling the magnitude of the magnetic field in the working gap.

The literature review of various researchers in the traditional and advanced finishing processes for the external surfaces has been deliberated in different categories and their brief remarks about the work is drawn in this chapter. After going through the literature review, the research gaps were analyzed which are also discussed. Based on the research gaps and the industrial applications, the objectives of the present research have been decided.

2.1 Literature related to the traditional finishing processes for the external surface of the workpieces

Hassan *et al.*, (1998) investigated the performance of brass cylindrical workpiece using response surface methodology. In this process, a ball burnishing tool was designed. The balls used in the tool were chromium steel with hardness value of 65 HRC. A cylindrical brass workpiece was used in this experiment. The experiment was performed on the colchester master 2500 lathe. The cylindrical workpiece was held in the chuck at one end and on the other

end by the revolving center on the lathe. The designed tool was held in the tool post on the lathe while finishing. Experimental parameters were taken as a number of passes of tools and force on the ball of burnishing tool. It was found that surface roughness was reduced to 0.172 μm from 5.2 μm at the force of 203 N in two passes.

Nathan et al., (1999) investigated the grinding burn in the cylindrical grinding of the steel cylindrical workpiece. The C60 steel cylindrical workpiece with a hardness value of HRC40. The A463-K5V10 grinding wheel was used for the grinding operation. The steel workpieces of 25.5-35 mm diameters were utilized for the experimentation. During the experimentation, the workpiece speed was varied from 40 to 200 rpm. The equivalent chip thickness was used as a variable to understand the grinding burn. The authors concluded that the surface quality of the ground workpiece was affected seriously by the grinding burn.

Pei et al., (1999) analysed the subsurface damage occurred on the flat surface of silicon wafer while performing the grinding process. The authors observed several configurations of cracks formed over the surface of a silicon wafer with cross-sectional microscopy. The study was performed on the design of experiments to analyse the effects of different grinding process parameters such as the rotational speed of the wheel and feed rate on the depth of the subsurface crack. Grinding wheels having diamond abrasives with different mesh size i.e. 360, 1200, 2000 and 4000 were used for the experimentations. Experimental parameters i.e. grinding wheel speed, chuck speed, and feed rate were ranged from 25-56.67 rev/sec, 0.33-1.33 rev/sec and 0.25-0.58 $\mu\text{m}/\text{sec}$ respectively. It was concluded that the depth of subsurface crack on the flat the surface of the silicon wafer was approximately equal to half of the grit size of diamond abrasive used for the grinding wheel.

Hwang et al., (2000) investigated progressive change in wheel topography during grinding and how it affects the grinding process. A statistical model is developed to characterize the wheel topography during grinding in terms of active cutting grains and wear flat area. According to this model, continued grinding is accompanied by an increase in both the number of active grains and the wear flat area on the wheel surface as the wheel wears down. The measured increase in grinding forces and power was found to be proportional to the wear flat area, which implies a constant average contact pressure and friction coefficient between the wear flats and the workpiece. Increasing the wheel speed from 85 to 149 m/s significantly reduced the contact pressure, which may be attributed to a reduction of the interference angle, but had almost no effect on the wear rate of the diamond abrasive.

Erik et al., (2001) investigated the effect of 3-D wheel surface configuration on the final geometry of the workpiece. A wheel surface model was built for the simulation of workpiece

surface texture by combining it with a surface grinding process model. The output of the model shows a good match with the experimentally ground surface. It is possible to calculate and predict roughness parameters such as Ra, Rq and Rmax associated with the generated surface. Further, information acquired from the simulated surface may be used to obtain various other statistical parameters such as the profile height distribution, spectral plots and autocorrelation functions. This 3-D model can also be used for friction, lubrication and wear studies. The role of vibration, cutting fluid, workpiece material, wheel wear, and grit deflection in altering the surface finish of the ground surface need to be studied not only by considering the variables independently, but also by taking into account their interactive effect.

Oliveira et al., (2009) examined the industrial demand-based research into grinding technology growth. The authors discussed the complexities of grinding in the industry. Automotive application is the essential driving force for grinding growth. Many problems were posed by today's industrial needs, including well-developed technologies such as automatic grinding wheel balancing device, scalable and predictive systems, increased use of CNC for grinding, multiple grinding in one stage, and so on.

Siddiquee et al., (2010) investigated the optimization design of the process parameters using the grey relational analysis in in-feed centreless cylindrical grinding. The major performance characteristics which were selected to evaluate the process were surface roughness, out of cylindricity of the valve stem and diametral tolerance. The experimentation was performed on the EN 52 austenitic valve steel cylindrical surface of the stem. The process parameters which affect the performance characteristics were grinding feed, dressing feed, cycle time and dwell time. The range of the process parameters was selected as dressing feed was 5 mm/min to 10 mm/min, grinding feed was 2 mm/min to 10 mm/min, dwell time was 1.5 sec to 3 sec and cycle time was 10 sec to 12 sec respectively. The authors concluded that the optimum process parameters were confirmed the surface roughness, out of cylindricity and diametral tolerance from the nominal diameters of the IC engine valve stem decreased by 24.17%, 50%, and 200% respectively.

Zhang et al., (2011) studied a new robot grinding machine configuration with new robot frame including active work element frame and passive support frame. Recently the belt grinding of complex material surfaces has been implemented in the industrial robot to achieve high productivity and reliably good surface consistency. The robot keeping the grinding wheel concentrated on early production to finish a component with purely geometric features with comparatively precision requires. Dexterity optimization ends are first to create an acceptable

co-ordination scheme for the general theoretical analysis, and secondly to ensure that the robot has ample dexterity of ground space in a fair relative location to the grinding machine.

El-Helieby and Rowe, (2013) studied the microstructural changes in ground EN-31 steel external flat workpiece after the grinding operation. The process parameters were taken as grinding wheel speed of 30.5 ms^{-1} , table speed of 17.5 mmmin^{-1} and grinding fluid of emulsion Osul EH (1:2). The authors concluded that the grinding burn changed the microstructural of the workpiece surface. During the finishing, the heat flux enters into the workpiece due to the uncontrollable finishing forces generated by the rigid abrasive stone over the workpiece surface. This finally causes the micro-cracks on the workpiece surface.

Kumar and Vettivel, (2014) evaluated the effect of the normal force, tangential force and specific energy generated during the finishing of Al (A356)/SiC composite. The finishing was carried out with three types of grinding wheel made of SiC, diamond and cubic boron nitride (CBN). The authors concluded that with the rise in both normal and tangential force, the intensity of cut increases. The larger intensity of cut induces high local contact forces which result in a micro-crack on the workpiece surface. Also, the specific grinding energy reduced with the rise in the intensity of cut.

Fergani et al., (2014) studied the effects of temperature on tensile residual stresses generated on the surface of a component while performing grinding. The authors developed a predictive model to evaluate the onset tensile temperature which generates the residual stresses over the workpiece. The model relied on stresses and strains generated over the surface of the workpiece due to heat produced while grinding operation performed. The empirical relation was built between the stress profile generated over the surface of the component and the temperature attained over the component's surface. The results predicted from the model were experimentally validated with grinding of AISI 52100 hardened steel. The authors concluded that it is important to evaluate the onset tensile temperature because this is the major factor which may affect the precision and productive life of the final industrial product. The model built a scientific basis for the configuration of grinding process parameters to avoid the generation of stress over the surface of the component.

Wegener et al., (2017) discussed to build grinding machines in order to increase productivity. This work describes the thorough examination of grinders. Authors discussed main game changing technologies used in grinding machines such as tool changers with sufficient accuracy so that reconditioning or rebalancing after tool change is no more necessary. Expert systems or simulation-based support systems for operators that drastically reduce the setup times in order to increase productivity.

Deresse et al., (2019) investigated the impact of the process parameters on the material removal rate of the EN 45 steel cylindrical workpiece in cylindrical grinding using the Taguchi method. The EN 45 steel workpiece of 40 mm diameter and 130 mm length was used for the experimentation. The machining process parameters were selected as the depth of cut, feed rate, and workpiece rotational speed. L9 orthogonal array was utilized to maximize the material removal rate of the EN 45 steel cylindrical workpiece during the cylindrical grinding. The optimum process parameters for the maximum material removal rate were obtained as 270 rpm of the workpiece rotational speed, feed rate of 0.02 mm and the depth of cut was 0.025 mm.

From the above-stated literature review, it is observed that traditional finishing processes are likely not suitable to result in the required surface finish with good surface integrity. The traditional finishing processes make use of rigid tools due to which finishing forces are uncontrollable in these processes. These traditional finishing processes may result in some surface defects such as heat affected zone and surface cracks etc, while finishing the surface of the components. These surface defects reduce the functional capability of the components for the various industrial applications (Lim et al., 2002). So, to attain the desired defect-free surface for the longer life span of functional applications of various industrial components, the advanced finishing processes need to be employed, where the finishing forces can be regulated externally with the control of the magnitude of the magnetic field.

2.2 Literature related to the advanced finishing processes for the external surface of the workpieces

Chang et al., (2002) performed experimentation on the cylindrical workpiece with unbonded magnetic abrasive. The unbonded magnetic abrasive is a mixer of the ferromagnetic and SiC abrasives with a SAE30 lubricant. The finishing investigation performed with steel and iron grit ferromagnetic particles on the cylindrical workpiece. After experimentation, it is concluded that the steel grit ferromagnetic particles are more suitable for finishing the external surface of the cylindrical workpiece because of its superior hardness and the polyhedron shape.

Singh et al., (2005) investigated on the static flexible magnetic abrasive brush (S-FMAB) process. This process has limitation of non-uniform strength of abrasive brush. The reason for non-uniform strength is non homogenous mixing of abrasive particles and iron particles. The surface roughness was reduced from 0.25 μm to 0.05 μm with the use of 180 μm steel grit mixed with 1.2 μm SiC abrasives. Fig.2.1 shows the initial and final MR finished surface images of the scanning electron microscopy and mirror, respectively. In S-FMAB, the current supplied is DC to the electromagnet, the chain of carbonyl iron particles (CIPs) with the abrasive particles is formed to perform the surface finishing.

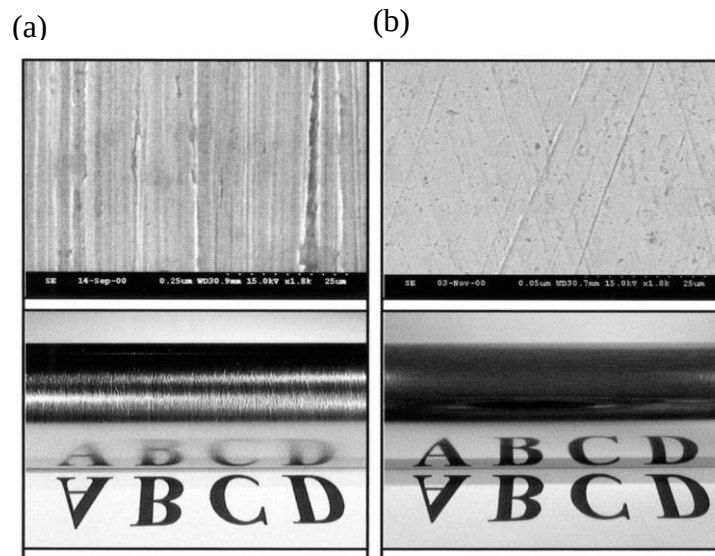


Fig. 2.1 Scanning electron microscopy and mirror images of (a) initial ground surface of cylindrical workpiece and (b) after finishing with 180 μm steel grit mixed with 1.2 μm SiC abrasives (Chang *et al.*, 2001).

After finishing on some places, the workpiece has high roughness peaks at some places and at some places have low roughness peaks, the reason behind that is the nonhomogeneous mixing of abrasives as well as CIPs. Limitation of S-FMAB was overcome by supplying the pulsating current to the electromagnet. This pulsating current allow the mixing of CIPs and abrasive particles in regular interval which improves the surface finishing obtained as compared to the S-FMAB.

Yamaguchi *et al.*, (2012) performed experimentation on the uncoated carbide tool surface to improve the wear of tool using magnetic abrasive finishing (MAF). The experimentation was performed on the flank, rake and nose surface of the uncoated carbide tool. For the appropriate distribution of the magnetic particles, the magnetic circuit was configured differently for the different surfaces like flank, rake, and nose respectively. The 5-axis high-speed machining center was used for the finishing of the flank, rack and nose surface of the tool. The experiments were performed for 20 minutes, 15 minutes, 20 minutes on flank, nose and rake surface respectively. After the experimentation, the R_a value was obtained on the surface of flank and nose was less than 25 nm and less than 50 nm R_a value obtained on the rack surface. The authors concluded that the finishing was performed with minimum damage to the cutting edges. This also helps decrease friction and improve tribological characteristics.

Judal *et al.*, (2014) developed the new vibration-assisted cylindrical magnetic abrasive finishing setup for cylindrical workpiece finishing. In this study, investigation of the various

parameters like magnetic flux density, rotary speed of workpiece, frequency of the vibration and size of the abrasive particles on the surface roughness reduction is done for the cylindrical workpiece. After the process parameters investigation, it was concluded that the frequency of vibration and size of the abrasive particles play a crucial role in the cylindrical surface finishing. The surface roughness value is reduced from $0.46\text{ }\mu\text{m}$ to $0.18\text{ }\mu\text{m}$ in 300 sec of finishing time. The microscope images and roughness profiles of the initial ground surface, and after magnetic abrasive finishing are depicted in Fig. 2.2.

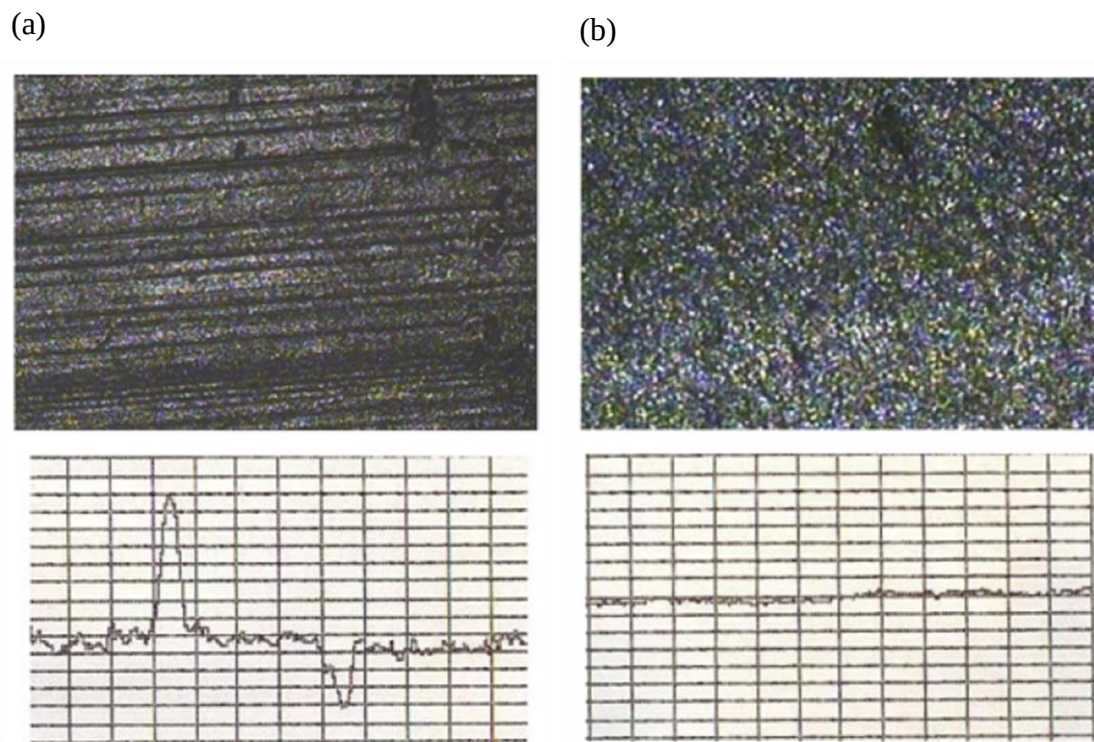


Fig. 2.2 Microscope images and roughness profiles of the (a) initial ground surface and (b) after magnetic abrasive finishing on the cylindrical workpiece surface (Judal *et al.*, 2013).

Saraeian (2016) optimized the magnetic abrasive finishing (MAF) process parameters like working gap, abrasive size and rotational speed for finishing of AISI321 steel cylindrical workpiece by applying the full factorial method at three levels. The magnetic abrasive tool fluid was prepared with the carbonyl iron particles (CIPs), silicon carbide (SiC) abrasive and carrier fluid (SAE 40 oil). The finishing was done on the cylindrical workpiece 50 mm length for 20 min finishing time. The three level for rotational speed (355 rpm, 500 rpm, 1000 rpm), working gap (0.5 mm, 1 mm, 2 mm) and abrasive sizes (100 mesh, 200 mesh, 300 mesh) was used. The best result was achieved at a 1 mm working gap, the rotational speed of 500 rpm,

and abrasive size of 100 mesh. The working gap was found the most effective parameter for finishing followed by rotational speed.

Sidpara et al., (2009) investigated the rheological behaviour of magnetorheological polishing fluid. The design of experiments (DOE) was performed to examine the rheological properties (yield stress and viscosity) of the MR polishing fluid. Authors characterised the rheological properties using the three models namely Bingham Plastic, Herschel-Bulkley, and Casson fluid. The experiments were performed using the rheometer. The authors concluded that based on a comparison of the R^2 value, the Herschel-Bulkley model represents better experimental data. The optimization study was performed on the components of the magnetorheological polishing fluid. After the optimization, the authors concluded that better rheological properties were obtained with the MR polishing fluid composition as carbonyl iron particles 38%, abrasive particles of 4% and 52% of the deionized water respectively.

Jung et al., (2009) used sintered iron-carbonyl nano-tubes (I-CNT) compound abrasives for magnetorheological (MR) finishing of brittle and hard material components. The experimentation was achieved on wheel type MR finishing setup using hard disk slider (Al_2O_3 - TiC) as workpiece material. While performing the experiment with diamond abrasives it was found that with an increase in RPM, the material removal rate increases upto some extent and start decreasing afterward. The main reason behind this was the domination of centrifugal force on the carbonyl iron particles (CIP) chains which resulted in the deformation of the CIPs chains. The problem was solved by using I-CNT abrasives, these abrasives have high cohesive strength and are ferromagnetic in nature. These abrasives chains do not get deform easily under the effect of centrifugal force. This results in an increase in material removal rate (MRR) even at high RPM as well as a reduction in tool aging effect i.e. constant MRR attained for the longer period.

Song et al., (2011) investigated the finishing performance with magnetorheological (MR) polishing fluid under the effect of the magnetic field. In this study, an experiment was performed on a pin-on-disk apparatus for the removal of surface asperities. The steel (SM45C), brass, and aluminium (Al 606I) were used as the workpiece material. It was found that steel samples achieve a better surface finish as compared to brass and aluminium which showed that surface roughness of material is inversely proportional to its hardness. The magnetic field has a great impact on the reduction of surface roughness and an increase in material removal rate (MRR) for steel samples. The MRR was increased by rising the rotational speed for steel samples and working load. This results in an improvement in surface finish. The better surface finish was attained with 40 % concentration of magnetic particles in MR polishing fluids.

Singh et al., (2013) investigated the in-depth mechanism of the material removal of the ball end magnetorheological finishing (BEMRF) process. In this study, an experiment was performed on an external flat surface of the ferromagnetic mild steel workpiece. There are two types of wear mechanisms investigated in this research based on the strength of the magnetic field namely three-body wear mechanism and two-body wear mechanism. In the two-body mechanism, the strength of magnetic flux density was sufficient to hold the abrasives. The abrasives in MR polishing fluid were held tightly and remove surface asperities. Whereas in three body mechanism, the strength of flux density was not sufficient to hold the magnetorheological (MR) polishing fluid firmly. Due to which, abrasive particles acted like a different body from the MR polishing fluid column and starts rolling over the workpiece surface during finishing. If the strength of the magnetic field is more, a two-body wear mechanism can take place else three-body wear mechanism. The main reason behind the change in the mechanism was the strength of the magnetic field holding the carbonyl iron particles (CIPs) as the chain structure in which abrasive particles were trapped. After investigating the mechanism, its effect on surface roughness and surface quality was studied. It was found that when magnetic normal force increased, the surface roughness got decreased and when normal force decreased, surface roughness got increased. Because at higher normal force abrasive particles not only remove the roughness peaks but also scratched the workpiece surface which results in an increase in the surface roughness.

Gheisari et al., (2014) studied the effect of the rotational speed of the aluminium cylindrical workpiece using magnetorheological polishing fluid-based finishing. The rotational speed of the non-ferromagnetic aluminium cylindrical workpiece was varied from 250 rpm to 1000 rpm. The best rotational speed of the aluminium cylindrical workpiece was found out as 500 rpm after the experimentation. The surface roughness (R_a) value was reduced from the initial ground value of 170 nm to 40 nm with 500 rpm rotational speed of the non-ferromagnetic aluminium cylindrical workpiece.

Saraswathamma et al., (2015) studied the influence of process parameters (fluid configuration and input process parameters) using the ball end MR finishing (BEMRF) process on the silicon wafer. The authors used cerium oxide as abrasives and deionized water as a carrier medium. The experimental plan was prepared using the statistical design of experiments. Tool core rotary motion, current and working gap were used as process parameters in the experimental design and %age reduction in surface asperities was considered as an outcome. Using ANOVA, the effect of each parameter was analysed. It was observed that maximum contribution was

made by the working gap followed by current and tool core rotary motion. The average R_a of silicon wafer decreased from 457nm to 89.8nm in 60 minutes finishing time.

Chen et al., (2015) developed a novel precision magnetorheological finishing process with a small ball end permanent magnet polishing head with 4mm diameter. The process was developed to finish the small curvature radius of concave type shapes. Ansoft software was used to check the distribution of magnetic flux density at the polishing head which was found in the range of 93.3%. The fluid was prepared with a volume concentration of 36% carbonyl iron particles (CIPs), water-based fluid medium at 57%, cerium oxide abrasives as 6% and stabilizing agent as 1%. A device is attached to supply the water in the MR fluid to stable the fluid concentration because the water can evaporate. A flat piece with a size 20×10×5 mm of a plane glass of fused silica was used to check the feasibility of non-metallic material. The final roughness was achieved as 0.517 nm from the initial 214 nm at C-axis angular position 65°, spindle speed 5000 rpm, feed 1.8 mm/min in 100 min. To check the feasibility of the process for the metallic workpiece a curve stainless steel workpiece of 6 mm×6 mm×0.8 mm with a 4 mm radius curvature was used. The final surface roughness value achieved was R_a 0.005 μm from the initial R_a 0.230 μm with parameter C-axis angular position 70°, spindle speed 5000 rpm, feed 4.8 mm/min in 300 min. Aluminium oxide abrasive was used for the metallic workpiece because cerium oxide abrasive is not suitable for stainless steel.

Wang et al., (2015) investigated the magnetorheological (MR) finishing method for wire electric discharge machined (WEDM) pierced die cavity. The pierced die cavity was fixed to the polishing tank. The permanent magnet with the core was attached to the electrical discharge machine (EDM) bar with the help of the bolt. The EDM bar helped to provide the up and down motion to the fixed permanent magnet. The unitary surface of the pierced die cavity was finished when the permanent core passing through the cavity. The authors concluded that the plane surface of the pierced die cavity was better than the corner position of the pierced die cavity. The different arc radius corner of the pierced die cavity was utilized. The results were stated that when the arc radius of the pierced die cavity was increased, the polishing effect was improved. After the experiment, it was found that flat surface roughness was reduced from 0.303 μm to 0.132 μm and surface roughness of corner with radius was decreased from 0.303 μm to 0.278 μm .

Wang et al., (2016) improved surface texture using the dual rotation magnetorheological finishing (DRMRF). In this study, the problem of directional texture and groove angles in magnetorheological (MR) finishing with the use of the signal finishing wheel was eliminated by using the dual rotation magnetorheological finishing. An experiment was performed in

which the rotating wheel was used as a tool and it was attached under the effect of magnetic flux density. A fresh MR polishing fluid is supplied at one end and collected at another end. In the dual rotation magnetorheological finishing process, the wheel rotated around two perpendicular axes simultaneously. The MR polishing consisted of 5 μm carbonyl iron powder and 2 μm cerium oxide abrasive mixed in carrier fluid of deionized water. The angular speed (ω_1) of both processes were the same at 165 r/min. But, angular speed (ω_2) of the second rotation which gives only in dual rotation MR finishing process was 100 r/min. The authors concluded that the dual rotation MR finishing process obtained a better surface texture than the single rotation MR finishing process.

Singh et al., (2017) investigated the effect of tip surface on the finishing external surface of the cylindrical workpiece and the experimentation was performed on the macaroni machine shaft material. The process performance analysed by comparing the existing flat surface tool tip with the developed curved tool tip surface. The finite element analysis (FEA) was used to check the magnetic flux distribution along both tool tip surfaces. The FEA results concluded that the curved tool tip surface provided the uniform magnetic flux density as compared to the flat tool tip surface. This resulted in uniform finishing of the external surface of the cylindrical workpiece. When the tool core with a flat tip surface was used for the experimentation, the percentage reduction in average roughness (R_a) value of the external cylindrical surface was observed as 54.41%. In another case, when the experimentation was performed using the tool core with curved shaped tip surface, the percentage reduction in average roughness (R_a) value of the external cylindrical surface was observed as 80.88% in the same experimental conditions.

Alam and Jha, (2017) proposed the mathematical model for surface roughness and mechanism of material removal in finishing the ferromagnetic workpiece with ball end magnetorheological finishing process. In the working gap, magnetic flux density was calculated by considering the magnetization of the ferromagnetic workpiece. BCC unit cell structure for 19 μm CIPs and 18 μm SiC particles was proposed. Normal indenting force as well as shear force model has been developed in this research. The indenting force has been calculated by using the Brinell hardness model. Roughness was calculated theoretically and compared to the experimental data. The experimentation was performed on the mild steel flat workpiece with different current intensity for 10 minutes. The error in theoretical and experimental data was found in the range of 7.23% to 31.19 %.

Maan et al., (2017) performed the nano finishing using the magnetorheological fluid-based finishing process on permanent mold punch. In this study, an experiment was performed on

two setups. One setup was employed for nano-finishing of the external cylindrical surface of the punch. The second experiment was employed for nano-finishing of the bottom surface of the punch. The P20 material punch with a hardness of 45 HRC was used as the workpiece. After the experiment, it was found that the R_a value of the flat surface of the permanent mold die punch was decreased to 30 nm from 1080 nm in 120 minutes of finishing time. The average roughness (R_a) value of the external cylindrical surface was decreased to 80 nm from 630 nm in 120 minutes of MR finishing time. The experimentation results showed a good enhancement in flat and cylindrical surface characteristics of the permanent mold die punch workpiece.

2.3 Research gaps

- The traditional finishing processes like grinding is available for the external surface of the cylindrical workpieces. But this process is not found much suitable to obtain fine finishing without any surface defects. Because this process uses a rigid grinding wheel without control of the finishing forces. Due to this, the workpiece surface gets substantial normal stress which causes various surface and subsurface defects such as micro-cracks, grinding burn, folded metals, heat affected zone, etc. (Jain, 2008). Also, the traditional finishing processes can finish the surface upto a certain level and after that, it cannot be found more effective for further finishing the workpiece surface due to the rigidity of their bonded abrasive grinding wheel. So, this process cannot be found more useful to fulfill the objective like fine finishing with almost no surface defects on the finished cylindrical workpiece.
- To achieve fine finishing on the external surface of the cylindrical workpieces with minimizing the surfaces and subsurface defects after the traditional finishing process, the advanced finishing process, the magnetic abrasive finishing (MAF) process has been developed by various researchers. In this process, the workpiece surface gets finished with the application of controlled forces by controlling the magnitude of magnetic flux density. In the MAF process, the dry brush of the magnetic iron particles and abrasive particles with the different compositions are used as a finishing medium as per the workpiece material to be finished. This process is used by various researchers to finish various hard material applications. Finishing forces can be regulated in this process. This advanced finishing process is found more effective for further reduction in surface roughness values at the nano-meter range after the traditional grinding process. This results in enhancing the functional applications of cylindrical components. But, in magnetic abrasive finishing, the dry brush of magnetic iron

particles and abrasive particles is used which generates the greater frictional forces between the abrasives and workpiece surface. This results in a high temperature in the working gap (Wu *et al.*, 2015). This may lower the finishing process performance. This limitation is further minimized by using the magnetorheological fluid-based finishing processes.

- Recently, limitations of this above-stated advanced finishing process have been overcome by the development of the magnetorheological (MR) finishing process as similar to turning operation for finishing the external surface of all types of cylindrical workpieces material by the authors (Singh *et al.*, 2016). The magnetorheological (MR) finishing processes used MR polishing fluid in which the carbonyl iron particles (CIPs) and the abrasive particles are suspended in the carrier fluid (Harris, 2011). The flexibility and controllability of the MR polishing fluid makes it effective for finishing hard as well as soft materials (Niranjan *et al.*, 2014). The presence of a magnetic field results in the formation of stiffened chains of CIPs in MR polishing fluid. These chains hold the abrasive particles strongly which help to remove the material from the surface of the metals or non-metals for achieving the desired surface finish (Shorey *et al.*, 2004). MR polishing fluid has rheological characteristics which make the process useful for nano-level surface finishing of complex and three-dimensional surfaces. In this work, the flat and curved tip surface of the tool core is used and found out the finishing performance on the external stepped cylindrical surfaces with the use of both types of the core tip surfaces. The standard lathe is used for providing the rotational motion to the cylindrical workpiece and feed is also provided. Curved tip surface was found better performance than the flat tip surface of the tool because of the uniformity of the flux density along the curved tip surface (Singh *et al.* 2016). The limitation of this process is that there was no precise and controlled arrangement for the feed either to the workpiece or the tool rotation. Because the standard lathe has not precise and controlled feed rate system and also a fixed set of feed rate and rotational speed were provided to the tool and workpiece. Also, the fixed rotational motion is provided to the workpiece and the tool core tip surface was kept stationary. Due to this, the lesser relative motion is provided to the active abrasives which may lower the process performance. Also, this process has no such arrangement for finishing the taper cylindrical surfaces because the electromagnetic tool is fixed on the tool post of the lathe machine. Also, the curved tool tip surface has fixed curvature to finished a fixed diameter workpiece. This tool tip has not finished the taper and stepped cylindrical

workpiece because the curvature of the taper cylindrical workpiece is changed at every point. Due to this, only straight cylindrical surfaces can be finished using the turning type MR finishing process.

- Mathematical modeling of external cylindrical MR finishing process is also required along with its experimental validation can give insight mechanism and prediction process performance of external cylindrical magnetorheological finishing process with a change of process parameters.

As many precision cylindrical components are required finishing even after traditional grinding for their better functional applications in today's industries. There are various industries which require a high precision external surface finish such as automotive, machine tool manufacturing, aerospace and die manufacturing, etc. The need of fine finishing is to produce high finish surfaces which lead to the reduces the frictional forces between mating parts, increases the life span and improves the fit and tolerances. In the turning type MR finishing process (Singh *et al.*, 2016), the controllable and precise motions of the rotational and reciprocation of cylindrical workpiece and tool respectively are not provided. Because these motions are provided through standard lathe which has a fixed set of rotational speeds and a fixed ratio of feed rate. The finishing performance in the MR finishing processes majorly depends upon the relative motion between tool and workpiece which is provided either by giving motion to the workpiece or tool with a controllable system. To achieve more relative motion with controllable speed and feed, a rotating core-based magnetorheological finishing process has to be developed in which rotational motion can be provided to the tool along with the workpiece with programmable logic control servo motors. The motion is provided both tool core and workpiece, reciprocation is also provided to the electromagnetic tool to achieve the more relative motion. This increased relative motion help to increase the kinetic energy of the abrasive particles which can significantly increase the material removal rate and better finishing performance. The slides are used to be precise motion with the least error for reciprocation of the electromagnetic tool. These slide's motion is controlled by programmable servo motors. The different cylindrical application of tapered external surface is also finished by this developed process with the help of a free rotating work fixture. This fixture can hold a tapered cylindrical surface and rotate at any angle to finish. This helps to any particular angle tapered cylindrical workpiece finishing as per the application. Mathematical modeling of forces and surface roughness in rotating core-based magnetorheological finishing process need to be done for analysing the mechanism and rate of material removal and its experimental validation. This developed rotating core-based magnetorheological (MR) finishing process

may result in better precise finishing performance for cylindrical external workpiece surfaces. This proposed rotating core-based MR finishing process can be used to finish external surfaces of various industrial components like cold rolling rolls, tapered cylindrical punches, tapered bearing races, steering rack bar, grooved winding drum, micro-extrusion punches, etc. This proposed rotating core-based MR finishing process also fine finish the non-ferromagnetic material industrial applications like printing cylindrical copper rollers. Based on the research gaps as identified through the literature survey and applications in various industries, the proposed research plan is developed. The following present research objectives are proposed as given below.

2.4 Research Objectives

- Development of a rotating core based magnetorheological finishing automatic motion controlled setup to finish the external surfaces of ferromagnetic as well as non-ferromagnetic cylindrical workpieces of different shapes and sizes such as tapered, grooved and stepped surfaces.
- Design of an electromagnetic tool which can be used to hold different tool tips and also taper surfaces can be finished with the same tool.
- To study the effects of process parameters (% volume of carbonyl iron particles, % volume of abrasives, rotational speed of tool, reciprocating speed of tool and rotational speed of workpiece) with steel alloy external cylindrical material on the process response such as surface finish improvement using Response Surface Methodology (RSM) in order to optimize the developed finishing process for better performance.
- To analyze the surface characteristics of the final finished surface with the developed rotating core based magnetorheological finishing process.
- A mathematical model for change in surface roughness is to be developed for magnetorheological finishing process of external cylindrical surfaces and validate experimentally.

2.5 Organization of the thesis chapters

Chapter 1 gives the introduction of the various traditional and advanced finishing processes with their applications for the external surface of the various workpieces. 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 represents the reviews of literature available related to various traditional and advanced finishing processes used for the different kind of external surface of the workpieces.

Also, based on the literature reviews the need of present work for fine finishing the external surface of the various cylindrical workpieces with more effectively has been identified. This chapter ends with the objectives of the present research work and organization of the thesis chapters.

Chapter 3 reports development of an automatic rotating core-based magnetorheological finishing setup to finish the external surface of the ferromagnetic as well as non-ferromagnetic cylindrical workpieces of different shapes and sizes such as tapered, grooved and stepped surfaces. Also, based on the finite element analysis results, the design of an electromagnetic tool with suitable core tip surface has been discussed.

Chapter 4 discusses the preliminary experiments performed to analyse the effectiveness of the present process developed over the existing process for fine finishing the external surface of the cylindrical workpieces. This chapter also briefly discuss about the indigenously preparation of the finishing medium as magnetorheological (MR) polishing fluid. This chapter also reports the effects of finishing parameters on the process response such as surface finish improvement using Response Surface Methodology (RSM) is conducted to obtain the optimum process parameters for better finishing on external surface cylindrical components.

Chapter 5 reports the magnetorheological finishing of the various real time industrial cylindrical external surface of the workpieces using rectangular tool core tip surface.

Chapter 6 reports the in-sight mechanism of the present MR finishing process with rectangular tool core tip surface by developing the mathematical model for change in surface roughness values while performing finishing on the external cylindrical workpieces and its experimental validation.

Chapter 7 gives the various conclusions and significant outcomes from the present research work and also tells the scope for future work.

CHAPTER 3

DEVELOPMENT OF A ROTATING CORE-BASED MAGNETORHEOLOGICAL FINISHING PROCESS WITH IMPROVED DESIGN OF THE MAGNETIC TOOL CORE TIP SURFACE

As discussed under research gaps (chapter 2), a turning type magnetorheological (MR) finishing process was developed (Singh *et al.*, 2016) for fine finishing the external surface of the cylindrical workpieces. The turning type MR finishing process was developed to improve the surface finish after the traditional cylindrical grinding process. In the present work, the limitations of the existing developed turning type MR finishing process have been identified and resolved after the development of a rotating core-based MR finishing process in the process with the improved design of the magnetic tool core tip surface for further improved performance. The identified limitations in the existing turning type MR finishing process are as follows.

- In that developed turning type MR finishing process, while finishing the external surface of the cylindrical workpieces, the tool core tip surface was kept stationary as depicted in Fig. 3.1. As the magnetized tool core tip surface was kept stationary, the active abrasive particles of the MR polishing fluid which perform finishing on the external surface of the rotating cylindrical workpiece could have less relative motion. So, if the active abrasive particles also allow to rotate with rotation of the magnetized tool core tip surface over the rotating cylindrical workpiece surface, the process performance can enhance with the enhancement of relative motion of the active abrasive particles. But, due to the curved tool tip surface, it was not possible to rotate it over the cylindrical external surface of the workpiece.

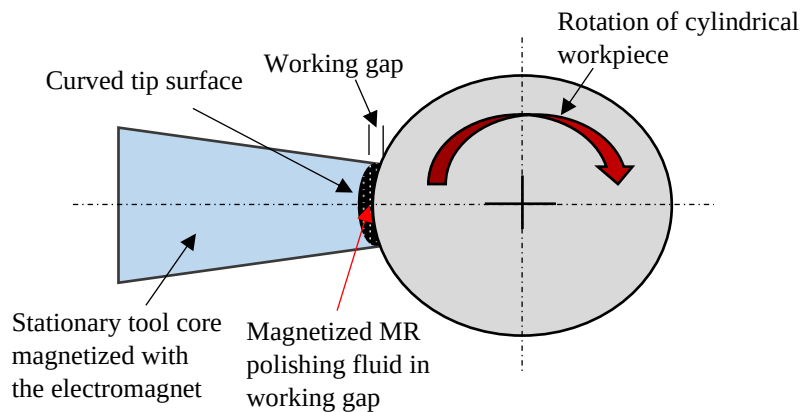


Fig. 3.1 Schematic of the existing turning type MR finishing process (Singh *et al.*, 2016).

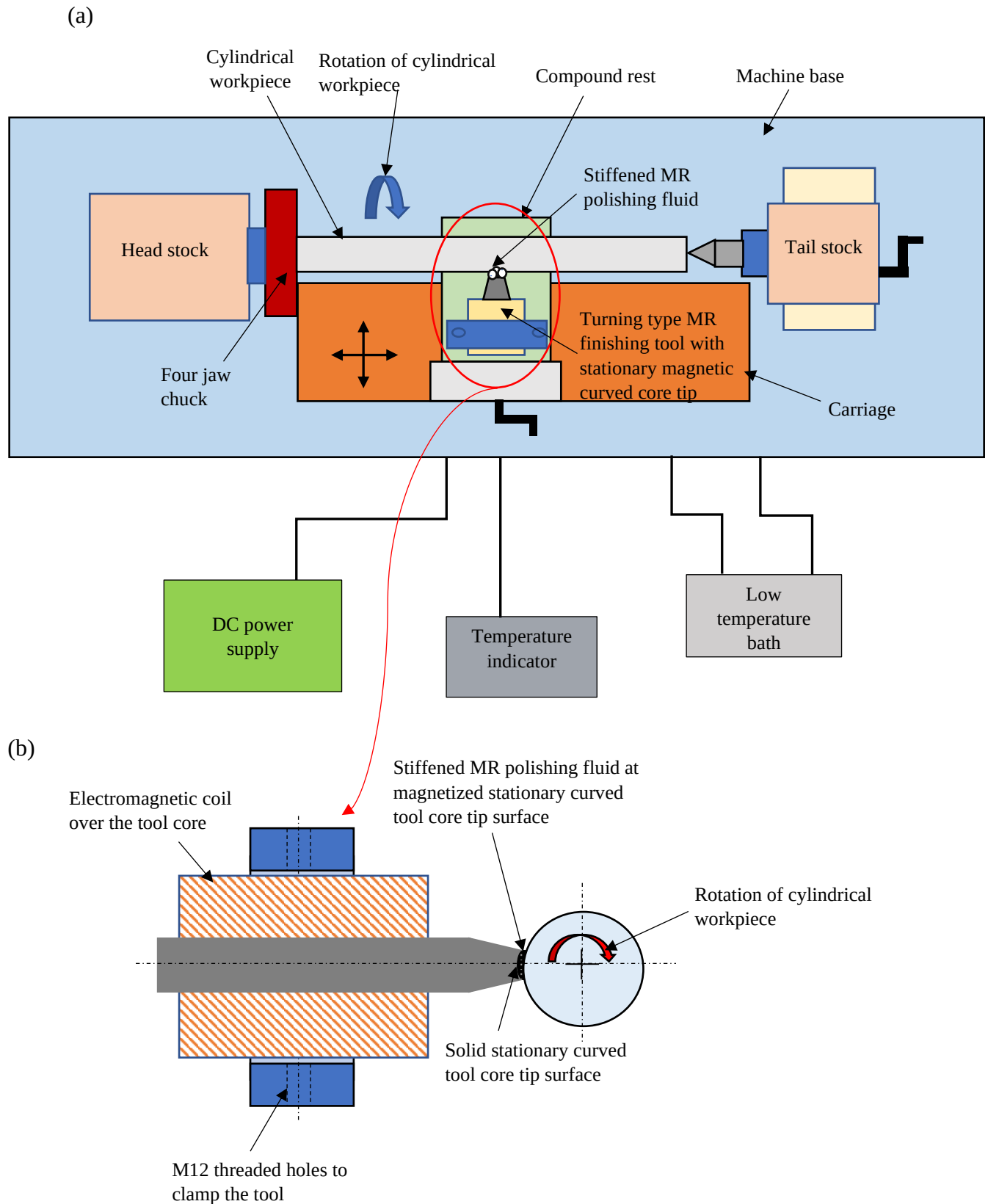


Fig. 3.2 Schematic diagram of the turning type MR finishing experimental setup on the standard conventional lathe machine and (b) stationary curved tool core tip surface in the existing turning type MR finishing process (Singh *et al.*, 2016).

- In the existing turning type MR finishing process (Fig.3.2 (a)), there was no provision had been provided to precise automatic control of tool's core feed motion and rotational motion of the cylindrical workpiece. Because, the finishing setup is mounted on the conventional lathe machine as depicted in Fig. 3.2 (a). The cylindrical workpiece was held in the chuck at one end and on the other end by revolving centre on the conventional lathe. The electromagnetic coil with stationary curved tool core tip surface was held on the tool post of the lathe machine to perform the MR finishing on the external surface of the cylindrical workpieces. The fixed rotational speed was given to the cylindrical workpiece because in the standard lathe, the fixed set of gear ratio was provided which gives the fixed rotational speed on the basis of gear ratio. Also, there was less flexibility in feed rate had been observed because of the fixed ratio of feed available in the standard conventional lathe. Thus, the low flexibility in motion control of the process may result in reduction in process performance.
- Further, the existing turning type MR finishing process has no such arrangement for finishing the taper cylindrical surfaces because the electromagnetic tool with curved core tip surface is completely fixed in straight direction on the tool post of the conventional lathe machine as depicted in Fig.3.2. Also, the curved tool tip surface had been made with the fixed curvature to finish a fixed diameter of the cylindrical workpiece. The curved tool core tip was not found much capable to finish the external surface of the taper and stepped cylindrical workpieces because the curvature of the taper cylindrical workpiece gets changed at every point while curvature of the curved tool core tip surface was fixed. Thus, the existing turning type MR finishing process was not found suitable to finish the taper external surface of the cylindrical workpieces.

To fulfill the above requirements for fine finishing the external surface of the cylindrical workpieces, a rotating core-based MR finishing process has been developed with the following modifications to further improve the effectiveness of the existing turning type MR finishing process.

- To increase the relative motion of the active abrasives of the MR polishing fluid over the external surface of the cylindrical workpieces, the stationary curved tool core tip surface (Fig. 3.2(b)) is first converted into the flat surface and then tool core tip surface allow to rotate over the external surface of the cylindrical workpiece as depicted in Fig. 3.3. To provide the rotational motion to the flat tool core tip surface with the tool core is made to rotate freely concentrically inside the stationary electromagnetic coil as likely similar to the

concept of ball end MR finishing tool (Singh *et al.*, 2012). The electromagnetic coiling was done on a separate hollow part instead of tool core itself as done in the existing turning type MR finishing tool. This separate hollow part is called bobbin and copper wire coiling has been wounded over the bobbin external surface. This bobbin allows the tool core freely rotates in it with the help of bearing support as depicted in Fig. 3.3. Now tool core gets rotational which means the active abrasive particles also rotate with rotation of the magnetized tool core tip surface over the rotating external surface of the cylindrical workpieces. This modification in tool enhances the relative motion of the abrasive particles over the external surface of the cylindrical workpiece which can improve the process performance. Because the rotational motion of the tool core increases the tangential force of the abrasive particles which are stiffened on the core tip surface with the magnetized MR polishing fluid. The increase in tangential force helps to shear off the roughness asperities with less time from the external surface of the cylindrical workpiece. This leads to increase in the process performance to fine finishing the external surface of the cylindrical workpiece.

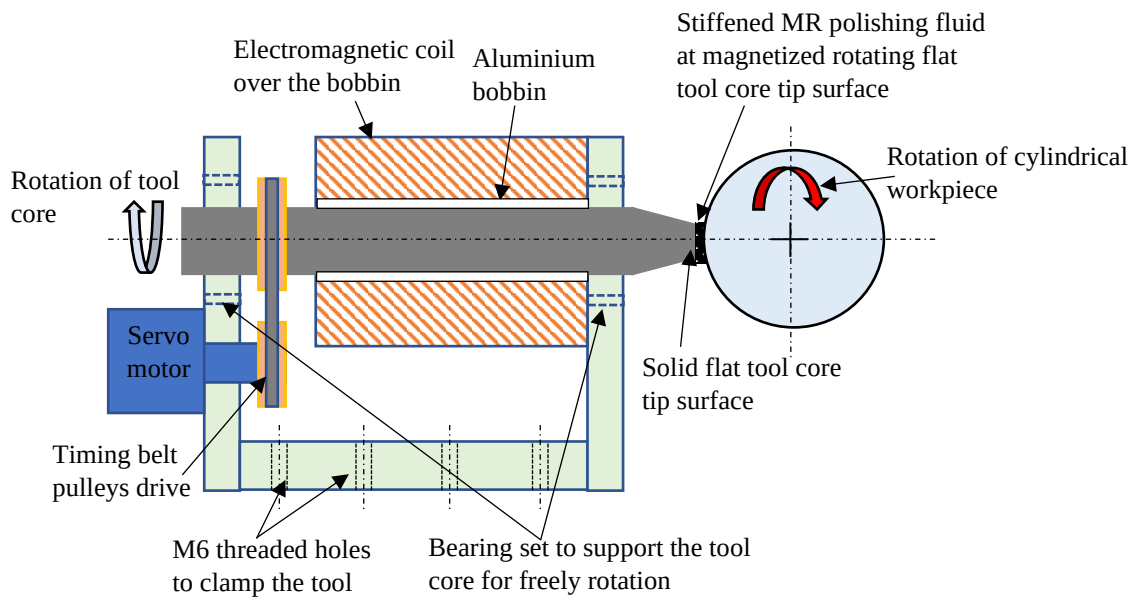


Fig. 3.3 A rotating flat tool core tip surface in the present improved magnetorheological (MR) finishing process to fine finish the external surface of the cylindrical workpieces.

- To provide the precise and controllable motions to the electromagnetic tool core and its feed, and rotation of the cylindrical workpiece, the precise linear slides with programmable logic controllable servo motors are used. These slides movement and cylindrical workpiece rotation are controlled precisely with the help of the programmable

logic controller (PLC) as compared to the existing motion controlled in the conventional lathe machine for the initial turning type of MR finishing process.

- Also, to resolve the problem in MR finishing of the taper cylindrical surfaces with the existing turning type MR finishing process, a rotating swivel vise has been developed which provide the flexibility to finish the taper cylindrical workpieces with different taper angles. Using this vise, any tapered angle surface of the cylindrical workpieces can be finished.
- After the development of a rotating core based magnetorheological (MR) finishing process, it has been realized to design the best shape of the tool core tip surface based on the uniform and maximum magnitude of magnetic flux density at the tool core tip surface. Therefore, the design of the circular shaped rotating tool core tip surface has been improved. Because the circular tip surface was provided the non-uniform magnetic flux density which reduces the process performance. Hence, the different types of tool core tip surfaces have been designed and their analysed the distribution of the magnetic flux density with the help of the finite element analysis. The rectangular tool core tip surface has been found because best tool tip surface as it provides uniform and higher magnitude of magnetic flux density.

3.1 Development of a rotating core based magnetorheological finishing process with automatic motion-controlled system to finish the external surface cylindrical workpieces

To accomplish the requirement of fine finishing the external surface of different diameters of cylindrical workpieces with more effectively, a rotating core-based magnetorheological (MR) finishing process is developed. The principal design requirement in the present rotating core-based MR finishing process is that the MR polishing fluid with on the rotating tool core tip surface should finish the different types of the external surface of the cylindrical workpieces with more effectively. This is due to the enhancement in relative motion of the active abrasive particles with the rotation of the tool core over the rotating cylindrical surface of the workpiece. Moreover, a rotating tool core with the retained MR polishing fluid on its magnetic tip surface should move over the external surface of the cylindrical workpiece with rotational as well as reciprocation movement simultaneously with controlled speeds. The rotating core-based MR finishing process has been developed in such a way that it can finish tapered cylindrical, stepped and grooved surfaces of the cylindrical components.

Before the final fabrication of the rotational flat tool core tip surface for finishing, a magnetostatic finite element analysis (FEA) has been performed in Maxwell Ansoft V13 software for analysing the distribution of the magnetic flux density at the proposed MR finishing tool core tip surface with respect to the external surface of the cylindrical workpiece. The effect of the different types of the external surface of the cylindrical workpieces rotation of the tool core is also examined on the process performance.

3.1.1 Magnetostatic finite element analysis for the magnetic flux density in the working gap of the existing turning type curved shape MR finishing tool core tip surface and proposed flat rotating MR finishing tool core tip surface for finishing the external surface of the cylindrical workpiece

In the MR fluid-based finishing processes, the magnetic flux density plays an important role in the process performance. In the influence of the magnetic flux concentration, the magnetorheological polishing fluid forms the chain-like arrangement and build a flexible rigid polishing fluid. The magnetic flux density governs the strength of the MR polishing fluid chain structure. Because the structure of the chain which hold the abrasive particles required sufficient shear strength to remove the surface roughness peaks with a particular value of shear strength. The magnetization is governed by the supply current and working gap. Therefore, magnetostatic finite element analysis (FEA) is performed to examine the magnetic flux density across the tip surfaces of both tools. The magnetic flux density variation was analysed across the stationary curve tool core tip surface and circular flat tool core tip surface by performing the magnetostatic FEA with the assistance of Maxwell Ansoft V13 as depicted in Figs. 3.4 and 3.5. Before analyse the magnetic flux density across both tip surfaces, the CAD model was created in the Creo 3.0 and saved as an IGES file. The IGES file of the CAD model of both tool cores, cylindrical workpieces and MR polishing fluid in the working gap was imported in Maxwell Ansoft V13 software. The material and their magnetic properties (magnetic permeability) were assigned to each component of the MR finishing process in both cases on the basis of available literature (Singh *et al.*, 2016) as reported in Table 3.1. To make a realistic analysis the environment is also considered around the model during magnetostatic FEA. The FEA analysis is automatically run for 10 iterations in the software. The dimensions of both tool cores are assigned. The cylindrical workpiece has a 30 mm radius is used for both cases. As the diameter of the cylindrical workpiece is increased, the curve area of the curved tool tip surface is also need to be increased to maintain the uniform curvature over the cylindrical workpiece. The curve tool tip curvature is decided on the basis of the cylindrical workpiece diameter.

Table 3.1 Assigned parameters to the model for finite element analysis

Component	Material	Relative permeability	Current	Number of turns
Bobbin	Aluminium	1	4A	2200
Both tool core	Mild steel	600		
Electromagnetic coil	Copper	0.99		
Finishing medium	MR polishing fluid	5		
Ferromagnetic cylindrical workpiece	Mild steel	600		

According to the 30 mm radius of the cylindrical workpiece, the curve area of the tool tip surface is taken as 83.52 mm^2 . The finite element analysis on the various dimensions of the electromagnetic tool core are performed to optimize the dimensions of the electromagnet and tool core for maximum magnetic flux density at magnetic tool core tip surface. The 210 mm length and 25 mm diameter of the tool core gives the highest value of the magnetic flux density at the tool core tip surface. The projected diameter of the curved tool core tip surface is 10 mm. Similarly, the flat circular tool tip surface is taken as 10 mm diameter of tip surface for finishing the external surface of the cylindrical workpieces. So, the surface area of the flat circular tool core is taken as 78.55 mm^2 which may not be changed even external surface diameter of the cylindrical workpiece changes because of the flat tip surface, while in case of curved tool core tip surface area gets changed when external surface diameter of cylindrical workpiece changes. However, in the present analysis, the similar diameter of tool core tip surfaces as 10 mm and radius of the cylindrical workpiece is taken as 30 mm for the both cases.

After the analysis, results reveal that the curve tool tip surface has uniform magnetic flux density over the curve tool tip surface as depicted in Fig. 3.4(a). The 2D plot of the magnetic flux density across the curve tip surface shows the uniformity in the magnetic flux density as depicted in Fig. 3.4(b). The magnetic flux density variation across the flat circular tip surface is shown in Figs. 3.5(a) and (b). The magnetic flux density variation is checked across the circular flat tool tip surface. It reveals that there is a negligible variation in magnetic flux concentration across the tip surface due to the variable working gap (0.6 mm to 1 mm). Therefore, it depicts that the strength of the MR polishing fluid does not vary much in the working space due to the external curved surface of the cylindrical workpiece. The magnetic field density in the curve tip type tool is uniform but less effective than the flat tip type tool under the same conditions as depicted in Figs. 3.4(b) and 3.5(b). Because the curve tool tip has a larger surface area than the flat circular tool tip surface to finish the same diameter cylindrical workpiece. Also, the result of the finite element analysis is revealed that the maximum

magnetic flux density at the curve tool tip surface (0.76 T) and the minimum magnetic flux density at the flat circular tip (0.75 T) (Figs. 3.4(b) and 3.5(b)).

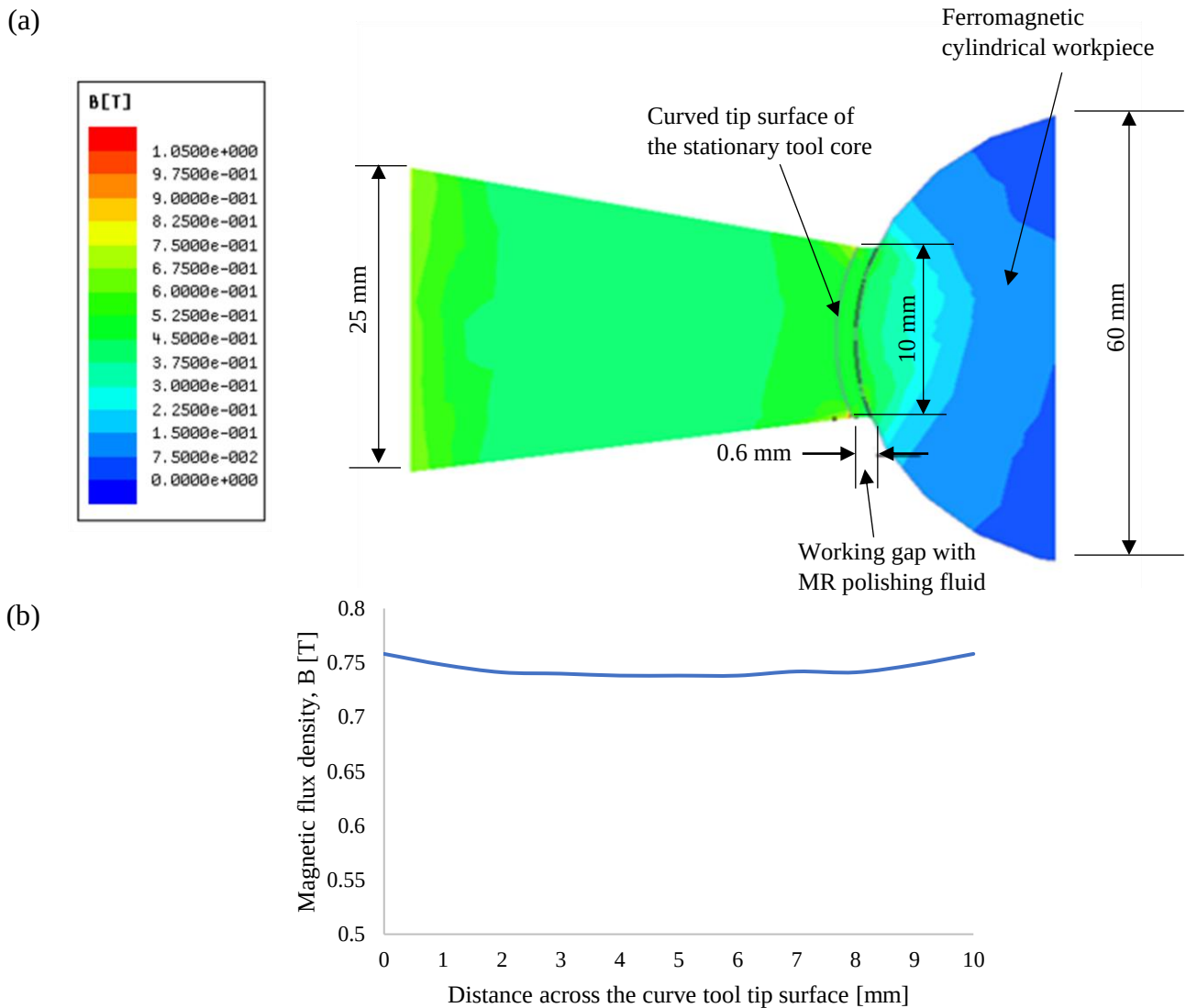


Fig. 3.4 (a) Magnetostatic finite element analysis in the working gap in between the curve tool tip surface and ferromagnetic cylindrical workpiece and (b) plot of magnetic flux density distribution across the curve tool tip surface with proximity of external surface of cylindrical ferromagnetic workpiece.

The reason behind the enhance in the magnetic flux density slightly at the centre of the flat tool core tip surface is the surface area. The flat circular tip has a smaller surface area than the curve tool tip for the same projected diameter of the tool core tip surface area. So, when the stationary curved tool core tip surface converted into a rotating flat tool core tip surface for finishing the different type of external surface of the cylindrical workpieces with improved performance, the

magnetic flux density in the variable working gap cannot reduced the strength of the MR polishing fluid during the fine finishing the external surface of the cylindrical workpiece. This enhances the magnetic flux density over the flat circular tip surface at centre where less working gap exist with respect to external surface of the cylindrical workpiece.

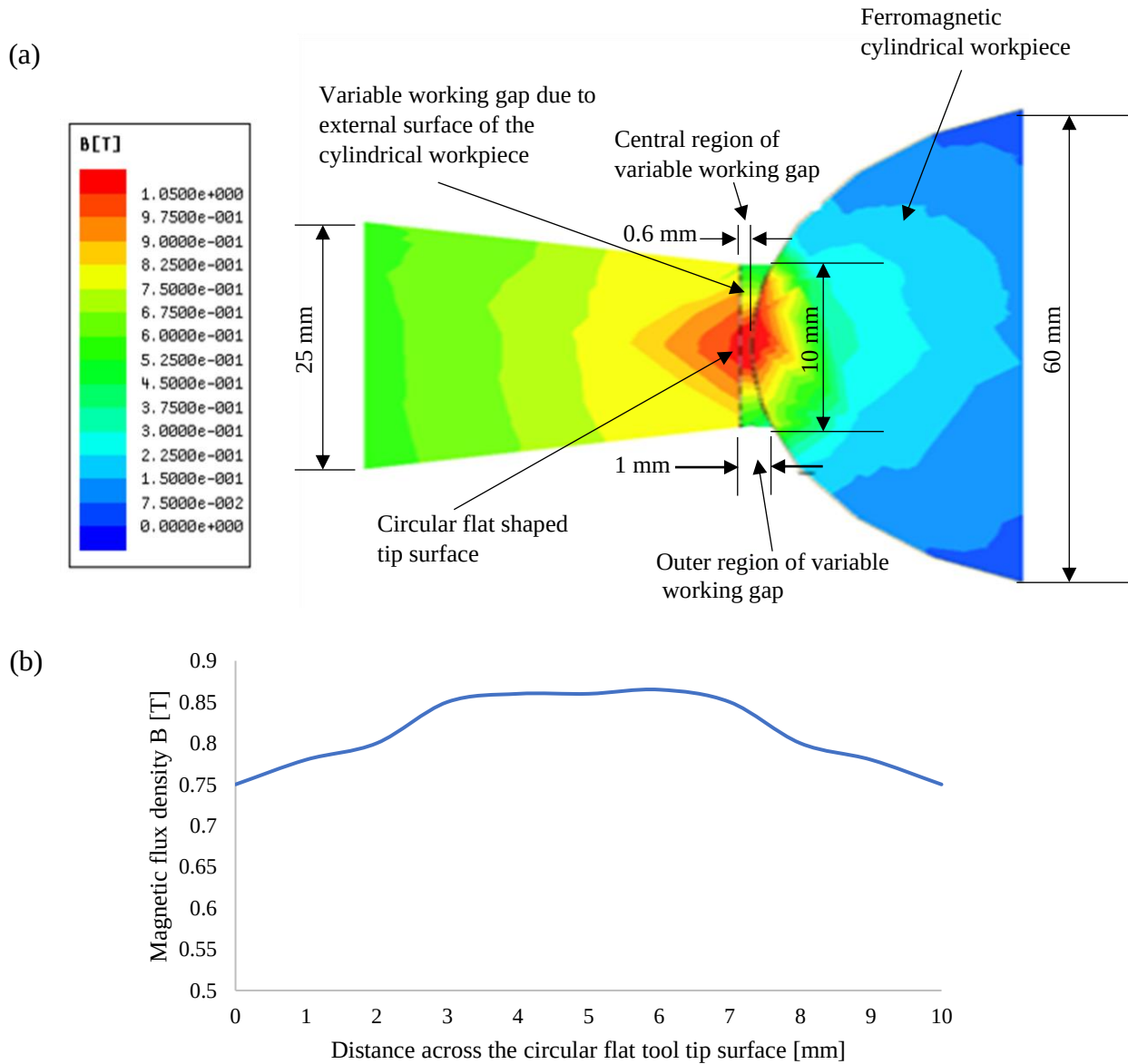


Fig. 3.5 (a) Magnetostatic finite element analysis in the working gap in between the flat circular tool tip surface and cylindrical workpiece and (b) plot of magnetic flux density distribution across the flat circular tool tip surface with proximity of external surface of cylindrical ferromagnetic workpiece.

The higher magnetic flux density results in stronger chain structure on the flat circular tool tip surface than the curve tool tip surface. This leads to provides higher strength of the MR polishing fluid to shear off the roughness crests which boost up the present process performance. Thus, strength of MR polishing fluid in variable working gap is not affected while developing the rotating core-based MR finishing process with the flat tip surface. Due to the

relative motion of the active abrasives on the external surface of the cylindrical workpiece. After analysis of magnetic flux density, next analysis has been done with the effect of tool core rotation in present process performance.

3.1.2 Effect of the tool core rotation in present process performance for MR finishing the external cylindrical surface

In the existing turning type MR finishing process, the tool core tip surface was made stationary for finishing the external surface of the cylindrical workpieces. As the magnetized tool core tip surface was kept stationary, the active abrasive particles of the MR polishing fluid which perform finishing on the external surface with the stiffened MR polishing fluid of the rotating cylindrical workpiece, may have less relative motion due to its fixed position. The same fixed position active abrasive particles perform the finishing operation. Due to this, the process performance may get reduce while in the present developed rotating core-based MR finishing process, the active abrasive particles allow to rotate with the rotation of the magnetized tool core tip surface over the rotating cylindrical workpiece surface. Due to this, the relative motion of the active abrasive particles gets increased and process performance in MR finishing the external surface of the cylindrical workpieces also get enhanced.

Using a rotating flat circular tool core tip, the indentation of active abrasive is followed more removal of material due to increase in relative movement. This is because of the simultaneously rotation given to the both workpiece as well as the tool core tip surface. Therefore, the higher material removal rate can be achieved in rotating flat core tool tip MR finishing process due to the increase in kinetic energy of the rotating active abrasives. This can help to remove the material in higher rate. The detailed mechanism of material removal in the rotating circular flat core tool tip can be understood in three stages as shown in Fig. 3.6.

Let the surface of the flat core tool tip is divided into the four portions i.e. I, II, III and IV. Consider the two chains A and B of carbonyl iron particles (CIPs) at I and II locations. Due to the cylindrical outer surface, the working gap between the rotating flat core tool tip surface and outer surface of the cylindrical workpiece is varied across the flat tool core tip surface. The strength of the magnetic field is less where the gap between the external surface of cylindrical workpiece and the rotating tool core tip surface is more and vice versa. As shown in the Fig. 3.6(a), the gap is more at the location I where the CIPs chains (A) presents and gap is less at the location II where CIPs chains (B) presents. This means that magnetic field strength is lesser at location I as compared to the location II. This indicates that the active abrasive held by the CIPs chains (A) is comparatively gripped with slightly lesser strength and the active abrasive

held by the CIPs chains (B) is comparatively strongly gripped. Now, when the flat core tool tip surface rotates which result in the rotation of the CIPs chains also along with it. After 90^0 rotation of the flat core tool tip surface from the location I, the CIPs chains (A) moves to the location II and the CIPs chains (B) moves to the location III as shown in the Fig. 3.6(b). The slightly loose gripped active abrasive by the CIPs chains (A) at the location I results in changing orientation of the cutting edges of the active abrasive particles during its travel from location I to location II. When active abrasive reaches to location II, a new cutting edge of the same active abrasive comes in contact with the cylindrical workpiece surface. Further, location II has lesser gap and it has high magnetic field strength. Thus, active abrasive strongly gripped with CIPs chains (A) performs more finishing operation at this location with the new cutting edge. At the same time CIPs chains (B) is at location III where again gap is more and comparatively there is lesser magnetic field strength. This results in slightly lesser gripping of the active abrasive with CIPs chains (B). After 180^0 rotation of the flat core tool tip surface from the location I, the CIPs chains (A) moves to the location III and the CIPs chains (B) moves to the location IV as shown in the Fig. 3.6(c). During the travel of CIPs chains (B) from the location III to IV, the orientation of the cutting edges of the slightly loosely bonded active abrasive with the CIPs chains (B) gets changed. Thus, at location IV, a new cutting edge of the active abrasive with strongly gripped by the CIPs chains (B) is available to perform more finishing operation where gap is less. At the same time, CIPs chains (A) after finishing at the location II moves to the location III where gap is more. Thus, this cycle is repeated continuously with the rotation of flat core tool tip surface. The active abrasive with CIPs chains is continuously changed the orientation of cutting edges from the slightly lower to higher magnetic field strength region and vice-versa. Also, the significant material removal can take place at locations II and IV because of low gap and high magnetic field strength. But, at locations I and III, the orientation of the cutting edges of the slightly loosely bonded active abrasive with the CIPs chains changes because of higher gap and lower magnetic field strength. Thus, on every rotation of the flat core tool tip surface, a different cutting edge of active abrasive with CIPs chains passes through locations I and III and available with greater strength at locations II and IV for performing more finishing on external surface of the cylindrical workpiece. Moreover, due to the rotation of a flat core tool tip, the gripped active abrasives with CIPs chains continuously moves from small to large working gap and from large to small working gap.

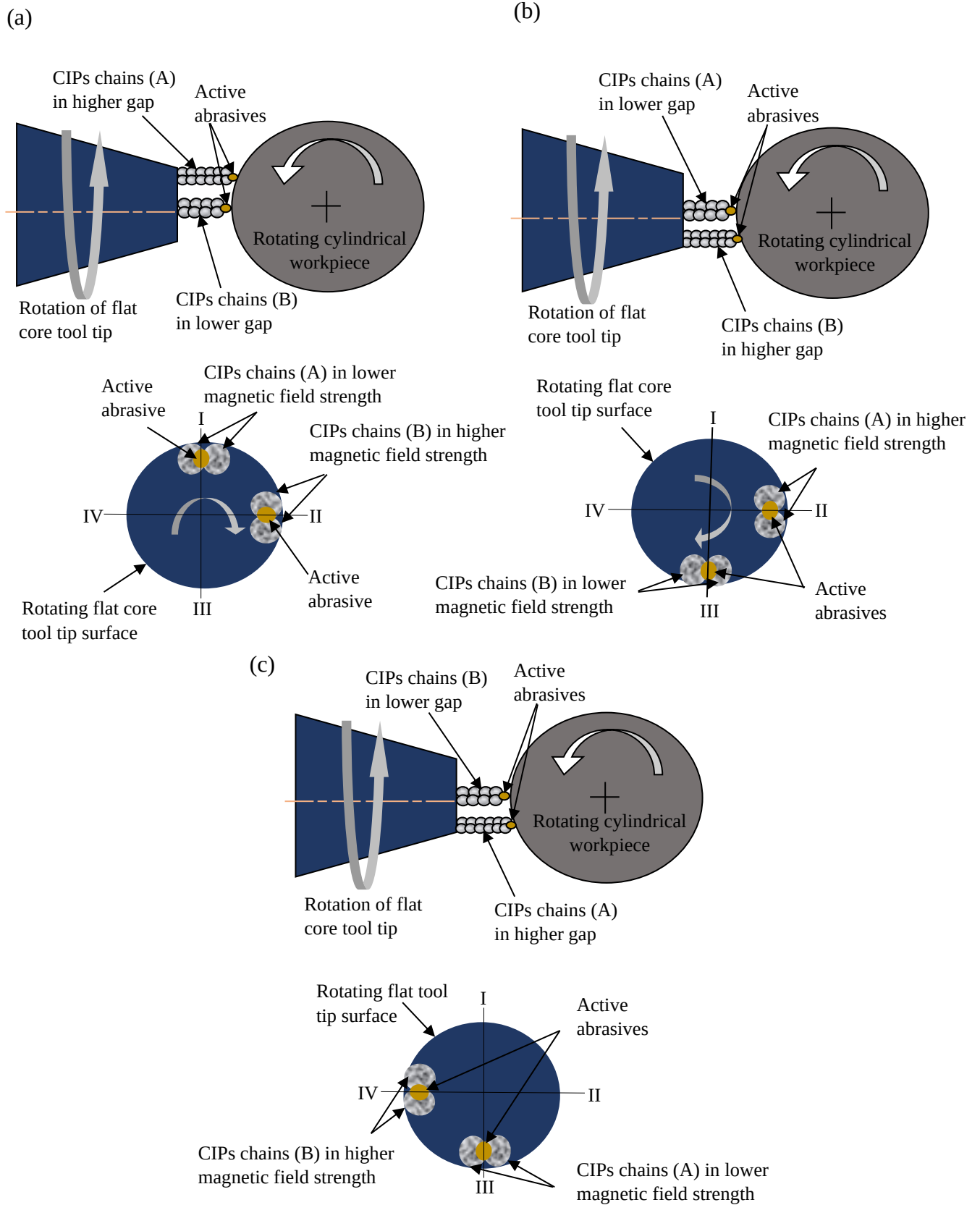


Fig. 3.6 Schematic representation of a rotation of active abrasive with CIPs chains during rotation of flat core tool tip surface (also view from right hand side) in high and slightly low magnetic field strengths (a) at any instant, (b) after 90° rotation and (c) after 180° rotation.

This result in varying the magnetic field strength. The orientation of the cutting edges of active abrasives changes whenever it passes through the region of the slightly lower magnetic field strength. This results in the availability of new cutting edges for finishing operation in each rotation of a flat core tool tip surface. This enhances the material removal rate of the rotating core-based MR finishing process and improves the process performances during the finishing of cylindrical workpieces.

3.1.3 Development of a rotating core-based MR finishing process

After analysis of the magnetic flux density at the flat circular tool core tip surface and the effect the tool core rotation in improving the process performance, a rotating core-based MR finishing process with automatic motion control system is developed for finishing the external surfaces of cylindrical workpieces. The 3D model of this developed process with automatic motion control system is shown in Fig. 3.7. To develop the electromagnetic tool, the stationary curved tool core tip surface (Fig. 3.2(b)) is first converted into the flat circular surface. So, tool core tip surface rotates over any external cylindrical workpiece surfaces as depicted in Figs. 3.3 and 3.7. The MR finishing setup contains four programmable servo motors (P1, P2, P3, P4) to perform the finishing operation. P1 and P2 servo motors are employed to control the reciprocatory and rotary motion of the flat circular tool core tip surface respectively. The P3 servo motor is utilized for maintaining the working space amid the tool core tip surface and external surface of the cylindrical workpiece. A P4 servo motor is utilized to control the rotary motion of the cylindrical workpiece. The X-axis slide, horizontal Z-axis slide are used to provide the controllable motions to the tool and cylindrical workpiece. The cylindrical workpiece is held by the two pillow bearings in a straight line on the workpiece holding fixture. The rotary motion to the cylindrical workpiece is given with the help of V-belt pulley drive. The setup is developed on the basis of Programmable Logic Controller (PLC) control with the help of servo drives. The PLC helped to provide very precise control over feed rates and speeds of the tool core and cylindrical workpiece. The input parameters to operate the servo motors are inserted with the help human-machine interface (HMI) panel. This panel help to operate the servo motors in manual mode or in auto mode with defined time. The coolant supply is provided to the electromagnetic tool to cool down the electromagnet during the finishing operation. The inlet and outlet openings are provided in the electromagnetic tool to supply the coolant as shown in Fig. 3.7. The transformer oil is used as a coolant. The refrigeration system is utilized to cool down the coolant during coolant circulation inside the electromagnet tool. MR polishing fluid is the suspension of magnetic iron particles, abrasives and, a carrier

medium. In the experiment, the contents of MR polishing fluid were taken as silicon carbide (SiC) abrasives, iron particles and carrier medium of heavy paraffin oil and AP3 grease.

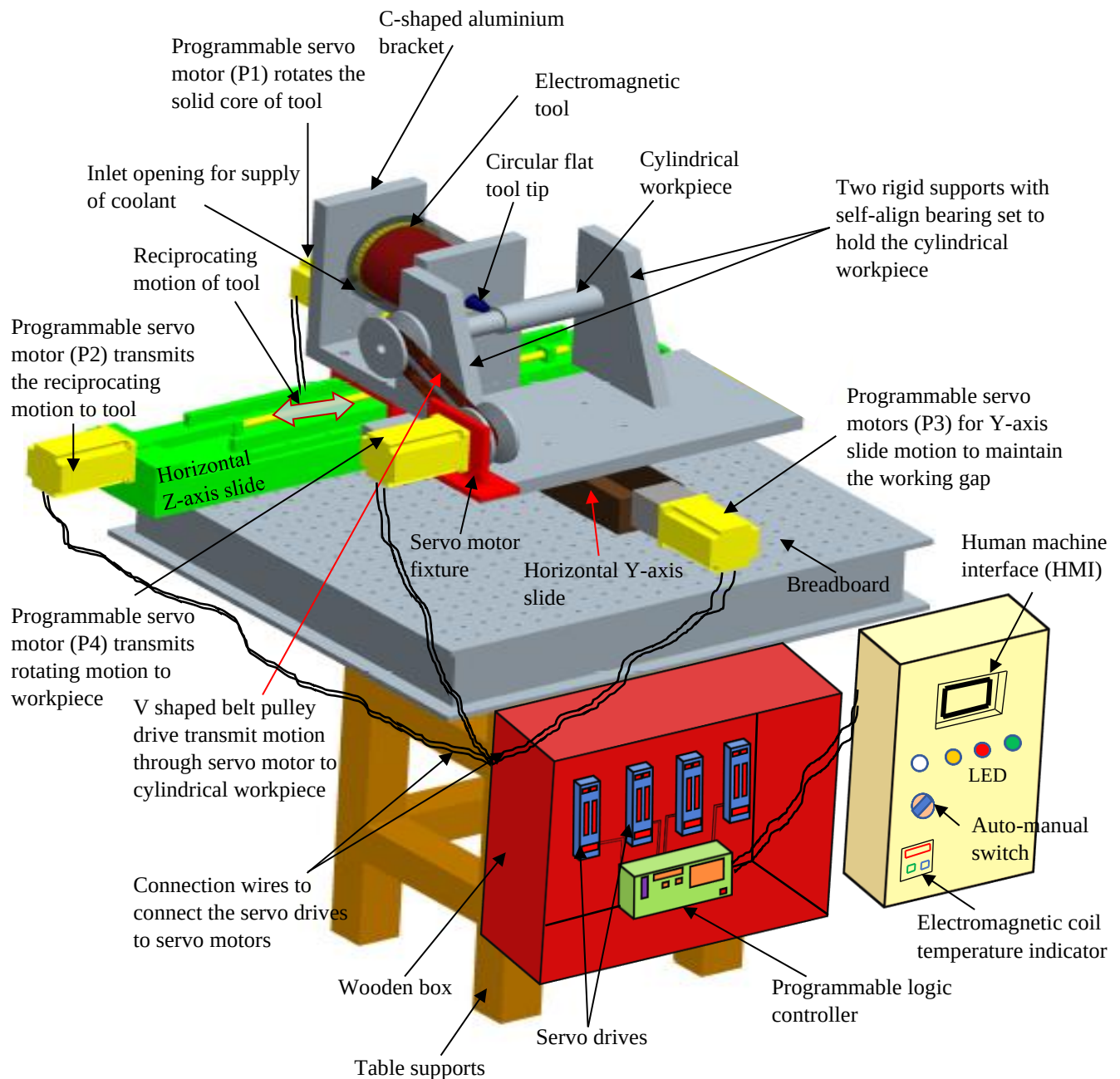


Fig. 3.7 3D model of complete a rotating core-based MR finishing experimental setup.

The DC controlled mixture is used to get the final MR polishing fluid which is used as a finishing medium during experimentation. The MR polishing fluid gets strengthened at the magnetisable core tool tip surface when magnetic field produced at tool tip surface due to the supply of DC current in electromagnet. This result in the stiffened chains of CIPs held the

active abrasive particles tightly and material gets removed from the surface of the workpiece by its relative movement.

3.1.3.1 Design and fabrication of an electromagnetic tool with a rotating core

Based on the magnetostatic finite element analysis (FEA) results obtained (Fig. 3.5) of the electromagnetic tool with a rotating core has been designed and fabricated. The coil turns, coil diameter, tool core dimensions are designed and selected on the basis of FEA results and literature review for the maximum magnetic flux density at the finishing tool core tip surface around 0.8 T- 9.0 T (Singh *et al.*, 2011). In order to optimize the dimensions of the tool core, the numbers of coil turns are analyzed using the FEA Ansoft Maxwell software at different current supplies. The tool core diameter and coil length over the rotating core are analyzed from 10 mm to 30 mm and 70 mm to 170 mm, respectively. Thus, the final obtained dimensions are the electromagnetic coiling length (L) of 130 mm with the outer radius (r_o) of 37.5 mm and the inner radius (r_i) of 14 mm over the rotating core diameter of 25 mm. These optimum combinations of the dimensions of the electromagnetic coil, tool core length, and diameter provide the maximum magnetic flux density over the tool core tip surface around 0.8 T- 9.0 T. The electromagnet tool has been assembled with the various components which design and fabrication are discussed below.

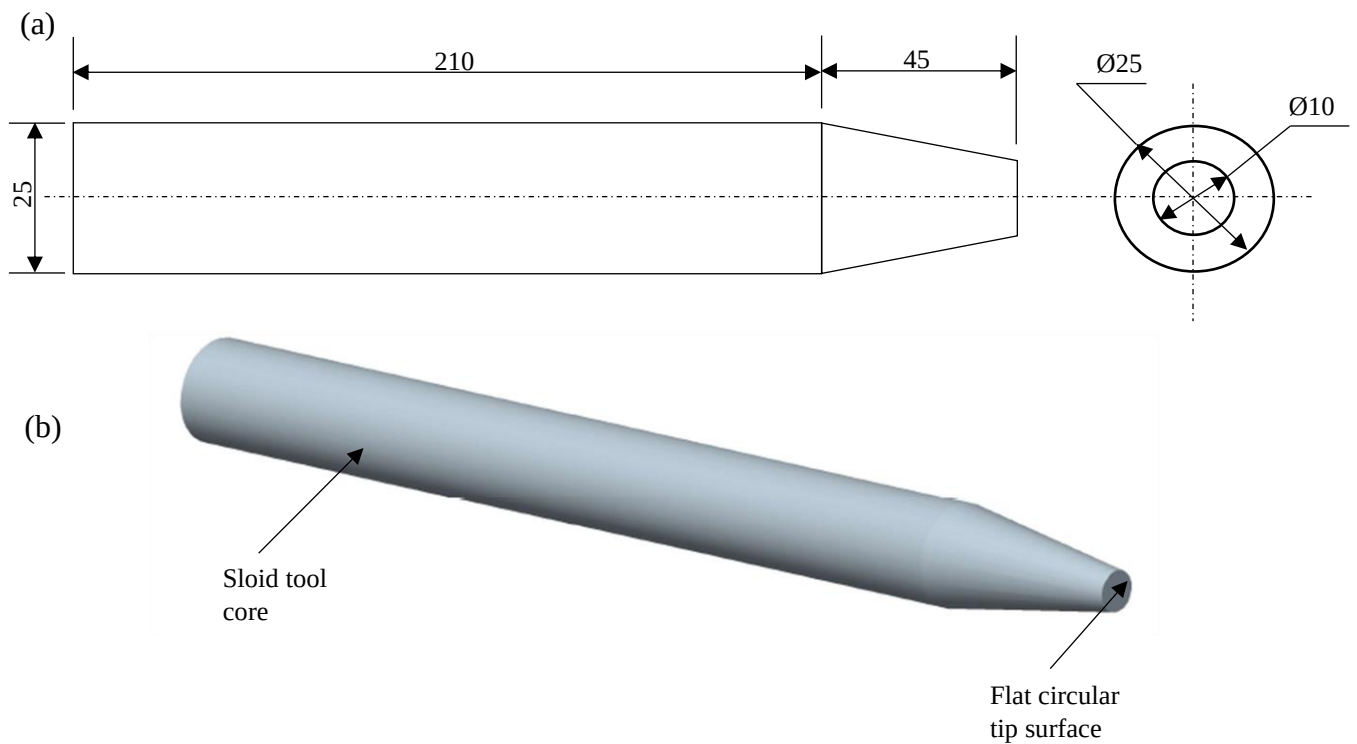


Fig. 3.8 (a) Detailed drawing of the rotating tool core with flat circular tip surface and (b) 3D model of the tool core.

A rotating flat circular shaped tool core tip surface is designed as shown in Fig. 3.8. The material for the rotating shaft has been selected as soft mild steel to have benefits like good permeability. The FEA results and experimentation with 210 mm length and 25 mm diameter of the tool core with 10 mm diameter of tip surface gives the highest value of the magnetic flux density at the tool core tip surface. The detailed drawing and 3D model of the tool core is depicted in Fig. 3.8. To concentrate the magnetic field lines at the tip surface of the tool core, the front side length is tapered at 9.5° . The tapered angle and length are also decided on the basis of finite element analysis (FEA) and preliminary experimentation outcomes. The tapered angle and length are finally made as 9.5° and 45 mm respectively. The electromagnetic coil is designed on the basis of the result obtained from the finite element analysis (Fig. 3.5).

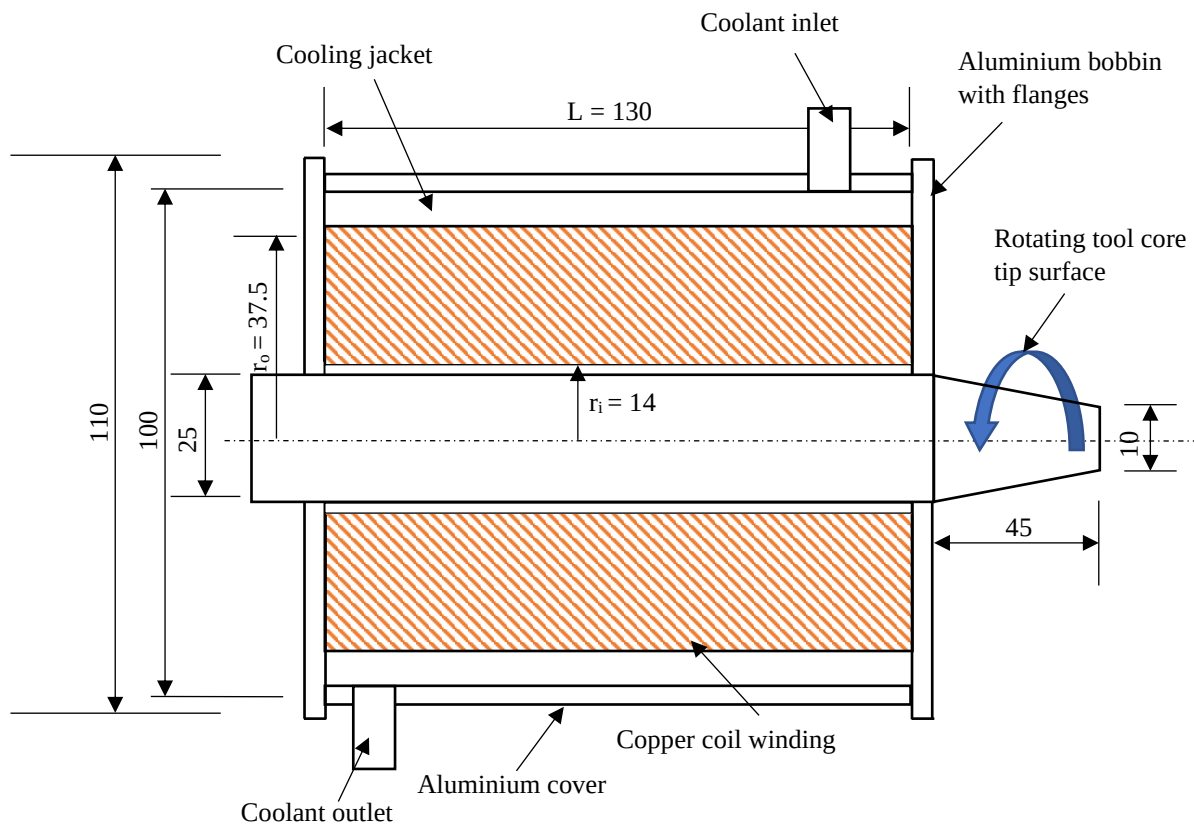


Fig. 3.9 Final geometrical dimensions of the electromagnetic coil over the aluminium bobbin.

The main component of the electromagnetic tool is copper coiling which generates the magnetic field by supplying the direct current through variable DC power supply. The magnetic flux density at the tool core tip surface is dependent on the copper wire size, supply current, radius of the wounded electromagnet coiling and number of turns of the copper coiling. The

comparative analysis of these dependent parameters was done through magnetostatic finite element analysis before selecting the final parameters of the electromagnet coil. The maximum flux density at the tool core tip surface was found with the 20-gauge size copper wire with 2100 turns at 2 A current. The geometrical optimized length of the electromagnetic coiling (L) is found as 130 mm and the outer radius (r_o), and inner radius (r_i) of the electromagnetic coil are found as 37.5 mm and 13.5 mm, respectively as depicted in Fig. 3.9. The bobbin is an internal part of the electromagnetic tool with flanges. It is a hollow pipe with a thickness of 2 mm and internal diameter is 26 mm and outer diameter is 28 mm as depicted in Fig.3.9. The dimensions of the aluminium bobbin decided based on the tool core and copper coil dimensions because tool core is to be rotated inside the aluminium bobbin and copper coil wounded over the bobbin. The internal diameter of the bobbin is decided on the basis of the minimum gap through which tool core can rotate and also minimum magnetic flux losses. The flange of the aluminium bobbin helps to hold the copper coil winding on a particular length (130 mm).

The copper wire wounded over the aluminium bobbin (Fig. 3.9) because the aluminium bobbin prevents magnetic flux losses from the electromagnet coil. The electromagnet coil is covered with the aluminium cover, which acts like a cooling jacket over the electromagnet coil. The detailed dimensions of the aluminium cover are depicted in Fig. 3.9. This cover provides the cooling jackets to the copper coil winding. During the MR finishing due to the DC current supply continuously to the electromagnet coil which heats up the coil. The heating of the coil increases the temperature at the tool core tip surface which further leads to loss in magnetic field. The shear yield stress is dependent on the temperature of the MR fluid. The shear yield stress value initially increases with temperature upto 50°C and subsequently, with more temperature increases, it continues to decrease (Laherisheth and Upadhyay, 2005). The reason behind that the tension between the particles and the carrier fluid reduces as temperature increases (due to a reduction in the viscosity of the carrier fluid) (Laherisheth and Upadhyay, 2005).

Table 3.2 Tool tip surface temperature without coolant at different magnetizing current values

Magnetizing current (A)	Tool tip surface temperature without coolant (°C)
1	46.7
2	48.8
3	56.7
4	68.7
5	80.5

The temperature is measured using the RTD (Resistance Temperature Detector) thermocouples that are positioned during fabrication at 2 different locations within the electromagnetic coil. The temperature indicator that shows the difference in temperature at different magnetizing current values. The measurement of temperature at the tip surface is achieved under the room temperature of 37 °C. The measurement is performed at the tip surface in 5 minutes of time interval because after that time, the temperature of the tip surface reached a saturation point. Table 3.2 represents tool tip surface temperature without coolant at different magnetizing current values. The temperature of the tip surface at 1 A and 2A is found below 50 °C which lies under the safe zone but after that decrement in temperature is required because after 50 °C shear yield stress of MR polishing fluid can start decreasing. Since it is evident from the literature that the shear yield stress of MR fluid decreases after 50 °C temperature (Laherisheth and Upadhyay, 2005). Therefore, to minimize the loss in shear yield stress of the MR polishing fluid due to increasing in temperature, the cooling jacket is provided to the electromagnetic coil. The coolant is supplied in the cooling jacket during the MR finishing to cool down the electromagnetic coil.

To hold the developed electromagnetic coil with the cooling jacket, it is fixed on the C-shaped bracket which hold stationary to the copper coiling. The dimensions of the C-shaped bracket plates are selected based on the size of the electromagnet coil, rotating tool core and the centre distance of the driver and driven pulley. The C-shaped bracket is a combination of three aluminium plates. Two side plates and one base plate. The side plates hold the bearing set to freely rotate the tool core and base plate help to clamp the electromagnetic tool on the horizontal Z-axis slide. The material for the C-shaped bracket is selected as aluminium so that it remains light weighted and to prevent magnetic flux losses from the magnetic tool core as aluminium is non-magnetic material in nature. The C-shaped bracket plates are fabricated and machined the slots for the servo motor, electromagnet coiled bobbin and bearing set. The slots dimensions are selected based on the servo motor dimensions and standard bearing dimensions which hold the 25 mm diameter of the tool core. On the basis the dimensions of the servo motor, tool core, coiled bobbin and bearing set, the C-shaped bracket is fabricated. The detailed drawing of the C-shaped bracket plates is depicted in Figs. 3.10 (a-c).

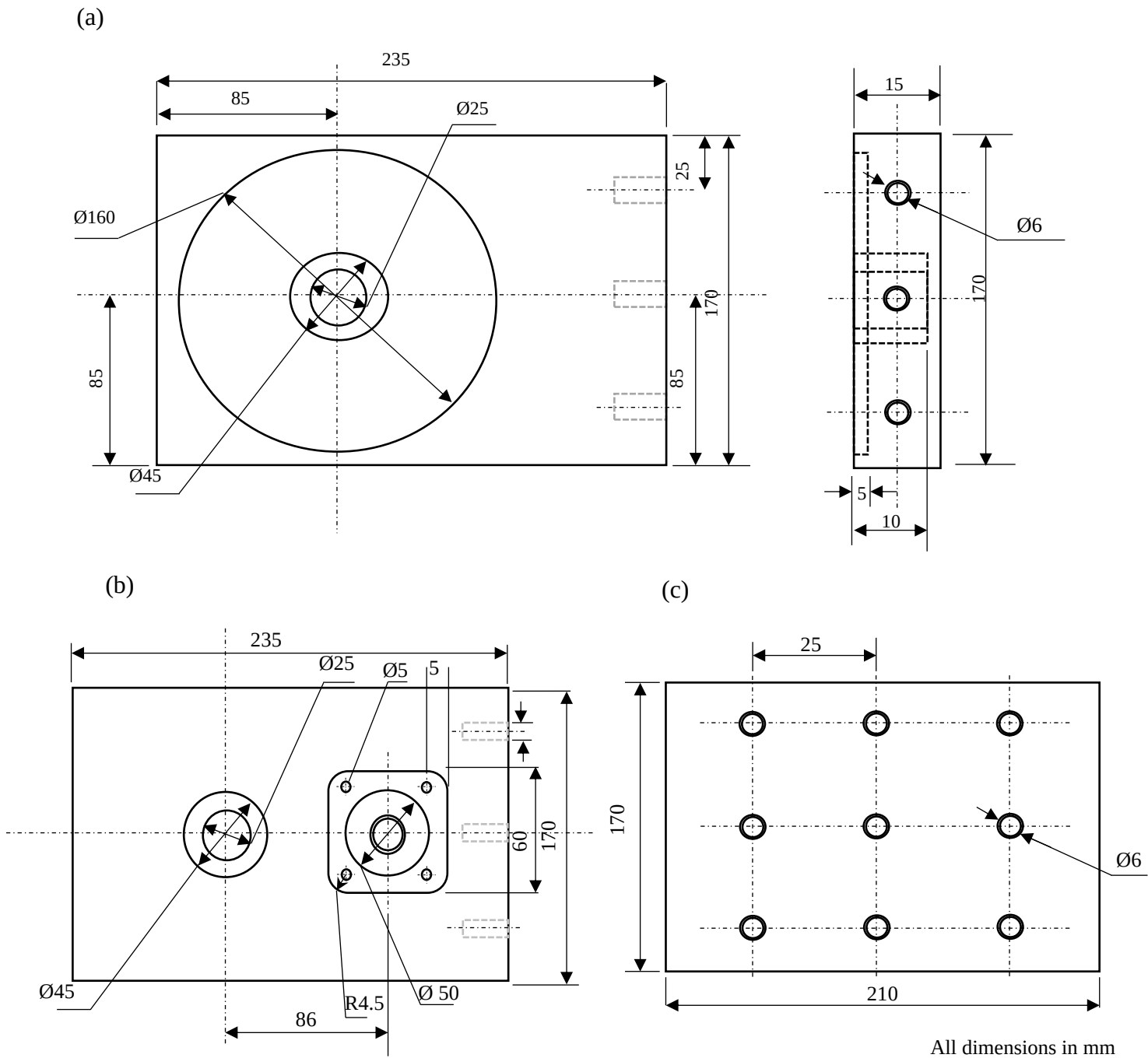


Fig. 3.10 Detailed drawing of the aluminium C-shaped bracket plates (a) side plate used to hold the electromagnet coil and ball bearing, (b) other side plate used to hold the servo motor and ball bearing and (c) base plate used to hold the both side plates.

The machining process like drilling, tapping, milling and threading, etc are used to fabricate the C-shaped bracket. All operations are performed on CNC lathe and milling machines to maintain the accuracy. Counter-bore holes for M6 screws have been made at the base plate of the C-shaped bracket to hold the bracket over the base plate of the horizontal Z-slide.

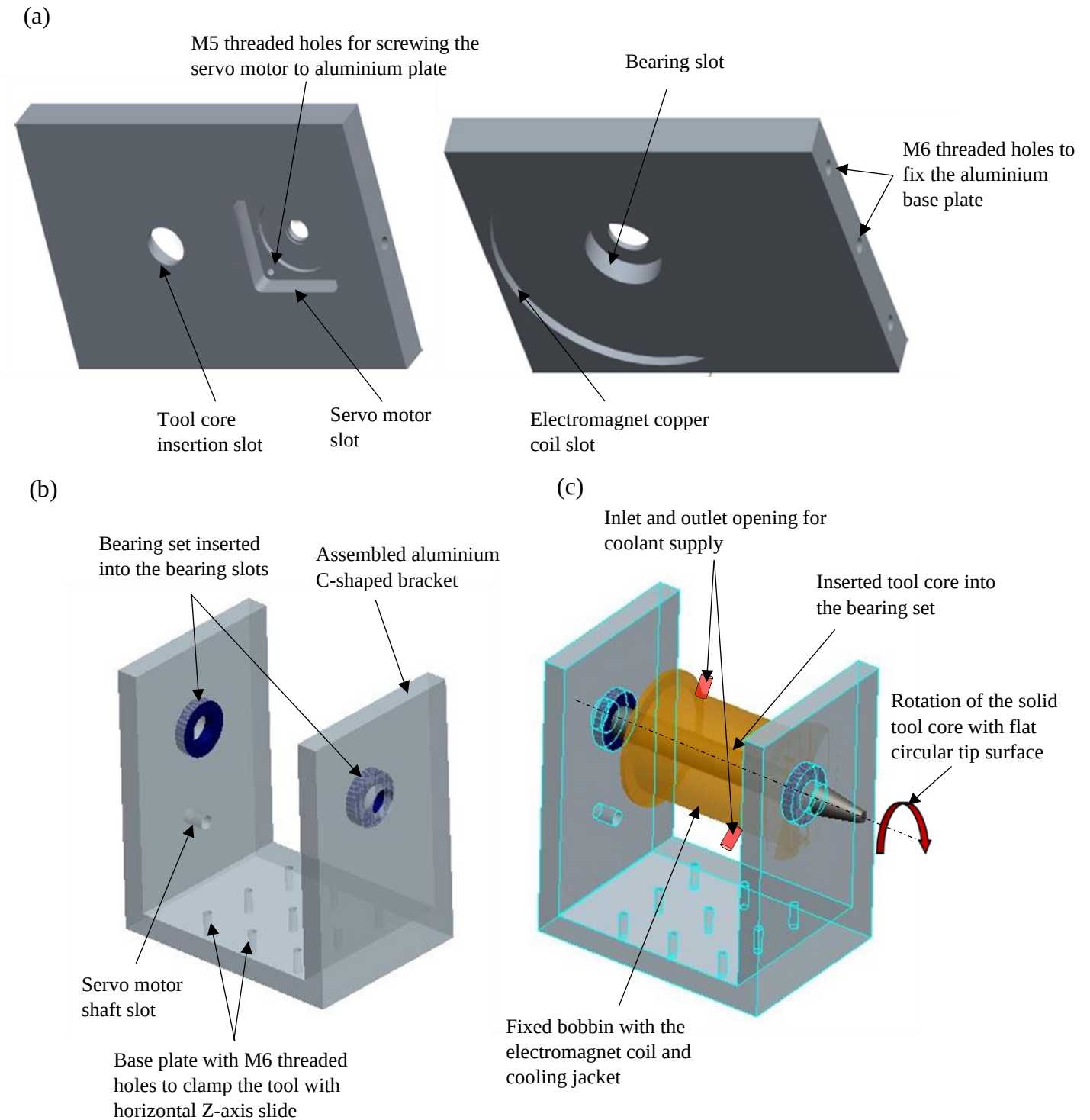


Fig. 3.11 (a) Aluminium C-shaped bracket side plates to hold the electromagnet coil with aluminium cooling jacket cover, the servo motor and bearing set, (b) 3D model of assembled aluminium C-shaped bracket with inserted bearing set and (c) rotation of the solid tool core with flat circular tip surface in bearing set inside the electromagnet coil.

The distance between the counter-bore holes have been kept according to the threaded holes available over the base plate of horizontal Z-axis slide. The 3D model of the C-shaped bracket

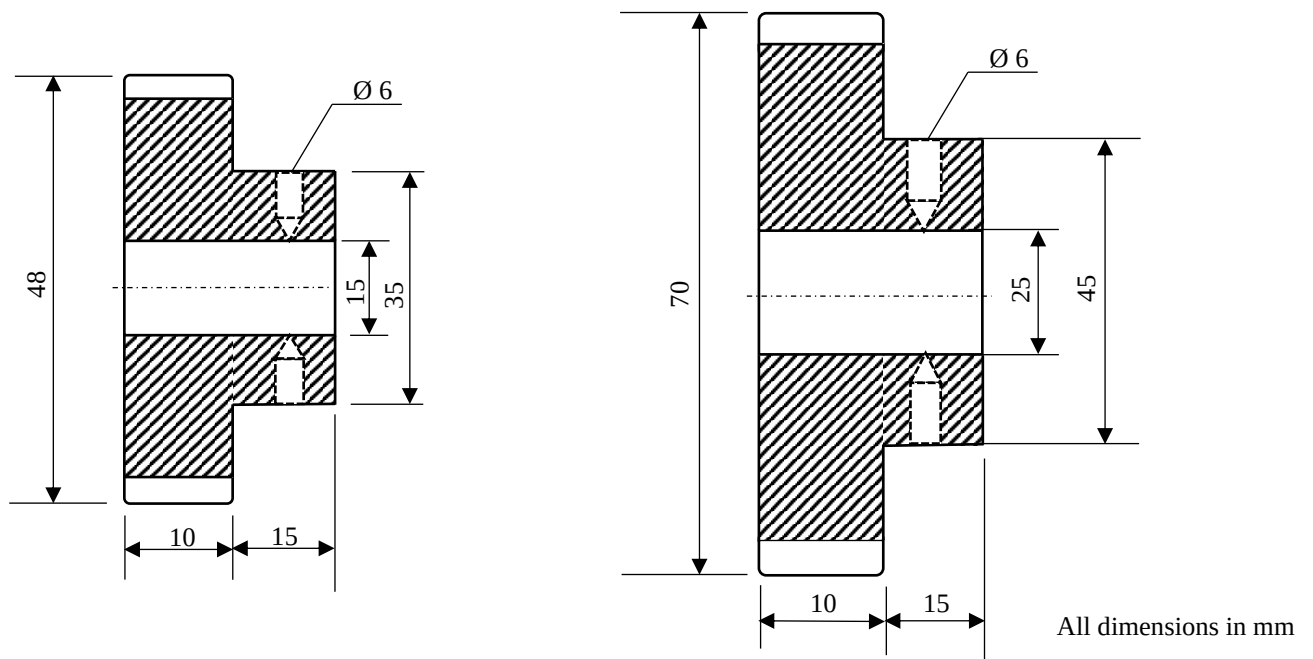
with the side plates and assembled C-shaped bracket is depicted in Figs. 3.11 (a-c). A slot for placing and holding the servomotor (used for rotating the tool core) is made on the side plate of the C-shaped bracket. Two slots (as one in the side plate and another in the other side plate of the C-shaped bracket) have been made for placement of the bearings through which rotating the tool core as depicted in Figs. 3.11 (b) and (c). The bearing set freedom to rotate the solid tool core freely with the help of servo motor. For the rotational motion of the tool core, the timing pulleys and belt transmission system has been used. The main benefits that can be obtained with selection of the timing pulleys and belt are no slippage, high mechanical efficiency, minimum vibrations and high drive ratio at a shorter distance. As per the literature, the rotational speed of the tool core may not be more than 2000 RPM (Singh *et al.*, 2017, Mann *et al.*, 2017). In previous literature, various industrial applications like a cylindrical shaft of the macaroni manufacturing machine (Singh *et al.*, 2017), permanent mould punch (Mann *et al.*, 2017), etc. got fine finished under the 2000 rpm of tool core speed. So, to keep the maximum speed limit of tool core as 2000 rpm, teeth ratio for the driver pulley to the driven pulley is kept as 1:1.4. At this gear ratio tool core achieve 2800 rpm rotational speed which is sufficient for finishing the any type of material using present developed MR finishing setup. Rotational motion is transmitted from the servomotor to the tool core with the help of the timing belt and pulleys. According to the gear ratio, the driving and driven pulleys are fabricated. Out of these two pulleys, one is used as a driving pulley which is attached to the shaft of the servo-motor having 30 number of teeth and another is used as the driven pulley which is attached to the rotating tool core having 42 number of teeth, respectively. The detailed 2D drawing and 3D model of both driver and driven pulley is depicted in Figs. 3.12(a) and (b) respectively.

Length of timing belt used for power transmission is calculated by using the Eq. (3.1).

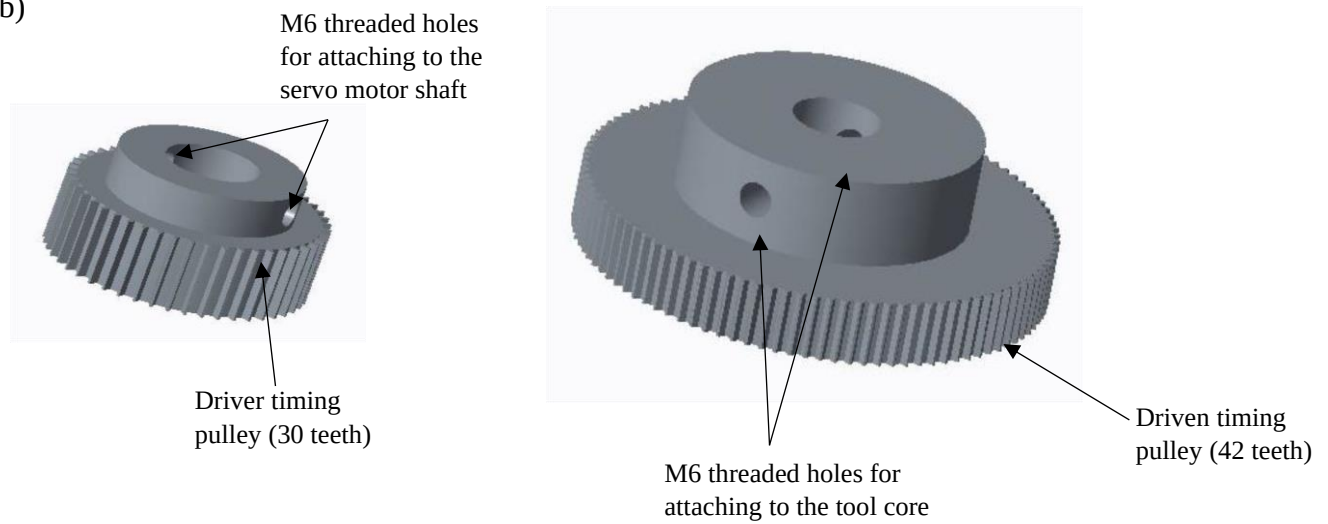
$$L = \frac{\pi}{2}(d_1 + d_2) + 2C_l + \frac{(d_1 - d_2)^2}{4C_l} \quad (3.1)$$

where d_1 is the pitch circle diameter of the driven pulley equal to 70 mm, d_2 is the pitch circle diameter of the driver pulley equal to 48 mm and C_l is the centre distance between two pulleys equal to 85 mm. Centre distance between the two pulleys is kept on the basis of commercial availability of the size of the timing belt as 140XL (355.5 mm in length and 9.4 mm in width). The timing belt has trapezoidal teeth which gives the good force transmitting capabilities and low backlash as depicted in Fig. 3.12(c). Threaded slots are made over each of the pulleys to attach them to the shaft of the servo motor and the rotating tool core as depicted in Figs. 3.12(a) and (b). Both the pulleys are made up of aluminium to keep them light weighted and non-magnetic to avoid the magnetic flux losses from the present electromagnetic tool.

(a)



(b)



(c)



Fig. 3.12 (a) 2 D drawing of the aluminium timing driver and driven pulley, (b) 3D model of the timing driver and driven pulley and (c) timing belt with trapezoidal teeth.

3.1.3.2 Selection of servo motors

Timing belt driven linear systems are common in applications that require high rotational speeds. The motors of choice for these systems are often servo motors, for their ability to accurately control position, speed, and torque. Sizing and selecting the servo motor requires determining both the continuous and intermittent drive torques required for the application. The continuous torque is calculated by taking the root mean square of all the torque requirements throughout the application torque required for acceleration, torque for constant velocity, and torque for deceleration. In most applications, the maximum (intermittent) torque occurs during acceleration. To determine the root mean square (continuous) torque, the torque values required during each phase of the move profile has been calculated.

For a timing belt drive system, the motor torque is required during constant velocity (T_c) which is simply the total axial force (F_{ta}) on the belt multiplied by the radius (r_d) of the driven pulley as expressed in Eq. (3.2) (Khurmi and Gupta, 2005).

$$T_c = \frac{F_{ta} r_d}{1000 \eta} \quad (3.2)$$

Where T_c is torque required during constant velocity in N-mm, F_{ta} is the total axial force in N, r_d is the radius of driven pulley of timing belt drive in mm and η is the efficiency of timing belt drive system. The efficiency (η) of the belt drive system is included in the torque equation because this efficiency accounts for losses such as friction between the timing belt and pulleys. The timing belt drive system has greater efficiency to transfer the linear motion to the driven to driver pulley. The efficiency of the timing belt drive system is taken as 0.90 (Khurmi and Gupta, 2005). The radius of the driver pulley (r_d) is 35 mm. Also, assumed that the driver and driven pulleys have the same radius, which is often the case for timing belt driven linear motion systems. So, the axial force (F_a) for a timing belt drive system consists only of the force required to move the load. The weight ($m \cdot g$) of the tool core is 0.510 kg, drive pulley is 0.110 kg and the timing belt is 0.050 kg which is multiplied by the coefficient of friction (μ) of the guide supports (ball bearings to support tool core). The axial force (F_a) for a timing belt drive system is calculated using Eq. (3.3).

$$F_a = (m_b + m_l) g \mu \quad (3.3)$$

Where m_b is mass of the timing belt in kg, m_l is mass of moving load (both the tool core and drive pulley) in kg, g is the gravity in m/s^2 and μ is coefficient of friction of ball bearing. The value of the μ for the ball bearing guide set is taken 0.02. This value is taken based on the bearing standards. The deep groove ball bearing set with dimensions of 20 mm inside diameter and 42 mm outside diameter with 5 kN static loading rating and 9.95 kN dynamic load rating.

The bearing model is SKF6004. After putting the values of the mass, coefficient of friction and gravity in Eq. (3.3) the value of the F_a is found as 0.1314 N.

The total axial force (F_{ta}) is the sum of the axial force by the load (F_{ax}) and magnetic force (F_n) induced between the working gap. The total axial force is calculated using Eq. (3.4).

$$F_{ta} = F_{ax} + F_n \quad (3.4)$$

The magnetic force (F_n) induced between the working gap is acting axially on the driver pulley. To rotate the tool core with the particular magnitude of the magnetic normal force sufficient torque is required which can easily rotate the tool core. The working conditions of the tool core are 2100 turns of an electromagnet, maximum working current is 4 A and 0.6 mm working gap between tool tip surface and cylindrical workpiece. Taking these conditions, the value of the F_n is found as 17 N (Singh *et al.* 2013). Further, the values of the F_n and F_a are added and the total axial force (F_{ta}) is found as 17.132 N. Furthermore, the value of the total axial force (F_{ta}) is putting into Eq. (3.2) and the servo motor torque required during constant velocity (T_c) is found as 0.667 N-mm. Fig. 3.13 shows the total axial force (F_{ta}) acting on the driver and driven pulley at a constant angular velocity (N).

The total torque required during acceleration (T_{ta}) includes the torque required at constant speed (T_c) plus the torque required to accelerate the load (T_{acc}) as expressed in Eq. (3.5).

$$T_{ta} = T_c + T_{acc} \quad (3.5)$$

Where T_{ta} is total torque required during acceleration in N-mm, T_{acc} is torque required due to acceleration in N-mm.

The torque due to acceleration (T_{acc}) is found by multiplying the total inertia of the system (J_t) by the angular acceleration (α) as expressed in Eq. (3.6).

$$T_{acc} = J_t \alpha \quad (3.6)$$

Where J_t is the total inertia of the timing belt drive system in kgm^2 , α is the angular acceleration in rad/s.

The total system inertia includes the inertia of the motor, the tool core and external load (magnetic force in working gap). Since, motor can overcome its own inertia hence during the selection of servo motors the inertia due to the tool core and external load (magnetic force in working gap) is only considered.

Since the motor has to generate enough torque to overcome the inertia of the belt and the external load. The total inertia of the timing belt drive system (J_t) is calculated using Eq. (3.7).

$$J_t = (m_l + m_b) r_d^2 \times 10^{-6} \quad (3.7)$$

Where m_l is the mass of external load in kg, m_b is the mass of belt in kg. The m_l is 0.660 kg and the m_b is 0.05 kg and the radius of the driven pulley is 35 mm. Further using the values of mass and radius into Eq. (3.7), the value of total inertia of the timing belt drive system (J_t) is found as $8.697 \times 10^{-4} \text{ kg-mm}^2$.

For the calculation of angular acceleration, it is assumed that the belt drive system is accelerating from zero to maximum velocity, with $N_{\max}$ being the maximum angular velocity and t_{ac} being the time to accelerate as expressed in Eq. (3.8) (Khurmi and Gupta, 2005).

$$\alpha = \frac{2\pi N_{\max}}{60 t_{ac}} \quad (3.8)$$

Where $N_{\max}$ is the maximum angular velocity which is required during experimentation in rpm, t_{ac} is the time for acceleration in s. The maximum angular velocity of the tool core is required during the experimentation is taken as 2500 rpm and the time for acceleration is taken as 60 s. The time for the acceleration, deceleration and for the constant velocity is considered per minutes, so, all the torque values are calculated based on per minutes. Further, putting the values of the angular velocity and time in Eq. (3.8), the value of the angular acceleration (α) is found as 4.36 rad/s.

Furthermore, the value of the torque due to acceleration (T_{acc}) is calculated by putting the values of angular acceleration and total inertia into Eq. (3.6) is found as $3.792 \times 10^{-3} \text{ N-mm}$. Further putting the values of T_{acc} and T_c in Eq. (3.5), the torque required during acceleration (T_{ta}) is found as 0.670 N-mm.

The motor drive torque required for deceleration (T_d) is equal to the torque at constant velocity (T_c) minus the torque due to acceleration (T_{acc}) as expressed in (Eq. 3.9)

$$T_d = T_c - T_{acc} \quad (3.9)$$

T_d is the torque required during deceleration in N-mm.

Further the values of the torque at constant velocity and the torque due to acceleration are put into Eq. (3.9) and value of the motor drive torque required for deceleration (T_d) is found as 0.663 N-mm. Further, the root mean square of these values (the motor drive torques required during acceleration, constant velocity, and deceleration) is taken to determine the continuous torque (T_{RMS}) required by the servo motor as expressed in Eq. (3.10).

$$T_{RMS} = \frac{\sqrt{T_{ta}^2 t_a + T_c^2 t_c + T_d^2 t_d}}{t_a + t_c + t_d} \quad (3.10)$$

Where T_{RMS} is the root mean square (continuous) torque in Nm, t_{ac} is the time for acceleration in sec, t_c is the time for constant velocity in sec and t_d is the time for deceleration in sec.

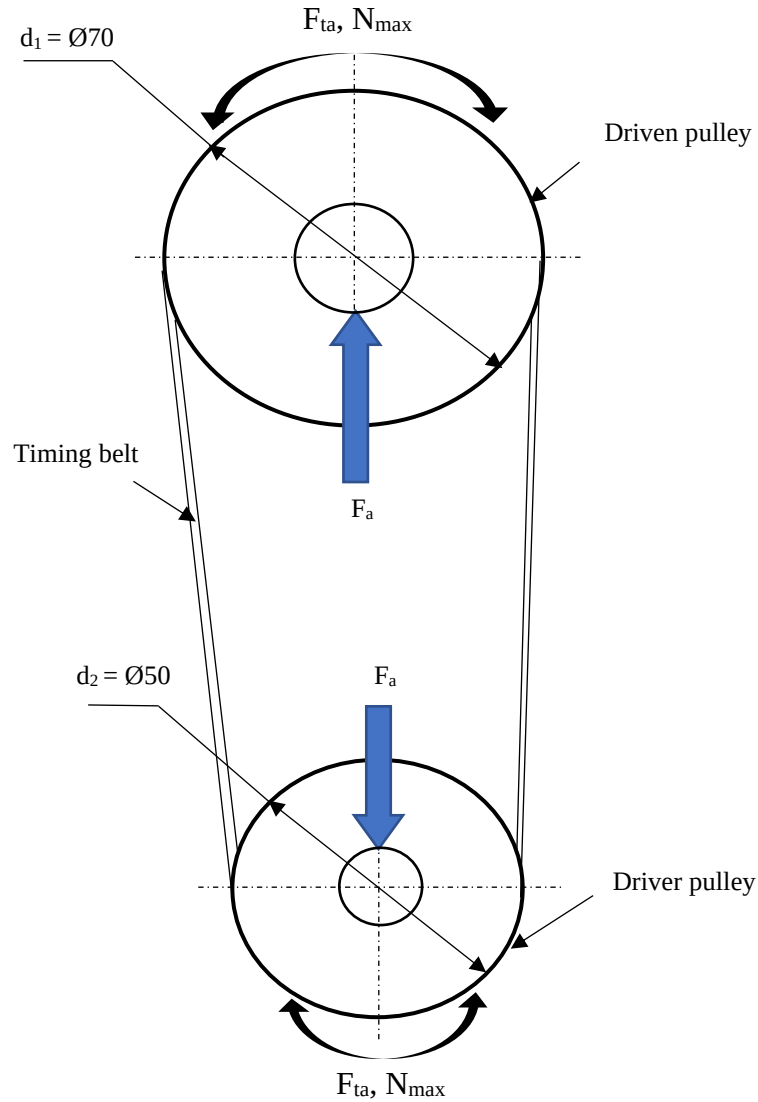


Fig. 3.13 Driven and driver pulleys forces representation during working condition.

Further, using the values of T_a , T_c and T_d into Eq. (3.10), the value of the continuous torque (T_{RMS}) is found as 0.150 N-mm. This continuous torque (T_{RMS}) is applied to the driver pulley during the working conditions. The torque required by the servo motor is greater than the continuous torque (T_{RMS}). So, the servo motor to easily rotate the tool core at constant velocity. Further, to reduce the value of the continue torque for the servo motor, the driven pulley diameter is lesser than the driver pulley. So, on the basis of the gear ratio, the value of the continuous torque for servo motor is decreased. The relationship between the gear ratio, diameters of driven and driver pulley, speed ratio and torque ratio of the driven and driver gear is calculated by Eq. (3.11) (Khurmi and Gupta, 2005).

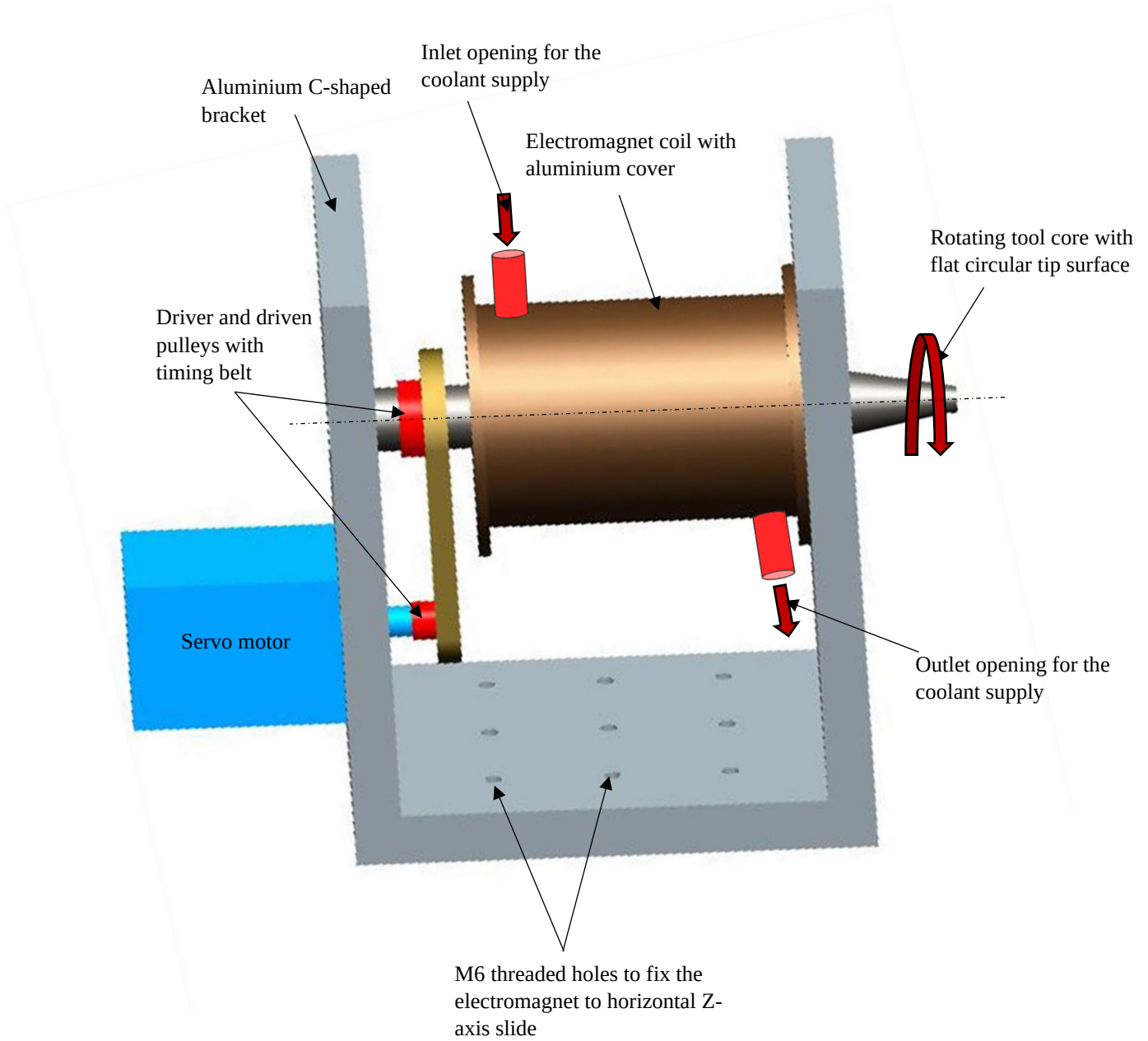


Fig. 3.14 3D model of assembled electromagnetic tool with all their associated components. The gear ratio of the driver and driven gears in the present work is 1:1.4. The continuous torque (T_{RMS}) is found as 0.150 N-mm is the required torque for servo motor.

$$\frac{N_{driven}}{N_{driver}} = \frac{T_{driver}}{T_{driven}} = \frac{d_{driver}}{d_{driven}} = \frac{\tau_{driver}}{\tau_{driven}} \quad (3.11)$$

Where N_{driven} and N_{driver} is the rotational speed of the driven pulley and driver pulley in rpm respectively and T_{driven} and T_{driver} is the number of teeth of the driven pulley and driver pulley respectively. d_{driven} and d_{driver} is the diameter of the driven pulley and driver pulley in meter respectively and τ_{driven} and τ_{driver} is the torque of the driven pulley and driver pulley in Nm respectively.

Using the Eq. (3.11) the torque for the servo motor is calculated by present gear ratio, the value of the continuous torque is found as 0.089 N-mm. From Eq. (3.11), it is cleared that for changing the gear ratio between the driver and driven pulley reduces the required torque. The value of the required continuous torque during the MR finishing is 0.0889 N-mm at present gear ratio of the driver and driven pulley.

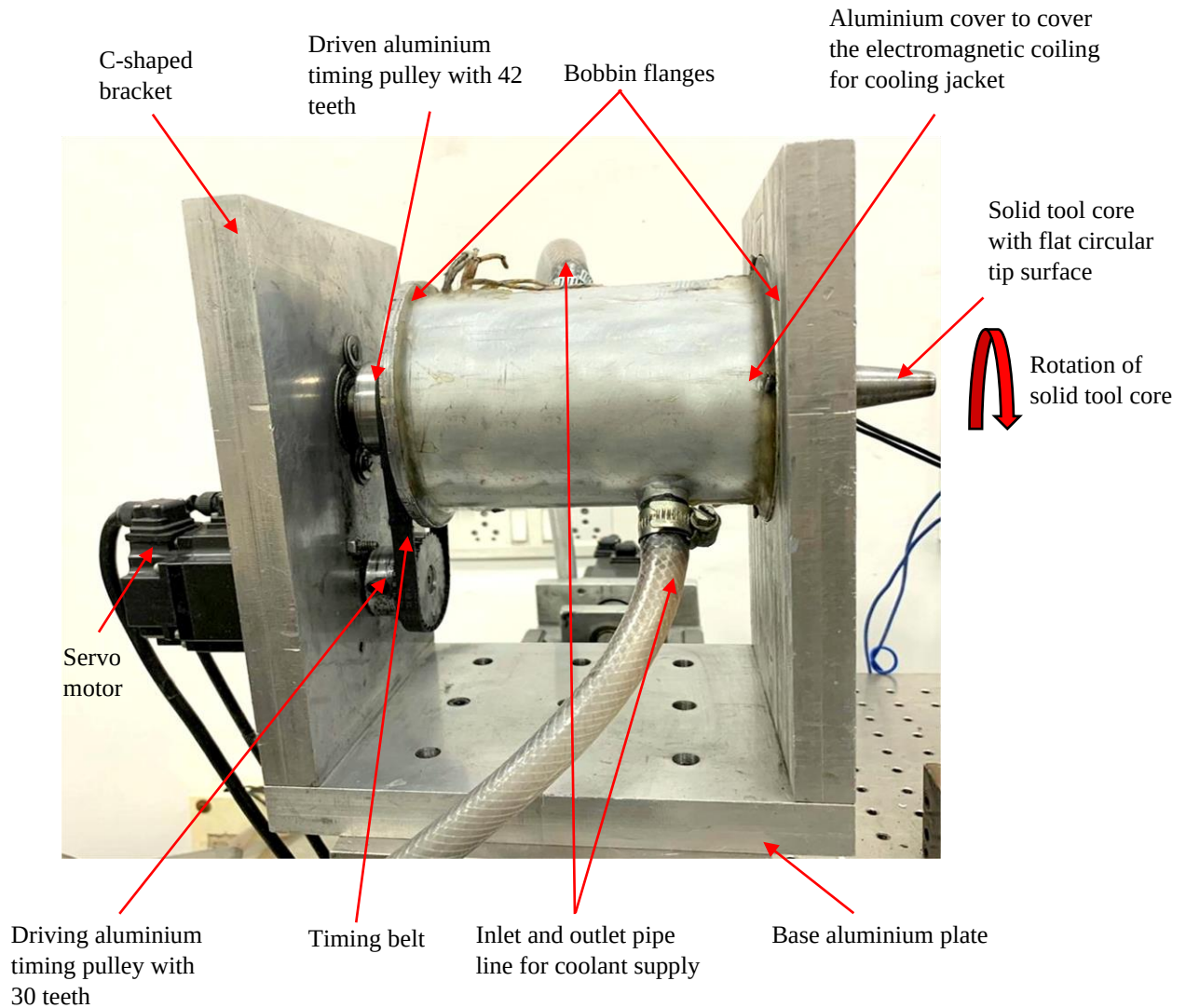


Fig. 3.15 Fabricated electromagnetic tool with all their assembled components.

Based on the torque requirement, the MITSUBISHI HG-KR43 model is selected for the presently developed MR finishing process. This servo motor has 400 W power and the rated torque is 1.3 Nm and the maximum torque is 3.8 Nm. The 1.3 Nm rated servo motor torque handles the upto 2.5 Nm torque at the tool core with present gear ratio. This torque value of the servo motor is higher than the required torque which easily rotates the tool core at different magnetic forces. The servo motor rated speed is 3000 rpm and maximum speed is 5000 rpm which is sufficient for present experimentation conditions. The weight of the servo motor is

1.4 kg which can easily handle and clamped. The 3D model of the assembled electromagnetic tool is depicted in Fig. 3.14. After fabrication of the components of the electromagnetic tool, all components are assembled. The C-shaped bracket has three plates, a base plate, and two side plates.

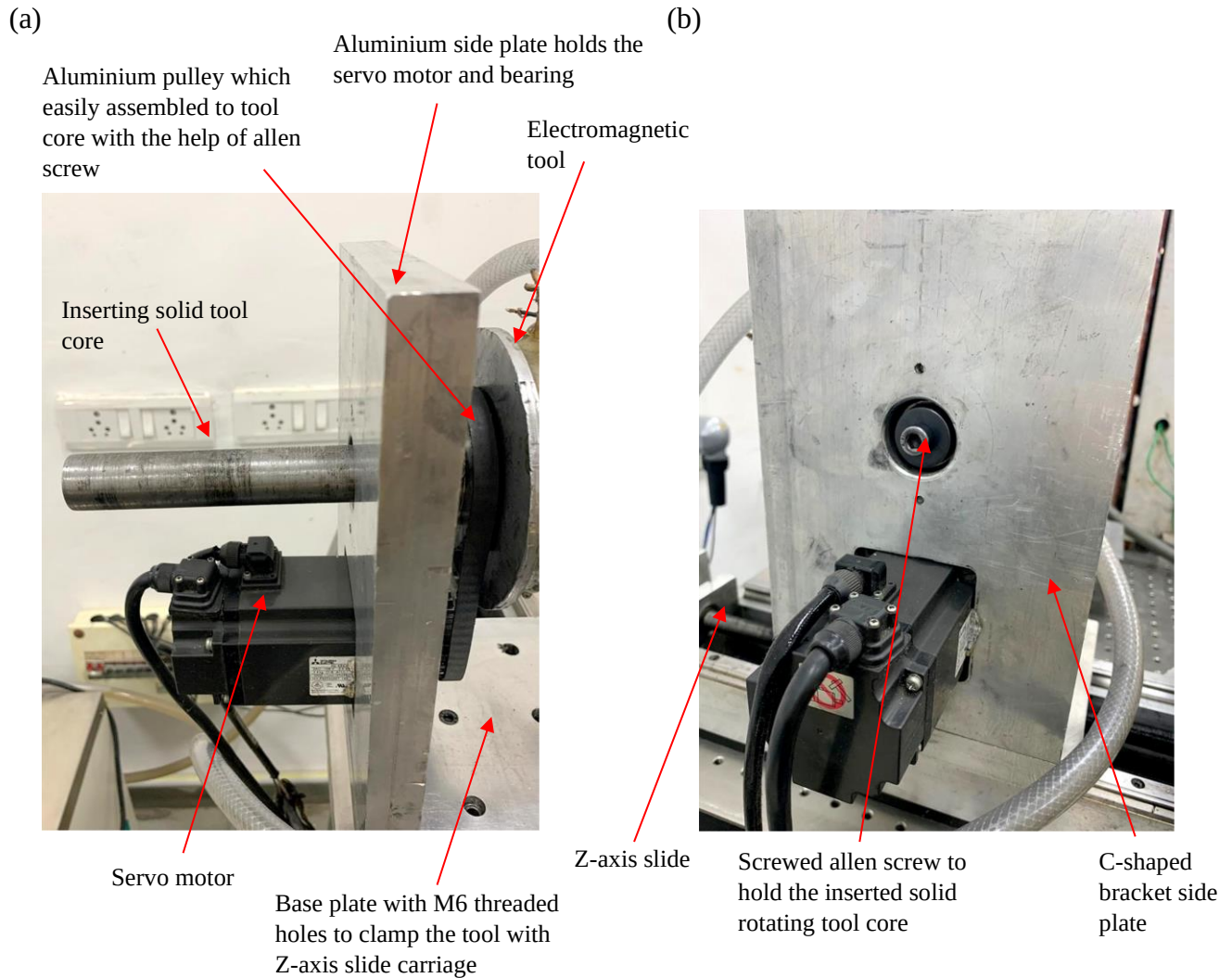


Fig. 3.16 (a) The solid tool core insertion into the tool fixture and (b) screwed tool core with the help of allen screw.

The side plates are screwed on the base plate and the C-shaped bracket is assembled. The other components like electromagnetic coiling, the servo motor and bearing are inserted into the slots in the C-shaped bracket. The fabricated electromagnetic tool with all their components which provide the rotational motion to the solid tool core is depicted in Fig. 3.15. The solid tool core is inserted from the backside of the C-shaped bracket as depicted in Fig. 3.16 (a). Further, this inserted tool core has a centred threaded hole which helps to hold the tool core at bearing seat. The washer is inserted to set the tool core with bearing seat and screwed the allen screw tighten

the tool core. The aluminium driven pulley is screwed to the tool core with the help allen screw. This assembly of the tool core easily unscrewed when the tool core replaced with other type tip shaped tool core can be inserted. So, this electromagnet tool can hold the different types of tool core tip surfaces.

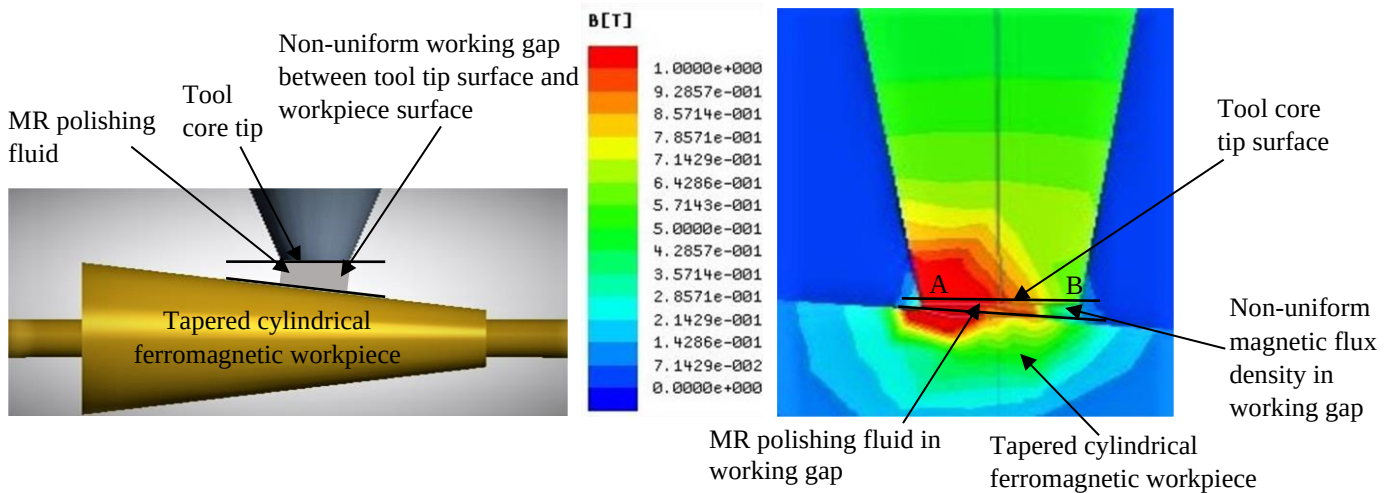
3.2 Development of the rotating swivel vise structure and the associated components for finishing the tapered external surface of cylindrical workpieces with different taper angles

Finishing of the components with an external tapered cylindrical surface is a challenge as compared to the straight uniform external cylindrical surface. To resolve the problem of taper cylindrical finishing surface, a rotating swivel vise is developed which provide the flexibility to finish the taper cylindrical workpieces with different taper angles. Using this vise, any tapered angle cylindrical workpiece is finished. The conicity of the workpiece is important to retain in tapered external cylindrical surface during the finishing operation. In the external cylindrical finishing, the tool tip reciprocates parallel to the cylindrical external surface. However, in the tapered cylindrical workpiece, the workpiece is set at taper angle which makes over the surface of the workpiece to maintain the conicity of the workpiece.

The need of swivel vise has been analysis with the help of the magnetostatic finite element analysis for the distribution of magnetic flux density in working gap without use of the swivel vise and with use of the swivel vise. The different material and other properties have been assigned for FEA in Maxwell Ansoft as same as it assigned for the previous analysis (Section 3.1.1 (Table 3.1)). The magnetostatic FEA results in the working gap when the swivel vise is set at the zero-degree position i.e. without any use of swivel vise and when swivel vise is set at 5 degree in the direction of the tapered surface i.e. with the use of the swivel vise as shown in Figs. 3.17 (a) and (b) respectively. Fig. 3.17(a) demonstrates the non-uniform working gap when the tool tip surface with swivel vise is set at the zero-degree position or initial position towards the taper workpiece surface. The non-uniform distribution of flux density has been obtained within the working gap as it can be seen in magnetostatic FEA (Fig. 3.17(a)). Also, magnetic flux density over the tip surface is examined from the point A to B as depicted in Fig. 3.17 (a). The variation in the magnetic flux density per angle over tip surface w.r.t. the tapered ferromagnetic cylindrical workpiece surface is evaluated with the help of FE analysis. Table 3.3 represents the variation in the magnetic flux density per angle over the tool tip surface w.r.t. the tapered ferromagnetic cylindrical workpiece surface. However, when swivel vise is set at 5 degrees in the direction of the tapered surface of the workpiece. The working gap (0.6 mm) between the end surface of the tool tip and the tapered external surface of the workpiece is

maintained constant over the length of the tapered workpiece as depicted in Fig. 3.17(b). The uniform spread of flux density is obtained in the working gap (0.6 mm) as it can be seen in magnetostatic FEA (Fig. 3.17(b)) and also the value of magnetic flux density over the tip surface from point A to B (Table 3.3) is validated.

(a)



(b)

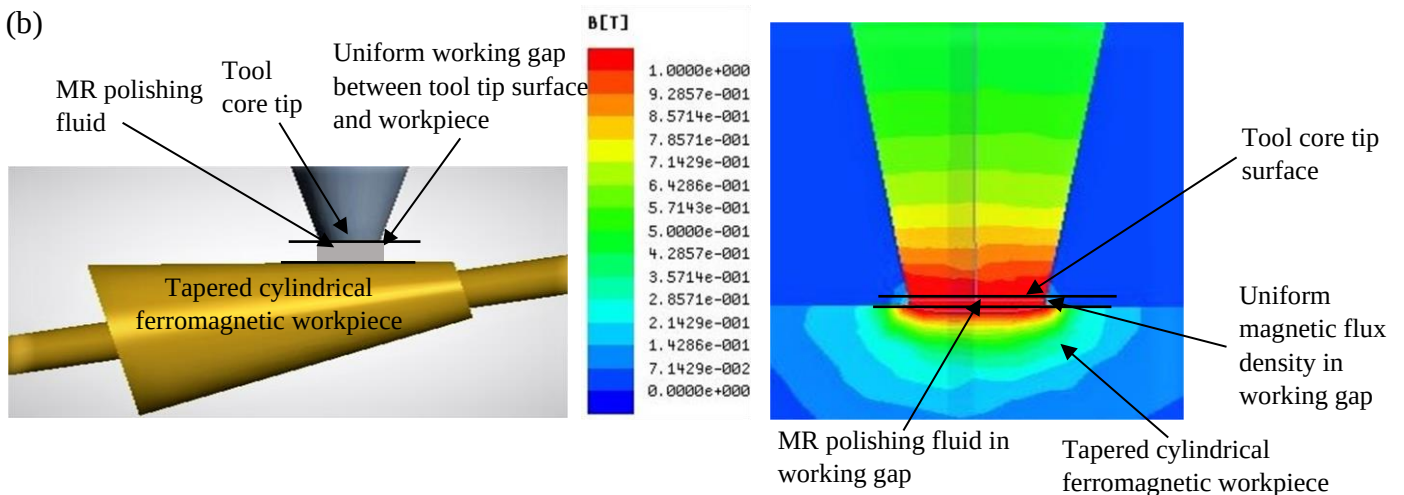


Fig. 3.17 Magnetostatic finite element analysis for variation of magnetic flux density in (a) non-uniform working gap due to tapered cylindrical workpiece external surface, and (b) uniform working gap between the tool tip surface and workpiece when the swivel vise is set at particular angle.

This, results as obtained from the FEA (Fig. 3.17) show that the use of swivel vise is necessary for fine uniform finishing the taper cylindrical surfaces with the effect of uniform magnetic flux density in working gap. So, swivel vise fixture is designed and fabricated for MR finishing the taper cylindrical external of the workpieces. The swivel vise fixture has a feature to set a tapered cylindrical workpiece at any angle. The swivel vise fixture consists of the rotating vise,

holding clamps, two plummer blocks, structure for holding the servo motor and V- belt pulley drive.

Table 3.3 Variation in the magnetic flux density per angle over the tool tip surface

Taper angle of the swivel vise with respect to the tapered cylindrical workpiece surface (degree)	Variation in magnetic flux density over tip surface (Point A to B (Fig. 3.17 (a)) by changing swivel vise angle (T)
0	0.977-0.590
1	0.979-0.684
2	0.980-0.745
3	0.982-0.817
4	0.995-0.892
5	0.997-0.996

3.2.1 Rotating swivel vise

In the rotating swivel vise fixture, the swivel vise is a main part of the fixture. The dimensions of the swivel vise are selected based on the different applications of the tapered cylindrical surface workpieces. The tapered cylindrical surface applications like tapered cylindrical punches, taper rollers in forging process, tapered bearing races and tapered cylindrical shafts can be easily be finished by the present MR finishing rotating tool with the help of the using this swivel vise fixture. Based on these different applications the dimensions of the swivel vise has been chosen. Further, the standard swivel vise is purchased. The present swivel vise base has dimensions like 300 mm in length, 100 mm in width and 110 mm in height. The M6 size holes are drilled on the base of the swivel vise to fix the clamping supports which hold the tapered cylindrical workpiece. This vise has a rotating base that can be rotated at a 360-degree angle and set any angle as per the requirement with the help of nut-bolt assembly.

The angle marking scale is attached to the base of the rotating vise for setting a particular angle. The detailed drawing and 3D model of the swivel vise is depicted in Figs. 3.18 (a) and (b) respectively.

3.2.2 Holding clamps and plummer blocks assembly to hold the tapered cylindrical workpiece

The dimensions of the clamping supports are selected based on the central axis distance of the tool tip surface and swivel vise. So, the central axis height of the tapered cylindrical workpiece is matched to the central axis height of the tool tip surface. This is important to maintain the uniform working gap for uniform MR finishing on the whole surface length of the tapered cylindrical workpiece. The clamping supports are fabricated by a welding process to join the strips of mild steel (5 mm thick). The strips dimensions are selected based on the size of the plummer blocks and the central distance of the tool tip surface and swivel vise.

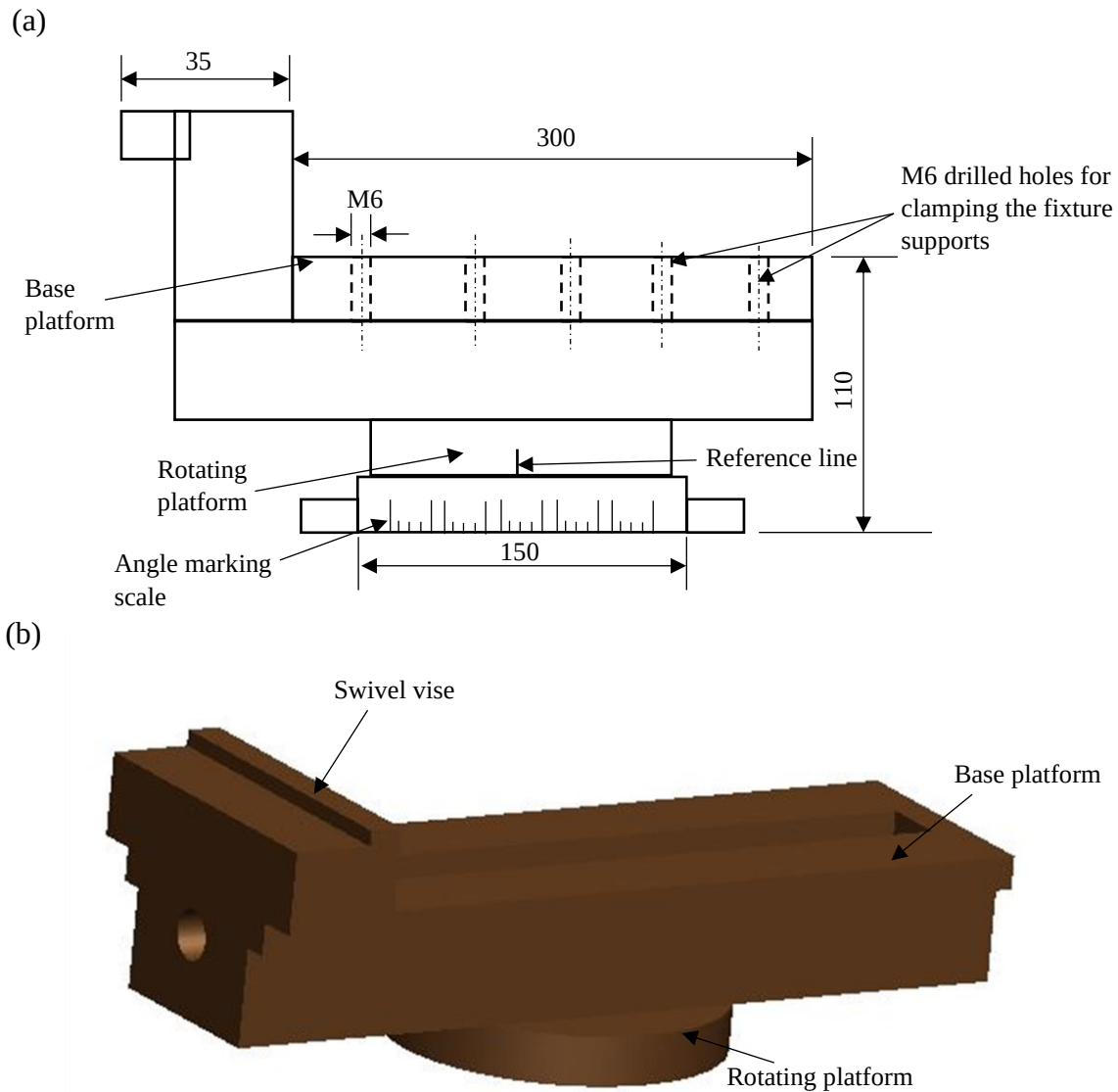


Fig. 3.18 Swivel vise with its all components (a) detailed drawing, and (b) 3D model.

These strips basically added the height to the tapered cylindrical workpiece for maintaining the centre distance and for holding the plummer blocks. The standard plummer block set is purchased. The plummer block (housed bearing unit) is a self-aligned bearing set that aligns the shaft in a straight line is clamped to the clamping supports. The clamping support is holding the servo motor which gives the rotational motion to the tapered cylindrical workpiece. The detailed drawing and 3D model of the clamping supports, plummer block and V belt pulley is shown in Figs. 3.19 and 3.20 respectively. The rotational motion is given through the V-belt pulleys drive. The length of the support is selected on the base of the vise width. The other clamping support length is selected on the basis of the central distance of the driving and driven pulleys of the servo motor and workpiece. The central distance and pulleys are decided based on the availability of the standard V-belt.

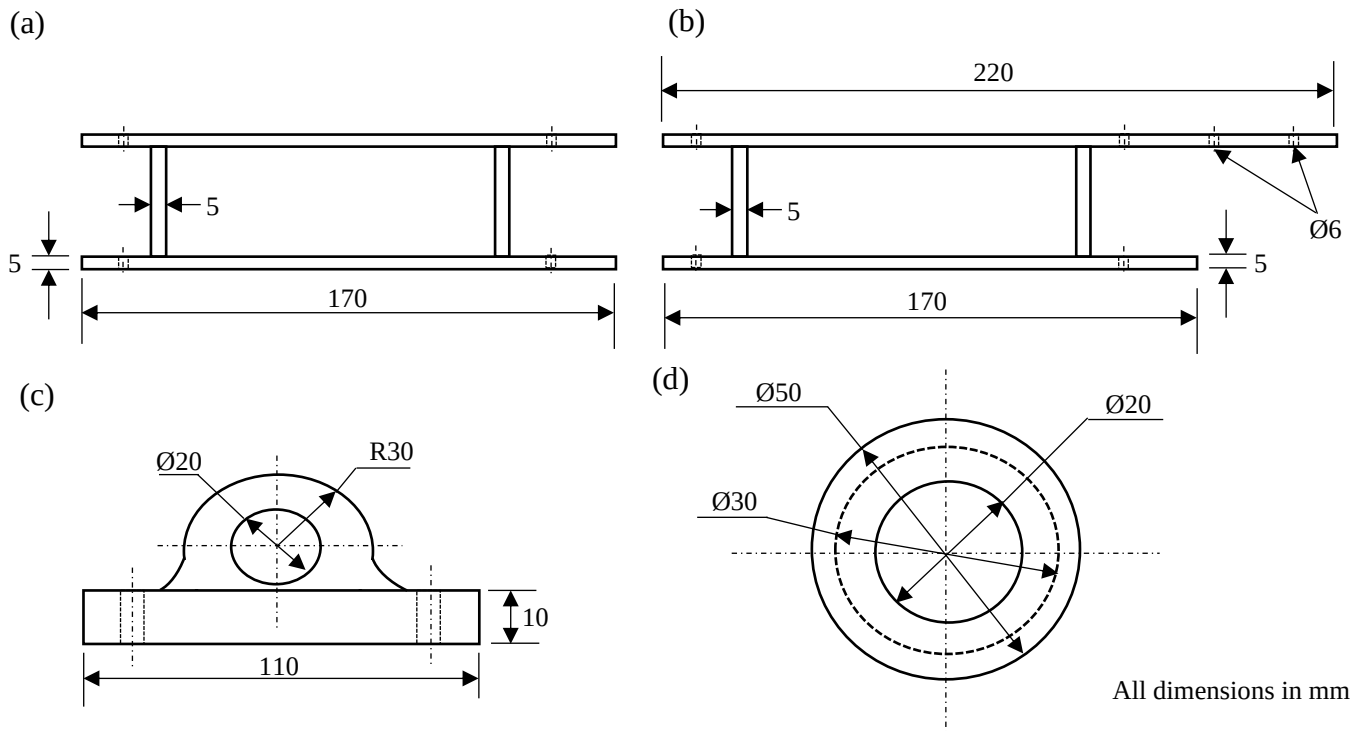


Fig. 3.19 Detailed drawing of (a) clamping support for holding the plummer block, (b) clamping support for holding the second plummer block and servo motor, (c) plummer block and (d) V-belt pulley.

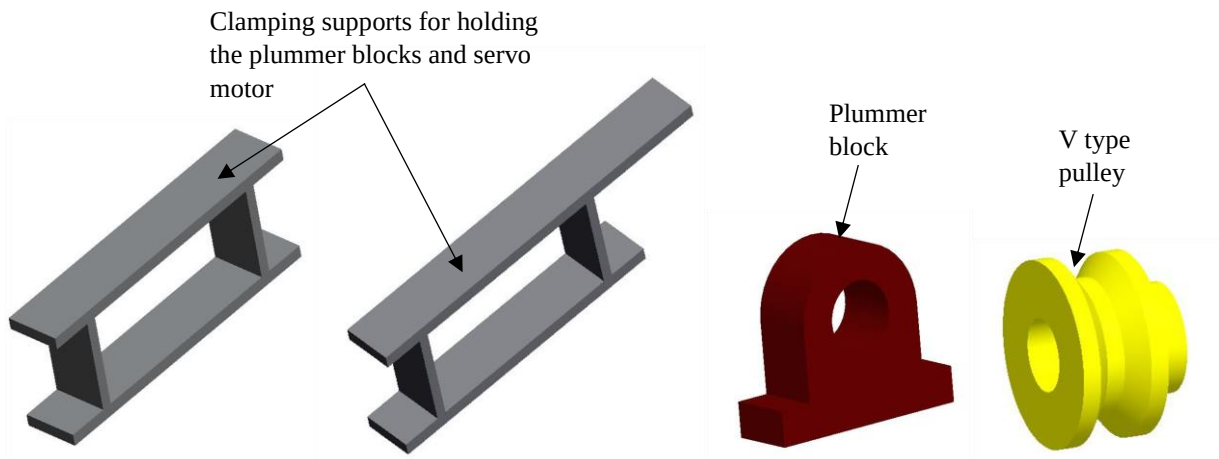


Fig. 3.20 3D model of the clamping supports, plummer block and V-belt pulley.

After the designing of all components, the complete assembled 3D model swivel vise fixture with the tapered cylindrical workpiece and its rotational system is depicted in Fig. 3.21. Further, the complete fabricated rotating swivel vise fixture used for finishing the tapered cylindrical workpieces is depicted in Fig. 3.22. For the experimentation, the rotating swivel vise is clamped to the breadboard with the align screws. As the cylindrical workpiece has a taper angle, the angle is set on the marking scale which straight the cylindrical workpiece to the tool core tip surface for uniform fine finishing the external tapered surface of the cylindrical

workpieces with the help of the uniform strength of the MR polishing fluid on magnetized tool tip surface in uniform working gap.

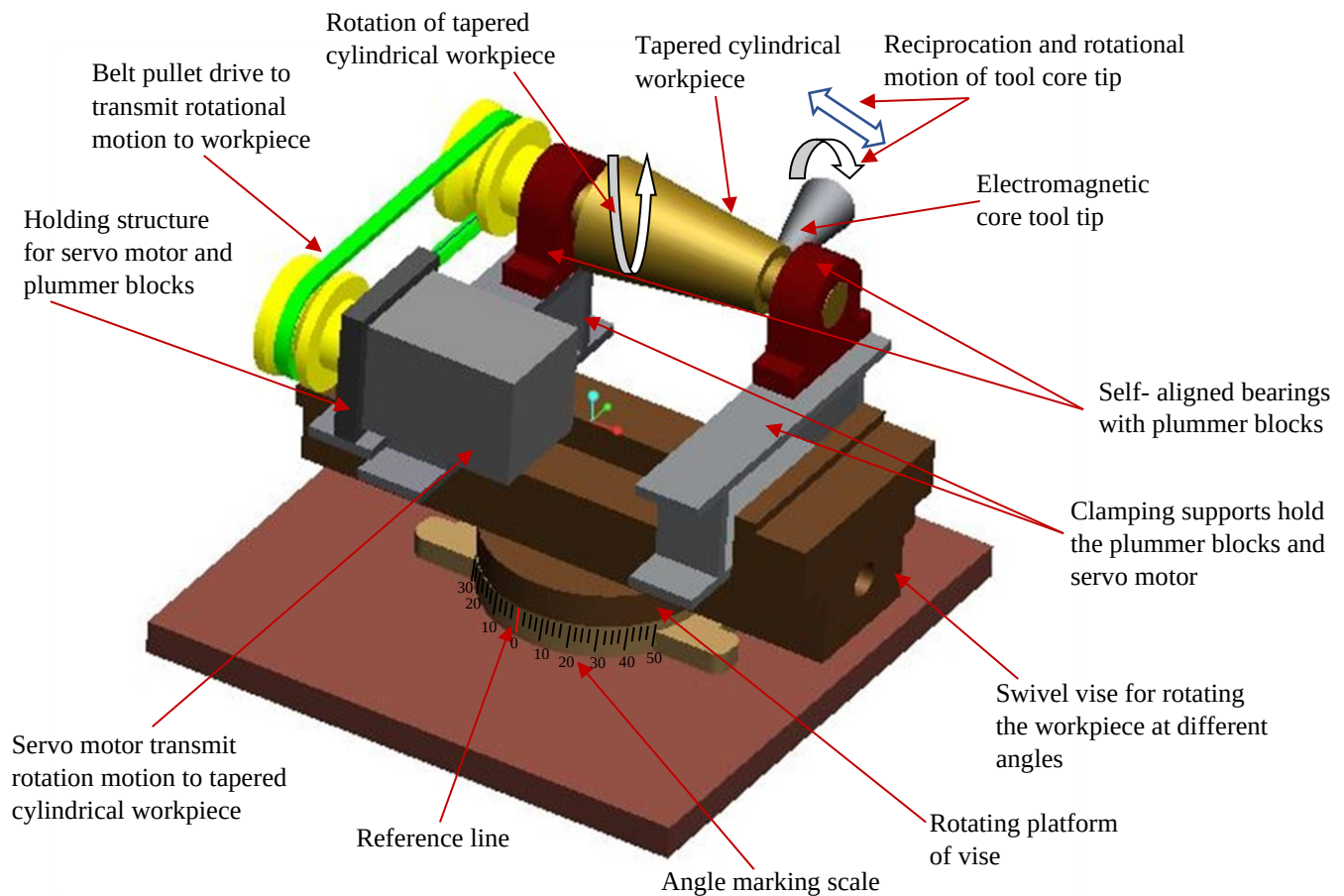


Fig. 3.21 3D model of the swivel vise fixture along with the tapered external cylindrical surface of the workpiece and tool core tip.

3.2.3 Limitations of the development of a rotating core-based MR finishing setup with the initial design of the circular tool core end surface for fine finishing the external surface of the cylindrical workpieces

After analysing the performance of developed a rotating core-based MR finishing setup with the initial design circular tool core end surface, the following limitations were observed.

- Non-uniform distribution of magnetic flux density over the circular tool core tip surface due to the edge effect around the circular tool tip surface as depicted in Fig. 3.23. The magnetic flux density is weak at the middle part of the circular tool core tip surface.
- Due to this, the weak carbonyl iron particles (CIPs) chains form over the middle part of the tool's circular tip surface. This weak CIPs chains may break down during the tool movement over the external surface of the cylindrical workpiece. Due to this effect

the finishing performance of the rotating core-based MR finishing process may get slow down.

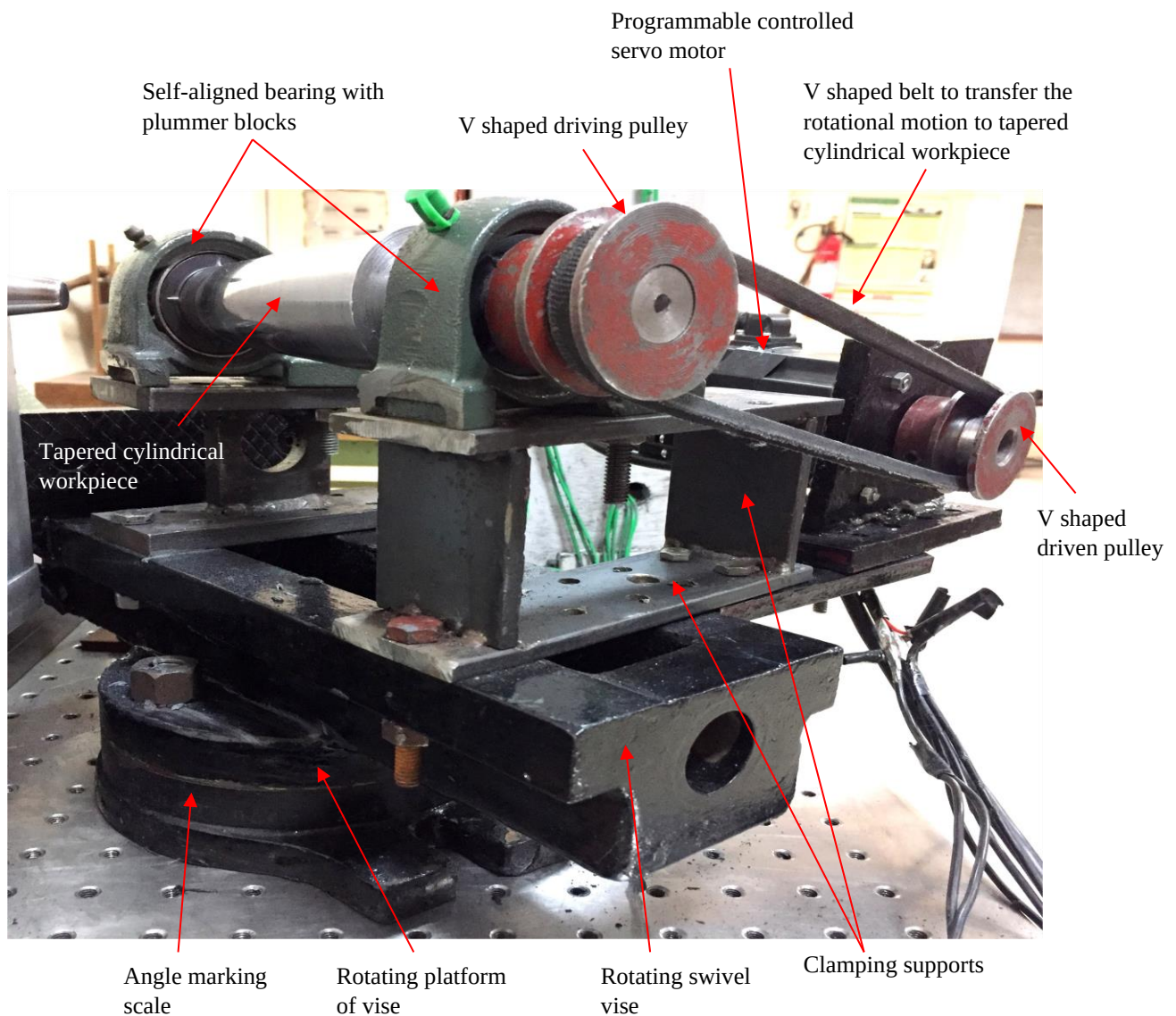


Fig. 3.22 Fabricated fixture of the rotating swivel vise to hold the different angle tapered cylindrical workpieces.

The above mentioned limitation in the initially designed of a rotating MR finishing tool core with circular tool tip surface may hinder the process performance. Therefore, this limitation has been to improve the directed initial design of a rotating circular tool tip surface for further improving the process performance.

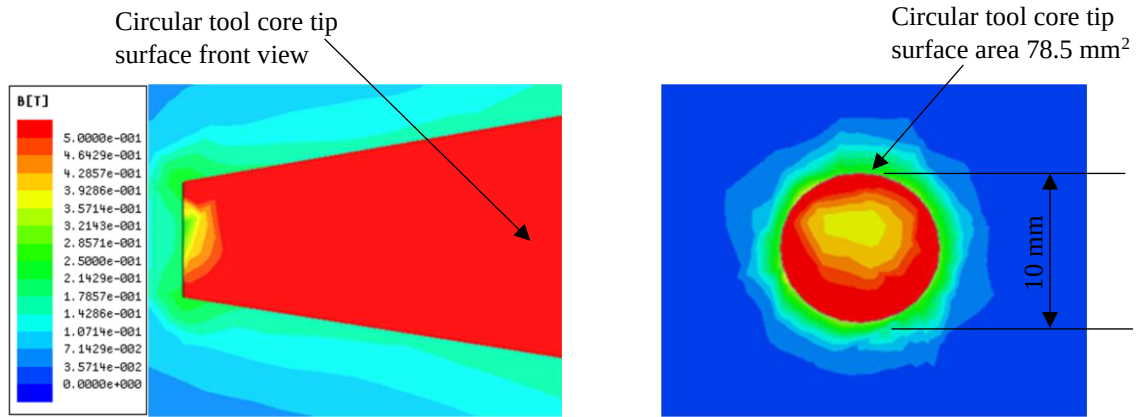


Fig. 3.23 Finite element analysis for analysing the distribution of magnetic flux density on tool core circular shaped tip surface.

3.3 Improved design of the rotating tool core tip surface for enhancing the process performance

After development of the electromagnet tool with the rotating core of circular tip surface, the finite element analysis is performed to select the best of the tool core tip surface for better process performance. Therefore, three new more shapes of the magnetic tool core tip surface have been designed, and their performance is evaluated. The shapes, i.e., square, triangular, rectangular and existing circular of the tool tip surface have been designed with the same tip surface area. For comparative analysis, the lengths of all these magnetic tool cores are also kept same as the existing circular shaped tool core tip. These all types of magnetic tool core tip surfaces are modeled using the Creo Parametric 3D Modeling 5.0. version software. The IGES files of the part modeled are used for magnetostatic analysis using Ansoft Maxwell V13 student version software. It helps to analyse the flux density at each shape of the magnetic tool core tip surface. The parameters and properties were assigned to the electromagnetic model for analysis. The material of the tool core and cylindrical workpiece were set as mild steel with a relative permeability of 600, magnetorheological polishing fluid with a relative permeability of 5, the input current is 2 A and material of the coil is copper with a relative permeability of 0.999 (Dutt and Singh, 2019). The results obtained of the density of magnetic flux from the Ansoft Maxwell on the four types of the tool core tip surfaces are depicted in Fig. 3.24 and Figs. 3.24(a) – (c). The results of flux density as shown in Figs. 3.24(a) – (c), are obtained in the absence of ferromagnetic cylindrical workpiece and MR polishing fluid. The number of turns of the copper coil in the electromagnet is kept as 2100 in the present study. It can be seen from Fig. 3.24 that the uniform and comparatively greater flux density are observed across the rectangular shaped tool core tip surface than the other designed tool core tip surfaces. After

magnetostatic finite element analyses, the rectangular shaped tool core tip surface is found to be the best with comparatively higher and uniform flux density. Therefore, the rectangular shaped tool core tip surface (Fig. 3.24) is selected and fabricated for further improving the process performance.

The magnetic field lines travel in closed loops and also, they do not intersect with each other. The iron tool cores make a pattern tracking field lines due to each fragment of the iron particle is itself a tiny dipole. The dipole tries to align itself with a magnetic field line (M_f) (Ebrahimi et al., 2008). But, on the edge of the tool core tip surface, the field lines are much closer to each other. Closer magnetic field lines provide stronger magnetization. When magnetic field lines are far away to each other, the magnetization can be found weak. In the circular tool core tip surface, the behaviour of magnetic field lines is depicted in Fig. 3.25(a). Due to the localization of the M_f at the edge of the circular tip surface, there is an increase in magnetization. The M_f towards the central axis of the circular tip surface is far away from each other which may result in comparatively weaken in the magnetization at the central portion of the circular tool core tip surface as depicted in Fig. 3.25(a). The localization of magnetic field lines is influenced by the edge effect phenomena which enhances the magnetization (Jha and Jain, 2008). The flow of magnetic flux in the magnetic core spreads out into the surrounding, this phenomenon is known as flux fringing (Guo et al. 2006). This edge effect depends on the geometry of the tool core tip surface (Davila et al. 2004). In rectangular shaped tool core tip surface, the edge effect is greater than the circular shaped tool core tip surface. This is because of the rectangular shaped tool core tip surface which has four corner edges that increase the localization of the magnetic field lines as depicted in Fig. 3.25(b).

Fig. 3.25(a) shows the direction of magnetic field lines (M_f) and the magnetic flux density (B) due to M_f generated on the edge of the circular tip surface. Fig. 3.25(b) depicts M_f direction, and the magnetic flux density (B) due to M_f generated on the edges of the rectangular tip surface. There is a sudden change in the edged area on the rectangular tip surface. This results in the concentration of flux density on the tip surface. In the rectangular shaped tip surface, the magnetic field lines are concentrated at one side of the tip surface while the other side distributes the magnetic field lines uniformly. The fabricated circular and rectangular tool core are shown in Fig. 3.26(a). After the fabrication of both the tool cores, they were inserted one by one into the fixture of the electromagnetic tool. The magnetic flux density has been measured experimentally over both the tool core tip surfaces without the proximity of the ferromagnetic workpiece and MR polishing fluid.

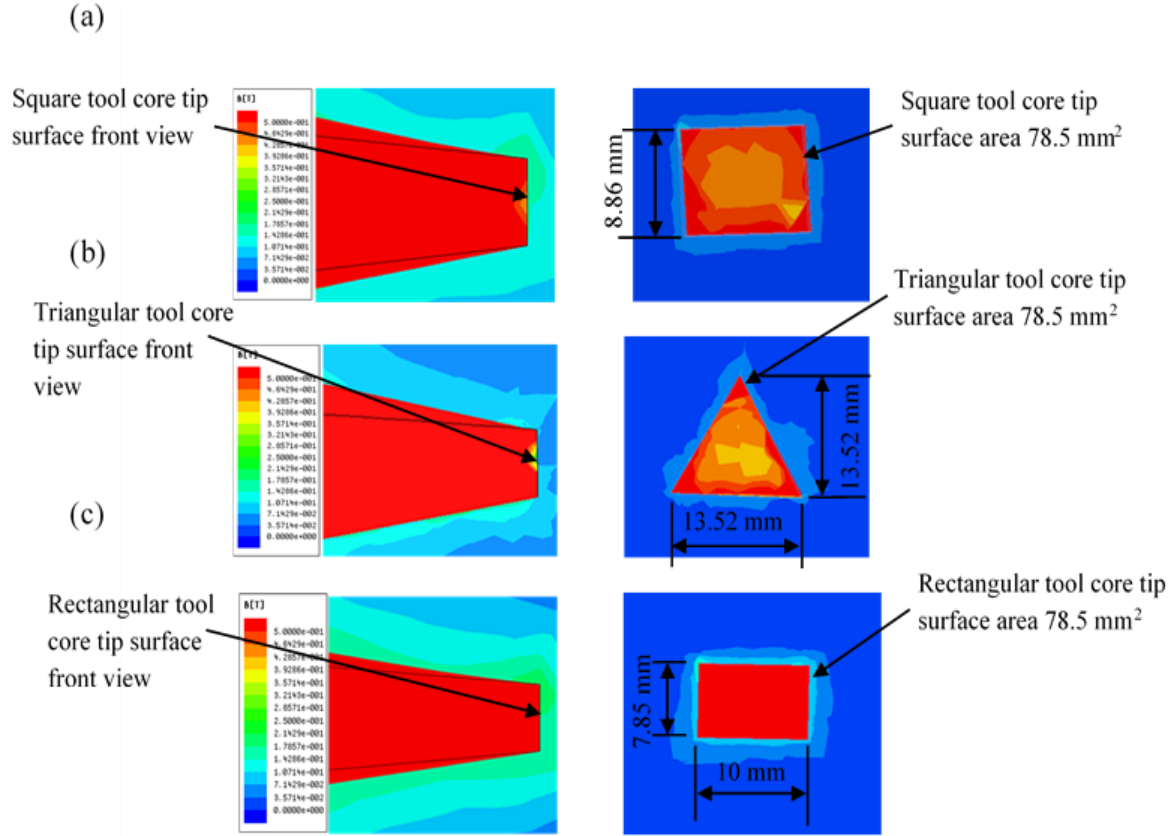


Fig. 3.24 Finite element analysis for analysing the distribution of magnetic flux density on tool core (a) square shaped tip surface, (b) triangular shaped tip surface and (c) rectangular shaped tip surface.

For measuring the magnetic flux density, the experimental setup is used along with digital gaussmeter as shown in Fig. 3.26(b). The flux density is measured at five different points on both the tip surfaces with the help of the digital gaussmeter as depicted in Figs. 3.26(c) and (d), respectively. Thus, it can be seen from Figs. 3.26(c) and (d), the rectangular shaped tool core tip surface has been found a suitable design to provoke better and uniformly distributed density of magnetic flux over the tip surface. The strength of the flux density over tool tip governs the MR finishing rate. Therefore, the present rectangular designed tool core tip surface can perform better finishing with lesser finishing time. The uniformly higher magnitude of flux density increases the strength of iron particles (IPs) chains on the rectangular tool core tip surface which leads to less time. The magnetic flux density is the controllable factor for the MR finishing process within the working gap. The process performance depends on the magnetization of the tool core tip surface. The magnitude of magnetization of the tool core tip surface is directly responsible for the degree of stiffness of the MR polishing fluid. When it gets stiffened, the abrasive particles are rigidly held by the IPs chains which lead to the

enhanced finishing. Therefore, the tool core tip surface is designed based on the magnetic flux density.

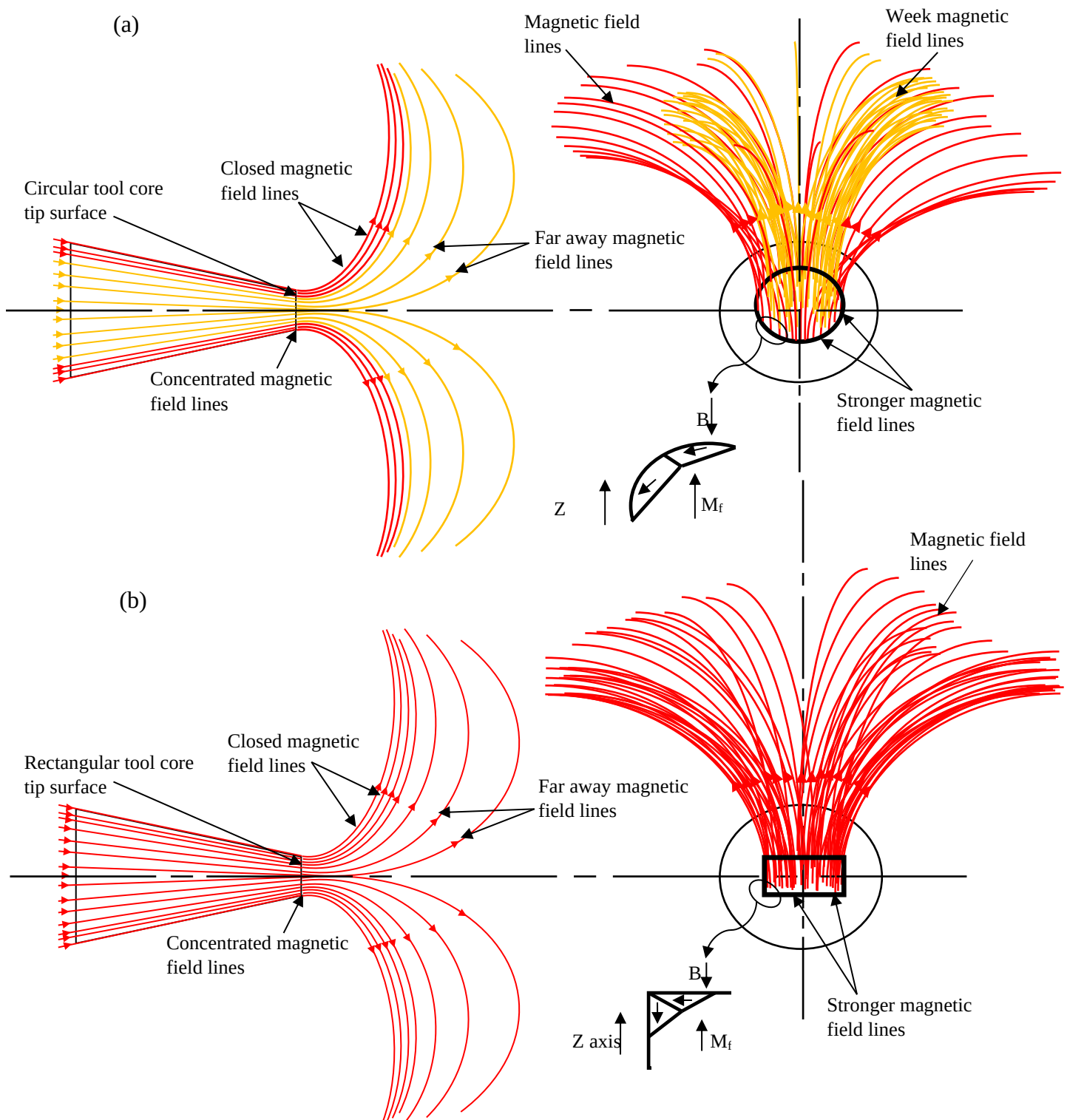


Fig. 3.25 Representation of the distribution of magnetic field lines in (a) circular shaped tool core tip surface and (b) rectangular shaped tool core tip surface. Further, the performances of the designed rectangular and circular tool core tip surfaces are evaluated in the presence of ferromagnetic cylindrical workpiece and MR polishing fluid in the

working gap through magnetostatic finite element analysis (FEA). During the performance analysis, the working gap is maintained with 0.6 mm for both types of tool core tip surfaces. From the FEA, the effect of magnetic flux density within the working gap and over the tool tip surface for both type of tool tip surfaces is analysed, and the plots of magnetic flux density are depicted in Fig. 3.27. The flux density gradient in the working gap is the major necessity for all the MR fluid-based finishing processes. Because of this, the iron particles (IPs) get attracted toward the magnetized tool tip surface. Figs. 3.27(a) and (b) show the FEA 2D plot for the magnetic flux density variation within the working gap and over circular tool core tip surface. Fig. 3.27(a) shows the flux density gradient that decreases from the circular tip surface to the external cylindrical surface as it is the necessary requirement during the MR finishing operation. Fig. 3.27(b) demonstrates the non-uniform flux density over the circular core tip surface even in the proximity of the ferromagnetic cylindrical workpiece and MR polishing fluid in the working gap. The IPs chains are strongly held on the outer edge of the circular tool tip surface. But, the strength of IPs chains can be found less at the centre portion of the circular tool core tip surface. The lesser strength of the IPs chains with abrasive particles at the centre portion and the higher strength at the outer edge of the circular tool tip surface due to the non-uniformity in flux density may result in lowering of the finishing efficiency. Similarly, Figs. 3.27(c) and (d) show the 2D plot of FEA for magnetic flux density variation within the working gap and over rectangular tool core tip surface. From the flux density variation plot, it could be easily depicted that magnetic flux density at the rectangular tip surface is stronger and more uniform than the circular tip surface of the tool core. As already discussed, the stronger magnetic flux density can make stronger iron particles (IPs) chains. Therefore, stronger IPs chains over the rectangular tip surface can grip more strongly the abrasive particles than the circular tip surface. Hence, rectangular tip surface can provide more shear strength to the MR polishing fluid for quick and uniform chipping off the roughness peaks in comparison to that of circular tip surface. Thus, the recently designed rectangular shaped tool core tip surface results in the increase in productivity (less finishing time) of the process. Also, it improves the better workpiece surface characteristics over the use of an existing circular shaped tool core tip surface because of uniformity in magnetic flux density.

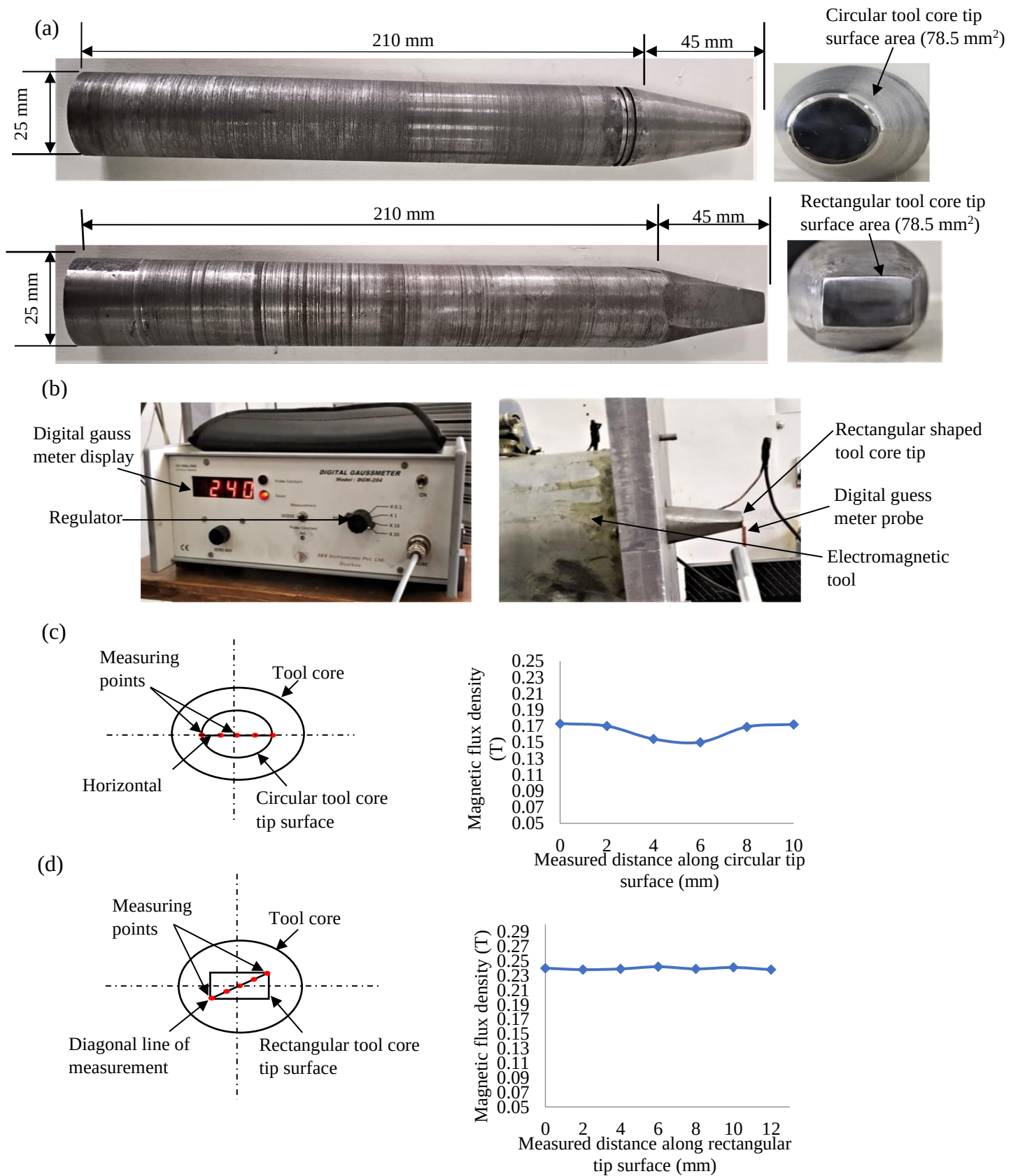


Fig. 3.26 (a) Fabricated iron core with circular and rectangular shaped tool core tip surfaces, (b) digital gaussmeter with the electromagnetic tool to measure magnetic flux density experimentally (c) along circular tip surface and (d) along rectangular tip surface, without using any proximity of the ferromagnetic cylindrical workpiece and MR polishing fluid.

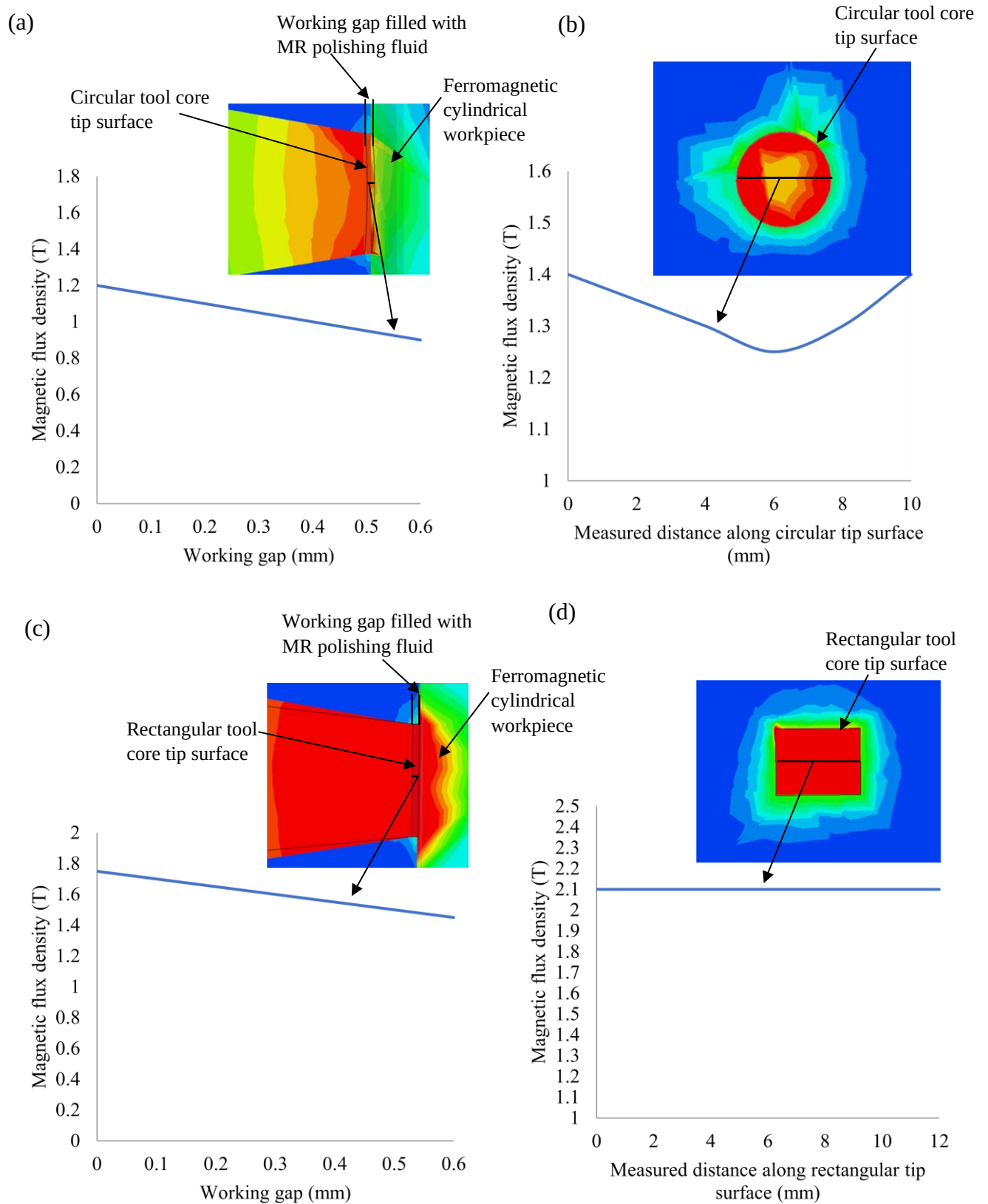


Fig. 3.27 2D plot of distribution of magnetic flux density with proximity of the ferromagnetic cylindrical workpiece and MR polishing fluid (a) in working gap with circular tool core tip surface, (b) along circular tool core tip surface, (c) working gap with rectangular tool core tip surface and (d) along rectangular tool core tip surface.

After developing the improved design of the rotating tool core tip surface with the rectangular shape over the circular shaped tip surface, uniform and higher magnitude of magnetic flux density distribution over the rectangular shaped tip surface of the tool core helps to provide the uniform strengthen of the iron particles (IPs) chains. Due to this, uniform IPs chains over the rectangular tip surface can grip the abrasive particles more strongly than the circular tip surface. The uniformity and higher magnitude of the flux density over the rectangular tool tip end surface, increases the flux density gradient between the rectangular tool core tip surface to the external surface of the cylindrical workpiece in working gap. Therefore, the present rectangular designed tool core tip surface can perform better finishing with lesser finishing time.

3.4 Development of the motion control system to precisely control the various required motions in the present rotating core-based MR finishing process

The developed rotating core-based magnetorheological (MR) finishing setup is required precise motion control system for providing the controllable motions to the tool core and cylindrical workpiece. To develop the automatic motion-controlled setup, the horizontal Z-axis and Y-axis slides are developed which provides the accurate and precise controlled motion. The motion control system is developed, based on the how much distance travel is required by the electromagnetic tool and cylindrical workpiece fixture to complete the MR finishing on the any industrial cylindrical workpieces. The horizontal Z-axis slide is utilized for the electromagnetic tool and Y-axis slide utilized for the cylindrical workpiece fixture. The linear motions of the tool and the cylindrical workpiece fixture is required to maintain the working gap and perform MR finishing on the whole surface of cylindrical workpiece. This requirement is fulfilled by the precise motion-controlled horizontal Z-axis and Y-axis linear slides. The fabricated electromagnet tool is clamped to the horizontal Z-axis slider which gives the reciprocation motion to the tool.

The horizontal Z-axis slide and Y-axis slide designed on the basis of loading condition and requirement in moveable distance. The linear guideways have state load rating (C), which resist the static permissible moment (M) as depicted in Fig. 3.28. The static permissible moment (M) is applied in the three direction, the static moment in the X-axis direction is denoted as M_p , the static moment in the Y-axis direction is denoted as M_Y and the static moment in the Z-axis direction is denoted as M_R as depicted in Fig. 3.28. Localized permanent deformation can be caused between the guideways surface and the blocks when a linear guideway is subjected to an excessively large load or an impact load while either at rest or in motion. If the amount of

this permanent deformation exceeds a certain limit, it becomes an obstacle to the smooth operation of the linear guideway.

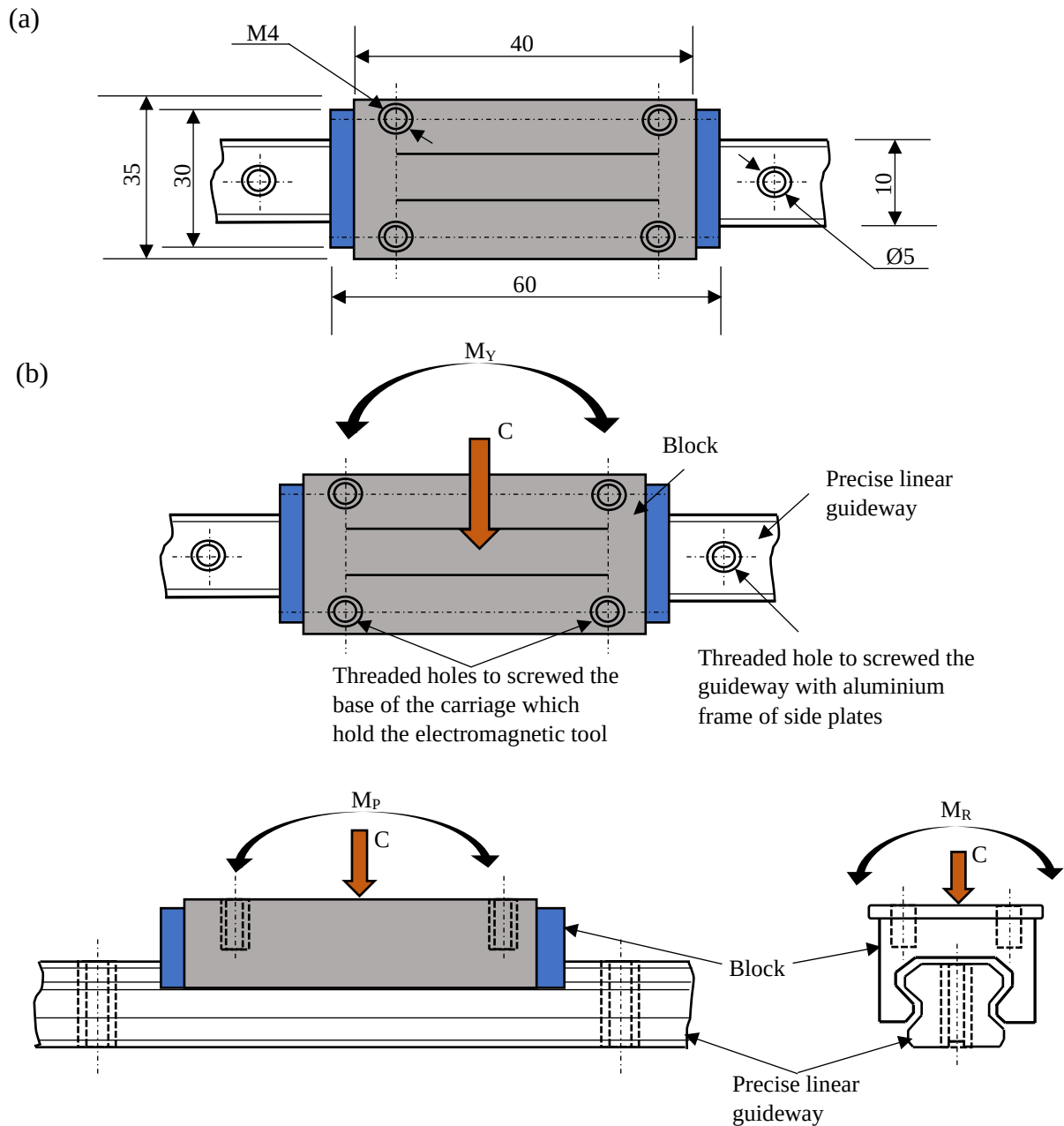


Fig. 3.28 (a) Detailed drawing of the square block with linear guideway and (b) schematic diagram of the loading conditions on the square type blocks during the working conditions.

The HG-15 series square type blocks are used to provide the reciprocation motion to the tool over the linear guideways. The HG series stands for heavy load ball type linear guideways. The HG series with square block the dimensional tolerances of height (H) and width (W) has $\pm 0.05 \mu\text{m}$ and $\pm 0.05 \mu\text{m}$ respectively. These values of dimensional tolerances give very good accuracy in the height and width direction to the tool. The basic dynamic and static load ratings of the linear guideways are 14.7 kN and 23.47 kN respectively. These values are maximum

loading conditions during working that sustain by the linear guideways. The detailed drawing with static loading and static moment acting on the square block is depicted in Figs. 3.28 (a) and (b) respectively.

The static rated moment acted on the three directions of the block as depicted in Fig. 3.28(b), the values of the M_R , M_P and M_Y are 0.12 kN-m, 0.10 kN-m and 0.10 kN-m respectively. The weight of the square block is 180 gram which is used in the present developed Z axis and Y axis slides. The weight of the electromagnetic tool is lies between the 8 to 10 kg which easily reciprocates by the HG-15 series blocks with precise motions and control. Because weight of the electromagnetic tool is produced very less moment due to lesser weight which easily handle by the heavy load ball type guideways with square type blocks. This weight produces the 79 to 98 N static loading which is very less than the basic dynamic and static loading rating of the linear guideways which easily handle by this motion control system. The size of the linear slides is selected based on the working area and required movement distances in both the slides. The horizontal Z-axis slide required greater length than the Y-axis slide because the horizontal Z-axis slide holds the tool which moves linearly over the external surface of the different cylindrical workpieces. The length of the slide decided on the basis of the industrial application of the cylindrical workpieces (cylindrical punches, cold rolling rolls, grooved winding drums, and tapered cylindrical punches etc) length to be finished. On the basis of the application length range, the horizontal Z-axis slide has been selected with the 600 mm long, 120 mm in width and 80 mm in height. The detailed drawing of the horizontal Z-axis slide and Y-axis linear slide is depicted in Fig. 3.29. The horizontal Z-axis linear slide consists of four aluminium plates, two side plates and two corner plates with the threaded screws slots to join each other. The corner has bearing seats to hold the bearings which hold the screw spindle in a straight line, therefore, screw nut smoothly operates on the screw spindle. The side plates hold the linear guideways with the help of bolt assembly. To achieve the reciprocation of the tool, the linear guideways with the square blocks are required. In the horizontal Z-axis and Y-axis slides, total 8 square blocks (4 for horizontal Z-axis and 4 for Y-axis) with 4 precise guideways are used. The assembly of the precise screw spindles (1 mm pitch) with precise ball screws are attached to the aluminium plates frame with the help of bearing set as depicted in Figs. 3.29(a) and (b). The Y-axis slide has 270 mm long, 120 mm in width and 50 mm in height of aluminium frame which holds the precise guideways and screw spindle assembly to provide the reciprocation to the workpiece fixture carriage (Fig. 3.29(b)).

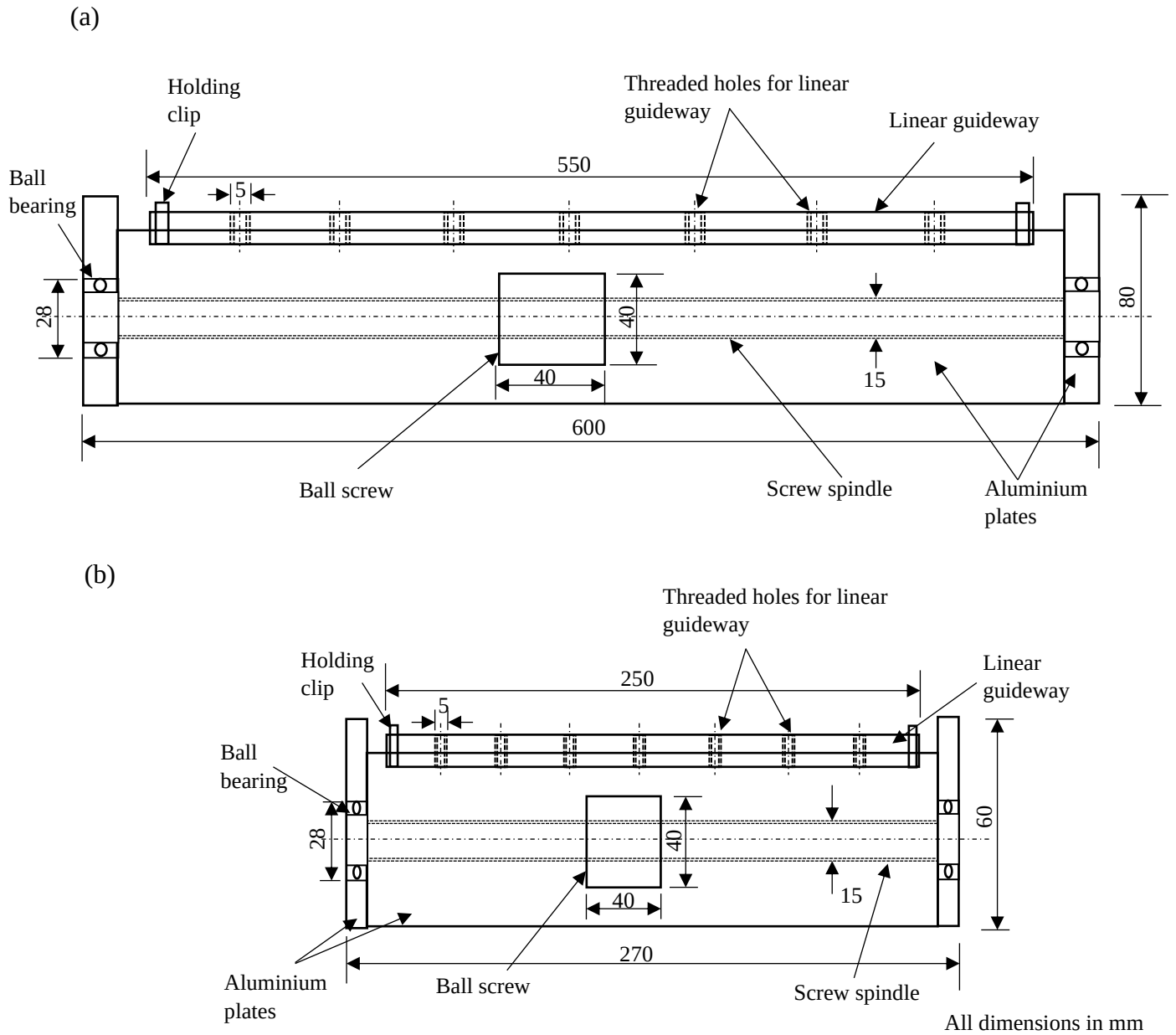


Fig. 3.29 (a) Detailed drawing of the horizontal Z-axis slide for provide the reciprocation to electromagnetic tool and (b) Y-axis slide for provide the reciprocation to the workpiece holding fixture for monitoring the required working gap.

These guideways are self-aligning capability, better interchangeability, high rigidity in all directions. Furthermore, it can achieve a well-balanced preload for increasing rigidity in all directions while keeping a low frictional resistance. The assembled horizontal Z-axis slide with the carriage plate to hold the electromagnetic tool is depicted in Fig. 3.30(a). The assembled Y-axis slide with all components to hold the workpiece fixture is depicted in Fig. 3.30(b). The motion of reciprocation and rotational is provided to the tool and workpiece fixture with the help of programmable logic-controlled servo motors via servo drives. These servo motors provide accuracy and precise control over the motions.

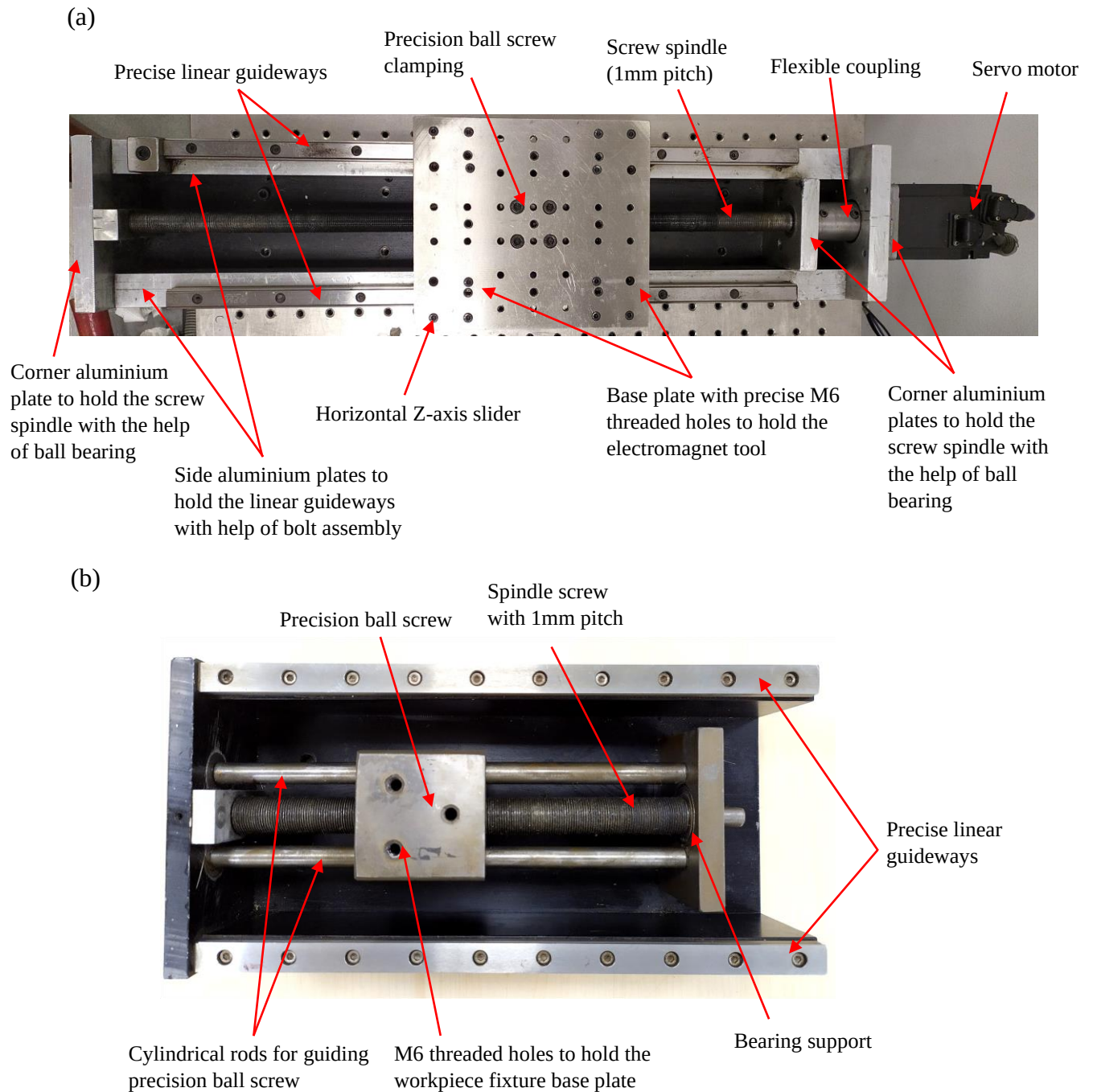
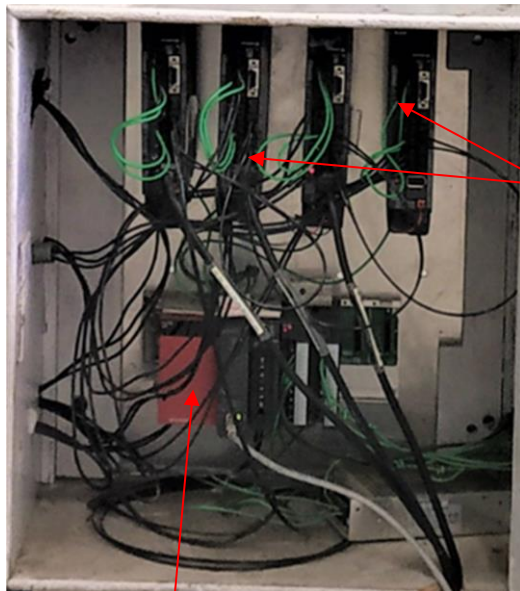


Fig. 3.30 (a) Horizontal Z-axis linear slide with carriage which holds the electromagnetic tool and (b) Y-axis slide with screw nut assembly to hold the workpiece fixture.

The required rotational and reciprocatory motions of electromagnetic tool and cylindrical workpiece are controlled through the programmable logic controller (PLC). Servo drives take the command pulses from PLC output and rotate the servo motors as per the required different motions. Four servo drives are connected to the PLC to control the four servo motors for different required motions to perform the MR finishing on the external surface of the cylindrical workpieces as depicted in Fig. 3.31(a). Based on the programmed input, PLC sends

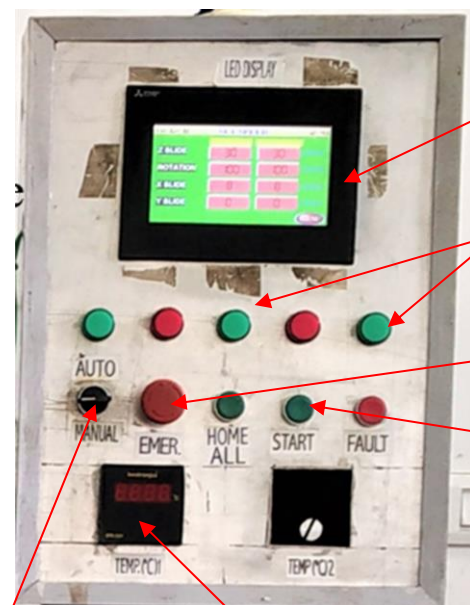
the pluses to servo drives that communicate the servo motors and rotates as per input parameters. The input parameters to operate the servo motors are mentioned with the help human-machine interface (HMI) panel. This panel help to operate the servo motors in manual mode or in auto mode with defined time. According to the material and plan of experiments, the input parameters like rotational speed of the tool core and cylindrical workpiece and feed rate of the tool is changed with the different input program instructions through HMI. This panel have 7 inches touch display which provides easily control over the input parameters as depicted in Fig. 3.31(b).

(a)



Programmable logic controller (PLC)

(b)



Human machine interface (HMI)

LED

Emergency button

Start push button

Auto- manual conversion switch

Electromagnetic coil temperature indicator

Fig. 3.31 (a) Panel of servo drives and programmable logic controller and (b) panel of human machine interface with control buttons.

There are push buttons in the panel which control the start and end of the program during the operation. The panel have auto manual switch which converts the system control in manual or auto condition as depicted in Fig. 3.31.

The MR finishing setup contains four programmable servo motors (P1, P2, P3, P4) to perform the MR finishing operation on the external surface of the cylindrical workpieces as depicted in Fig. 3.32. P1 and P2 servo motors are employed to control the reciprocatory and rotary motion of the rectangular tool core tip surface respectively. The P3 servo motor is utilized for

maintaining the working space amid the tool core tip surface and cylindrical work-part external surface. These servo motors are controlled with the help of a programmable logic controller (PLC) via servo drives.

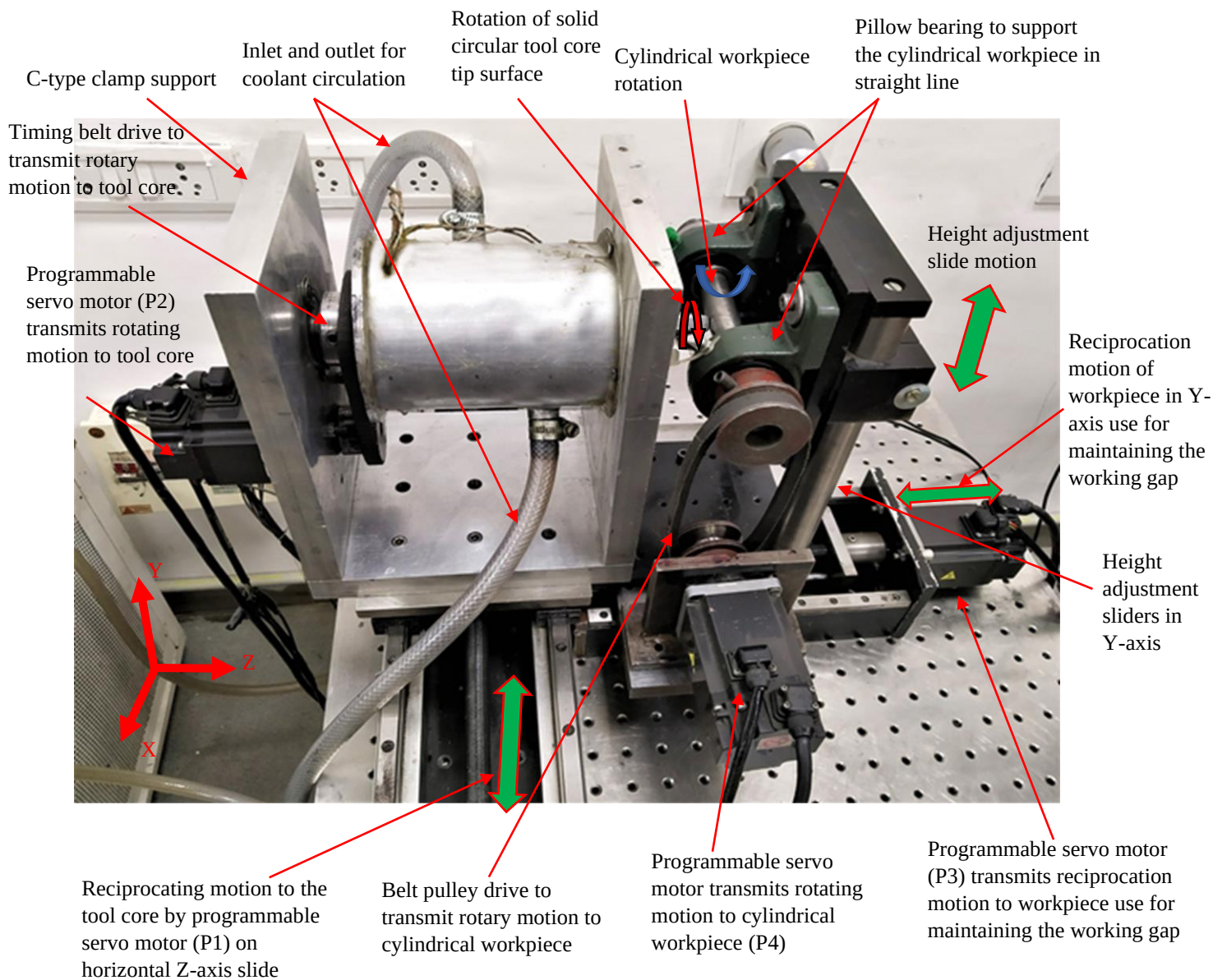


Fig. 3.32 Experimental setup of rotary rectangular core magnetorheological finishing process.

The human-machine interference (HMI) panel is connected to the PLC which response to the manual and auto commands. Thus, the developed rotating core-based MR finishing setup with motion control system can be found more effective to finish the external surface of different cylindrical workpieces.

3.5 Mechanism of material removal in finishing with the developed rotating core-based MR finishing process

Under the effect of the magnetic field in the working gap, iron particles of the MR polishing fluid get arranged in the form of chains and abrasive particles get trapped in these chain structures. Also, the iron particles shift towards the region of high magnetic field gradient (tool core tip surface) and abrasives are pushed toward the region of the low magnetic field gradient workpiece surface. These active abrasive particles are accountable for removal of peaks from the external surface of the cylindrical workpiece. Fig. 3.33(a) shows that material is removed along with the helical path from the external surface of the cylindrical workpiece. The helical path is created along the central axis of the workpiece due to the rotational and translational motion of magnetic tool core tip surface along the length of over the rotating external surface of the cylindrical workpiece. Fig. 3.33(b) represents the interaction before the collision of active abrasive particles (AAPs) with the roughness peaks on the external surface of the cylindrical workpiece. After the interaction of the abrasive particle with the roughness peaks, there are three forces acting on the active abrasive particle namely magnetic normal force (F_n), tangential force (F_t), and axial force (F_a) as shown in Fig. 3.33(c). The magnetized iron particles push the abrasives on the external surface of the cylindrical workpiece because of the magnetic normal force (F_n). The magnetic normal force is responsible for indentation of active abrasives into the external surface of the cylindrical workpiece. The finishing performance depends on the force acting normally on the AAPs which is accountable for indentation. The magnetic force (F_n) is calculated using Eq. (3.12) (Stradling, 1993).

$$F_n = \frac{m_{ip}\chi_m B_{t(z)} \frac{dB_{t(z)}}{dz}}{\mu_0} \quad (3.12)$$

Where the iron particle's mass is denoted as m_{ip} in Kg. The iron particle magnetic mass susceptibility denoted as χ_m in m^3/kg . The flux density variation in the working space is denoted as $B_{t(z)}$. The mass of the iron particle (m_{ip}) is 2.3989×10^{-11} kg (Alam and Jha, 2017). The tangential and axial force is responsible for shearing of roughness peaks from the workpiece surface as shown in Fig. 3.33(c). The net tangential force (F_t) is generated due to the rotation of the tool core and cylindrical workpiece. The tangential force (F_{tt}) is generated due to the rotation of the tool core. The active abrasive also experiences the tangential cutting force (F_{tw}) because of the rotary speed of the cylindrical work-part. In this work, the cylindrical work-part rotates in the clockwise direction and the rectangular tool core rotates in the anticlockwise directions. The tangential shear force is owned to the tool core rotation (F_{tt}) and the tangential force due to the cylindrical work-part rotation (F_{tw}) act over the external surface of the cylindrical work-part through the active abrasive.

These two forces get added to result in net tangential finishing force (F_t) as given in Eq. (3.13).

$$F_t = F_{tt} + F_{tw} \quad (3.13)$$

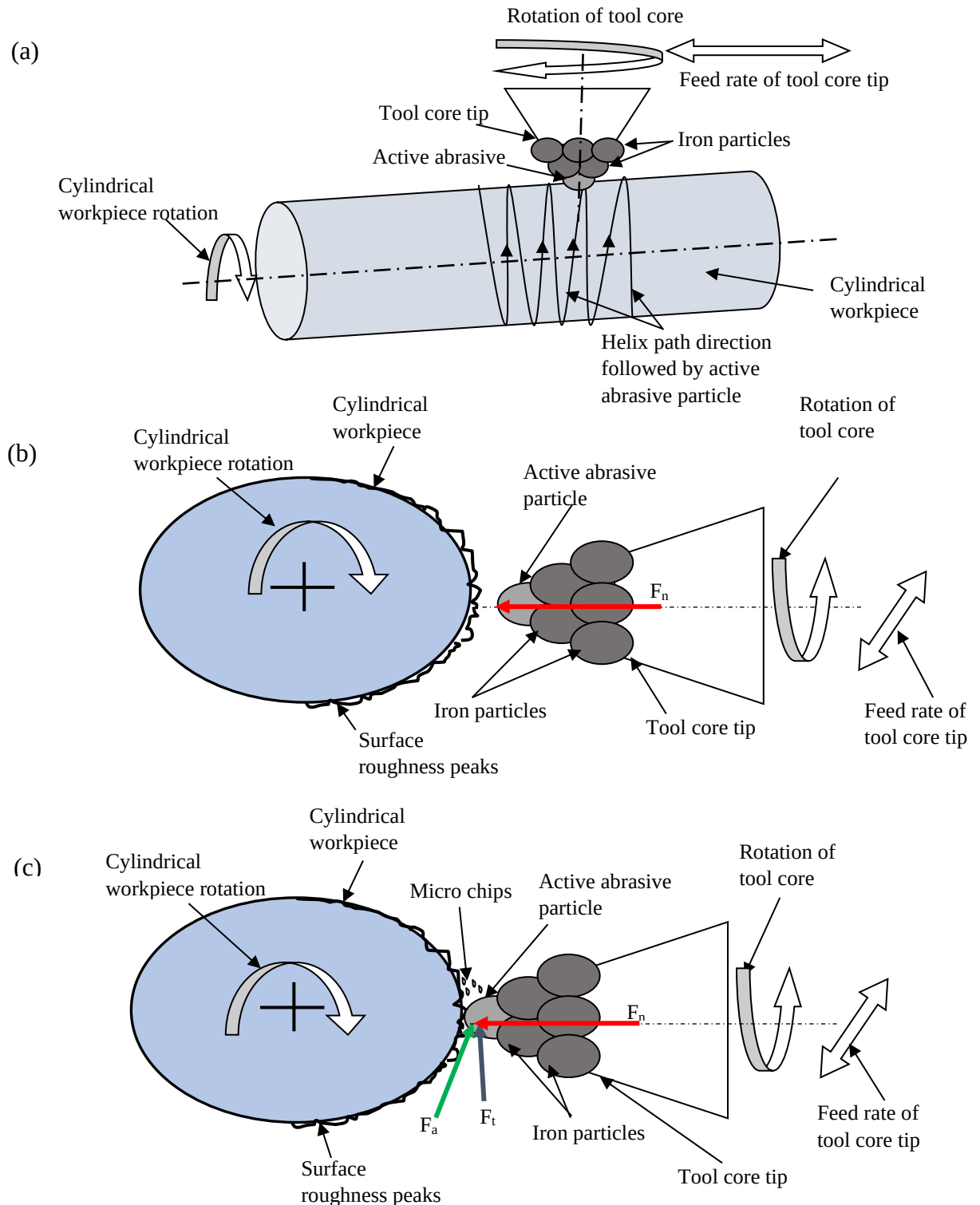


Fig. 3.33 Mechanism of material removal (a) helical path of the active abrasive over the external surface of the cylindrical workpiece, (b) force acting on abrasive particle before interaction with roughness peaks and (c) forces acting during the interaction of active abrasive particle with roughness peaks to finish the cylindrical workpiece surface.

Axial force (F_a) is generated because of the reciprocating motion of tool along the axis of the cylindrical workpiece. This F_a is acting in the parallel direction of the reciprocatory movement of the rectangular tool core tip and calculated by Eq. (3.14) (Gregory, 2006).

$$F_a = \tau_s \times (A_{sic} - A_h) \quad (3.14)$$

Where, the shear strength of the cylindrical work-part is denoted as τ_s in N/m^2 . The area of the single active abrasive is denoted as A_{sic} in m^2 . The area of cross-section of the helical path is denoted as A_h in m^2 . The net tangential (F_t) and axial forces (F_a) on the active abrasive particle experience the resistance offered by the roughness peaks. When the resultant of tangential and axial forces is greater than the resistance shear force of the roughness peaks, the removal of roughness peaks takes place. From the mechanism it is cleared that the rotational motion of the both tool core and cylindrical workpiece enhances the relative motion which further increases the finishing rate of the workpiece surface with the use of the present rotary core-based MR finishing setup.

3.5.1 Selection of best possible direction of the rotational motions of the tool core and cylindrical workpiece for the developed rotating core MR finishing process

The best possible direction of the rotational motions of the tool and cylindrical workpiece is found out on the basis of the direction of the relative motion and their effect on the tangential shear force. When the cylindrical workpiece and tool core both rotate in the anti-clockwise directions, the tangential force due to tool core rotation (F_{tt}) and the tangential force due to the cylindrical workpiece rotation (F_{tw}) acts over the active abrasive in the opposite direction as shown in Fig. 3.34(a). Since these two forces are acting in opposite directions, so the net cutting tangential finishing force (F_{ta}) on the cylindrical workpiece surface gets subtracted which is expressed in Eq. (3.15).

$$F_{ta} = F_{tt} - F_{tw} \quad (3.15)$$

The axial force (F_a) due to the tool core feed rate and centrifugal force (F_{cf}) due to tool core rotation in the anticlockwise direction act in the same direction as shown in Fig. 3.34(a).

The net cutting axial finishing force (F_{af}) is calculated by using Eq. (3.16).

$$F_{af} = F_a + F_{cf} \quad (3.16)$$

The resultant cutting force (F_{S1}) acting over the external surface of the cylindrical workpiece through the active abrasive particle is shown in Fig. 3.34(a). When the tool core and the cylindrical workpiece both rotates in the anticlockwise directions, the resultant cutting shear force (F_{S1}) can be evaluated by using Eq. (3.17).

$$F_{S1} = \sqrt{F_{ta}^2 + F_{af}^2} \quad (3.17)$$

Now, when the cylindrical directions, the tangential force due to tool core rotation (F_{tt}) and the tangential force due to workpiece rotation (F_{tw}) acts over the external surface of cylindrical shaft workpiece through the active abrasive in the same direction as shown in Fig. 3.34(b).

These two forces get added to result in net cutting tangential finishing force (F_{tc}) and can be calculated by using Eq. (3.18).

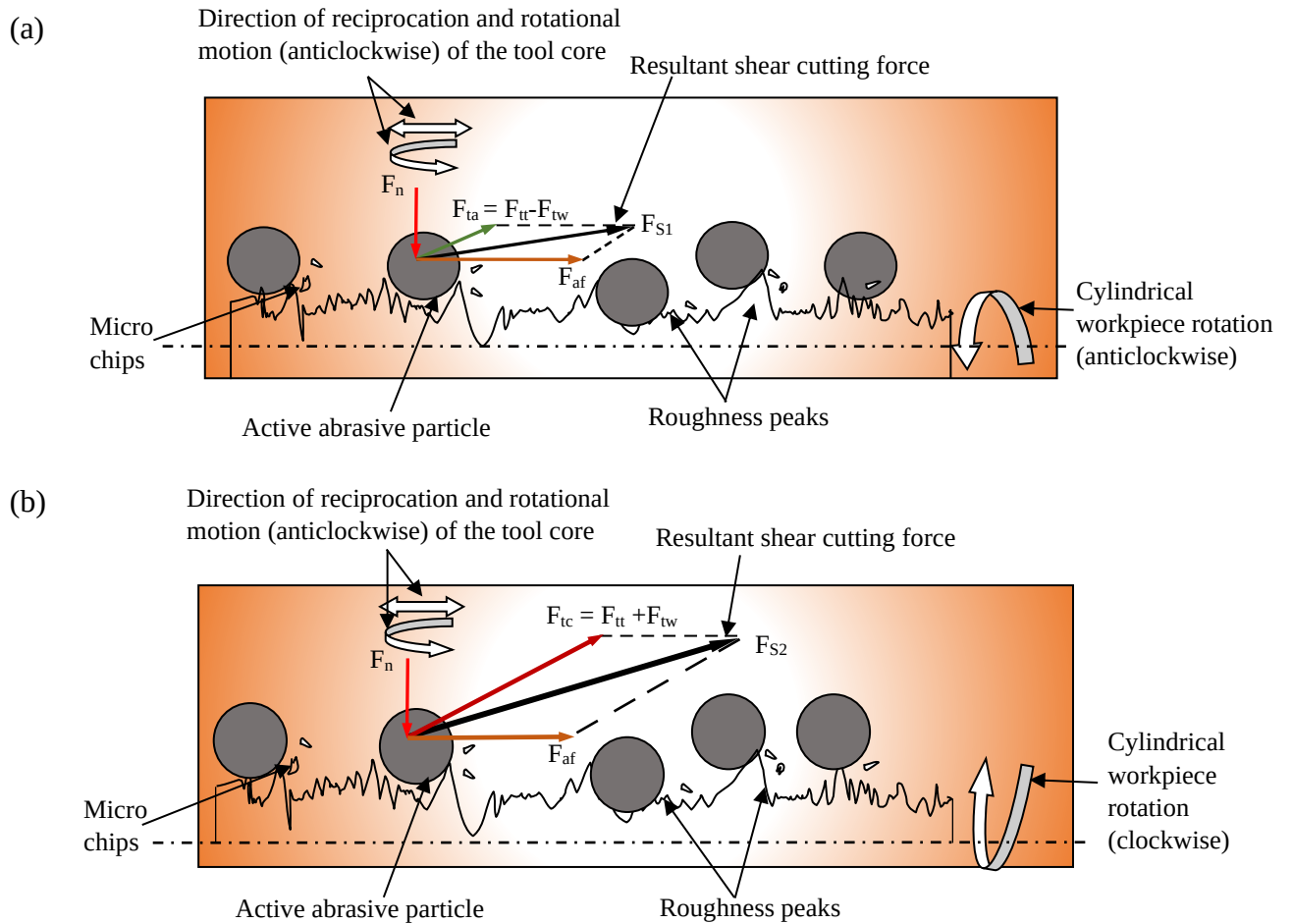


Fig. 3.34 Exaggerated view of finishing forces acting over the active abrasive particle (a) when cylindrical workpiece rotates in the anticlockwise direction with respect to the same anticlockwise rotation of the tool core during the finishing of the cylindrical external surface and (b) when cylindrical workpiece rotates in the clockwise direction with respect to the same anticlockwise rotation of the tool core during the finishing of the cylindrical external surface.

$$F_{tc} = F_{tt} + F_{tw} \quad (3.18)$$

As the tool core rotational and reciprocation directions are same as in previous case and only direction of rotational speed of the cylindrical workpiece has been changed as clockwise from

the anticlockwise direction, therefore the net cutting axial finishing force (F_{af}) can be considered as same as given in the Eq. (3.19).

The resultant cutting force (F_{S2}) acting over the cylindrical surface through the active abrasive particle is the resultant of the tangential and axial forces as represented in Fig. 3.34(b) when the tool core rotates in the anticlockwise direction, and the cylindrical workpiece rotates in the clockwise direction. Therefore, the resultant cutting shear force (F_{S2}) in this case can be evaluated by using Eq. (3.20).

$$F_{S2} = \sqrt{F_{tc}^2 + F_{af}^2} \quad (3.20)$$

Thus, it can be observed that when the cylindrical workpiece rotates in the anticlockwise direction with a same anticlockwise rotary movement of the tool core tip, the net tangential finishing force (F_{ta}) get reduced because of the tangential finishing forces F_{tt} and F_{tw} act in opposite directions as shown in Fig. 3.35(b). Due to this, the resultant cutting shear force (F_{S1}) (Eq. (3.18)) gets decreased as shown in Fig. 3.35(b). But, when the cylindrical workpiece rotates in the clockwise direction and tool core rotation in the anticlockwise direction, the net tangential finishing force (F_{tc}) get increased due to the tangential finishing forces F_{tt} and F_{tw} act in the same direction (Eq. (3.19)) as shown in Fig. 3.34(b). With this, the resultant cutting shear force (F_{S2}) (Eq. (3.20)) also gets increased as shown in Fig. 3.34(b). Due to this increased resultant cutting shear force (F_{S2}), more amount of material gets removed when the cylindrical workpiece rotates in clockwise direction with an anticlockwise rotation of the tool core. Hence, in the present developed MR finishing setup, the tool core rotation is considered as anticlockwise and the direction of the cylindrical workpiece rotation is considered as clockwise for the effective fine finishing of the external surface of the cylindrical workpiece.

3.6 Conclusions

The following conclusions have been drawn after the design and fabrication of the electromagnet tool with rotating different tool core for nano-finishing of the various external surface cylindrical workpieces.

- The finite element analysis shows slightly higher magnetic flux density at the circular flat tip surface than the stationary curved tip surface because of smaller surface area than the curve tool tip for the same projected diameter of the tool core tip surface area. Finite element analysis shows that the strength of magnetorheological (MR) polishing fluid in the variable working gap is not affected while developing the rotating core-based MR finishing process with the circular flat tip surface.

- Kinetic energy of the abrasive particles with rotation of a flat core tool tip can affect on the material removal rate and better finishing performance. Due to the rotation of a circular flat core tool tip surface, the CIPs chains get transferred from the lower magnetic field strength to higher magnetic field strength in the working gap which results in changing orientation of the active abrasives and new cutting edges are available for finishing operation instead of same cutting edges as in stationary curved core tool tip. This enhances the process performance.
- Magnetostatic finite element analysis reveals the uniform distribution of the magnetic flux density at the end surface of the magnetic tool core due to the uniform working gap between the end surface of the magnetic tool tip and the tapered workpiece surface. This is necessity in order to get uniform and effective fine finishing on the tapered cylindrical workpiece surface by using fabricated rotating swivel vise.
- The flux density over the designed rectangular shaped tool core tip surface is found uniformly in higher magnitude as compared to the circular or other shapes of the tool core tip surfaces. The edge effect plays a major role in improving the magnitude and uniformity of flux density over the rectangular shaped tool core tip surface as the localization of magnetic field lines are influenced by the edge effect phenomena which enhanced the magnetization.
- The rectangular shaped tool core tip surface improved the efficiency of the process for nano-finishing in the industrial applications as the nature of variation in flux density, and its magnitude significantly impacts the efficacy of MR finishing process.
- This developed precise motion control system helps to control the different motions of the tool and cylindrical workpiece fixture. This helps to provide the precise and uniform finishing of the various real-time external cylindrical surface industrial applications.
- The process performance mechanism found better when the workpiece rotates clockwise with an anticlockwise rotation of the tool core. This signifies that the direction of motions of tool core and workpiece influences process performance in terms of finishing forces.

CHAPTER 4

EXPERIMENTAL VALIDATION OF A DEVELOPED ROTATING CORE-BASED MAGNETORHEOLOGICAL FINISHING PROCESS

In this chapter, the performance of the developed rotating core based magnetorheological (MR) finishing process as compared to the existing turning type MR finishing process (Singh *et al.*, 2016) is examined through preliminary experimentation at the same input variables. Furthermore, the improved rectangular shaped tool core tip surface compares with the circular tool core tip surface through the preliminary experimentation at the same input variables for validation of the improvement in process performance.

4.1 Preliminary experimentations with the existing turning type and the present developed rotating tool core-based magnetorheological process

To analyze the finishing performance of the developed rotating core-based MR finishing process with the circular tool core tip surface as compared to the existing turning type magnetorheological (MR) finishing process with the stationary curved tool core tip surface, the preliminary experimentations were performed. The experimentations were performed on the external surface of the ferromagnetic stepped cylindrical workpiece (made of mild steel) for investigating the change in surface roughness (R_a) values with same finishing time.

Table 4.1 Chemical composition of the stepped cylindrical workpiece

Constituting elements	%age content
Fe	98.2
C	0.273
Si	0.217
Mn	0.577
P	0.042
S	0.074
Cr	0.124
Mo	0.010
Ni	0.140
Al	0.013
Co	0.010
Cu	0.180
Nb	0.005
Ti	0.023
V	0.018
W	0.025
Pb	0.050

The composition of the workpiece material is given in Table 4.1. Stepped mild steel cylindrical shaft which act as a workpiece, is used in macaroni machine (Singh *et al.*, 2017). To provide smooth and noiseless operation by reducing the friction and wear of the cylindrical shaft, fine finishing is needed on the outer surface of the shaft workpiece. The experimentation was performed to finish the outer surface of shaft using the magnetorheological finishing process with stationary curved core tool tip and rotating flat core tool tip as shown in the Figs.4.1 (a) and (b), respectively.

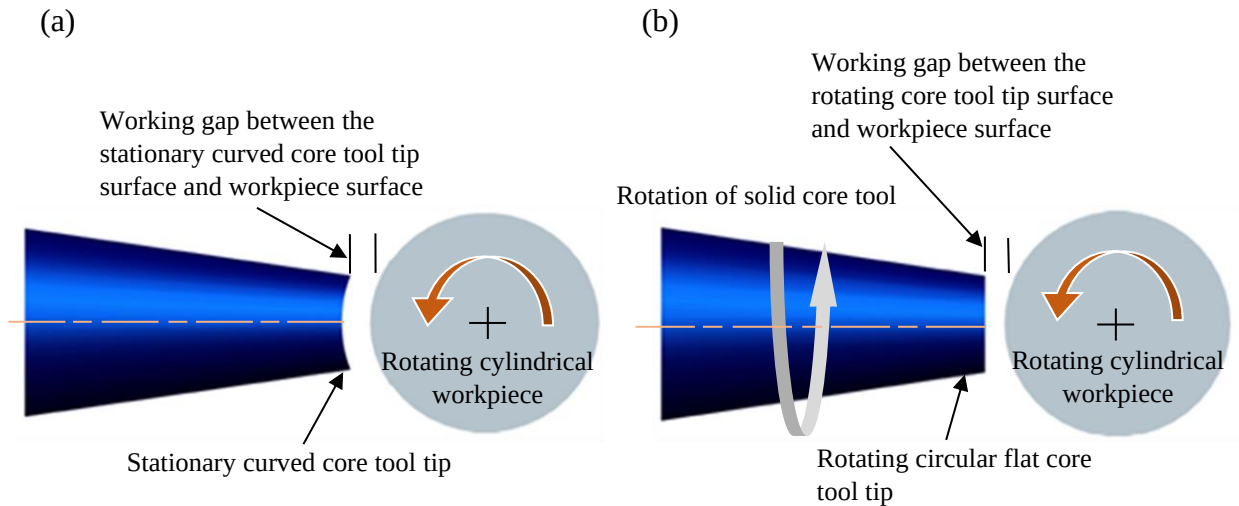


Fig. 4.1 Enlarged view of a working gap with (a) a stationary curved core tool tip surface and (b) a rotating flat core tool tip surface.

The top view of the actual experimental setup with a stationary curved core tool tip and a rotating flat core tool tip is demonstrated in the Figs. 4.2 (a) and (b), respectively. The electromagnetic tools with the existing stationary curved core tip and with the newly developed rotating flat core tip are horizontally stalled on the programmable horizontal Z-axis slide of the experimental set up. The programmable logic controller (PLC) helps to provide very precise control over feed rates and speeds of the tool and cylindrical workpiece. The experimentation is completed in two phases. In the first phase, the electromagnetic stationary curved core tool tip is used while in the second phase the electromagnetic rotating flat core tool tip is used. The programmable servo motor transmits rotary motion to the flat core tool tip while the curved tool tip is kept stationary. Another programmable servo motor transmits reciprocating motion to the tool mounted on the horizontal Z slide as feed rates in both the phases. In present experimentation, the feed rate of 30 mm/min is provided to both the tool cores.

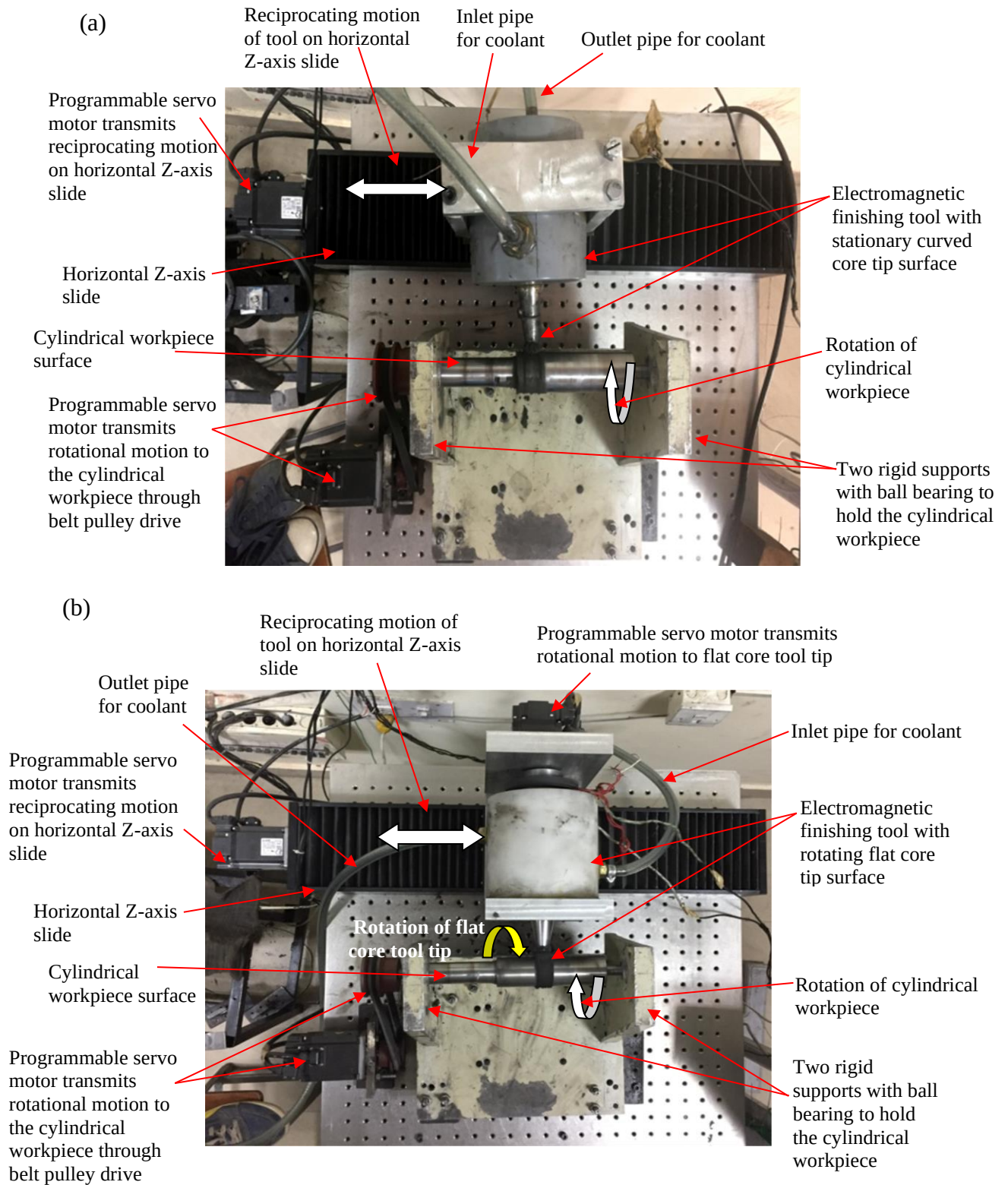


Fig. 4.2 Top view of the magnetorheological finishing process (a) with a stationary curved core tool tip surface and (b) with a rotating flat core tool tip surface.

The cylindrical workpiece is held in between the two supports fitted with the ball bearings and is rotated by a separate programmable servo motor through the belt pulley drive. During trials, various combinations of rotational speeds of the cylindrical workpiece and the tool core are

selected and their effect on the material removal rate in terms of surface roughness value was observed. It has been noted that the lower rotational speed of cylindrical workpiece and higher rotational speed of the flat solid tool core tip results in significant material removal. Higher rotational speed of the tool results in high movement of the gripped active abrasives over the cylindrical outer surface. However, a too high rotational speed results in dispersion of magnetorheological (MR) polishing fluid in between the working gap. This is because of large centrifugal force at too high rotational speed of tool core. The best results are found at the tool core rotation speed of 500 rpm during the trial experimentation. The primary purpose of the workpiece rotational speed is to finish its external circumferential surface. Finally, the cylindrical workpiece rotation is set at 100 rpm. To generate the same magnetic flux density in both the cases, same value of current is applied using a d.c. regulated power supply. Roughness values are measured by Mitutoyo surftest SJ-400 with the cut off length of 0.25 mm. The experimental parameters and conditions based on the preliminary trial experiments are given in the Table 4.2. The same experimental parameters and conditions are used for the improved MR finishing process with the rotating flat tool core tip surface and the stationary curved tool core tip surface.

Table 4.2 Experimental processes parameters and conditions

Parameters	Stationary curved core electromagnetic tool tip	Rotating flat core electromagnetic tool tip
Magnetizing current	2 A	2 A
Working gap	0.6 mm	0.6 mm
Feed rate	30 mm/min	30 mm/min
Rotational speed of cylindrical workpiece	100 rpm	100 rpm
Rotational speed of core tool tip	----	500 rpm
Finishing length on workpiece	20 mm	20 mm
Each finishing cycle time	30 minutes	30 minutes
Total finishing cycle time	90 minutes	90 minutes

4.1.1 Results and discussion

The effect of change in average surface roughness (R_a) value at different MR finishing cycle time using stationary curved core tool tip and rotating flat core tool tip on outer surface of cylindrical workpiece with their corresponding percentage variation is reported in Table 4.3. Using MR finishing process with stationary curved core tool tip, the average surface roughness value R_a is reduced from the initial value of 740 nm to 450 nm in first 30 minutes, 450 nm to 290 nm in second next 30 minutes and 290 nm to 210 nm in third next 30 minutes of finishing

cycle. When MR finishing process with a rotating flat core tool tip is used, the average roughness value R_a is reduced from the initial value of 740 nm to 250 nm in first 30 minutes, 250 nm to 90 nm in second next 30 minutes and 90 nm to 40 nm in third next 30 minutes of finishing cycle.

Table 4.3 Effect of the change in surface roughness values at different time during MR finishing on the external surface of stepped cylindrical mild steel workpiece using the stationary curved tool core tip surface and rotating flat core tool tip surface

Working cycle time (min)	With stationary curved core tool tip		With rotating flat core tool tip	
	External cylindrical surface roughness (nm)	% change in roughness in each cycle time	External cylindrical surface roughness (nm)	% change in roughness in each cycle time
0	740	-	740	-
30	450	39.18	250	66.2
60	290	35.55	90	64
90	210	27.58	40	55.55

Also, it can be noticed from the Table 4.3 that the R_a value obtained after first 30 minutes of the experiment with rotating flat core tool tip is even less than the R_a value obtained after first 60 minutes of the experiment with stationary curved core tool tip.

This proves the effectiveness of the present developed process with respect to finishing time. Also, comparatively there is more reduction in percentage variation in R_a values from first to last 30 minutes of experimentation. The surface roughness profiles of initial and final cylindrical external surface after 90 minutes of MR finishing operation using stationary curved core tool tip and rotating flat core tool tip are shown in the Figs. 4.3(a), (b) and (c) respectively. Using stationary curved core tool tip, the R_a , R_q and R_z values are reduced to 0.21 μm , 0.25 μm and 1.2 μm from the initial values of 0.74 μm , 0.91 μm and 4.1 μm in 90 minutes of finishing cycle. Using rotating flat core tool tip, the R_a , R_q and R_z values are reduced to 0.04 μm , 0.05 μm and 0.3 μm from the initial values of 0.74 μm , 0.91 μm and 4.1 μm in 90 minutes of finishing cycle. Therefore, the roughness values of R_a , R_q and R_z are reduced to 71.62%, 72.53% and 70.73% with the stationary curved core tool tip while with rotating flat core tool tip, these values were reduced to 94.59%, 94.51% and 92.68% in 90 minutes of finishing with the same experimental parameters and conditions. The main reason for the better finishing performance with the flat rotating core tool tip is because of the higher relative movement in

between the cylindrical outer surface and gripped active abrasives due to the rotation of flat tool core tip surface over the rotating external surface of the cylindrical workpiece.

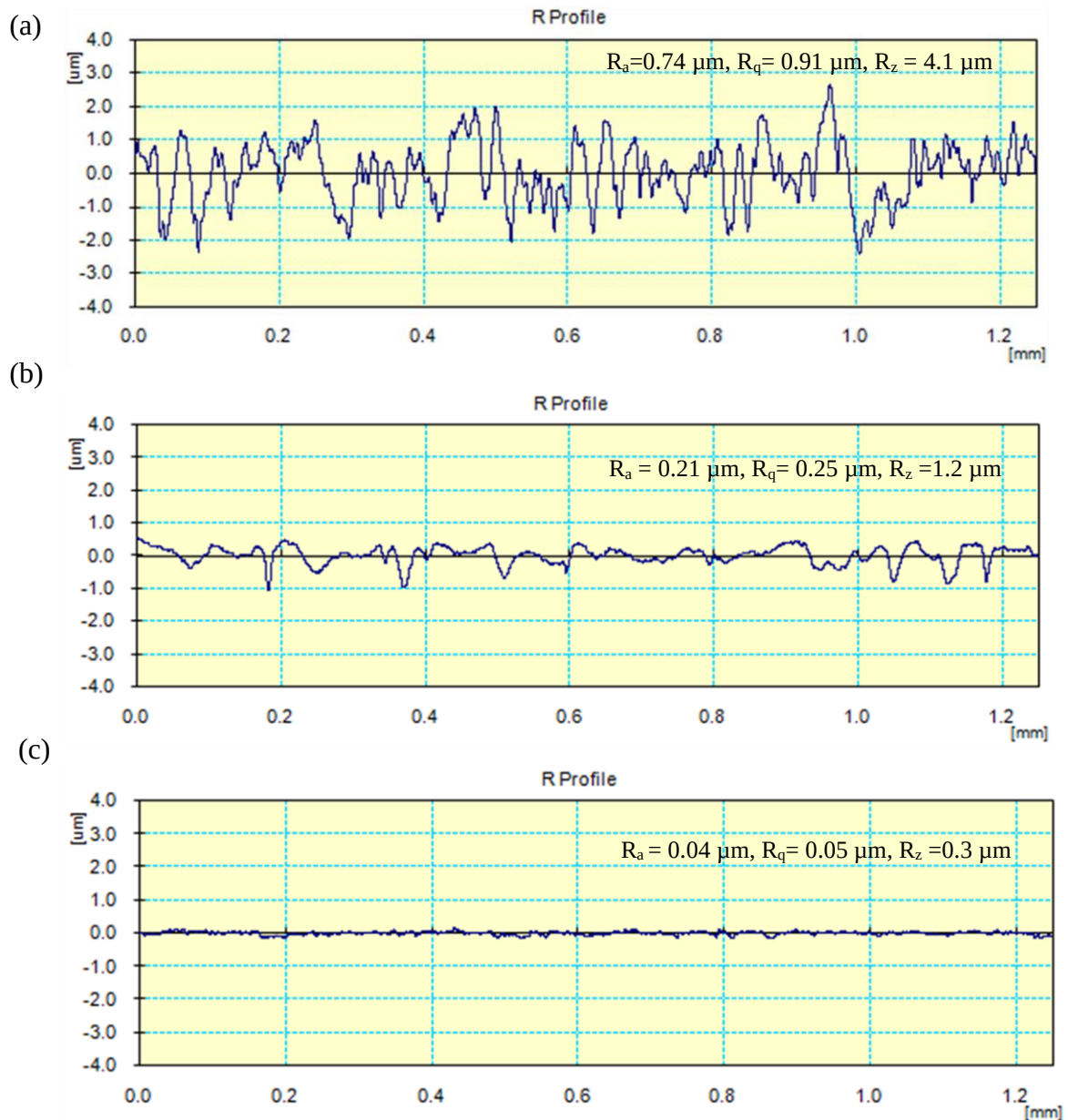


Fig. 4.3 Surface roughness profiles of external cylindrical mild steel workpiece, (a) initial ground surface, (b) after 90 minutes of MR finishing with stationary curved core tool tip and (c) after 90 minutes of MR finishing with rotating flat core tool tip.

The active abrasives obtained high kinetic energy for removal of roughness peaks while flat core tool tip is rotated with 500 rpm. Moreover, due to the rotation of a flat core tool tip, the gripped active abrasives with iron particles chains continuously moves from small to large working gap and from large to small working gap. This outcomes in variation of magnetic field

strength. The orientation of the cutting edges of active abrasives changes whenever it passes through the areas of higher to low magnetic field strength. This results in the availability of new cutting edges for finishing operation in each rotation of a flat core tool tip surface which improves the finishing performance. The scanning electron microscope (SEM) photographs at 1000x optical zoom of the initial surface roughness and after 90 minutes of MR finishing with the stationary curved core tool tip and the rotating flat core tool tip with the same experimental parameters and conditions are shown in the Figs. 4.4(a), (b) and (c), respectively.

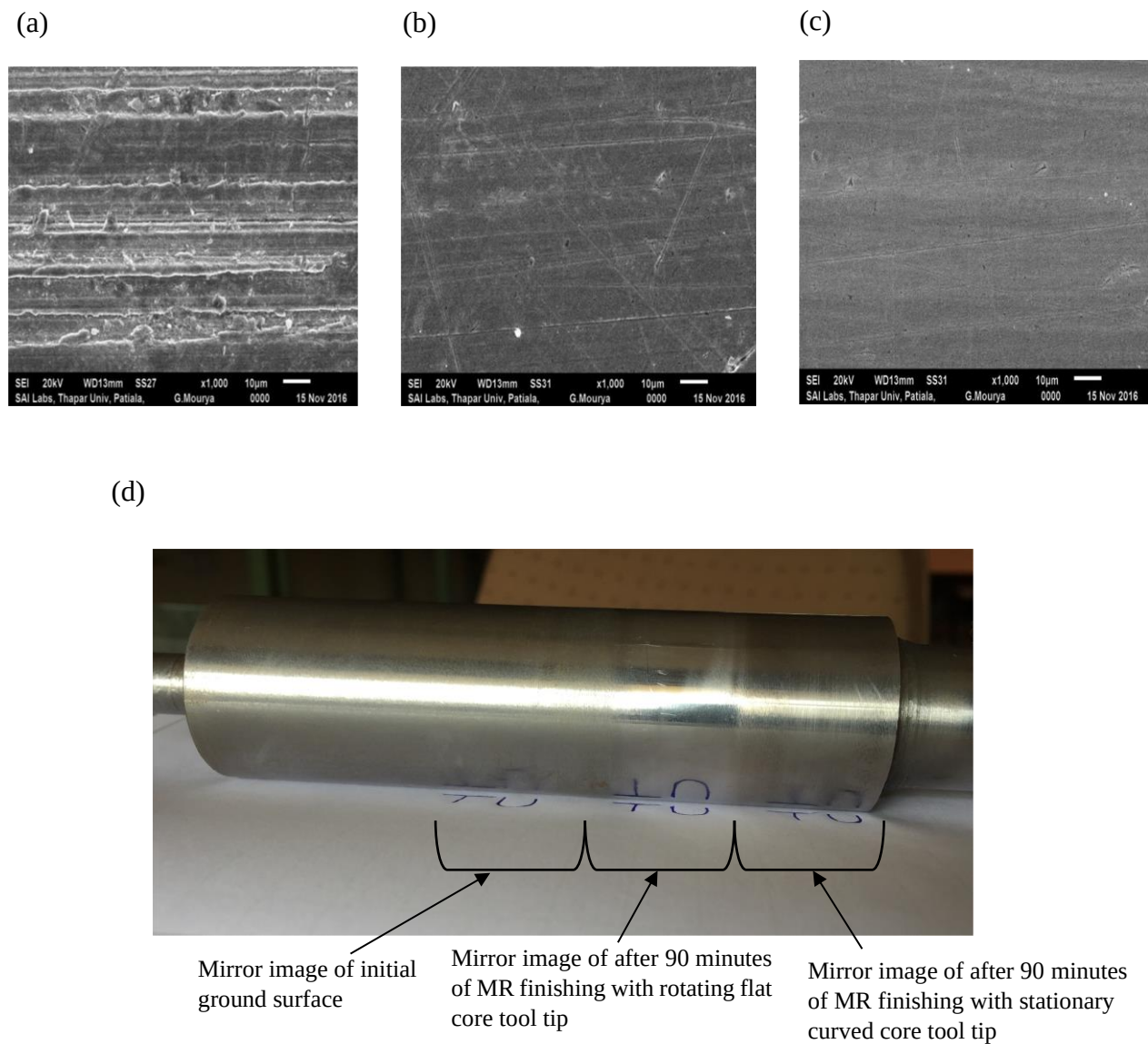


Fig. 4.4 Scanning electron microscope (SEM) photographs at 1000x of external surface of cylindrical mild steel workpiece (a) initial ground surface, (b) after 90 minutes of MR finishing with stationary curved core tool tip, (c) after 90 minutes of MR finishing with rotating flat core tool tip and (d) mirror images of initial ground surface, and after 90 minutes of MR finishing with the rotating flat core tool tip and stationary curved core tool tip.

Before the MR finishing, the external cylindrical surface showed scratches and marks (Fig.4.4(a)). After 90 minutes of MR finishing using stationary curved core tool tip, there is lesser enhancement in the surface quality of the external cylindrical surface (Fig.4.4(b)) as compared to the rotating flat core tool tip (Fig.4.4(c)). A mirror image test was also conducted as shown in the Fig. 4.4(d). The mirror image test showed the better surface characteristics obtained while using the rotating flat core tool tip as compared to stationary curved core tool tip after 90 minutes of MR finishing. It is depicted from the SEM and mirror image analysis that there is great improvement in outer surface characteristics of the cylindrical mild steel workpiece using a rotating flat core tool tip than the stationary curved core tool tip with same experimental parameters and conditions. Hence, the present improved magnetorheological (MR) finishing method with the rotating flat core tool tip is found more effective process for finishing the external cylindrical surfaces than the stationary curved core tool tip.

4.2 Conclusions

The present developed magnetorheological finishing process with rotating flat core tool tip has been found more effective to finish the external cylindrical surfaces in comparison with the stationary curved core tool tip. The conclusions are drawn based on comparison of developed rotational tool core finishing setup with stationary curved tool core finishing setup.

- Kinetic energy of the abrasive particles with rotation of a flat core tool tip has a significantly effect on the material removal rate and better finishing performance. Due to the rotation of a flat core tool tip, the iron particles chains get transferred from the lower magnetic field strength to higher magnetic field strength in the working gap which results in changing orientation of the active abrasives and new cutting edges are available for finishing operation instead of same cutting edges as in stationary curved core tool tip.
- R_a value is reduced from 740 nm to 210 nm in 90 minutes of MR finishing with the stationary curved core tool tip, R_a value is reduced from 740 nm to 40 nm in 90 minutes of MR finishing with the rotating flat core tool tip.
- Scanning electron microscope (SEM) photographs and mirror images have verified the major enhancement in surface characteristics with the rotating flat core tool tip as compared to the stationary curved core tool tip.

4.3 Experimental validation of present rotating core based magnetorheological (MR) finishing process for the typical tapered cylindrical punch surface

The rotating core-based MR finishing process is found more effective than the stationary core-based turning type MR finishing process. Now, this developed rotating core-based MR finishing process is utilized for the finishing of the typical tapered external surface of the cylindrical punch as depicted in Fig. 4.5. The rotating swivel vise is fabricated which helps to perform the tapered cylindrical punch finishing as depicted in Fig. 4.5. The rotating core-based finishing process with circular tip surface shows their effectiveness than the turning type stationary curved tip surface MR finishing process. This swivel holds the tapered cylindrical workpieces as depicted in Fig. 4.5.

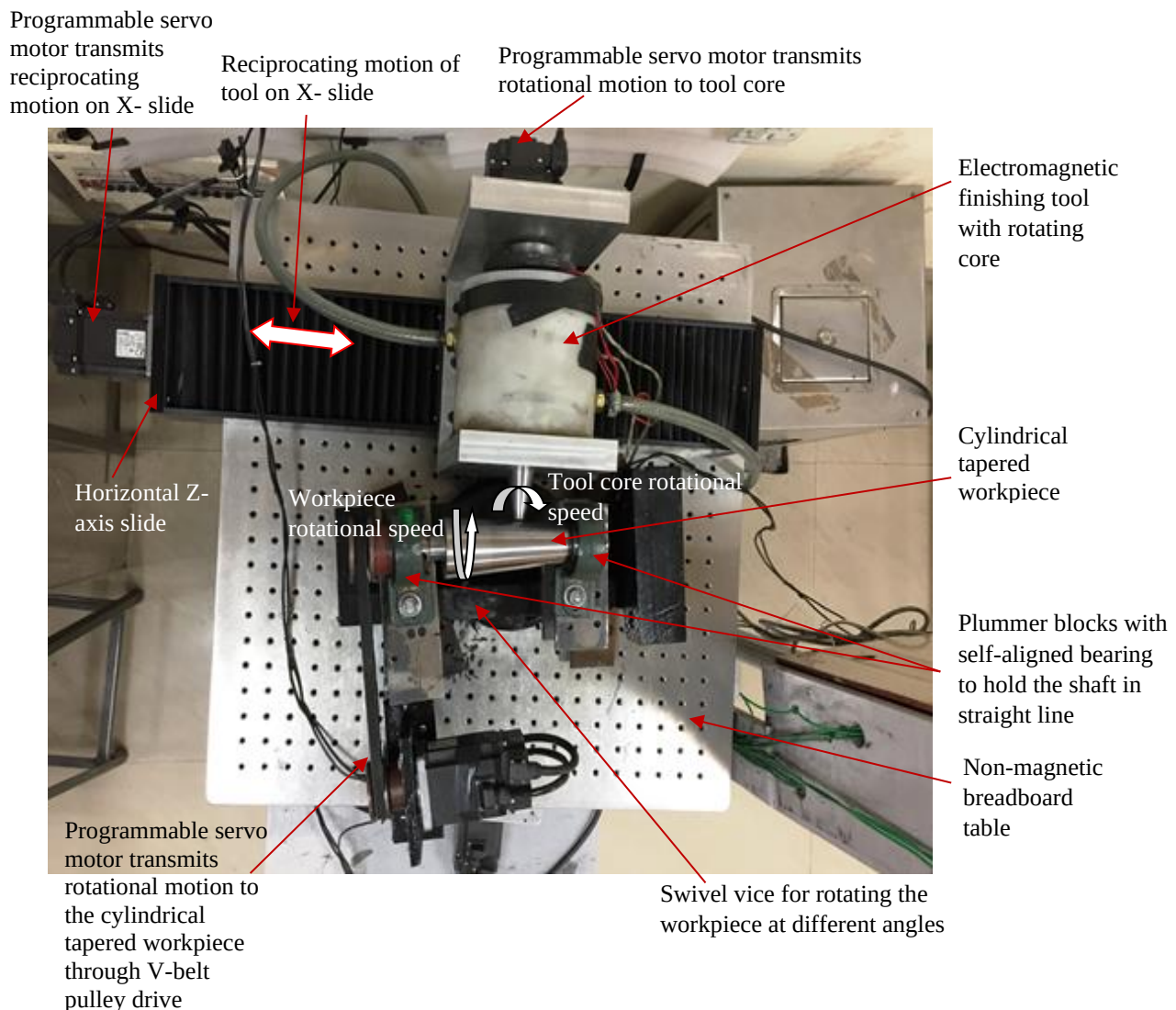


Fig. 4.5 Top view of a rotating core magnetorheological finishing process with the tapered cylindrical workpiece.

The final surface roughness (R_f) value (average surface roughness (R_a) value) for any finishing processes is an extremely vital factor to recognize the process productivity and performance. Therefore, the final average surface roughness (R_f) value for the present MR finishing process is analysed. Various industrial applications of the tapered external surface are found under the 3 to 5-degree tapered angle. Due to this, the 5-degree tapered angle on the steel alloy shaft is opted for the work.

4.3.1 Analysis of mechanism for magnetorheological finishing of tapered cylindrical workpiece

The following assumptions are considered to simplify the analysis of mechanism for magnetorheological finishing process.

- The dispersion of the abrasive particles and iron particles (IPs) are assumed to be uniform in the magnetorheological fluid.
- The abrasives and iron particles are considered to be spherical in nature with their diameters of 21 μ m and 25 μ m, respectively.
- The basic for indentation of the active abrasive particles on the variable diametric external surface of the tapered cylindrical workpiece is considered as similar to the flat external surface of the workpiece.

The magnetorheological polishing (MRP) fluid gets stiffed over the circular flat tip surface of the tool core due to their maximum flux density. The iron particles of the MRP fluid are formed a chain pattern in the influence of magnetic flux density. In real condition, IPs chains face the multifaceted nature of forces due to other various neighboring iron particles chains in the MRP fluid. The IPs levitation force gives significant involvement to the active abrasive particles on the tapered cylindrical workpiece surface which further shear off the roughness peaks after their rotation and reciprocation motion over the rotating tapered cylindrical workpiece surface. In the present work, the working space (gap) is varied from the central axis to the upper end of the circular tool core tip surface due to the effect of the tapered external cylindrical surface of the work-part as shown in Fig. 4.6(a). The working space is filled with the MRP fluid. The variable diametric external surface of the tapered cylindrical workpiece is varied from the radius in R_1 to R_2 over the length of L_w (Fig. 4.6(a)). Also, the projected area of the circular tool core tip surface on the variable diametric external surface of the tapered cylindrical workpiece (PWMJP) is shown in Fig. 4.6 (b) where active abrasive particles exist during the MR finishing operation. So, the projected area (PWMJP) on the tapered cylindrical workpiece surface is used in calculation of the number of active abrasive particles. Let's assume that the

projected area (PWMJP) on the tapered cylindrical workpiece surface (A_{tp}) is varied from the radius in r_{m1} to r_{m2} over the length of L_m as shown in Fig. 4.6 (b). Suppose, the projected area subtends an angle θ at the circular central axis (Fig. 4.6(b)). Then, using the simple trigonometry relation, the subtended angle θ can be found using the Eq. (4.1).

$$\cos \frac{\theta}{2} = \frac{r_{m2}}{r_{m1}} \quad (4.1)$$

The projected area (PWMJP) on the tapered cylindrical workpiece surface (A_{tp}) is calculated using Eq. (4.2).

$$A_{tp} = \frac{r_{m1}^2}{2} (\theta - \sin \theta) \quad (4.2)$$

After putting the value of θ in Eq. (4.2), Eq. (4.3) is obtained.

$$A_{tp} = \frac{r_{m1}^2}{2} \left(2 \cos^{-1} \frac{r_{m2}}{r_{m1}} - \sin \left(2 \cos^{-1} \frac{r_{m2}}{r_{m1}} \right) \right) \quad (4.3)$$

Further simplification of Eq. (4.3), the projected area on the tapered cylindrical workpiece surface (A_{tp}) for the active abrasive particles can be obtained using Eq. (4.4).

$$A_{tp} = r_{m1}^2 \cos^{-1} \frac{r_{m2}}{r_{m1}} - r_{m1} \sqrt{r_{m1}^2 - r_{m2}^2} \quad (4.4)$$

Further, the number of active abrasives (N_a) on the projected area on the tapered cylindrical workpiece surface (A_{tp}) is calculated using Eq. (4.5).

$$N_a = \frac{\text{Projected area of active abrasive particles on the tapered cylindrical workpiece surface } (A_{tp})}{A_{ab}} \quad (4.5)$$

Where, A_{ab} is projected area of the single active abrasive which is assumed as spherical in shape and it is calculated using Eq. (4.6).

$$A_{ab} = \pi \frac{d_{ab}^2}{4} \quad (4.6)$$

Where d_{ab} is a diameter of the active abrasive particle (21 μ m).

These number of active abrasives (N_a) are mainly liable to shear off the roughness peaks during the MR finishing on the variable diametric external surface of the tapered cylindrical workpieces.

Further, the finite element analysis (FEA) is performed to examine the variation of flux density within the working gap. FEA is performed by Maxwell Ansoft student version software. Before performing the analysis, all parts are modelled in the Maxwell software and after that the material properties of all parts are assigned in the software. The relative permeability (P_R) is assigned as 600 for tool core and the workpiece material.

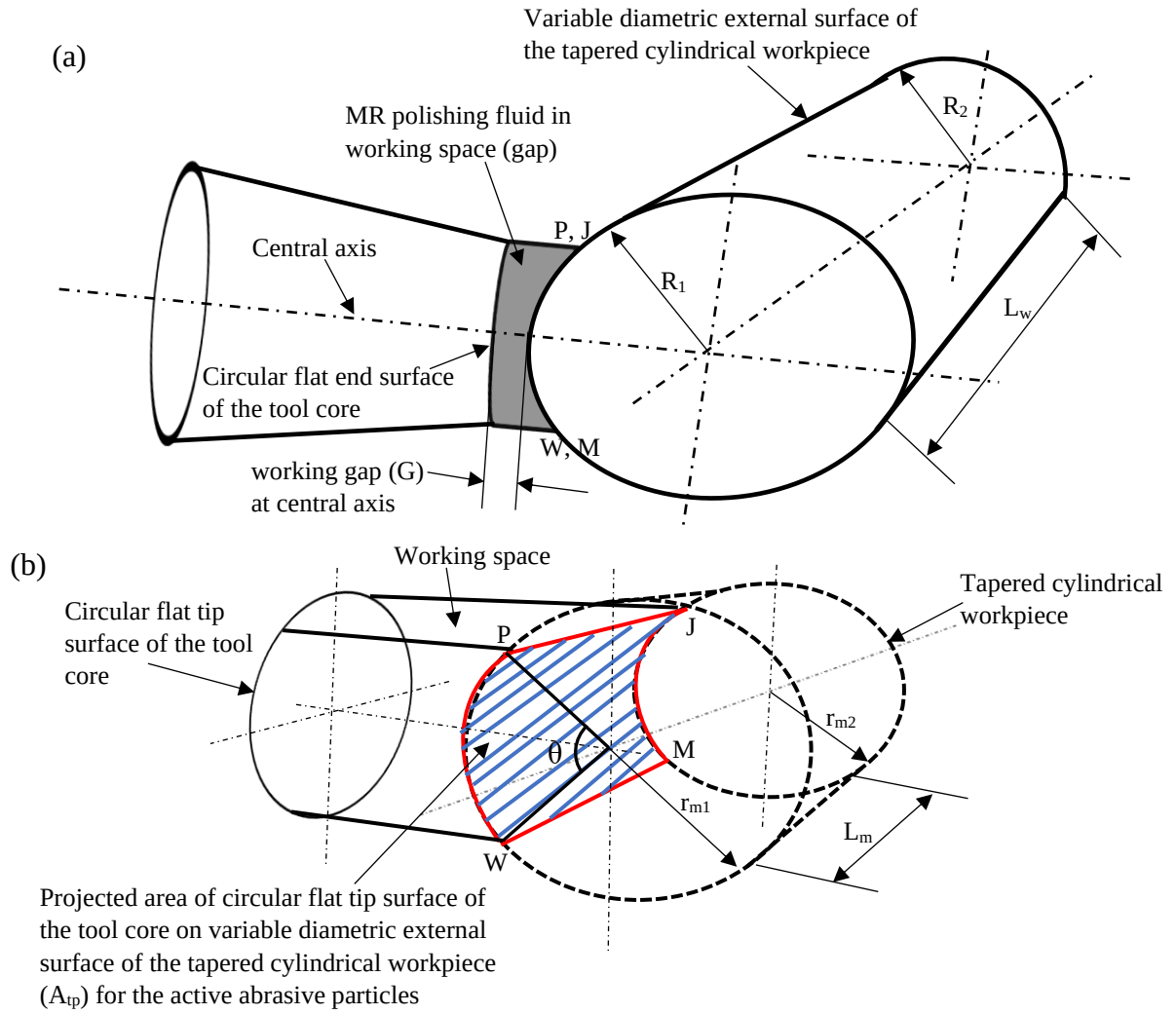


Fig. 4.6 (a) Schematic of MR polishing fluid in the working gap between circular flat tip surface of the tool core and tapered cylindrical workpiece surface and (b) projected area of the circular flat tip surface of the tool core on variable diametric external surface of the tapered cylindrical workpiece for the active abrasive particles.

The P_R of tool electromagnet coil is assigned as 1 for copper, and P_R of magnetorheological polishing (MRP) fluid is assigned as 5 from the library of the Maxwell Ansoft software. Current 2 A is supplied to the electromagnetic coil (2100 turns) during the analysis. The non-uniform distribution of flux density has been obtained within the working gap when it observed on the cross-sectional area of a plane passing through the central axis of the tool core and workpiece as it can be seen in magnetostatic FEA. However, when swivel vise is set at 5 degrees in the direction of the tapered cylindrical workpiece surface.

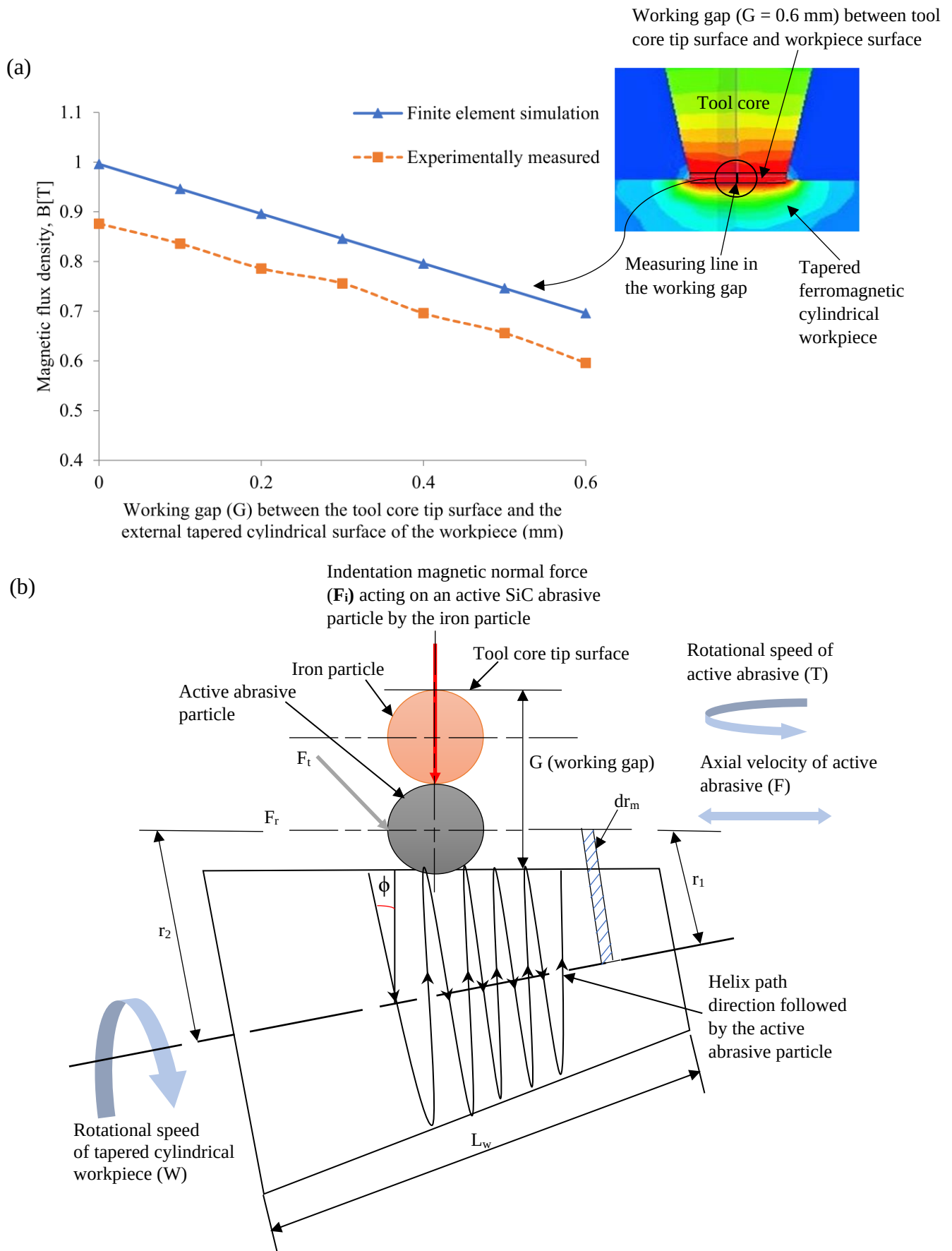


Fig. 4.7 (a) Variation of magnetic flux density in the working gap, and (b) schematic diagram of active abrasive rotation and reciprocation motion generate helical motion over the external surface of the tapered cylindrical workpiece.

The working gap (0.6 mm) between the flat circular tip surface of the tool core and the variable diametric external surface of the tapered cylindrical workpiece is maintained uniform when it is observed on the cross-sectional area of a plane passing through the central axis of the tool core and workpiece (Fig. 4.7(a)). The uniform flux density distribution is obtained when the swivel vise is set at 5-degree taper angle for the variable diametric external surface of the tapered cylindrical workpiece towards the tool core tip surface. The uniform spread of flux density leads to uniform MR finishing on the variable diametric external surface of the tapered cylindrical workpiece.

Also, the variation in flux density gradient has been obtained after the FEA in the working gap from the tool core tip surface to the variable diametric external surface of the tapered cylindrical workpiece as shown in Fig. 4.7(a). The result of FEA is observed on the cross-sectional area of a plane passing through the central axis of the tool core and workpiece. The variation in flux density gradient is obtained in the working along the measuring line as shown in Fig. 4.7(a). Further, the flux density gradient is experimentally measured in the accessible working gap with the help of digital gauss meter. Then, the experimentally obtained flux density gradient from the accessible working gap is plotted by the best curve fitting method as depicted in Fig. 4.7(a). The working gap (G) is the distance from the tip surface line of the tool core to the top most external surface line of the tapered cylindrical workpiece when it is observed on the front cross-sectional area of a plane passing through the central axis of the tool core and workpiece (Figs. 4.). The working gap is taken upto 0.6 mm for the magnetic field analysis. The obtained magnetic flux density gradient in the working gap shows that the higher magnetized tool core tip surface rigidly holds the MR polishing (MRP) fluid to finish the variable diametric external surface of the tapered cylindrical workpieces.

As magnetic flux density over the tapered cylindrical workpiece surface is lesser than the magnetic tip surface of the tool core in the working gap (Fig. 4.7(a)), therefore, the magnetized rigid MRP fluid at the tip surface of the tool core can move smoothly over the tapered cylindrical workpiece surface and can perform finishing.

The indentation of the active abrasive particle pushed by the normal magnetic force (F_i) into the roughness peaks of the variable diametric external surface of the tapered cylindrical workpiece (Fig. 4.7(b)), is obtained by using Eq. (4.7).

$$F_i = \frac{m\chi_m}{\mu_0} B_{MR}(G) \frac{dB_{MR}(G)}{dG} \quad (4.7)$$

Here μ_0 is the magnetic permeability of free space in H/m, m is mass of the iron particle in kg, and χ_m is the magnetic susceptibility of an iron particle in m^3/kg . H is the intensity of the

magnetic field in ampere/meter. B_{MR} (G) is the variation of total magnetic flux density in the working gap (G) for MRP fluid. The general expression of the variation in total magnetic flux density ($B_{MR}(G)$) in terms of the working gap (G) is obtained from the plot of experimental analysis (Fig. 4.7(a)) with 98% accuracy of the R^2 value as given in Eq. (4.8).

$$B_{MR}(G) = -0.460G + 0.896 \quad (4.8)$$

The normal magnetic force (F_i) helps the active abrasive to indent over the roughness peaks of the tapered cylindrical surface with a cross-sectional area of indentation (A_i) as depicted in Fig. 4.8(a). The indented active abrasive diameter (d_i) can be obtained by using Eq. (4.9).

$$d_i = \sqrt{d_a^2 - \left(d_a - \frac{2 \times 10^{-6} F_i}{9.81 H_{BHN} \pi d_a} \right)^2} \quad (4.9)$$

Here, d_a is the active abrasive diameter in μm and H_{BHN} is the number of brinell hardness for the tapered cylindrical workpiece in kgf/mm^2 .

The depth of indentation (d_p) of the active abrasive particle on the tapered cylindrical workpiece surface is calculated from the Eq. (4.10) which is derived from ΔOPQ as shown in Figs. 4.8(a) and (b).

$$d_p = \frac{d_a}{2} - \frac{1}{2} \sqrt{d_a^2 - d_i^2} \quad (4.10)$$

The axial force (F_r) is applied to the active abrasive because of the reciprocation speed of the tool core (F) as depicted in Fig.4.7(b). Tangential force (F_t) is also applied to the active abrasive owing to the net effect of the rotational speed of the tool core (T) and the tapered cylindrical workpiece (W) as depicted in Fig.4.7(b). The active abrasive follows the helical route on the rotating variable diametric external surface of the tapered cylindrical workpiece because of the simultaneous rotational and reciprocating motions of the tool core.

Time taken by the active abrasive to complete single stroke of reciprocation motion along the variable diametric external surface of the tapered cylindrical workpiece, i.e. cycle time (t_a) is evaluated by Eq. (4.11).

$$\text{Cycle time } (t_a) = \frac{\text{Tool core movement over the length of tapered cylindrical workpiece surface } (L_w)}{\text{Feed rate of tool core } (F)} \quad (4.11)$$

Here, F is the reciprocation speed of the tool core in mm/min which is same as the feed rate, L_w is the length of variable diametric external surface of the tapered cylindrical workpiece to be finished.

The helix angle (ϕ) as shown in Fig. 4.7(b), is made because of the rotary and reciprocating movements of the active abrasive on the rotating tapered cylindrical workpiece surface which is evaluated by using Eq. (4.12).

$$\phi = \int_{r_1}^{r_2} \tan^{-1} \left(\frac{30 F}{\pi dr_m N_w} \right) \quad (4.12)$$

Here, dr_m is the variable radius strip through which active abrasive rotates from the longitudinal central axis of the tapered cylindrical workpiece (Fig. 4.7(b)) and it varies from minor radius (r_1) to major radius (r_2) from the longitudinal central axis of the tapered cylindrical workpiece. N_w is the net rotating speed of the active abrasive because of the rotational speed of tool core and cylindrical tapered workpiece.

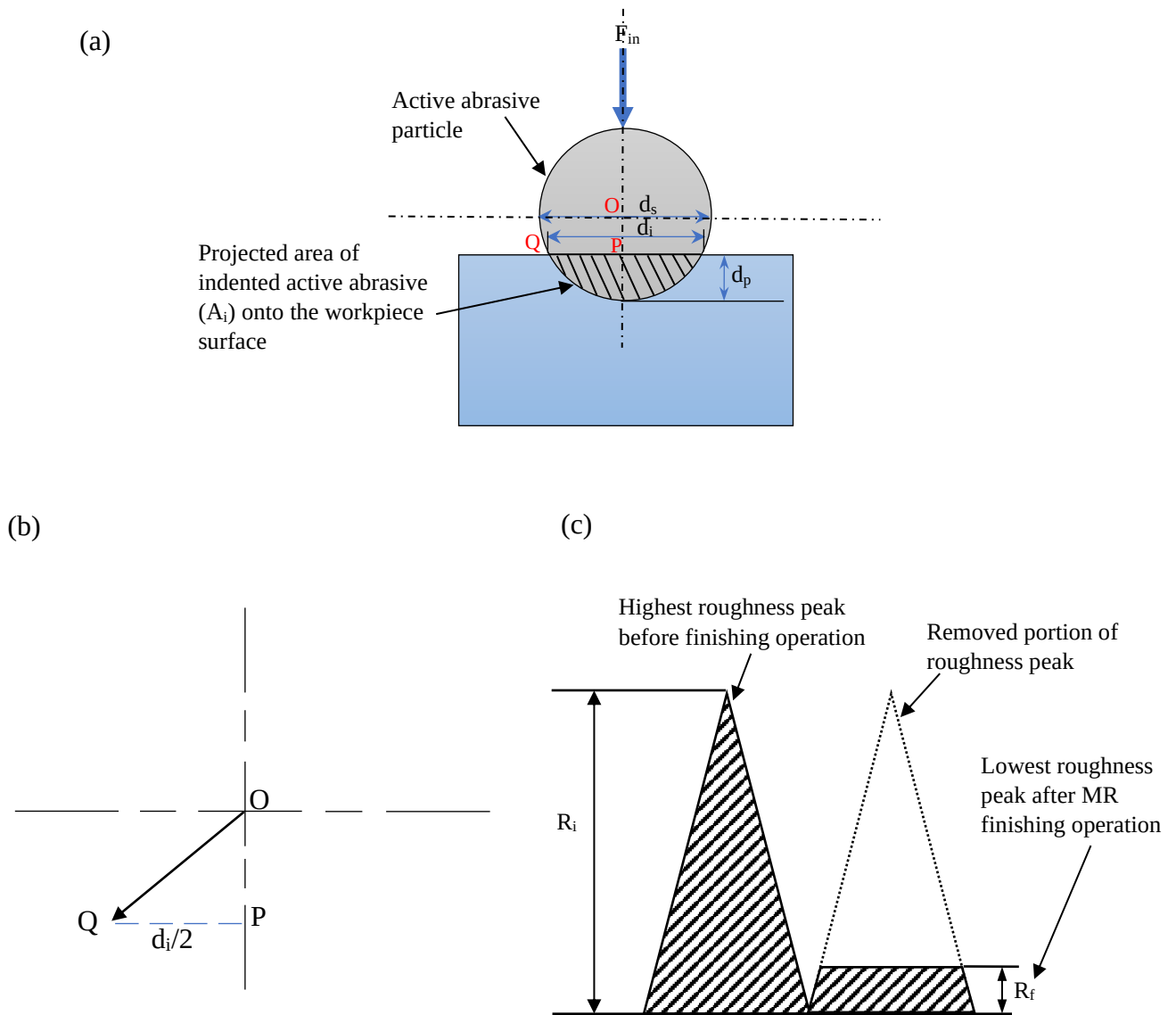


Fig. 4.8 (a) Schematic diagram of an active abrasive particle indenting onto the external surface of the tapered cylindrical workpiece, (b) calculation of depth of indentation (d_p), and (c) simplify geometry of roughness peaks before and after the present MR finishing operation.

Thus, due to the taper angle on the external surface of the tapered cylindrical workpiece, the arbitrary strip of radius dr_m is varied which leads to the variation in the helix angle (ϕ) from the radius r_1 to r_2 . This can be observed from Eq. (4.12) and Fig. 4.7(b). The single active abrasive particle travelled the actual length (l_a) along the helical route on the rotating variable diametric external surface of the tapered cylindrical workpiece is calculated by using Eq. (4.13).

$$l_a = \frac{F t_a}{\sin \phi} \quad (4.13)$$

The active abrasive's linear velocity is varied on the variable diametric external surface of the tapered cylindrical workpiece as the radius from the longitudinal axis is varied from r_1 to r_2 . The variation in linear velocity (dV) in terms of the variable strip radius (dr_m) (Fig. 4.7(b)) can be calculated by using Eq. (4.14).

$$dV = \frac{2\pi N_w}{60} \times dr_m \quad (4.14)$$

On integrating both side of Eq. (4.14), the total variation in linear velocity of the active abrasive particle (V) along the variable diametric external surface of the tapered cylindrical workpiece is calculated by using Eq. (4.15).

$$V = \int_{r_1}^{r_2} dV = \frac{2\pi N_w}{60} \int_{r_1}^{r_2} dr_m \quad (4.15)$$

The time is taken (t) to complete the total helical length (l_a) on the variable diametric external surface of the tapered cylindrical workpiece with the variation in linear velocity (V), is calculated by using Eq. (4.16).

$$t = \frac{l_a}{\int_{r_1}^{r_2} dV} \quad (4.16)$$

Thus, the total calculated time (t) from Eq. (4.16) is utilized for uniform fine finishing the variable diametric external surface of the tapered cylindrical workpiece which radius varies from r_1 to r_2 . This total calculated time (t) from the Eq. (4.16) takes care of the variation in linear velocity (V) (Eq. 4.15), helix angle (ϕ) (Eq. 4.12) and the length of the helical path (l_a) (Eq. 4.13) made by the active abrasive due to variation in the radius from r_1 to r_2 from the longitudinal axis of the tapered cylindrical workpiece.

The theoretical final average surface roughness (R_f) value is predicted by the number of finishing cycles which help to decide the process productivity. The number of finishing cycles (n_f) is evaluated by using Eq. (4.17).

$$\text{Number of finishing cycles } (n_f) = \frac{\text{Total duration } (t)}{\text{Cycle time } (t_a)} \quad (4.17)$$

The final average surface roughness (R_f) value is calculated by using Eq. (4.18).

$$R_f = R_i - 2 d_p n_f N_a \quad (4.18)$$

Here, R_i is the highest average roughness peaks at the initial surface level in μm , n_f is a total required finishing cycles, d_p is a depth of indentation of the single active abrasive in μm , N_a is the number of active abrasives on the projected taper cylindrical surface area (A_{tp}), and R_f is the lowest or final average surface roughness peaks after the MR finishing in μm as depicted in Fig. 4.8(c).

The final R_f value depends on the depth of indentation. The depth of indentation further depends on the hardness of the workpiece material. The normal magnetic force which is accountable to the indentation of the active abrasive in the material of workpiece is calculated from Eq. (4.7). After calculating the normal magnetic force or indentation force (F_i), the indented abrasive diameter (d_i) can be calculated. The indented abrasive diameter (d_i) depends upon the hardness value of the workpiece material. The abrasive indent diameter gets changed as the material hardness value changes. Therefore, the workpiece material is brought as a parameter to predict the final average surface roughness (R_f) value. Suppose the AISI 52100 steel with the hardness (H_{BHN}) value of 420 Kg/mm^2 and die steel material with the hardness (H_{BHN}) value of 680 Kg/mm^2 is used as a workpiece to predict the final R_f value theoretically. The final theoretical R_f value can be reduced more for the AISI 52100 steel because the depth of indentation of active abrasives to be more on it for the same number of finishing cycles as compared to the more harden workpiece material (die steel). Thus, the final average roughness (R_f) value of the variable diametric external surface of the different tapered cylindrical materials can be predicted with the required number of finishing cycles and the same can be achieved experimentally after the present advancement of the MR finishing process for their functionality improvement.

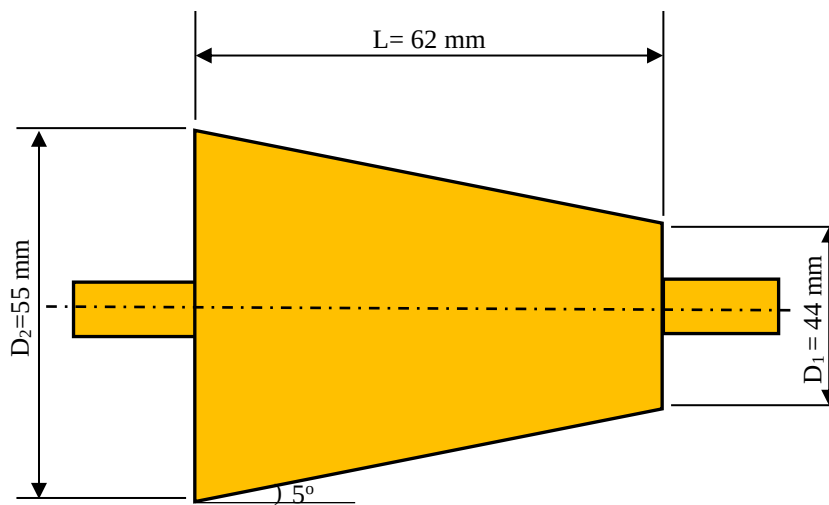


Fig. 4.9 Schematic diagram of the tapered cylindrical workpiece with actual the dimensions.

Cylindrical steel alloy workpiece is tapered turned on the lathe machine at 5-degree taper angle. After the taper turning, the cylindrical rod workpiece surface is ground by the universal cylindrical surface grinder and set the initial ground R_a value over the surface of the workpiece. After preparation of the workpiece, it is set on the self-aligned bearings by locking with the help of allen screws as depicted in Fig. 4.5. The workpiece used as a prototype of the industrial tapered cylindrical punch as depicted in Fig. 4.9.

4.3.2 Experimentation

The Mitutoyo surfest SJ-400 was used for measurement of surface roughness values, and surface roughness profiles with 0.25 mm cut off length. In the Mitutoyo surfest SJ-400, the maximum resolution is achieved $0.0001\mu\text{m}$ at a range of $8\mu\text{m}$ and minimum resolution is achieved $0.01\mu\text{m}$ at a range of $800\mu\text{m}$. In the present analysis, the instrument resolution was set at a range of $80\mu\text{m}$ for measuring the surface roughness profiles. According to the roughness value range of the components, the resolution and range are selected in the instrument which enhances the accuracy of the measurement. The composition of the tapered workpiece AISI grade D2 tool steel is represented in Table 4.4. The R_a value of the tapered cylindrical workpiece at the initial stage after the grinding operation is measured as 700 nm.

Table 4.4 Chemical composition of AISI grade D2 tool steel tapered cylindrical workpiece

Constituting elements	%age content
C	1.4
Mn	0.6
P	0.03
S	0.03
Si	0.3
Cr	12
V	0.3
Mo	0.8

The tapered cylindrical workpiece (5° taper angle) with the hardness of 431 VHN has been finished with the present modified MR finishing process (Fig. 4.5). The complete specifications of the tapered cylindrical workpiece which has been used in the present MR finishing analysis as represented in Fig. 4.9. For a detailed experimental analysis, the literature review depicts the parameters and their range (Mann and Singh, 2018). The process parameters like rotary speed of rectangular tool core (T), the rotary speed of tapered workpiece (W), the feed rate of tool core (F), the working gap (G), current (I), and the %age concentration of SiC abrasive particles

in MR polishing fluid were selected for the experimentation. The selected process parameters and their ranges are reported in Table 4.5.

Table 4.5 Experimental process parameters and conditions

S. No.	Parameters	Units	Range		
1	Feed rate (F)	cm/min	30	50	70
2	Rotational speed of tapered cylindrical workpiece (W)	rpm	50	100	150
3		rpm	2000	2500	3000
4	Current (I)	A	1	2	3
5	Working gap (G)	mm	0.6	1.15	1.7
6	Concentration of SiC abrasive particles in MR polishing fluids (S)	Vol. %	10	15	20

In the response surface methodology (RSM), a Box-Behnken method is used to generate experimental combinations. The Box-Behnken design has no axial points which make sure that all the parameter points lie within the estimated working region. The Box-Behnken designs also ensure that not all factors are simultaneously set at their high levels. Total of 54 experiments was conducted for the %age change in Ra value and the corresponding change in surface waviness. During the experimentation each experiment was conducted over the length of 15 mm on the tapered cylindrical surface for 40 min finishing time. As the workpiece is cylindrically tapered, the radius of the external surface varies continuously with respect to the longitudinal central axis. Therefore, the time taken is also varied for finishing the tapered cylindrical surface at each radial distance. Hence, to obtain the uniform finishing on the variable diametric external surface of the tapered cylindrical workpiece, the time taken is estimated on the tapered cylindrical length of the workpiece for the experimentation with the help of Eq. (4.9). Three types of MR polishing fluid compositions were prepared with the selected range of the %age concentration of SiC abrasive particles and other corresponding concentration of the components such as iron particles and base fluid as reported in Table 4.6. Since the workpiece surface mainly finishes by the abrasive particles which are highly gripped by the iron particles rigidly in MR polishing fluid under the influence of flux density. Therefore, only abrasive particles with different %age concentrations were selected in MR polishing fluid to study their effects on surface finishing of the tapered cylindrical workpiece. Each MR polishing fluid was prepared separately in DC controlled conical mixing chamber by mixing uniformly the compositions as reported in Table 4.6.

Table 4.6 Synthesized MR polishing fluids for experimentation

Fluid No.	Vol.% SiC abrasive particles (21 μ m)	Vol.% iron particles (25 μ m)	Vol.% base fluid (80% paraffin oil and 20% AP3 grease by weight)
1	10	30	60
2	15	30	55
3	20	30	50

The prepared MR polishing fluids were used as per the experimental combinations as given in Table 4.6. During the experimentation, the conditioning of the MR polishing fluid is done as per each trial of 20 min. Thus, the fresh active abrasives in the working space are maintained during the total finishing cycle time of 40 min. The initial and final average R_a values of each experimental combinations are measured. The responses such as the %age change in R_a ($\% \Delta R_a$) and surface waviness (W_a) for each parametric combination are recorded as given in Table 4.7. On the basis of the literature review, it was found that the MR polishing (MRP) fluid with the composition of 30% iron particles, 15% abrasives, and 55% base or carrier fluid by volume yields a good result for steel materials (Chana and Singh, 2018, Mann *et al.*, 2017). Therefore, the developed MRP fluid with these compositions was used for the rheological measurements. Using a parallel plate type magnetorheometer (MRC 301 rheometer), the rheological measurements of the indigenously developed MRP fluid was done in shear mode at the magnetizing current (1 A - 3 A), shear rate (100 s⁻¹), a gap of 1 mm, and surrounding cooling temperature (25°C). The results of the rheological test of the selected MRP fluid for finishing the present workpiece material AISI grade D2 tool steel is shown in Figs. 4.10 (a) and (b). Fig. 4.10(a) shows a variation in viscosity of the MRP with the variation in the induced magnetic flux density values for the magnetizing current (1 A - 3 A). Further, Fig. 4.10(b) shows a variation in the shear stress with the variation in viscosity values during which the current values vary from 1 A to 3 A. Fig. 4.10(a) shows that when the magnetic flux density increases due to the increase in magnetizing current (1 A to 3 A), the viscosity of the MRP fluid also increases almost linearly. This leads to an increase in the stiffness of the MRP fluid which is an important requirement for tightly holding the abrasive particles during the MR finishing operation.

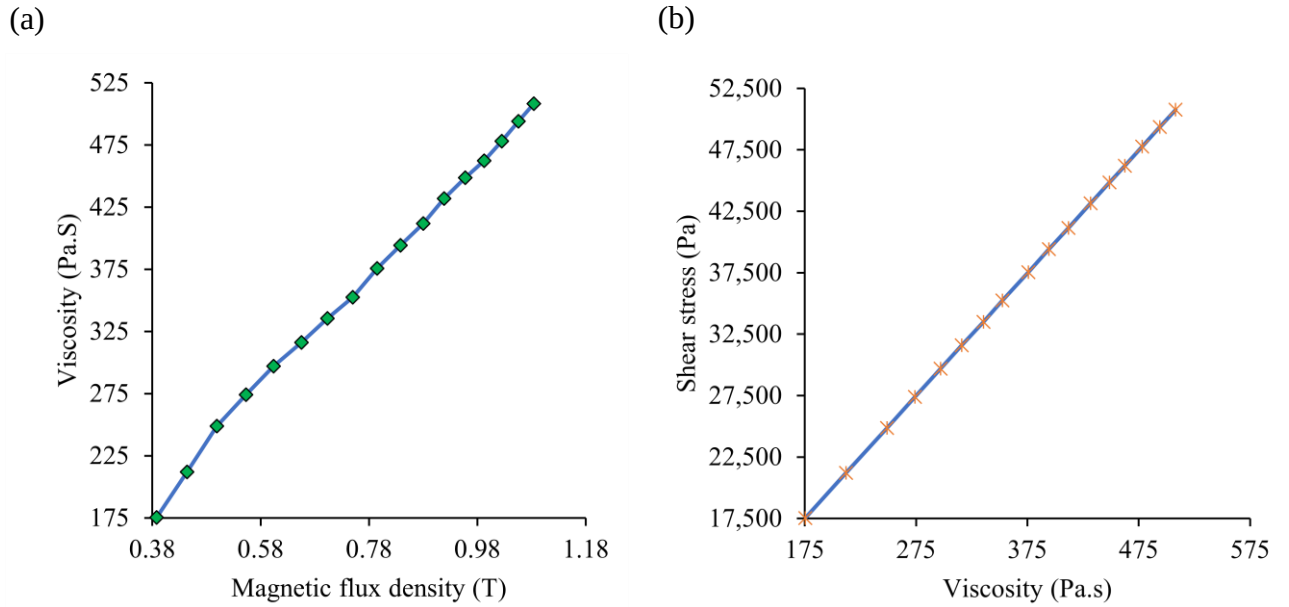


Fig. 4.10 Results of rheological test of the MR polishing fluid (a) variation in viscosity with the variation in magnetic flux density values and (b) variation in the shear stress with the variation in viscosity values due to increase in magnetizing current (1 A to 3 A) and at shear rate of 100 s^{-1} .

Similarly, Fig. 4.10(b) shows that the shear stress of the MRP fluid increases linearly when the viscosity increases due to the increase in magnetic flux density at magnetizing current (1 A to 3 A). This increase in the shear stress of the MRP fluid due to the increase in the viscosity leads to an increase in shear strength of the MRP fluid which is an important requirement for shearing the roughness peaks from the workpiece surface during the MR finishing operation. The linear relationship of the magnetic field vs viscosity and viscosity vs shear rate (Fig.4.10) shows the good response in rheological properties of the present MRP fluid due to the increase in the magnetic field at magnetizing current (1 A to 3 A). Also, these linear relationships are obtained at a shear rate of 100 s^{-1} which shows the good stability of the MRP fluid. However, in the present work, the MRP fluid rigidly attached on the tool core tip surface and rotates with the rotation of the tool core at 2000 rpm to 3000 rpm i.e. at a shear rate of 33.33 s^{-1} to 50 s^{-1} on the rotating tapered cylindrical workpiece surface during the finishing operation. It can be seen that the shear rate of 33.33 s^{-1} to 50 s^{-1} in the present MR finishing is much less than the shear rate of 100 s^{-1} as maintained during the rheological test. So, the MRP fluid which shows good rheological properties linearly at the shear rate of 100 s^{-1} during the rheological test then the same indigenously developed MRP fluid when it is to be used for a shear rate of 33.33 s^{-1} to 50 s^{-1} at magnetizing current (1 A to 3 A) can exhibit better stability and find suitable for the present experimental work.

During the experimentation, the MR polishing fluid is conditioned after 20 min in each trial of 40 min. Thus, the fresh active abrasives in the working space are maintained during the total finishing cycle time of 40 min. The initial and final average Ra values of each experimental combination are measured. The responses such as a %age change in Ra value and surface waviness (Wa) for each parametric combination are recorded as given in Table 4.7.

Table 4.7 Experimental plan and responses

S.No.	Process parameters						Initial	Avg. final	%age	Surface
	F (cm/min)	W (rpm)	T (rpm)	I (A)	G (mm)	S (%vol)	Ra value (nm)	Ra value (nm)	change in Ra	waviness, Wa (μm)
1	10	100	2000	2	1.15	10	710	230	67.6	0.39
2	30	100	3000	1	1.15	20	700	290	58.5	0.43
3	50	150	2500	3	1.15	15	690	180	73.9	0.36
4	10	100	2500	3	1.7	15	705	320	54.6	0.44
5	30	50	3000	2	0.6	15	700	120	82.8	0.25
6	10	150	2500	1	1.15	15	710	330	53.5	0.43
7	30	50	2000	2	1.7	15	700	350	50	0.45
8	10	50	2500	1	1.15	15	705	250	64.5	0.39
9	10	100	2500	1	1.7	15	700	390	44.2	0.46
10	30	150	2000	2	0.6	15	680	100	85.2	0.24
11	10	50	2500	3	1.15	15	690	260	62.3	0.38
12	50	100	2500	1	0.6	15	705	240	66	0.37
13	30	150	2500	2	0.6	10	710	110	84.5	0.26
14	30	50	2500	2	1.7	10	700	340	51.4	0.43
15	50	100	2500	3	0.6	15	700	90	87	0.24
16	50	100	3000	2	1.15	20	710	250	64.7	0.39
17	50	150	2500	1	1.15	15	700	320	54.2	0.43
18	30	50	2500	2	1.7	20	680	300	55.8	0.44
19	30	150	2000	2	1.7	15	690	350	49.2	0.45
20	30	50	2500	2	0.6	20	690	120	82.6	0.25
21	30	100	3000	1	1.15	10	705	290	58.8	0.43
22	50	100	3000	2	1.15	10	700	240	65.7	0.38
23	50	100	2000	2	1.15	10	700	250	64	0.38
24	30	50	2500	2	0.6	10	700	120	82.8	0.26
25	30	100	2500	2	1.15	15	700	170	75.7	0.35
26	30	100	2500	2	1.15	15	710	220	69	0.36
27	10	100	3000	2	1.15	10	705	270	61.7	0.37
28	30	150	3000	2	0.6	15	700	140	80	0.29
29	30	150	3000	2	1.7	15	700	340	51.4	0.43
30	30	100	2500	2	1.15	15	690	240	65.2	0.35
31	30	100	2000	3	1.15	10	680	250	63.2	0.36
32	10	100	3000	2	1.15	20	680	230	66	0.35

33	10	100	2000	2	1.15	20	690	290	57.9	0.41
34	10	100	2500	1	0.6	15	700	150	78.5	0.33
35	50	100	2500	1	1.7	15	705	360	48.9	0.45
36	10	150	2500	3	1.15	15	700	220	68.5	0.35
37	30	50	2000	2	0.6	15	705	110	84.3	0.23
38	30	100	2000	1	1.15	20	700	290	58.5	0.41
39	30	50	3000	2	1.7	15	710	280	60.5	0.4
40	30	100	2500	2	1.15	15	710	250	64.7	0.35
41	50	50	2500	3	1.15	15	700	170	75.7	0.31
42	30	100	2000	1	1.15	10	705	300	57.4	0.42
43	30	150	2500	2	1.7	10	700	370	47.1	0.46
44	50	100	2500	3	1.7	15	690	330	52.1	0.43
45	30	100	3000	3	1.15	10	680	320	52.9	0.43
46	10	100	2500	3	0.6	15	690	150	78.2	0.26
47	30	150	2500	2	0.6	20	700	120	82.8	0.24
48	30	100	3000	3	1.15	20	710	220	69	0.35
49	30	100	2500	2	1.15	15	700	250	64.2	0.36
50	30	150	2500	2	1.7	20	705	320	54.6	0.44
51	30	100	2000	3	1.15	20	700	240	65.7	0.36
52	50	50	2500	1	1.15	15	690	330	52.1	0.46
53	30	100	2500	2	1.15	15	690	200	71	0.34
54	50	100	2000	2	1.15	20	700	190	72.8	0.35

4.3.3 Results and discussion

The distribution of the flux density is found non-uniform when the longitudinal axis of the tapered cylindrical workpiece is set at parallel with respect to the flat tool core tip surface as depicted in Fig. 3.17(a) (Chapter 3). But, when the longitudinal axis of a tapered cylindrical workpiece is set at a 5-degree angle with respect to the flat tool core tip surface, the uniformity in distribution of the flux was obtained as it can be seen in Fig. 3.17(a) (Chapter 3). Thus, at this position, the end surface of the magnetic tool tip was observed more effective in a contribution for fine finishing the variable diametric external surface of the tapered cylindrical workpieces as revealed from the finite element analysis.

The AISI 52100 steel and die steel is used as tapered cylindrical workpieces to predict the final roughness value after the MR finishing on their surfaces. The magnetic indentation force (F_i) is calculated on the finishing surface of both the workpieces for the same magnetic flux density using Eq. (4.7) which is found as 2.578×10^{-7} N. Eq. (4.9) signifies that the indentation diameter of the abrasive particle (d_i) relies on the hardness value of the workpiece material. From the literature, the hardness of AISI 52100 (heat-treated) material is found as H_{BHN} value 420

Kgf/mm² which is also finished with almost similar kind of MR finishing process (Mann et al., 2017). For the current die steel workpiece material, the hardness (H_{BHN}) value is found as 680 Kgf/mm² as reported in Table 4.8.

Table 4.8 Comparison of experimental and theoretically calculated final average surface roughness value (R_f) after magnetorheological finishing on the variable diametric external surface of the tapered cylindrical workpieces with the present finishing process

Workpiece hardness value in kgf/mm ² (H_{BHN})	Finishing cycles (n_f), Eq. (4.17)	Number of active abrasives (N_a), Eq. (4.5)	Depth of indentation d_p , (m), Eq. (4.10)	Initial Ra value (nm)	Experimentally obtained final average roughness value, R_f (nm)	Theoretically obtained final average roughness value, R_f (nm) Eq. (4.18)	% error
420	34838	71830	8.85×10^{-8}	460	18	17.07	5.16
420	25129	71830	8.85×10^{-8}	350	30	30.51	-1.70
680	34838	71830	8.42×10^{-8}	460	40	39.09	2.27
680	25129	71830	8.42×10^{-8}	350	50	46.39	7.22
680	56433	71830	8.42×10^{-8}	700	19	18.39	3.21

When the hardness values of these workpiece materials are substituted in Eq. (4.9), the values of the indentation diameter (d_i) of the abrasive particle is predicted on both AISI 52100 and die steel workpiece materials as 2.72697×10^{-7} m and 2.21027×10^{-7} m, respectively. After putting these values in Eq. (4.10), the depth of indentation (d_p) is predicted on both AISI 52100 and die steel workpiece materials as 8.85322×10^{-8} m and 8.41599×10^{-8} m. Further, the experiment was also performed on the same tapered surface area of both the workpiece materials as dimensions shown in Fig. 4.9. The finishing cycles (n_f) are calculated using Eq. (4.17) and found as 34838 for 90 min of cycle time, 26129 for 60 min of cycle time, and 56433 for 120 min of cycle time (Table 4.8). Table 4.8 represents the experimental and predicted final average roughness values (R_f) for both the workpiece materials. The % error between the experimental and theoretical values of R_f was found with in the range of -1.70% and 7.22% respectively for both the workpieces. This % error validates the theoretically predicted value of R_f , and further it is helpful in predicting the final roughness value on the tapered cylindrical workpieces made with different materials while it needs to be performed finishing with the present MR finishing process.

From the regression analysis, the regression model Eqs. (4.19) and (4.20) are obtained for %age change in Ra and surface waviness (W_a) in regard to variable parameters as feed rate (F), the working gap (G), current (I), the rotational speed of tool core (T), the rotational speed of tapered cylindrical workpiece (W), and %age concentration of SiC abrasive particles (S).

$$\begin{aligned} \text{\%age change in } Ra = & 153.41 - 2.91F + 40.4 \times 10^{-2}W - 6.13 \times 10^{-3}T + 24.91I - 41.70G + 1.57S \\ & + 2.40 \times 10^{-2}F^2 + 1.14 \times 10^{-5}T^2 + 74.40 \times 10^{-2}I^2 + 1.82G^2 - 11.5 \times 10^{-2}S^2 - 2.25 \times 10^{-4}FT + 5.50 \\ & \times 10^{-2}FS - 1.75 \times 10^{-4}WT - 2.50 \times 10^{-3}WI + 1.50 \times 10^{-3}WS - 6.75 \times 10^{-3}TI + 1.5IS + 0.95GS \end{aligned} \quad (4.19)$$

$$\begin{aligned} \text{Surface waviness } (W_a) = & 4.28 - 0.030F - 0.012W - 2.90 \times 10^{-5}T + 0.33I - 1.45G + 0.5S - \\ & 2.97 \times 10^{-4}F^2 + 1.135 \times 10^{-7}T^2 - 4.40 \times 10^{-2}I^2 + 2.92G^2 - 1.25 \times 10^{-4}FT + 0.70 \times 10^{-4}FS - 1.75 \times 10^{-4}WT \\ & - 2.50 \times 10^{-5}WI + 0.75 \times 10^{-3}WS - 0.26 \times 10^{-4}TI \end{aligned} \quad (4.20)$$

The R^2 value of the regression model is a measure of regression model accuracy for calculating the outcome. The R^2 value of the regression model for %age change in Ra value and change in surface waviness (W_a) was found as 95% and 96% respectively.

4.3.3.1 Interaction effect of feed rate and tool core speed on %age change in surface roughness (Ra) and surface waviness (W_a)

Fig. 4.11(a) represents the %age change in Ra for the interaction of tool feed rate with varying the tool core speed while considering the workpiece speed at 50 rpm, the working gap is 0.6 mm, current at 2 A and the %age concentration of SiC is 15 %. The %age change in Ra increases with increases in feed rate up to 30 cm/min, and after that %age change in Ra decreases as the feed rate increases. As feed rate increase to 30 cm/min with a tool core speed of 2500 rpm, this increases the interaction between the active abrasives and surface roughness of the tapered cylindrical workpiece. At feed rate beyond 30 cm/min with a tool core speed of 2000 rpm, the %age change in Ra is slightly increased due to the interaction between the active abrasives and roughness peaks boost up. However, as the feed rate goes beyond 30 cm/min along with tool core speed of 2500 rpm, the interaction of the active abrasives gets very less time to shear off the roughness peaks. The same trend is followed at 3000 rpm tool core speed. This may result because of the excessive increase in the centrifugal force (F_c) due to the higher tool core speed. As the tool core rotation speed increases, the value of angular velocity (ω) of the active abrasives also increases as expressed in Eq. (4.21).

$$F_c = m_a r_a \omega^2 \quad (4.21)$$

where the mass of the active abrasive particle is m_a in kg, the radius of the active abrasive particle from the tool core rotational axis is r_a in m and the angular velocity of the active abrasive particle is ω in rad/s. Therefore, due to excessively increase in the centrifugal force, the sufficient amount of interaction is not provided by the active abrasives for clipping off the roughness peaks which lead to a decrease in the %age change in Ra .

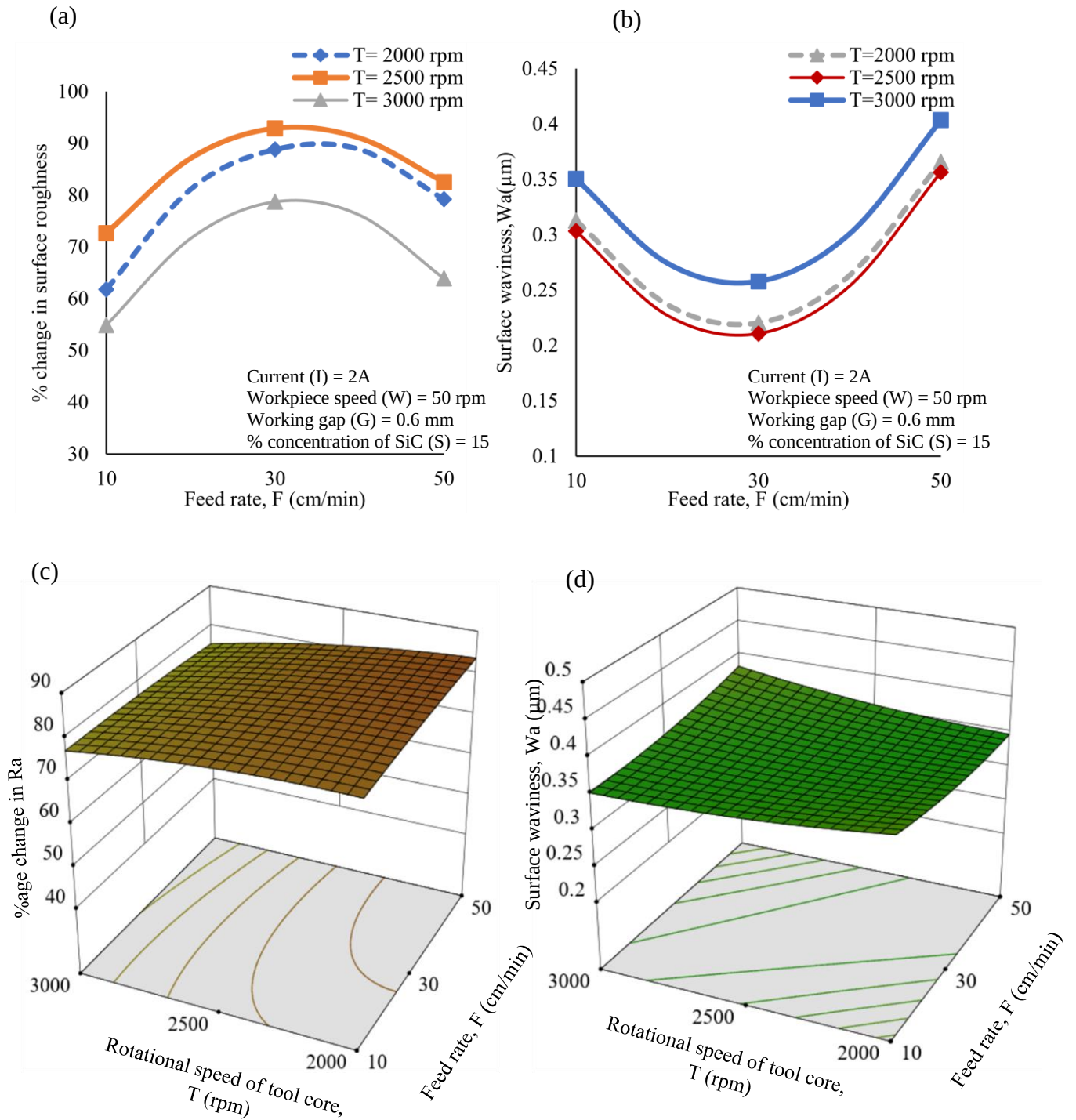


Fig. 4.11 Effect of feed rate (F) at different rotational speeds of tool core (T) on (a) %age change in surface roughness (R_a) value and (b) surface waviness (W_a), 3D plot of the effect of feed rate (F) and rotational speeds of tool core (T) on (c) %age change in R_a value and (d) surface waviness (W_a).

Fig. 4.11(b) represents the surface waviness (W_a) for the interaction of tool feed rate with varying the tool core speed while considering the workpiece speed at 50 rpm; the working gap

is 0.6 mm, current at 2 A and %age concentration of SiC is 15 %. The reverse pattern is obtained at the same optimum conditions of the tool's speed and feed rate. This is owing to the fact that there is an increased value of the %age change in Ra which results in a decrease in the value of surface waviness.

Figs. 4.11(c) and (d) show the 3D plots of the %age change in Ra and surface waviness for the interaction of tool feed rate and the rotational speed of tool core. The contour lines show that the maximum %age change in Ra is achieved at the tool's rotation speed of 2500 rpm and the feed rate of 30 cm/min. Similarly, 3D plot of surface waviness shows that the minimum value of surface waviness is achieved at a combination of similar parameters.

4.3.3.2 Interaction effect of the current and working gap on %age change in surface roughness (Ra) and surface waviness (Wa)

Fig. 4.12(a) represents the %age change in Ra for the interaction of the current with varying the working gap while considering the workpiece and tool speed at 2500 rpm and 50 rpm, feed rate at 30 cm/min and %age concentration of SiC is 15 %. The maximum %age change in Ra is obtained in a 0.6 mm working gap with 2 A current. Current is the main source to generate the magnetic field intensity in the working gap and the working gap triggers the magnetization of the MR polishing fluid. The current potentializes the magnetic field intensity that leads to intensifying magnetic indentation force (F_i) on the workpiece surface through the gripped active abrasives with the iron particles chain structure as expressed in Eq. (4.7). Beyond 1 A current, the F_i gets increased which maximize the %age change in Ra. With 1.15 mm and 1.7 mm working gap, the %age change in Ra is lower as related to the 0.6 mm working gap. At the higher working gap, lowering the value intensity of magnetization, F_i imposed between the two iron particles also reduced. As the intensity of the magnetization is more at 0.6 mm working gap and 3 A current which also uproots the excess material along with the roughness peaks from the workpiece surface. This may result in creating a rough surface rather than a smooth surface. Due to this, there is a decrease in %age change in Ra.

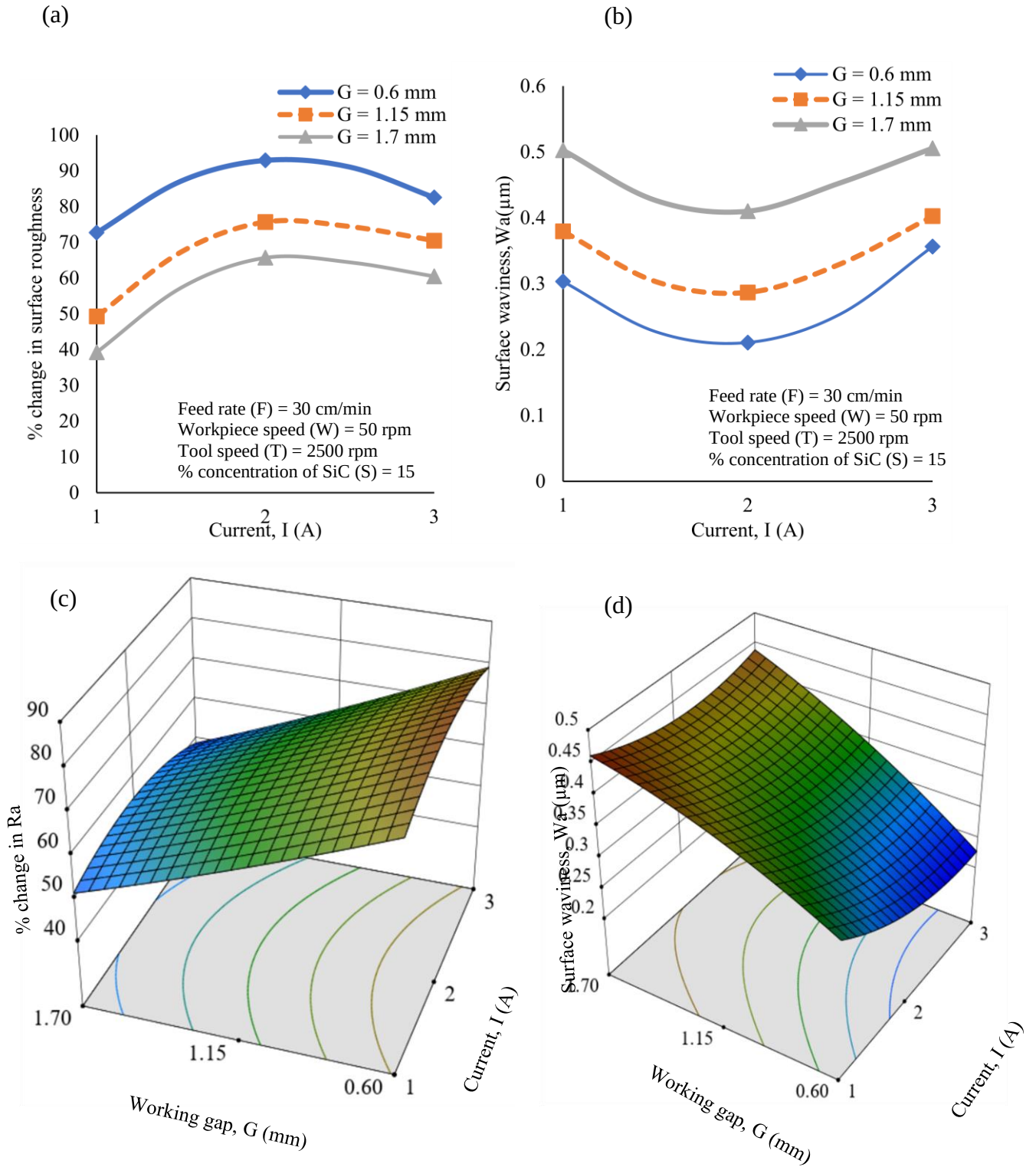


Fig. 4.12 Effect of current (I) and at different working gap (G) on (a) %age change in surface roughness (Ra) value and (b) surface waviness (Wa), 3D plot of effect of current (I) and working gap (G) on (c) %age change in Ra value and (d) surface waviness (Wa).

From Fig. 4.12(a), it is observed that at 1.15 mm and 1.7 mm working gap and current around 2A, the %age change in Ra is slightly increased. This happens because of the higher magnetic field intensity in the working gap.

Fig. 4.12(b) represents the surface waviness (Wa) for the interaction of the current with a varying working gap while considering the workpiece and tool speed at 2500 rpm, and 50 rpm, feed rate at 30 cm/min, and %age concentration of SiC is 15 %. The reverse pattern is obtained at the same optimum condition of the current and working gap as obtained in effect on %age change in Ra. This is owing to the fact that there is an increased value of the %age change in Ra, which results in a decrease in the value of surface waviness.

Figs. 4.12 (c) and (d) show the 3D plots of the %age change in Ra and surface waviness for the interaction of working gap and the current of tool. The contour lines show that the maximum %age change in Ra is achieved at the electromagnetic tool's current of 2 A and the working gap of 0.6 mm. Similarly, 3D plot of surface waviness shows that the minimum value of surface waviness is achieved at a combination of similar parameters.

4.3.3.3 Interaction effect of the rotational speed of the tapered cylindrical workpiece and tool core rotation on %age change in Ra and surface waviness (Wa)

Fig. 4.13(a) represents the %age change in Ra for the interaction of the rotational speed of tapered cylindrical workpiece with the variation of the tool core rotation while considering the tool feed rate at 30 cm/min, the working gap is 0.6 mm, %age concentration of SiC particles at 15 % and current at 2 A. The maximum %age change in Ra is obtained at 50 rpm of rotation of the tapered cylindrical workpiece along with the tool core rotation of 2500 rpm. During the MR finishing of the tapered cylindrical workpiece surface, when the tool core is rotated at 2500 rpm with the workpiece rotation of 50 rpm, the relative motion of the active abrasives on the workpiece surface increases in such way that they can shear off the roughness peaks from the surface with more interaction time. Due to which the %age change in Ra gets increased. However, when the rotational speed of the tapered cylindrical workpiece increases to 100 rpm and 150 rpm against the tool core rotational speed of 2000 rpm and 3000 rpm, the %age change in the Ra value decreases.

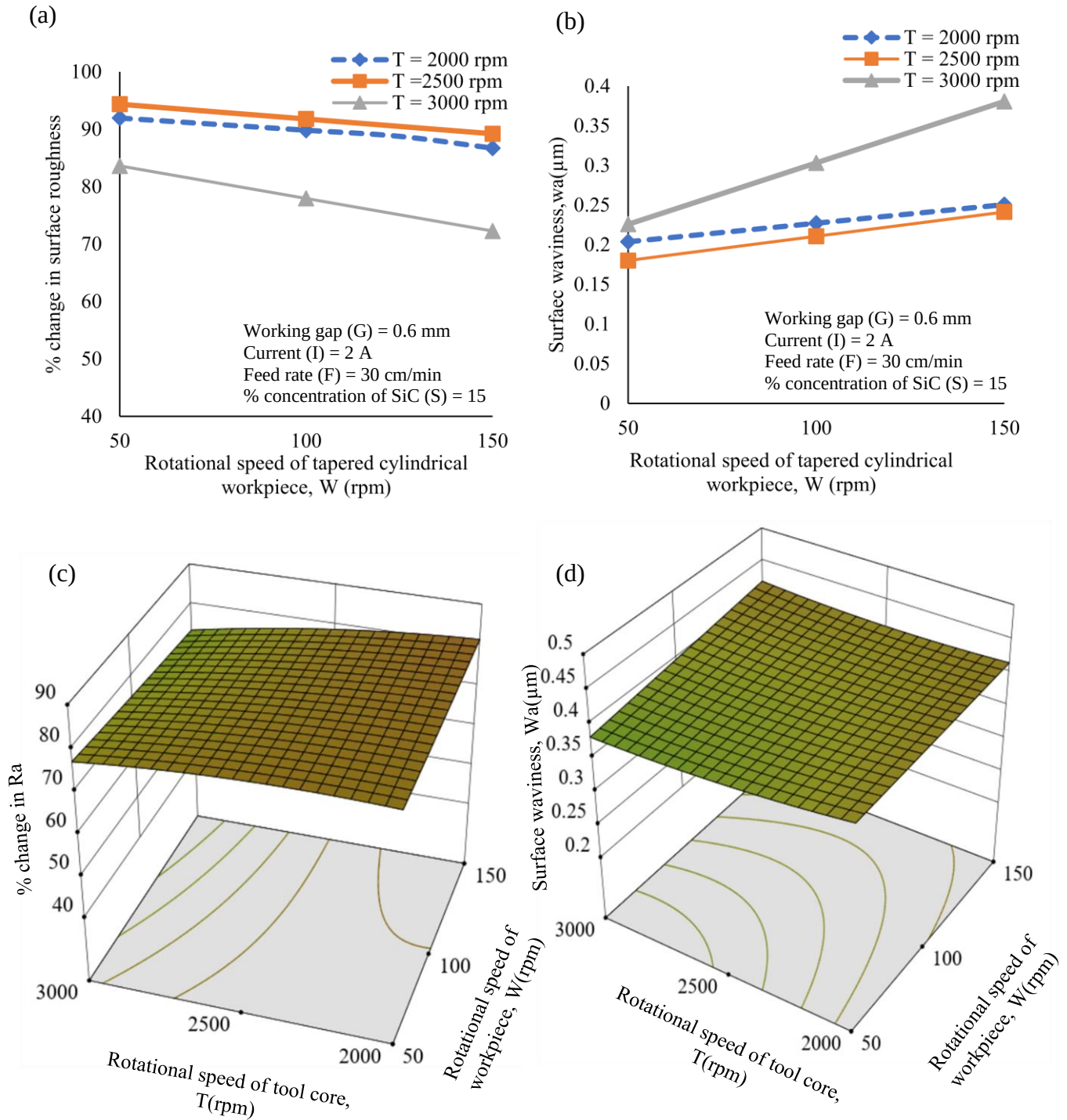


Fig. 4.13 Effect of rotational speeds of the tapered cylindrical workpiece (W) at different rotational speeds of tool core (T) on (a) %age change in surface roughness (Ra) value and (b) surface waviness (Wa), 3D plot of the effect of rotational speeds of the tapered cylindrical workpiece (W) at different rotational speeds of tool core (T) on (c) %age change in Ra value and (d) surface waviness (Wa).

This is because of the higher rotational speed of the tapered cylindrical workpiece surface against the rotating stiffed MR polishing fluid (MRP) with the tool core rotation creates a

disturbance to the MRP fluid which causes less interaction time of the active abrasives with the roughness peaks. Due to which many active abrasive particles may pass over the roughness peaks without shearing it. Also, in addition to this, the centrifugal force can act more on the active abrasives when tool core rotational speed increase to 3000 rpm and workpiece rotation of 150 rpm. This results in a decrease in the %age change of the Ra value.

Fig. 4.13(b) represents the surface waviness (Wa) for the interaction of the tapered workpiece speed with the variation of the tool core rotational speed while considering the same other constant parameters as considered in effect on %age change in Ra. The reverse trend is observed at the same optimum conditions. This is due to the fact that the value of surface waviness gets decreased with an increase in the value of the %age change in Ra.

Figs. 4.13(c) and (d) show the 3D plots of the %age change in Ra and surface waviness for the interaction of rotational speed of the tapered cylindrical workpiece and rotational speed of tool core. The contour lines show that the maximum %age change in Ra is achieved at the tool's rotational speed of 2500 rpm and tapered workpiece speed at 100 rpm. Similarly, the 3D plot of surface waviness shows that the minimum value of surface waviness is achieved at a combination of similar parameters.

4.3.3.4 Interaction effect of %age concentration of SiC particles and current on %age change in Ra value and surface waviness (Wa)

Fig. 4.14(a) represents the %age change in Ra value for the interaction of %age concentration of SiC particles with varying the current while considering the tool and workpiece speed at 2500 rpm and 50 rpm, feed rate at 30 cm/min, and the working gap is 0.6 mm. The %age concentration of SiC abrasives plays a significant role in the MR finishing process. As the concentration of the abrasive particles increases, the magnetic interaction force (F_{AB}) per SiC abrasive reduces due to the consecutive space between the two iron particles (Q) increases as expressed in Eq. (4.22). Due to this, the magnetic indentation force (F_i) (Eq. 4.7) decreases which leads to decrease the %age change in Ra.

$$F_{AB} = \frac{\mu_p \pi}{9} \left(\frac{r_s^2 Y Z}{Q} \right) \quad (4.22)$$

Where μ_p is the absolute permeability in vacuum space, r_s is the radius of the iron particle, Y is the collect coefficient and Z is the intensity of magnetization.

As depicted in the graph, the value of the %age change in Ra value boosts upto 15% of abrasives concentration with the current of 2A. However, the value of the %age change in Ra decreases with further rises in abrasive particles concentration.

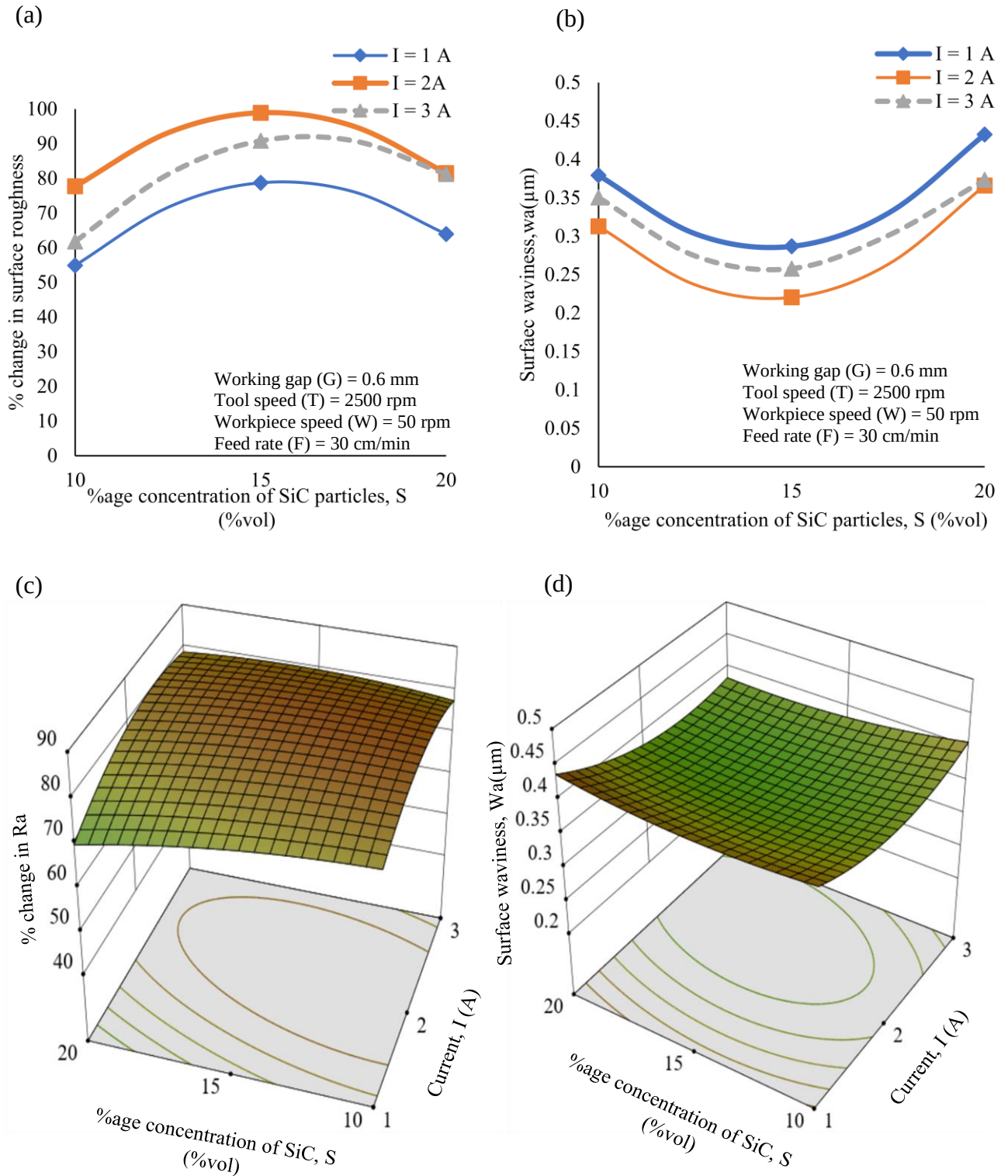


Fig. 4.14 Effect of %age concentration of SiC particles (S) at different current (I) on (a) %age change in surface roughness (Ra) value and (b) surface waviness (Wa), 3D plot of the effect of %age concentration of SiC particles (S) and current (I) on (c) %age change in surface roughness value and (d) surface waviness (Wa).

This trend is owing to the fact that the abrasive particles at higher %age concentrations begin to break the iron particles chain structure which ultimately results in a decrease in stiffness of MR polishing fluid during the shearing action. At 20% concentration of SiC abrasives with 3A current slightly rises in the %age change in Ra. This trend is owing to the fact that at 3A current the magnetic field intensity is greater which help to hold the abrasive particles strongly. At 1A current, the iron particles chains are not capable of holding the active abrasives strongly due to lesser magnetic field intensity which results in a decrease in the %age change in Ra as depicted in Fig. 4.14(a).

Fig. 4.14(b) represents the surface waviness (Wa) for the interaction of %age concentration of SiC particles with the varying current while considering the same other constant parameters as considered in effect on %age change in Ra. The reverse trend is observed at the same optimum conditions. This is due to the fact that the value of surface waviness gets decreased with increase in the value of the %age change in Ra. Figs. 4.14(c) and (d) show the 3D plots of the %age change in Ra and surface waviness for the interaction of %age concentration of SiC particles at different current values. The contour lines show that the maximum %age change in Ra is achieved at the electromagnetic tool's current of 2 A and %age concentration of SiC particles at 15%. Similarly, 3D plot of surface waviness shows that the minimum value of surface waviness is achieved at a combination of similar parameters.

Thus, the optimum parametric combination was predicted as the tapered cylindrical workpiece speed of 50 rpm, the tool core speed of 2500 rpm, the tool feed rate of 30 cm/min, working gap of 0.6 mm, %age concentration of SiC particles of 15 % and current at 2 A. So, when the variable diametric external surface of the steel tapered cylindrical workpieces finishes with the predicted optimum parameters using the present MR finishing technique, the maximum %age change in Ra value and minimum value of surface waviness can be achieved. The experiments with these optimum parameters were executed on the variable diametric external surface of the tapered cylindrical workpiece with the surface area of 62 mm in length and 49.5 mm in average diameter. The Ra value gets decreased from the initial ground value of 700 nm to 250 nm, 90 nm, 40 nm, and 19 nm in a total of 4 finishing cycles of 30 min each as depicted in Fig. 4.15. Thus, the %age change in Ra value achieved is 64.28%, 62%, 55.55%, and 52.5% in each finishing cycle, respectively. The more %age change in Ra value is observed in the first cycle of 30 min. This is because of the initially low shear area available at the uppermost sharp roughness peaks.

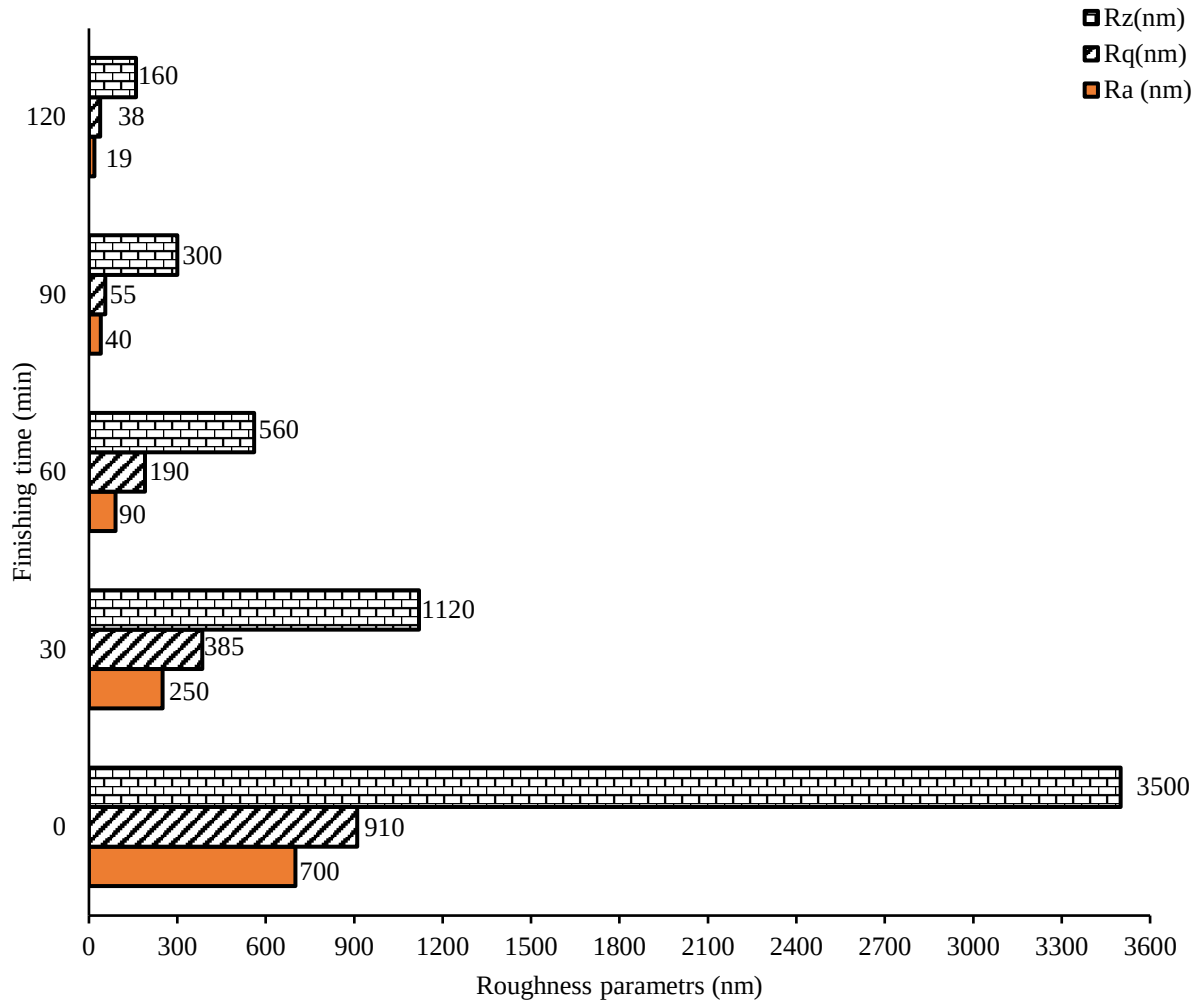


Fig. 4.15 Change in surface roughness values at different finishing time during MR finishing on the variable diametric external surface of the tapered cylindrical workpiece with optimized parametric conditions.

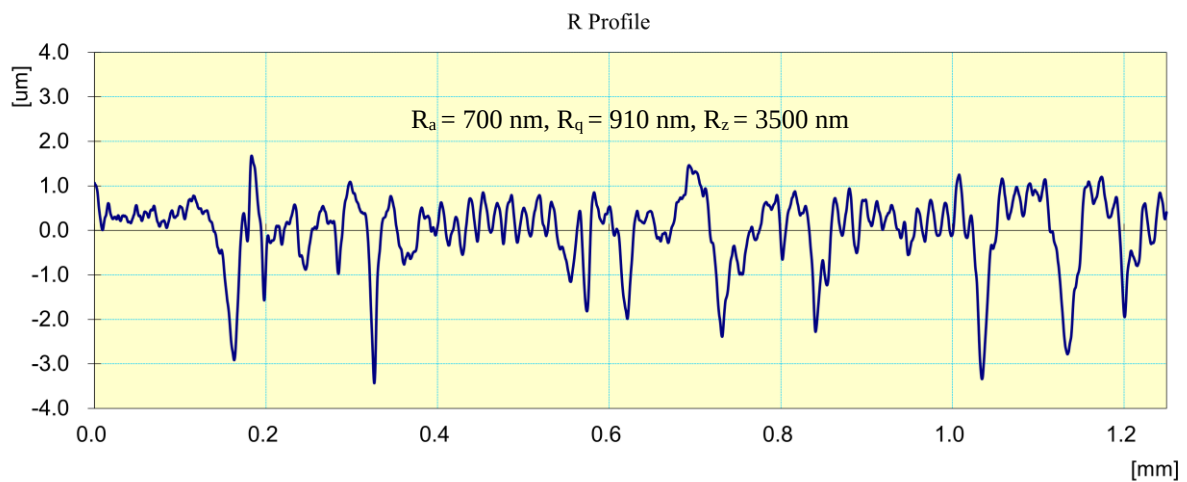
Due to this, the smaller magnitude of the shear force is required to clip off the roughness peaks in the first finishing cycle of 30 min. However, during the third and fourth trials of finishing a cycle, less %age change was observed in the value of Ra as compared to the first trial. This is because the shear area left out at the base of the roughness peaks gets increased which requires a greater magnitude of shear force.

Figs. 4.16(a) and (b) show the Ra profiles of the initial and final variable diametric external surface of the cylindrical tapered workpiece after 120 min MR finishing with optimum process parameters. The Ra, Rq, and Rz values were reduced to 19 nm, 38 nm, and 160 nm from the initial values of 700 nm, 910 nm, and 3500 nm respectively on a 62 mm length of the tapered cylindrical workpiece with a diameter of 55 to 44 mm after MR finishing with the optimum parametric combination. Hence, the total %age reduction in Ra, Rq, and Rz values was found

as 97.28%, 95.82%, and 95.42% respectively in 120 min of finishing time with optimized parametric conditions.

Also, this significant reduction in roughness values verifies that the induced magnetic field gradient in the working gap has been found sufficient to keep holding the MR polishing fluid rigidly on the magnetized tip surface of the tool core and moved smoothly on the variable diametric external surface of the tapered cylindrical workpiece during the finishing operation. This demonstrates the effectiveness of the advancement in the present process for fine finishing the variable diametric external surface of the tapered cylindrical workpieces.

(a)



(b)

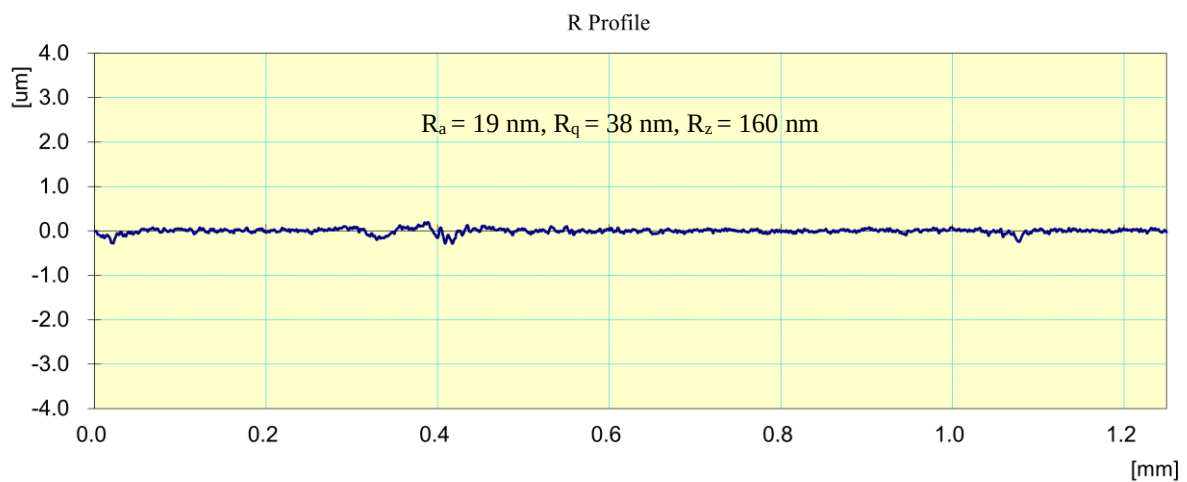


Fig. 4.16 Surface roughness profiles over the variable diametric external surface of the tapered cylindrical workpiece (a) at the initial ground surface and (b) finished surface after the 120 min of MR finishing operation with optimized parametric conditions.

The surface waviness parameters are the arithmetic average deviation (W_a), waviness root mean square (W_q), the maximum peak height of waviness (W_p) and a total height of the profile (W_t). Correspondingly, the average surface waviness (W_a) value of the tapered cylindrical workpiece gets decreased from the initial ground surface of $0.8410\text{ }\mu\text{m}$ to $0.2057\text{ }\mu\text{m}$ after 120 min of MR finishing on a 62 mm length of the tapered cylindrical workpiece with a diameter of 55 to 44 as shown in Figs. 4.17(a) and (b), respectively.

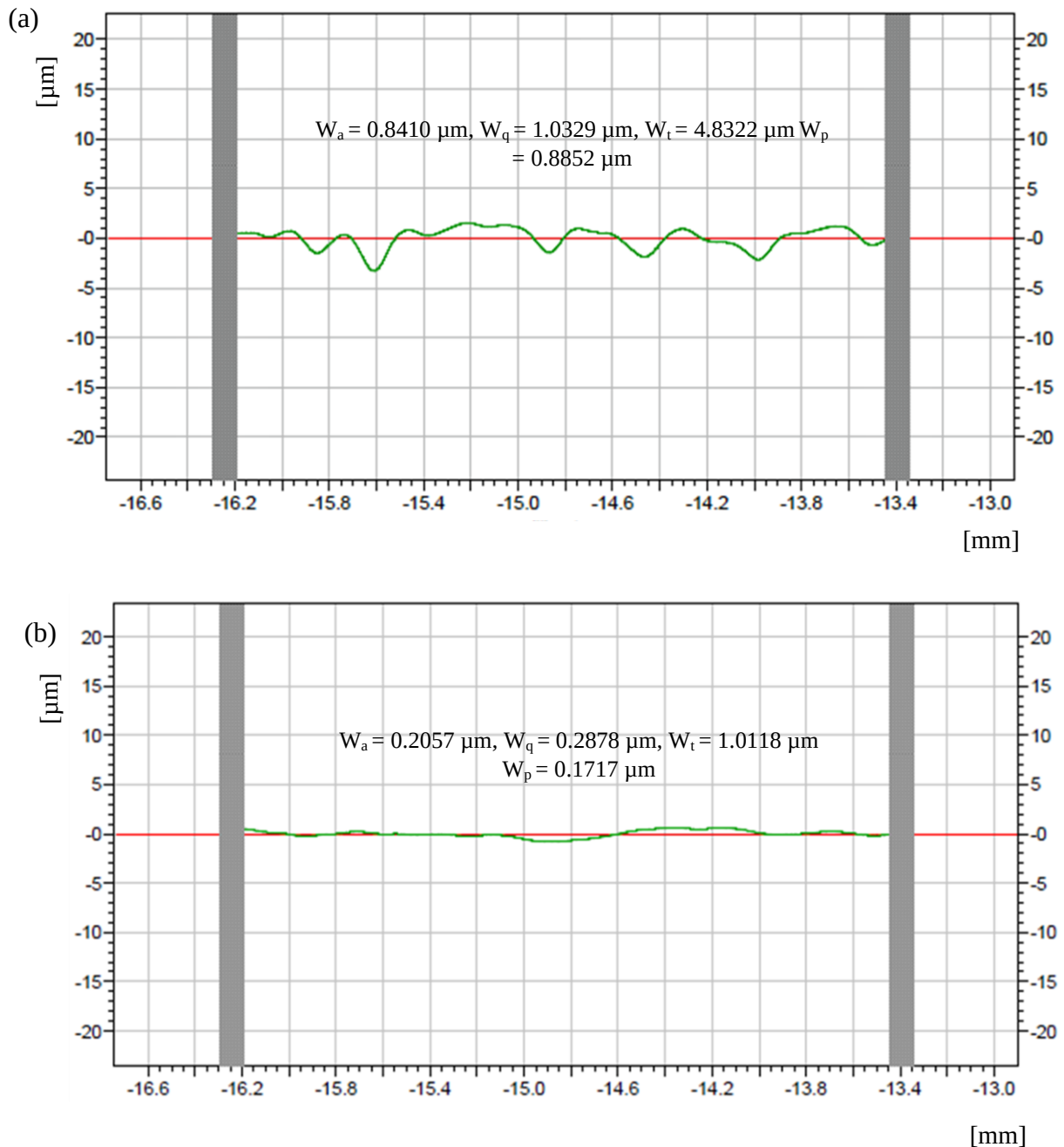


Fig. 4.17 Waviness profiles over the variable diametric external surface of the tapered cylindrical workpiece (a) at the initial ground surface and (b) finished surface after the 120 min of MR finishing operation with optimized parametric conditions.

The net reduction in the waviness parameters W_a , W_q , W_t , and W_p were observed to be 0.6353 μm , 0.7451 μm , 3.8204 μm , and 0.7135 μm respectively after 120 min of MR finishing over the variable external surface of the cylindrical tapered workpiece with the obtained optimum parametric combination. Thus, the %age change in the surface waviness parameters W_a , W_q , W_t , and W_p are found as 75.54 %, 72.13%, 79.06%, and 80.60% respectively (Fig. 4.17).

A reflection image test was also performed which is shown in Figs. 4.18(a) and (b), respectively. For the reflection test, the text 'MRF' is written on the white sheet and place in front of the variable diametric external surface of the tapered cylindrical workpiece. In Fig. 4.18(a), it is seen that at the initial ground surface ($R_a = 700 \text{ nm}$) the text 'MRF' is not readable due to the grinding lays. But after the MR finishing, the grinding lays are removed and the smooth surface is attained. As it is seen in Fig. 4.18(b), the text 'MRF' is easily readable due to the fine finished surface ($R_a = 19 \text{ nm}$) after 120 min of MR finishing on a 62 mm length of the tapered cylindrical workpiece with a diameter of 55 to 44.

The scanning electron microscopy (SEM) captures the topography of the initial and final MR finished external tapered cylindrical surface at an optical scale of 1500X after 120 min of MR finishing on a 62 mm length of the tapered cylindrical workpiece with a diameter of 55 to 44 is shown in Figs. 4.18(c) and (d), respectively. SEM reveals the surface topography through the highly zoomed photographs of the variable diametric outer surface of the tapered cylindrical workpiece before and after the MR finishing. Fig. 4.18(c) shows the SEM image of the initial ground variable diametric external surface of the tapered cylindrical workpiece. The grinding lay lines are seen due to the substantially normal force acted during the grinding operation on the surface. This causes to generate grinding lay lines on the surface as seen in Fig. 4.18(c). The SEM image of the final MR finished variable diametric external surface of the tapered cylindrical workpiece is shown in Fig. 4.18(d). The SEM photograph of the MR finished surface shows that the grinding lay lines have been removed and the smooth surface achieved after 120 min of MR finishing with the optimum parametric combination as seen in Fig. 4.18(d). This is due to the less deterministic magnetic normal force applying on the variable diametric external surface of the tapered cylindrical workpiece during the MR finishing operation as compared to the traditional grinding operation.

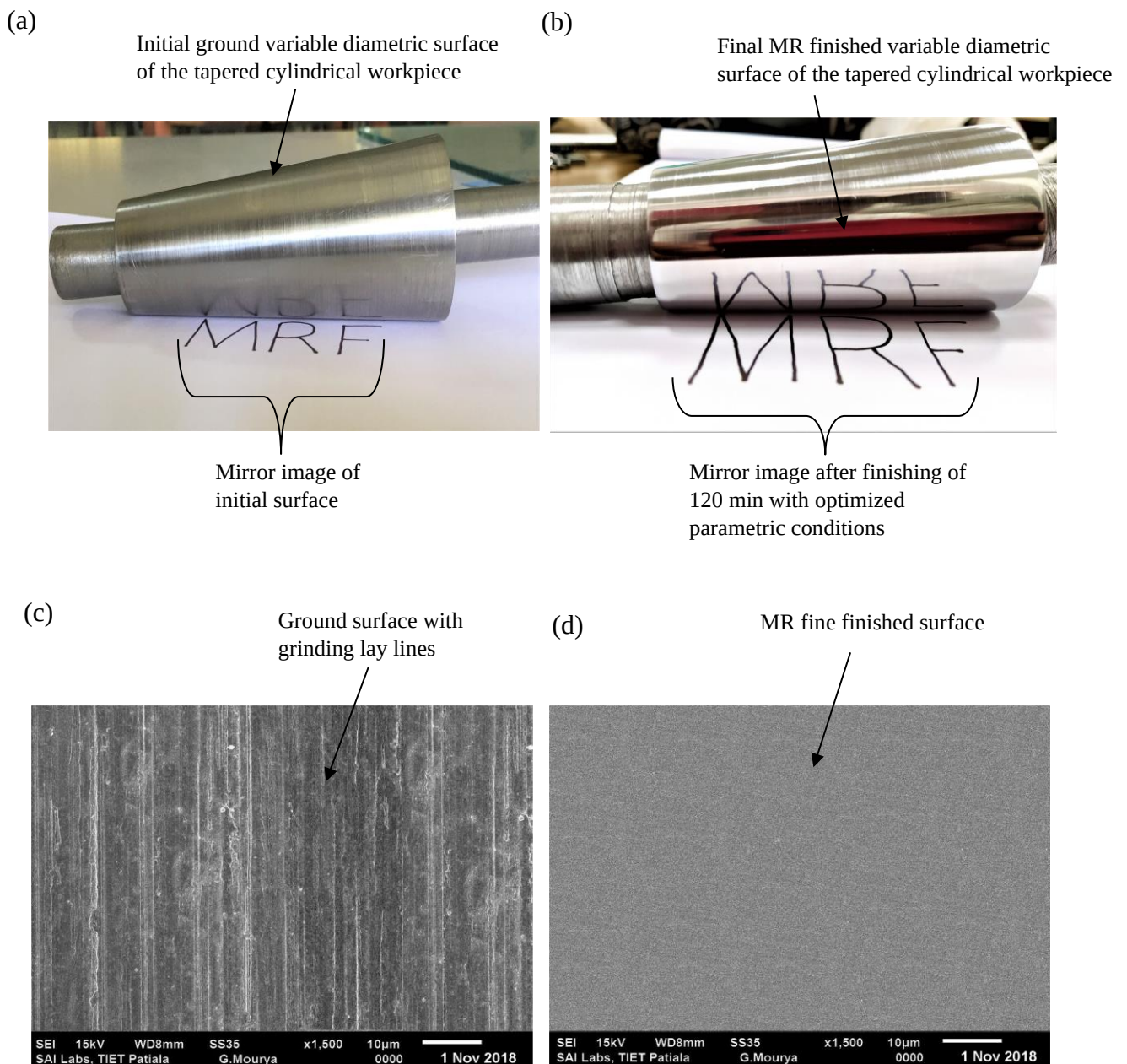


Fig. 4.18 Mirror images of the variable diametric external surface of the tapered cylindrical workpiece (a) initial ground surface and (b) finished surface after 120 min of MR finishing with optimized parametric conditions. Scanning electron microscope photographs at 1500x of the variable diametric external surface of the tapered cylindrical workpiece (c) initial ground surface and (d) finished surface after 120 min of MR finishing with optimized parametric conditions.

Thus, the SEM and reflection image analysis reveal a more significant improvement in surface characteristics of the tapered cylindrical workpiece after the MR finishing. Also, the surface roughness profile gets significantly reduced after the MR finishing (Fig. 4.16). Hence, the present advancement in MR finishing process finds its greater application in fine finishing the

variable diametric external surface of the tapered cylindrical workpieces such as taper punches, tapered bearing races, tapered cylindrical shafts, and tapered roller bearings, etc. for their functionality improvement in the manufacturing industries.

4.4 Conclusions

The present advancement in the magnetorheological finishing process shows very useful for fine finishing of the external tapered surface of the workpieces. On the basis of result obtained from the fine finishing of the external surface of the tapered cylindrical workpiece, the following conclusions are made.

- Magnetostatic finite element analysis reveals the difference in magnetic flux density in the working gap between the tip surface of the electromagnetic tool core and the tapered cylindrical workpiece surface as it is necessary to keep holding the MR polishing fluid rigidly on the higher magnetized tip surface of the tool core and move smoothly on the variable diametric external surface of the tapered cylindrical workpiece during the finishing operation. This demonstrates the effectiveness of the present process.
- The time required to get uniform fine finishing on the variable diametric external surface of the tapered cylindrical workpiece take cares the variation in linear velocity, helix angle and the helical path made by the active abrasives. Also, the hardness value of the workpiece material influences a significant role in reducing the final average surface roughness value as it decides the degree of indentation of the active abrasives through the magnetic indentation force.
- The theoretical analysis predicts the final roughness value of the variable diametric external surface of the different tapered cylindrical materials with the required number of finishing cycles using the present MR finishing process for their functionality improvement.
- The maximum %age reduction in average Ra value and minimum the average surface waviness reveals with the optimum parameters as 50 rpm of tapered cylindrical workpiece speed, 2500 rpm of the tool core tip speed, 30 cm/min of feed rate, 15% concentration of SiC abrasive particles, 0.6 mm of working gap, and the input current of 2A.
- The average Ra value gets decreased significantly to 19 nm from 700 nm on the variable diametric external surface of the tapered cylindrical workpiece (60 mm length and 49.5 mm average diameter) after 120 minutes of MR finishing with the optimum parametric combination. The corresponding surface waviness gets decreased to 0.2057 μm from

an initial value of 0.8410 μm . This shows the fine finishing obtained on the variable diametric external surface of the tapered cylindrical workpieces using the present magnetorheological finishing process.

- SEM and reflection images confirm that the surface characteristics of the cylindrical tapered workpiece get improved significantly after fine finishing with the present MR finishing process as compared to the initial ground surface. Thus, present advancement in the MR finishing process is found to be more useful in improving the functional application with fine finishing the variable diametric external surface of the tapered cylindrical parts such as tapered punches, tapered roller and races of the bearings used in various machines.

4.5 Improved magnetorheological finishing process with a rotating rectangular core tip surface for external cylindrical surfaces

After the analysis of flux density on the rectangular and circular tip surfaces of the tool cores (Figs. 3.23 and 3.24 (Chapter 3)) where the rectangular tool core tip surface has been demonstrated uniform magnetic flux density with higher magnitude. Now, the experiments are performed for the finishing of the external surface of the cylindrical ferromagnetic workpiece using these two tool core tip surfaces. The workpiece is made of the mild steel shaft. For the preparation of workpiece, first turning operation is performed on the mild steel shaft to achieve the required diameter of 30 mm. After achieving the required diameter on the cylindrical workpiece, the grinding operation is performed. Next, the workpiece is fixed between the two aligned bearing sets (Fig. 4.19). On the right side of the workpiece, a driven pulley is attached. This driven pulley is operated by a driver pulley with the assistance of a belt drive. The servo motor provides the controllable rotating motion to the cylindrical workpiece. The whole operating setup of the workpiece is mounted on the holding fixture. The MR polishing fluid is utilized as a finishing medium, which is comprised of the base fluid (paraffin oil and grease), abrasive particles (SiC) and iron particles. These three components of fluid are mixed up with the help of a d.c. controlled mixer. The fluid components are mixed with a ratio of transporting oil (base oil) being 60%, 20% iron particles (IPs) of 400 mesh number, and 20% abrasive particles of 600 mesh number.

The volume concentration of MR polishing fluid is taken on the basis of preliminary investigation and available literature. Initial workpiece surface is prepared with the help of cylindrical grinder. The roughness value of the initial ground cylindrical external surface of the workpiece is measured using the surface roughness tester (surftest). The surface roughness

values were deliberated at 10 measuring points on the overall cylindrical workpiece external surface, and the average surface roughness value is found as 310 nm. The R_a , R_q , and R_z (surface roughness parameters) for the initial ground surface were measured as 310 nm, 450 nm, and 2800 nm, respectively. The surface waviness values of initial ground surface and final MR finished surfaces with both tool tip surfaces are measured by the Taylor Hobson profilometer. The experiments were performed by using both tool core tip surfaces on the same ground cylindrical workpiece with the same initial surface roughness value. The experimental conditions for MR finishing with both tool core tip surfaces are given in Table 4.9.

Table 4.9 Experimental processes parameters and conditions

Parameters	Conditions
Magnetizing current	2 A
Working gap	0.6 mm
Horizontal to and fro feed rate	30 cm/min
Rotational speed of cylindrical workpiece	90 rpm
Rotational speed of circular and rectangular tool core tip surfaces	700 rpm
Each finishing cycle time	20 minutes
Total finishing cycle time	60 minutes
Finishing length of workpiece	30 mm

The controllable d.c. supply with current 2 A is provided to the electromagnetic tool. Due to the supply of current, the magnetic flux density is generated over the tip surface. The iron particles (IPs) form the chain like pattern. These are directed towards the field lines for strongly holding the abrasive particles. Workpiece surface and tool core tip surfaces were rotated at 90 rpm and 700 rpm, respectively. For the validation of the process performance with the circular and rectangular shaped tip surfaces, the experiments were performed three times with the help of the experimental conditions as given in Table 4.9.

The average value of the change in final surface roughness was measured and reported in Table 4.10. Each trial was performed with both tool core tip surfaces in total 60 minutes of finishing time. The total finishing time was divided into three sets of finishing cycles, and each set of the finishing cycle took 20 minutes.

Table 4.10 Final surface roughness and surface waviness values after MR finishing with circular and rectangular tool core tip surfaces

Experimental trials	Experimental responses				
	Initial surface roughness value of cylindrical workpiece (nm)	Final surface roughness value with circular tool core tip surface (nm)	Final surface roughness value with rectangular tool core tip surface (nm)	Final surface waviness value with circular tool core tip surface (μm)	Final surface waviness value with rectangular tool core tip surface (μm)
t1	310	45	18	0.0410	0.0210
t2	315	46	21	0.0415	0.0213
t3	317	47	19	0.0413	0.0215
Average	314	46	19.33	0.04126	0.02126

4.5.1 Results and discussion

The four shapes such as square, triangular, rectangular and existing circular tool tip surfaces have been analysed with a similar surface area. The magnetostatic finite element analysis and experimental analysis show that the design of tool core with rectangular tip surface was found to be better in achieving uniformly greater flux density at the tool core tip surface as demonstrated in Figs. (3.17) and (3.18) (Chapter 3). This is because of the edge effect has a sudden change in the rectangular shaped tool core tip surface resulted in the concentration of the magnetic field lines. This leads to the elevated magnitude of uniform flux density over the tip surface. This improves finishing performance as compared to the circular tip surface with the same parametric conditions. The finishing experiments with the circular and rectangular shaped tool core tip surfaces are performed in three trials (t1, t2, and t3), and final average surface roughness value (R_a), and surface waviness value (W_a) are obtained as reported in Table 4.10.

When finishing experiments with the circular and rectangular shaped tool core tip surfaces were performed, the final roughness R_a value was obtained as 45 nm and 18 nm in 60 minutes of finishing cycle from the initial ground roughness value of 310 nm as depicted in Figs. 4.19(a) and (b). Final roughness R_a value was found to be a mere 18 nm with the rectangular shaped tool core tip surface than the final R_a value of 45 nm with the circular shaped tool core tip surface. It is because of the uniformity and higher magnitude of flux density at the rectangular shaped tool core tip surface. The reduction in R_a value at different finishing time with both the tool core tip surfaces is depicted in Fig. 4.19.

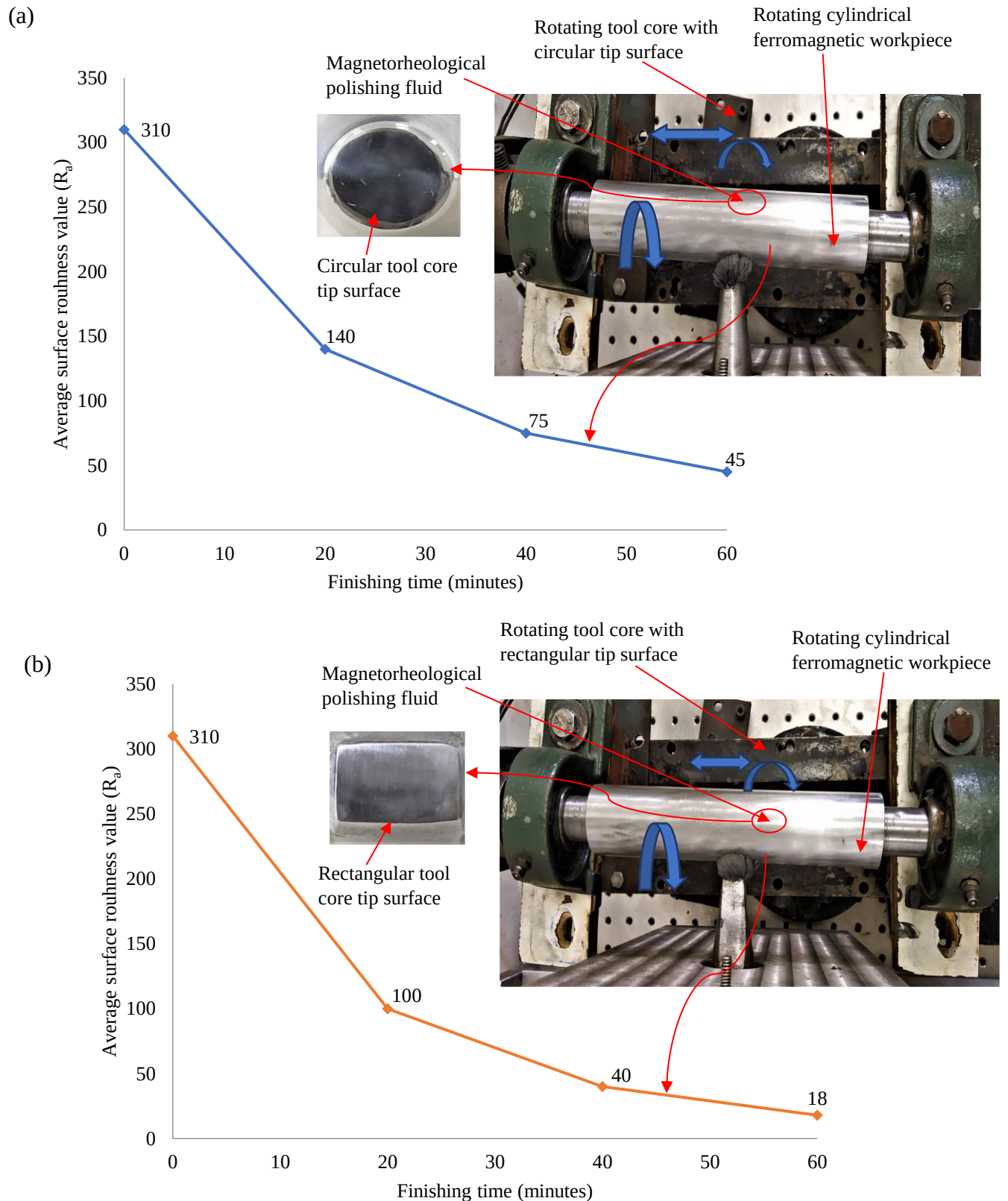
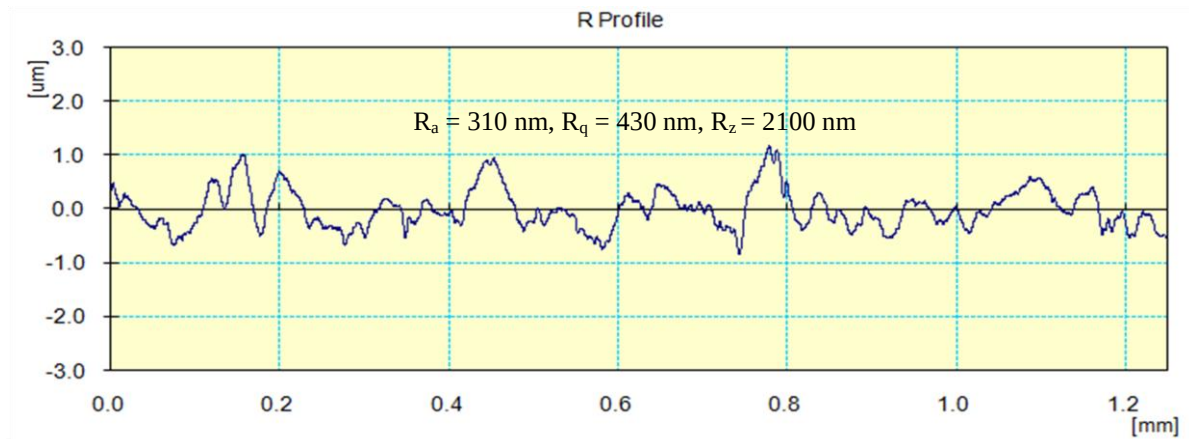
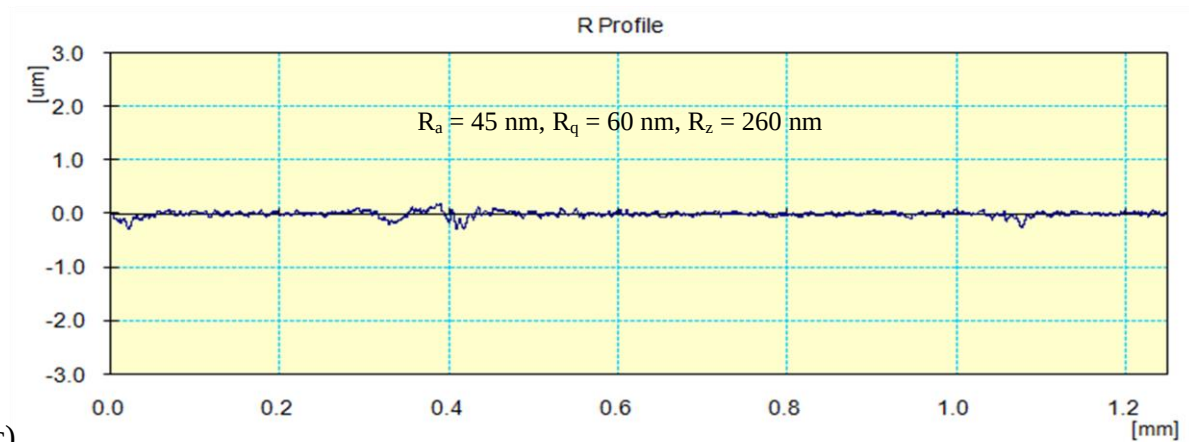


Fig. 4.19 Effect of the change in surface roughness value at different finishing time during magnetorheological finishing on the external surface of the ferromagnetic cylindrical workpiece using the tool core with (a) the circular tip surface and (b) rectangular tip surface.

(a)



(b)



(c)

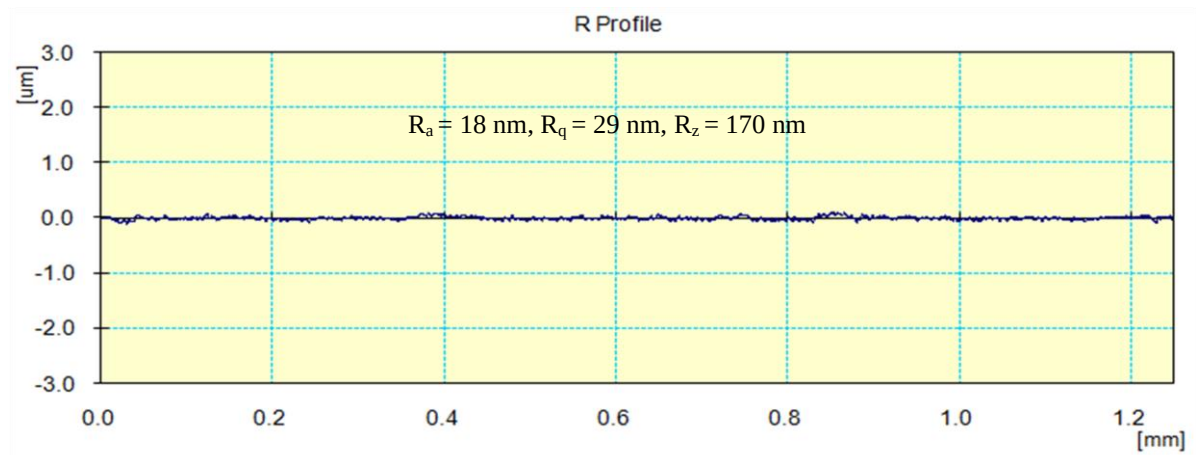


Fig. 4.20 Surface roughness profiles (a) initial ground surface, and after 60 minutes of MR finishing with (b) a circular tool core tip surface, and (c) a rectangular tool core tip surface.

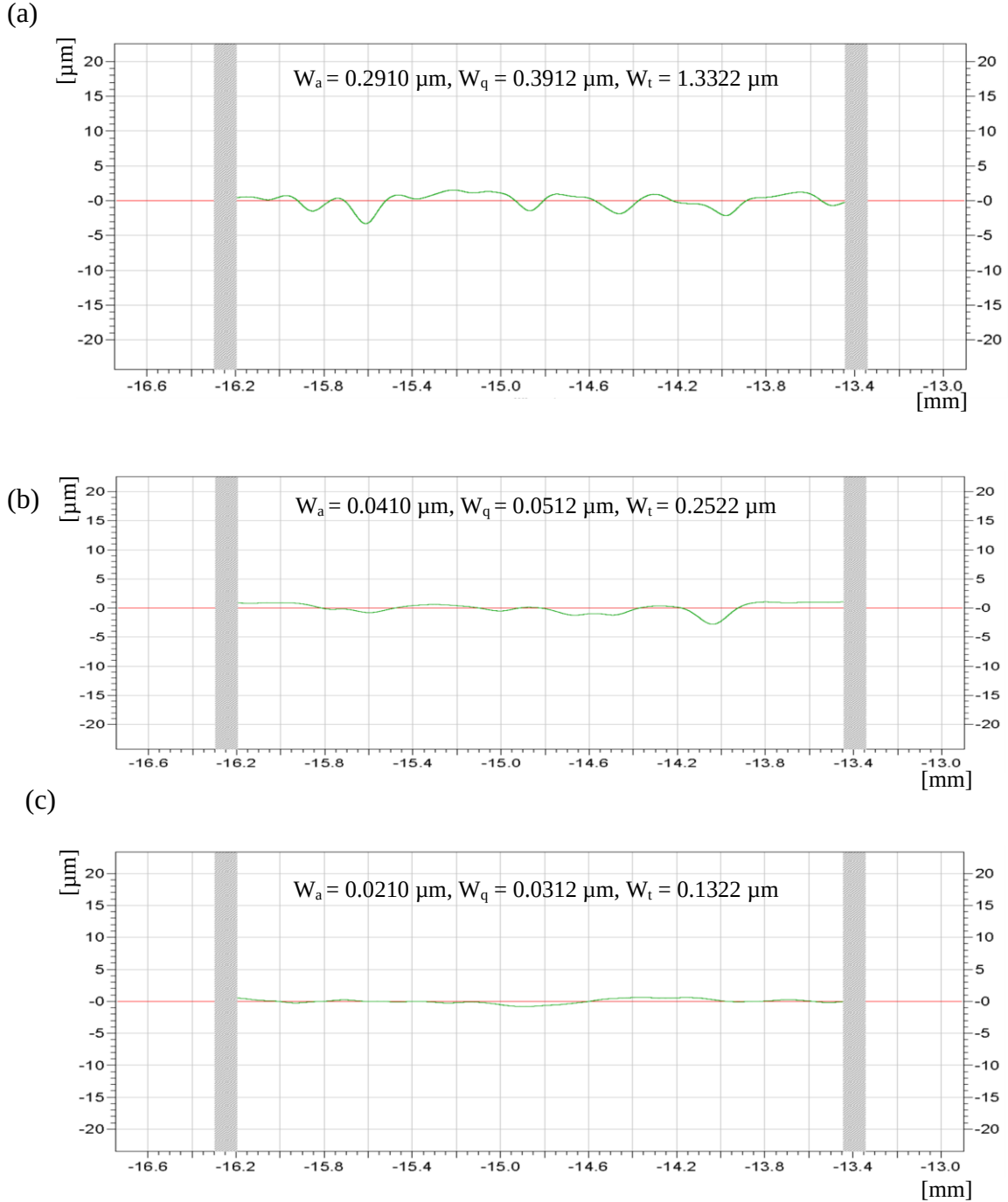


Fig. 4.21 Surface waviness profiles (a) initial ground surface, and after 60 minutes of MR finishing with (b) a circular tool core tip surface, and (c) a rectangular tool core tip surface.

It shows that the initial ground R_a value of 310 nm is same for both the tool core tip surfaces and the final R_a value obtained from the circular, and rectangular tool core tip surfaces are 45 nm and 18 nm respectively. The surface roughness profiles of the initial ground surface and final MR finished surface with the circular and rectangular magnetized tool core tip surfaces are depicted in Figs. 4.20(a), (b), and (c). Also, the initial surface waviness (W_a) value was

measured to be 0.291 μm on the initial ground workpiece surface. The initial ground surface values of waviness root mean square (W_q) and the total height of the profile (W_t) were found to be 0.391 μm and 1.332 μm as depicted in Fig. 4.21(a). After 60 minutes, MR finishing with circular and rectangular tool tip surfaces, the surface waviness (W_a) value of the external surface of the cylindrical workpiece were found to be 0.041 μm and 0.021 μm as depicted in Figs. 4.21(b) and (c). After 60 minutes, MR finishing with the circular tip, the value of waviness root mean square (W_q) and the total height of profile (W_t) were found to be 0.051 μm and 0.252 μm , respectively as shown in Fig. 4.21(b). Whereas after 60 minutes, MR finishing with the rectangular tool tip, the value of waviness root mean square (W_q) and the total height of profile (W_t) were found to be 0.031 μm and 0.132 μm , respectively as shown in Fig. 4.21(c).

The surface waviness profiles revealed that the MR finishing with rectangular tool tip surface provides the uniform and maximum reduction in surface waviness parameters over the MR finishing with circular tool tip surface. The mean and standard deviation were also calculated for 10 measured roughness values at 10 different locations on the MR finished surface with circular and rectangular tool core tip surfaces using the Eqs. (4.23) and (4.24).

$$\mu = \frac{P_1 + P_2 + P_3 \dots + P_{10}}{10} \quad (4.23)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - \mu)^2} \quad (4.24)$$

where μ is the mean of 10 random measured surface roughness R_a values $P_1, P_2, P_3, \dots, P_{10}$ on the workpiece external surface, P_i is the individual R_a value, n is the number of R_a values reading measured on the workpiece external surface and σ is the standard deviation. Therefore, using the Eqs. 4.23 and 4.24, the mean and standard deviation values of the initial ground external surface were found as 310 nm and 20.6 which are depicted in Fig. 4.22(a). Further, the circular tool core tip surface was used for the finishing of the cylindrical workpiece external surface, and then the surface roughness values were obtained at 10 randomly chosen points which are depicted in Fig. 4.22(b). By using these values, the mean and standard deviation values were evaluated from Eqs. 4.23 and 4.24 that are found as 45.6 nm and 8.4, respectively. Later, the same procedure was followed for the rectangular tool core tip surface, and the surface roughness values were measured at 10 random points on the external surface of the cylindrical workpiece are depicted in Fig. 4.22(c). The mean and standard deviation values obtained are 18.1 nm and 2.1, respectively. From the standard deviation values of MR finishing with circular and rectangular tool tip surfaces, it is proven that the uniformity of the surface finishing is improved.

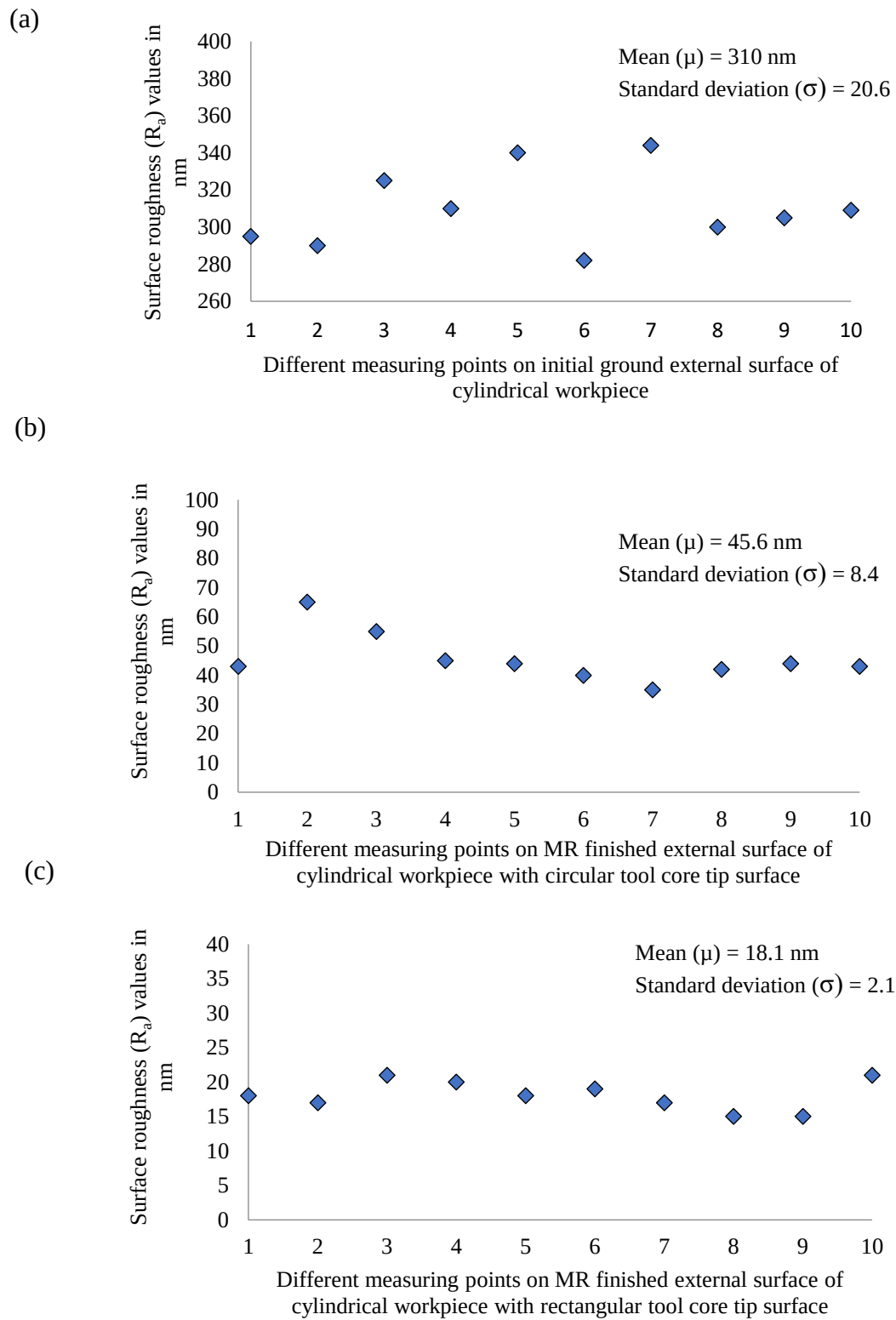


Fig. 4.22 Plot between the surface roughness values and different measuring points on the external surface of the cylindrical ferromagnetic workpiece for mean and standard deviation values at (a) initial ground surface, after 60 minutes of MR finishing with (b) a circular tool core tip surface, and (c) a rectangular tool core tip surface.

But, from the Figs. 4.22(b) and (c), it is clear that the greater uniformity of the surface finishing is obtained by using the rectangular tool tip surface over the circular tool tip surface.

The scanning electron microscopy (SEM) has been executed to identify the surface characteristics of unfinished and finished surfaces using both tool core tip surfaces. The SEM images were captured at 500x magnification on the initial ground, and the final MR finished the external cylindrical surface with both the tool core tip surfaces as depicted in Figs. 4.23(a), (b), and (c). On the SEM image of the ground initial surface, the grinding marks are observed on the workpiece surface as demonstrated in Fig. 4. 23(a). After finishing with both rectangular and circular shaped tool core tip surfaces, the improved MR finish SEM images with their finishing mechanism are demonstrated in Figs. 4.23(b) and (c), respectively.

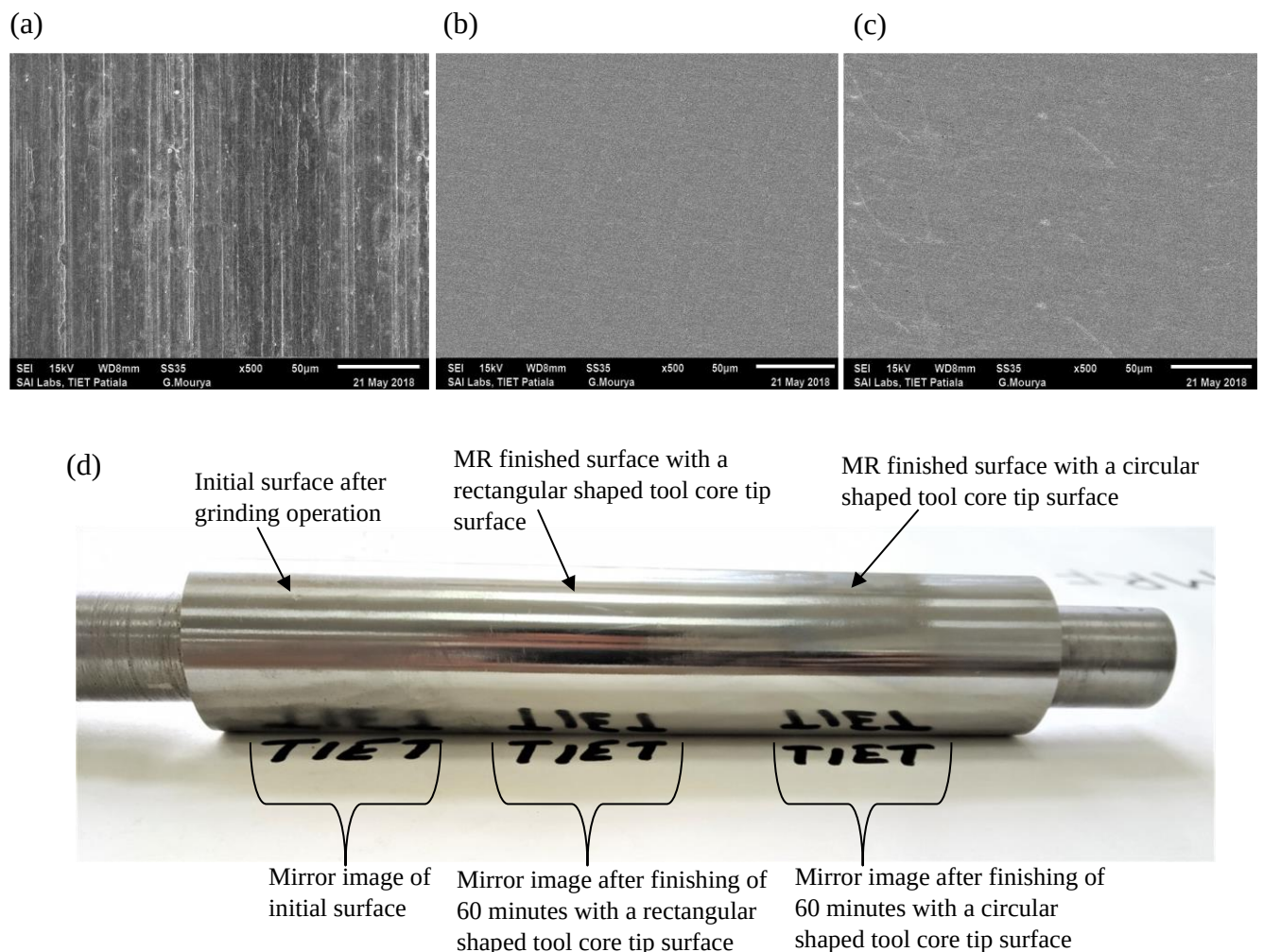


Fig. 4.23 Scanning electron microscope (SEM) photographs at 500X of external surface of cylindrical workpiece (a) at initial ground surface, and after 60 minutes of MR finishing with (b) a rectangular tool core tip surface, (c) a circular tool core tip surface and (d) mirror images.

These SEM images are evidenced by the finishing results obtained after MR finishing with the rectangular and circular tool core tip surfaces. The SEM images revealed that the rectangular shaped tool core tip surface provided better surface characteristics as compare to the circular shaped tool core tip surface. The reflection image test was also performed on the initial and final MR finished surface to observe the effect of finishing with both the tool core tip surfaces as demonstrated in Fig. 4.23(d). The SEM and mirror images confirmed that the rectangular shaped tool core tip surface is capable of producing better surface characteristics than the circular shaped tool core tip surface. The rectangular shaped tool core tip surface possesses a lower R_a value as compared to the circular tip surface in same finishing time and conditions. This is due to the shear strength of MR polishing fluid at the rectangular tip surface was greater than that of the circular tip surface. The flattened roughness peaks possess greater shear strength (Grover and Singh., 2017). Therefore, to remove these peaks, it requires active abrasive particles that possess higher shear strength value. The active abrasive particles along with MR polishing fluid at rectangular shaped tool core tip surface possesses greater shear strength value in comparison to that of circular tool core tip surface. This is also one reason that the rectangular shaped tool core tip surface is capable of reducing R_a value more than the existing circular shaped tool core tip surface.

The experimental results obtained with the rectangular shaped tool core tip surface indicates the better productivity of the process. Also, the uniform flux density over the rectangular shaped tool core tip surface leads to the uniform finishing. This results in good geometrical accuracy, improved process effectiveness, closer tolerances and fits. Thus, the present designed rectangular shaped tool core tip surface enhances the efficiency of the MR finishing process for the external surfaces. The improved MR finishing process with rectangular shaped tool core tip surface can find its application in uniform nanofinishing of various cylindrical industrial components for better surface characteristics.

4.6 Conclusions

The present MR finishing process is further improved with the rotating rectangular tool core tip surface. The following conclusions are drawn based on comparison of the initial flat circular rotational tool core tip surface and improved rectangular rotational tool core tip surface.

- The flux density over the designed rectangular shaped tool core tip surface is found uniformly in higher magnitude as compared to the circular or other shapes of the tool core tip surfaces. The edge effect plays a major role in improving the magnitude and uniformity of flux density over the rectangular shaped tool core tip surface as the

localization of magnetic field lines is influenced by the edge effect phenomena which enhanced the magnetization.

- The average surface roughness value was decreased to 18 nm and 45 nm from the initial ground surface roughness value of 310 nm after 60 minutes MR finishing with the rectangular and circular shaped tool core tip surfaces.
- The surface waviness values 0.081 μm and 0.021 μm were achieved using the rectangular and circular shaped tool core tip surfaces from the initial ground value of 0.291 μm in 60 minutes of MR finishing. Also, surface characteristics were found better with the rectangular shaped tool core tip surface as compared to the circular shaped tool core tip surface. This is revealed by the SEM and reflection images.
- The mean and standard deviation after 60 minutes, MR finishing with the circular tip surface gets reduced to 45.6 nm and 8.4, and with a rectangular tip surface, it reduced to 18.1 nm and 2.1. This showed that the greater uniformity of the surface finishing is obtained by using the rectangular tool core tip surface over the circular tool core tip surface.
- The experimental decreased in roughness value up to 18 nm, and significant enhancement in surface characteristics evidenced that the rectangular shaped tool core tip surface effectively improve the efficiency of the MR finishing process. This is useful in achieving the close tolerances and to enhance the geometrical accuracy of the external cylindrical surfaces for the precise industrial applications.

CHAPTER 5

MAGNETORHEOLOGICAL FINISHING OF THE VARIOUS REAL TIME INDUSTRIAL CYLINDRICAL EXTERNAL SURFACE OF THE WORKPIECES USING RECTANGULAR TOOL CORE TIP SURFACE

In this chapter, various real-time industrial applications are fine finished using the improved rectangular rotating core-based magnetorheological finishing setup. The real-time industrial applications like cold rolling rolls, micro extrusion punches, grooved winding drum, splined shaft, and copper cylindrical roller is required fine finishing. The fine finishing of the external surface of these cylindrical components enhances the functional performance for their process application in industries.

5.1 Magnetorheological finishing of cold rolling rolls for evaluating their functional performance in metal forging industry

In the modern world, the metal rolling process is one of the most vital manufacturing processes. Most of the sheet metal products are produced by the metal rolling process. The main component of the rolling process is a roll. Rolls are made of gray iron, alloy iron, cast steel, and forged steel. The steel rolls are stronger and tougher than the iron rolls. There are various applications of the cold rolling process which are generally found in industries of transportation, aviation, agriculture and in many other types of processes. The fine finishing of the rolls is greatly demanded nowadays in the industry due to the undesirable defects associated with the higher surface roughness of the rolls in the cold rolling process. The defects associated with the higher surface roughness are basically the heterogeneity in the final product and excessive use of power to overcome the friction loss. Mechanical wear is also occurring on the external surface of the rolls in a cold rolling process due to the higher surface roughness. Factors influencing the mechanical wear of the rolls are the surface finish, contact area, shape, and the type of motion. A rectangular-rotating core-based MR finishing process is utilized to finish the external surface of the cold rolling rolls to improve its functional performance. The improvement in the external surface finishing of the rolls improves the overall efficiency of the process which validates in this work. The process parameters of the MR finishing process are optimized to finish the external surface of the actual cold rolls for improving its functional operation in the industry. In order to check the effect of MR finished rolls, the rolls are sent to the industry for evaluating their functional performance.

5.2. Materials and methods

5.2.1 Selection of material for the present work

The material is generally selected on the basis of operational conditions. The material that is being used in the cold rolling process must be able to maintain its strength and must have minimum deformation during the operation. Forged steel is generally used for manufacturing of the rolls in the industries because they are having a good combination of high ultimate strength, high hardness, and good fracture toughness at elevated temperature.

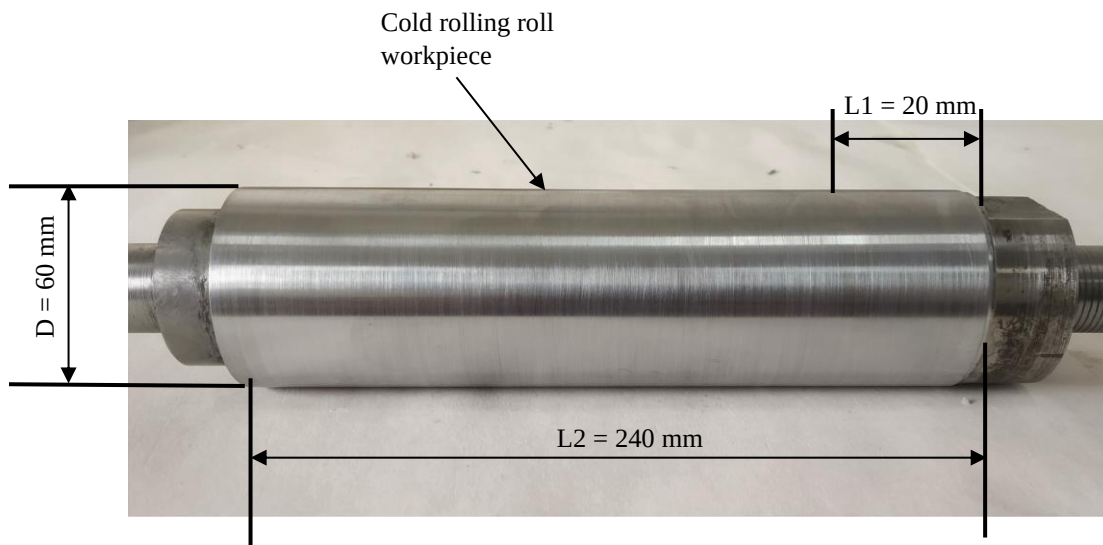


Fig. 5.1 Actual roll workpiece with actual dimensions.

The cold rolling rolls have 240 mm length (L_2) and 60 mm diameter (D) as shown in Fig.5.1. For each trial, 20 mm length (L_1) on the external surface of the rolls has been selected as the evaluation length during the experimentation.

5.2.2 Experimental setup

Fig.5.2 shows the present experimental setup. The cold rolling rolls are held between the two self-aligned pillow blocks. Rolls outer end portions were turned with turning operation and screwed to the pillow blocks with the help of align screws as shown in Fig.5.2. The holding fixture is provided to hold the pillow blocks with cold rolling roll in a straight line and rotated by the servo motor through a belt drive system. This is important because the uniform gap between the tool core tip surface and roll external surface is compulsory to achieve the uniform finishing. This arrangement was fixed on a vise which was placed in front of the tool. The working gap is maintained at 0.6 mm between the tool core rectangular tip surface and the workpiece external surface. In rolling operation, the rolls are in rotational motion and the ingot flat strip of thickness (h_i) passes through the gap in the rolls with the velocity (V_i) as shown in Fig.5.3.

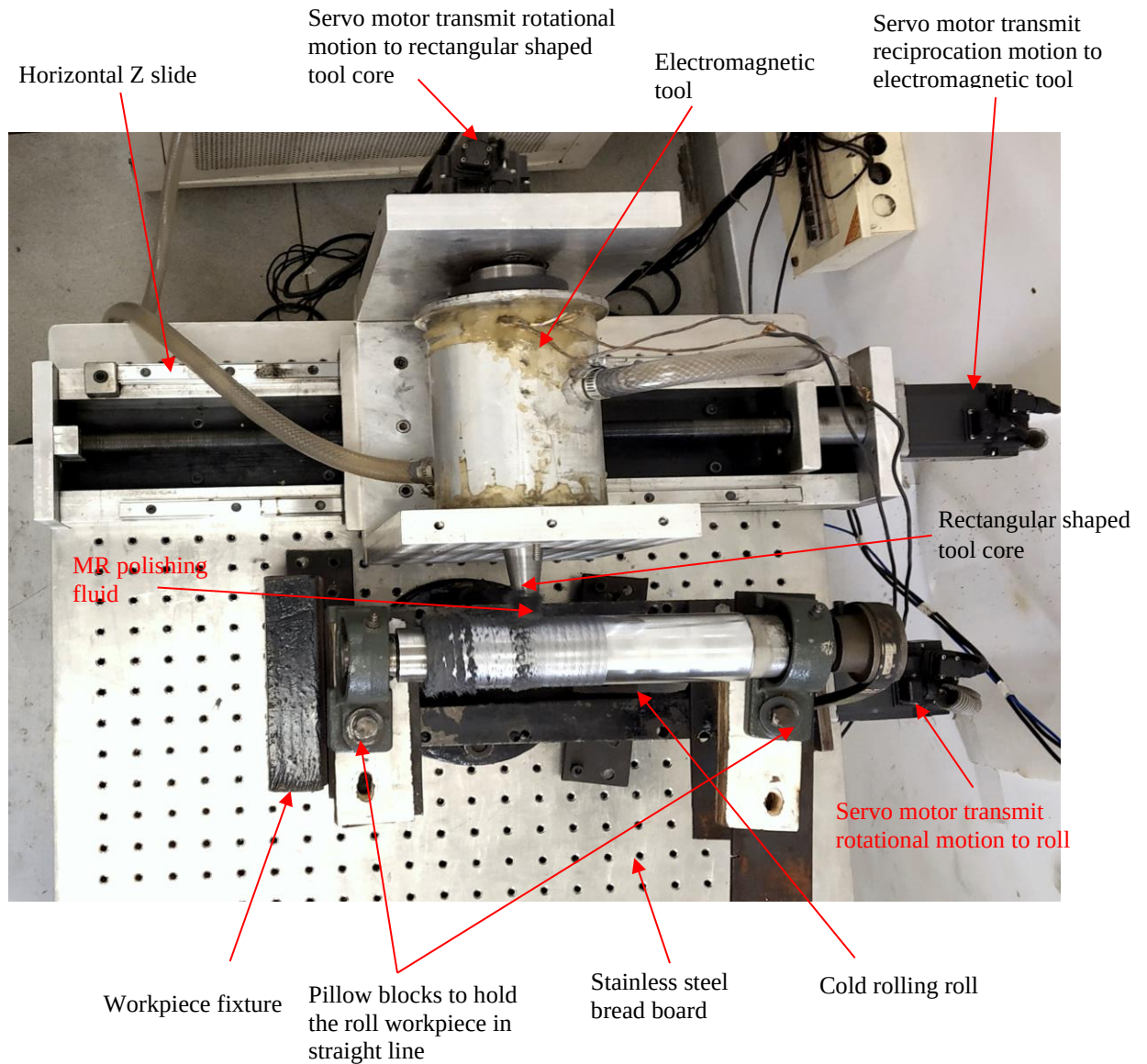


Fig. 5.2 Photograph of a rotating core based magnetorheological finishing process.

The roll gap is maintained on the basis of the requirement of the final flat strip thickness (h_f). In Fig. 5.3, h_i is the initial thickness of the ingot strip, r is the radius of the rolls, L is the contact length of the roll with the strip, s is the reduction in the strip after the rolling operation, V_i is the velocity of the ingot strip, and F_f is the frictional force acting on the surface of the rolls.

5.3 Experimentation

Response surface methodology (RSM) was utilized to plan and analyse the effect of process parameters. Also, their effect was optimized for the maximum %age improvement in the surface finish. The tool rotational speed (T), workpiece rotational speed (W), working gap (G), current (I), tool feed rate (F) and best suitable composition of MR polishing fluid were selected in the present experimentation.

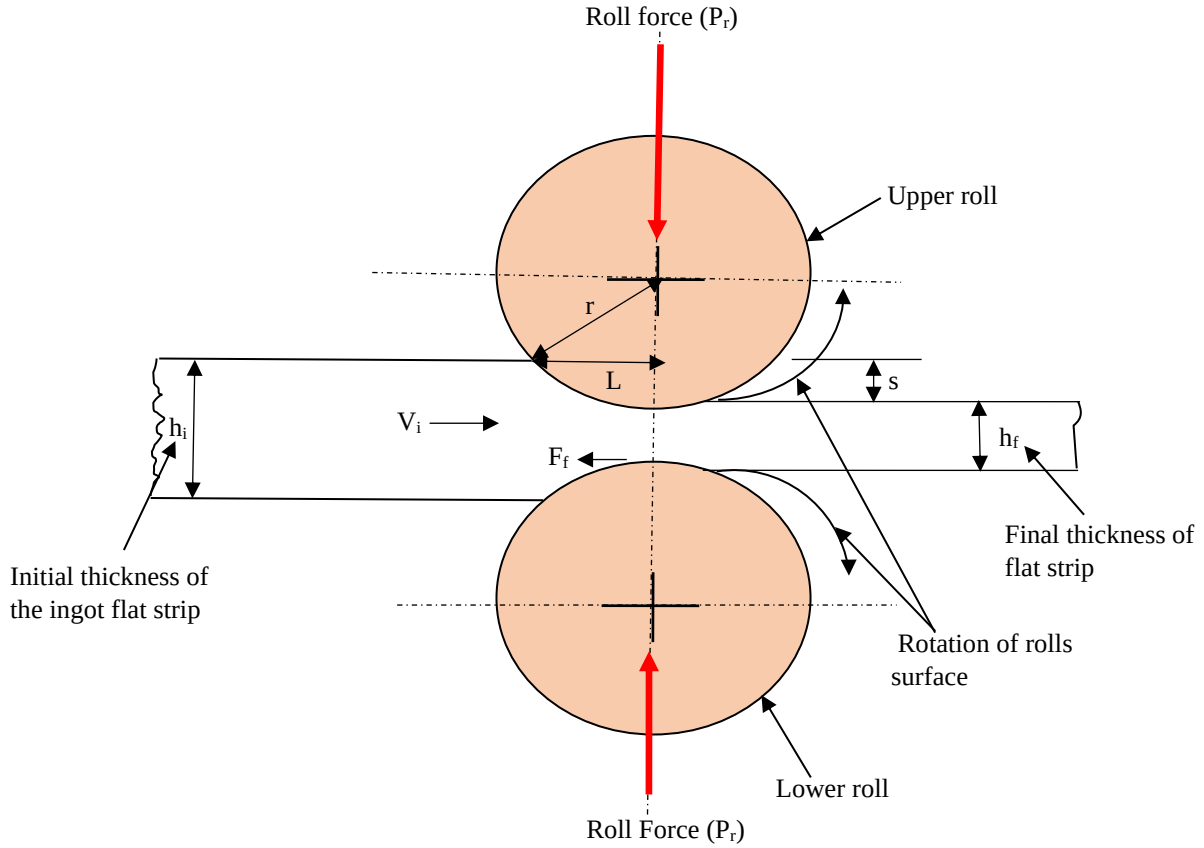


Fig. 5.3 Schematic diagram of the rolling process with force representation.

5.3.1 Selection of parametric range of the finishing machine

The analysis of various parameters on the H13 cold rolling roll material was done by using the response surface methodology (RSM). For the experimentation, the process parameters and their range were selected on the basis of literature review (Maan and Singh, 2018), preliminary experiments and machine capability as reported in Table 5.1. The magnitude of current plays a vital role in the MR finishing process. Magnetic field strength is dependent on current intensity which passes through the electromagnetic coil. The range of the current is selected based on the role of this parameter in the MR finishing process. The magnetizing current is the source of the change of magnetic flux density in the working gap. As the magnetizing current increases magnetic flux density also increases which results in an increase in indentation force. In present experimentation, the range of the current was selected from 1 to 3 A. The range of tool feed rate was selected from 100-500 mm/min and tool rotation was selected from 300-1900 rpm. The contribution of workpiece rotation can be seen in the research done on cylindrical finishing and its range was selected from 40-120 rpm (Maan *et al.*, 2017). The rotational speed of the tool core and workpiece is an important parameter to govern the relative motion between the active abrasive particles and the external surface of the workpiece. The

rotational speed of the tool core governs the magnitude of the centrifugal force which acts on iron particles. The centrifugal force acting on the iron particle chain increases when tool core speed increases which reduce the effect of a magnetizing force acting on iron particles in the working gap. As the workpiece rotation increases, the number of roughness peaks passing through the region of active abrasive particles increases. The feed rate of the tool core is also an important parameter which governs the collision between abrasive particles as well as roughness peaks. This results in fine finishing of the entire surface of the workpiece. The working gap is the most important parameter in MR finishing process which governs the magnetic strength of the MR polishing fluid. On the basis of these findings, the different finishing process parameters and their ranges were selected for the present experimentation as reported in Table 5.1.

Table 5.1 Experimental parameters and their ranges

Finishing process parameters			Range				
Representation	Description						
T	Tool rotational speed (rpm)	300	700	1100	1500	1900	
W	Workpiece rotational speed (rpm)	40	60	80	100	120	
G	Working gap (mm)	0.3	0.6	0.9	1.2	1.5	
I	Current (A)	1	1.5	2	2.5	3	
F	Feed rate (mm/min)	100	200	300	400	500	

5.3.2 Design of experiments

To examine the effect of process parameters on response such as %age reduction in average surface roughness or %age improvement in the surface finish, the response surface methodology (RSM) was used. For optimization of the process, RSM uses statistical, mathematical and graphical techniques. The influence of several selected parameters on the response was studied. The relationship between the variables and response is given by Eq. (5.1).

$$R = f(T, W, G, I, F) \quad (5.1)$$

Where R is the response as %age improvement in the surface finish which is the function (f) of the tool rotational speed (T), workpiece rotational speed (W), working gap (G), current (I) and tool feed rate (F).

The influence of process parameters was studied by fitting the second order polynomial response surface as given in the Eq. (5.2).

$$R = \alpha_0 + \sum_{i=1}^k \alpha_i a_i + \sum_{i=1}^k \alpha_i a_i^2 + \sum_i \sum_j \alpha_{ij} a_i a_j + \varepsilon \quad (5.2)$$

Where R is the response, a_i is the i^{th} process parameter, α is regression coefficient and ε is the residual measurement from the experimental error.

The analysis was performed using the Design Expert 6.0.8 software. The central composite design was created for five finishing process parameters with five levels. The response of each experiment was calculated in terms of the %age improvement in the surface finish. As surface roughness (R_a) value of workpieces was not the same, therefore the response was measured in the term of the %age improvement in the surface finish value. Total of 52 experiments was conducted and examined at different parametric conditions as reported in Table 5.2. The measurement of the surface roughness values of the finished surface was done by using the Mitutoyo SJ-400 surfest with a cutoff length of 0.25 mm. The verification of the effectiveness of the model generated at 95% confidence level was done by comparing F-value obtained in the model to that of standard F value. After performing the finishing operation, Eq. (5.3) was used to calculate the %age improvement in the surface finish ($\% \Delta R_a$).

$$\% \Delta R_a = \frac{\text{Initial average surface roughness} - \text{Final average surface roughness}}{\text{Initial average surface roughness}} \times 100 \quad (5.3)$$

Experiment trials are performed on the external surface of the rolls. Each finishing trial was performed over 20 mm finishing length of the external surface of the rolls. The finishing time for each finishing trial was 40 minutes. The MR polishing fluid is changed after every 20 minutes in each trial for maintaining the fresh active abrasives. Experimentation has been performed three times at each parametric combination and the average value of %age improvement in the surface finish is taken. The trials response X1, X2, and X3 are obtained. The %age improvement in the surface finish at each parametric combination are obtained by using Eq.5.3. Responses and the average values of the initial and the final surface roughness as reported in Table 5.2.

Table 5.2 Plan of experiments and their responses

S. No.	Finishing process parameters					Initial R_a value (nm)	Final R_a value (nm)				$\% \Delta R_a$
	T (rpm)	W (rpm)	G (mm)	I (A)	F (mm/min)		X1	X2	X3	Avg.	
1	1100	80	0.9	2	300	200	85	90	89	88	56
2	700	60	1.2	2.5	200	205	80	84	82	82	59
3	1500	60	0.6	1.5	400	210	105	96	102	101	51
4	700	60	0.6	2.5	400	195	72	66	66	68	65
5	700	100	1.2	1.5	200	190	100	95	96	97	49
6	300	80	0.9	2	300	201	140	135	139	138	31
7	1500	60	1.2	2.5	400	200	68	60	70	66	67

8	1500	100	1.2	2.5	400	204	60	56	61	59	71
9	1100	100	0.6	2.5	400	210	42	45	48	45	78
10	700	80	0.9	2	300	212	65	56	53	58	72
11	1500	60	0.6	1.5	200	190	52	60	59	57	70
12	700	100	0.6	1.5	200	198	58	62	60	60	69
13	1500	100	1.2	1.5	400	192	90	84	90	88	53
14	1500	60	0.6	2.5	200	210	70	75	80	75	64
15	1100	80	0.9	2	100	203	98	108	106	104	48
16	1900	80	0.9	2	300	185	105	100	104	103	44
17	1100	80	0.9	3	300	182	80	85	81	82	54
18	1100	80	0.9	1	300	186	85	90	86	87	53
19	1100	80	0.9	2	300	189	90	84	81	85	55
20	1500	100	0.6	2.5	400	200	110	100	108	106	47
21	700	60	0.6	2.5	200	189	80	82	78	80	57
22	700	60	1.2	1.5	200	203	75	80	79	78	61
23	1100	80	1.5	2	300	215	92	88	90	90	58
24	700	100	0.6	2.5	200	202	100	105	101	102	49
25	1100	40	0.9	2	300	197	138	140	130	136	30
26	1100	80	0.9	2	300	194	100	105	110	105	46
27	1500	60	0.6	2.5	400	191	112	110	108	110	42
28	1500	100	1.2	2.5	200	192	92	90	100	94	51
29	1500	100	0.6	2.5	200	212	40	45	47	44	79
30	700	100	0.6	1.5	400	205	57	62	55	58	72
31	1500	100	0.6	1.5	200	202	68	65	62	65	67
32	1100	80	0.9	2	300	210	82	80	78	80	61
33	1500	60	1.2	1.5	400	195	75	84	75	78	59
34	1500	60	1.2	2.5	200	198	52	48	50	50	74
35	1100	80	0.9	2	300	201	62	58	57	59	69
36	1500	100	0.6	1.5	400	214	55	60	56	57	73
37	700	100	1.2	2.5	400	216	105	112	107	108	50
38	700	100	1.2	1.5	400	208	58	60	56	58	72
39	1100	120	0.9	2	300	200	121	117	116	118	41
40	700	60	0.6	1.5	200	202	45	50	49	48	76
41	1100	80	0.9	2	300	190	38	42	40	40	78
42	1100	80	0.3	2	300	195	120	116	118	118	39
43	1500	100	1.2	1.5	200	198	108	103	104	105	46
44	700	60	1.2	2.5	400	200	55	58	61	58	71
45	700	100	1.2	2.5	200	204	63	58	65	62	69
46	1100	80	0.9	2	500	205	46	44	51	47	77
47	1100	80	0.9	2	300	210	102	100	98	100	52
48	1500	60	1.2	1.5	200	215	128	122	125	125	42
49	700	60	0.6	1.5	400	207	90	95	94	93	54
50	700	60	1.2	1.5	400	200	80	76	78	78	61

51	1100	100	0.6	2	400	212	62	58	54	58	72
52	700	80	0.9	2	300	218	65	75	64	68	68

5.4 Results and discussion

Analysis of variance (ANOVA) was performed on the experimental data as reported in Table 5.3. Regression analysis was performed to obtain a multi-regression model. On performing the ANOVA, it was found that p-value of the model was less than 0.05 which is significant and a p-value of lack of fit is greater than 0.05 which is not significant. After removal of the non-significant parameters, the ANOVA is given in Table 5.3.

Table 5.3 Analysis of variance (ANOVA) for percentage improvement in the surface finish

Source	Sum of squares	Degree of freedom	Mean square	F value	P value	Remark	%contribution
Model	8083.13	17	652.75	95.91	<0.0001	Significant	
T	600.63	1	600.63	87.33	0.0001		7.43
W	78.54	1	78.54	11.42	0.0231		0.98
G	1218.86	1	1218.86	177.22	0.0055		15.07
I	1679.43	1	1679.43	245.19	0.0002		20.77
F	221.16	1	221.16	32.16	0.0121		2.73
T ²	353.42	1	353.42	51.39	0.0091		5.37
W ²	381.83	1	381.83	55.52	0.0086		5.72
G ²	209.58	1	209.58	30.47	0.0131		2.59
I ²	1511.16	1	1511.16	219.72	0.0015		18.69
TW	569.53	1	569.53	82.81	0.0071		7.04
TG	195.03	1	195.03	28.36	0.0129		2.41
TF	295.03	1	295.03	42.75	0.0068		3.63
WG	33.06	1	33.06	5.81	0.0357		0.40
WF	69.03	1	69.03	10.04	0.0034		0.85
GI	215.28	1	215.28	31.30	0.0124		2.66
GF	247.53	1	247.53	35.99	0.0119		3.06
IF	205.03	1	205.03	29.81	0.0132		2.53
Residual	220.08	32	6.88			Not significant	
Lack of fit	130.53	23	5.68	0.57	0.8666		
Pure error	89.56	9	9.95				
Total	8523.3	49					

For all the terms namely T, W, G, I, F, T², W², G², I², F², TW, TI, TG, WI, WG, IF, IG and FG p-values are less than 0.05. The R-square predicted value (96%) measure how accurately the

model is developed to measuring the value of the response. From the regression analysis, the regression model is obtained as given in Eq. (5.4).

$$\begin{aligned} \% \Delta R_a = & -105.20 + 0.0789 T + 1.99 W - 176.09 G + 95.94 I + 0.124 F - 21.09 \times 10^{-6} T^2 - 61.28 \times \\ & 10^{-4} W^2 + 100.90 G^2 - 19.31 I^2 - 85.80 \times 10^{-6} F^2 - 52.73 \times 10^{-5} TW + 20.57 \times 10^{-3} TI + 37.90 \times \\ & 10^{-6} TG - 0.171 WI - 3.67 \times 10^{-4} WG - 8.65 IF - 46.35 \times 10^{-3} IG - 12.66 \times 10^{-3} FG \end{aligned} \quad (5.4)$$

5.4.1 Effect of significant parameters on process performance

After regression analysis for %age improvement in the surface finish (% ΔR_a), the result has been summarized in the form of graphs. The effect of all the significant parameters is discussed in this section. Fig. 5.4(a) represent the % ΔR_a with respect to tool feed rate and the rotational speed of tool core at the workpiece rotational speed 100 rpm, current 2 A and working gap as 0.6 mm. As the feed rate increases, the %age improvement in the surface finish increases up to 300 mm/min along with the tool rotational speed 1100 rpm and after that it starts decreasing as the feed rate increases. The reason for this behavior is that as the feed rate increases up to 300 mm/min along with the tool rotational speed 1100 rpm, the interaction between the active abrasive particles with surface roughness peaks gradually increases. This results in more %age improvement in the surface finish. But, when the feed rate is increased beyond 300 mm/min along with the tool rotational speed 1100 rpm, the MR polishing fluid at the magnetic tool core may have very quick interaction to the surface roughness peaks. This allows very less time to the active abrasive particles for removing the surface roughness peaks. Therefore, the % ΔR_a decreases beyond the feed rate of 300 mm/min. Whereas when feed rate increases from 100 mm/min to 300 mm/min value along with the tool rotational speed 1100 rpm, the MR polishing fluid at the magnetic tool core may have much time to remove the roughness peaks. So, more %age improvement in the surface finish was found. For tool core rotational speeds of 1500 rpm and 1900 rpm with a tool feed rate of 300 mm/min, the value of %age improvement in the surface finish decreases. The reason for this change is that at high tool core rotational speeds, the deformation of MR polishing fluid column take place due to the centrifugal force. At tool core rotational speeds of 300 and 700 rpm with a tool feed rate of 300 mm/min, the collision of abrasive particles with roughness peaks is reduced. Due to this, the chipping off the surface roughness peaks get reduced with a tool feed rate of 300 mm/min. But at the rotational tool core speed of 1100 rpm with a tool feed rate of 300 mm/min, the maximum %age improvement in the surface finish was achieved. This may due to the optimum collision between the active abrasive particles and surface roughness peaks were achieved at this combination.

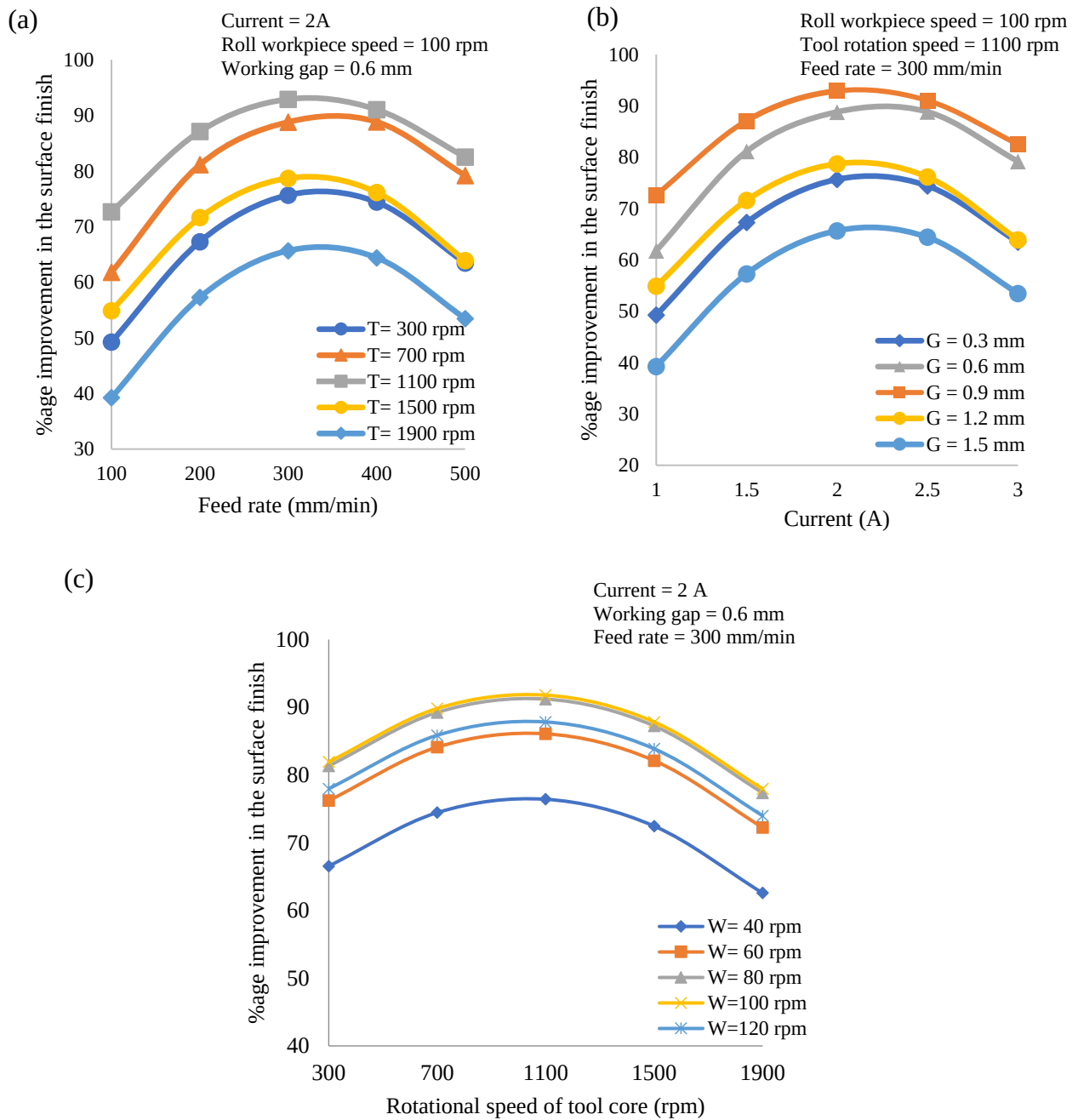


Fig. 5.4 (a) Effect of feed rate (F) at different tool core speeds (T) on %age improvement in the surface finish ($\% \Delta R_a$), (b) effect of current (I) at different working gaps (G) on %age improvement in the surface finish ($\% \Delta R_a$) and (c) effect of roll workpiece speed (W) at different tool core speeds (T) on %age improvement in the surface finish ($\% \Delta R_a$).

Fig. 5.4(b) represent the $\% \Delta R_a$ with respect to current and the working gap at the workpiece rotational speed 100 rpm, tool rotational speed 1100 rpm and feed rate of 300 mm/min. As the current increases, the $\% \Delta R_a$ increases up to around 2 A and after that, it starts decreasing as

the current increases. The main reason behind that the variation of $\% \Delta R_a$ with increasing current is due to the change of magnetic flux density in the working gap.

As the magnetizing current increases, the magnetic flux density strengthens which results in rising indentation force on the abrasive particles. When the current is increased beyond 2 A, the greater indentation force and shear force is acting on the active abrasive particles. The working gap governs the magnetic flux strength of the iron particles chains. At the higher working gap of 1.2 mm and 1.5 mm, the lesser %age improvement in the surface finish is observed as compared to the working gap values of 0.6 and 0.9 mm. The reason behind this is that the magnitude of magnetic flux density within the working gap decreases with the increase of the working gap. At the higher working gap, magnetic force (which also help iron particles to bind) acting between the two-carbonyl iron (CI) particles decreases due to the decrease in intensity of magnetization. But at the working gap of 0.3 mm, the magnitude of the magnetization is high, which not only removes the roughness peaks but also uproots excess material which results in pit formation (Mann *et al.*, 2018). Due to pit formation, there is decreased in $\% \Delta R_a$. The maximum %age improvement in the surface finish was achieved at the current of 2A and the working gap of 0.6 mm.

Fig. 5.4(c) represent the $\% \Delta R_a$ with respect to the rotational speed of tool core and the rotational speed of workpiece at the feed rate 300 mm/min, current 2 A and working gap as 0.6 mm. As the tool core rotational speed increases, the $\% \Delta R_a$ increases up to 1100 rpm and after that it starts reducing as the rotational speed of tool core increases. This type of variation in $\% \Delta R_a$ value is due to the rise in centrifugal force acting on iron particles with an increase in rotation of the tool core. The centrifugal force magnitude is not sufficient up to 1100 rpm, therefore $\% \Delta R_a$ increases. The centrifugal force acting on the iron particle chain increases beyond the 1100 rpm, which reduces the effect of a magnetizing force acting on iron particles in the working gap. Due to the reduction of magnetizing force on iron particles in the working gap, the indentation force acting on the abrasive particles is reduced which results in a reduction in $\% \Delta R_a$ at high tool rotation. As the workpiece rotation increases, the number of roughness peaks passing through the region of active abrasive particles increases. This results in an increase of stresses induced in the MR polishing fluid column due to an increase in the collision of peaks and abrasives. Deformation of MR polishing fluid column take place. The maximum %age improvement in the surface finish was obtained at 1100 rpm rotational speed of tool core and 100 rpm rotational speed of roll workpiece.

Percentage contribution tells about the percentage weightage of each parameter in the regression model of $\% \Delta R_a$ value. It was calculated from the ANOVA (Table 5.3). The

percentage contribution (%C) is the ratio of the sum of squares (S.S.) of each significant parameter to that of the total sum of square (T.S.S.) as given in Eq. (5.5).

$$\%C = \frac{S.S}{T.S.S} \times 100 \quad (5.5)$$

Percentage contribution of each significant parameter is calculated and their results are shown in Fig. 5.5. A bar chart is used to display the percentage share of each significant parameter and their interactions on the response during experimentation. The major contributing parameters are found as current with 20.77%, working gap with 15.07% and tool speed with 7.43% as shown in Fig. 5.5. The least but significant contributors are the feed rate and workpiece speed (Fig. 5.5).

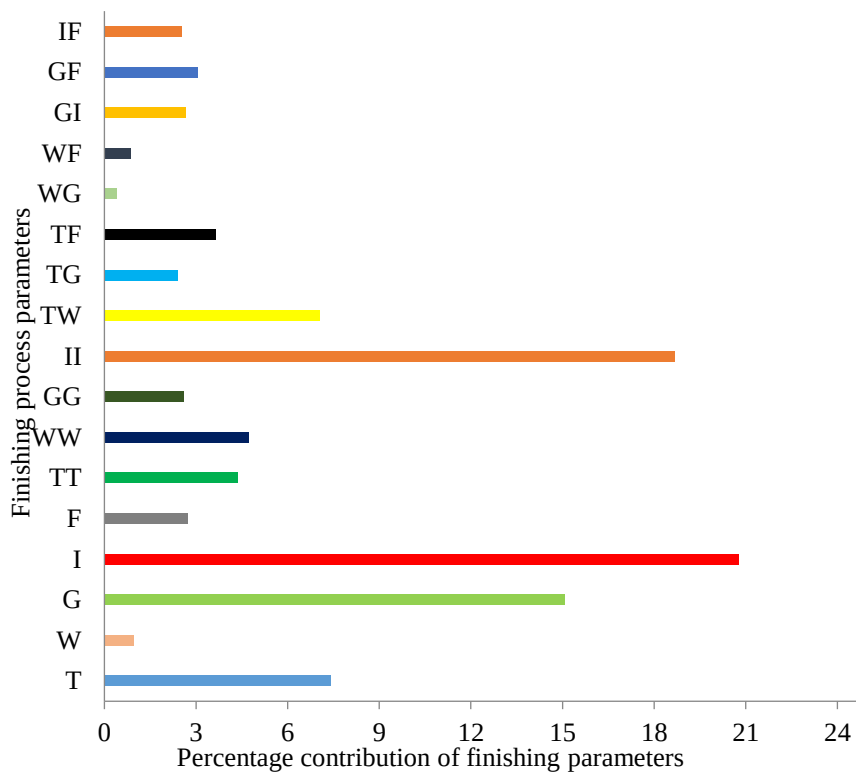


Fig. 5.5 Percentage contribution of the significant process parameters.

5.4.2 Process parameters optimization and validation

After the regression analysis, optimization of parameters was done to check for the best combination of parameters which gives the maximum %age improvement in the surface finish. In order to obtain the minimum value of R_a , the optimized quadratic mathematical model is obtained from the experimental data using Eq. (5.4) which would maximize the %age improvement in the surface finish ($\% \Delta R_a$).

Maximize $\% \Delta R_a$

Subjected to

$$300 \text{ rpm} \leq T \leq 1900 \text{ rpm}$$

$$40 \text{ rpm} \leq W \leq 120 \text{ rpm}$$

$$0.3 \text{ mm} \leq G \leq 1.50 \text{ mm}$$

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

$$100 \text{ mm/min} \leq F \leq 500 \text{ mm/min}$$

Optimum machining parameters were predicted based on the effects of process parameters on the %age improvement in the surface finish. From the quadratic mathematical model, the Eq. (5.4) is utilized to obtain the maximized value of %age improvement in the surface finish. The optimized parameters were found as tool rotation 1100 rpm, workpiece rotation 100 rpm, tool feed rate 300 mm/min and current 2 A, and working gap 0.6 mm for maximum %age improvement in the surface finish. The confirmatory test was carried out for checking the model accuracy. Three trials were carried out with the optimized parametric conditions. The $\% \Delta R_a$ was measured after experimentation and calculated theoretically from the regression Eq. (5.4). It can be seen that percentage error between the experimental and theoretical observation is in the range of -2.49% to 3.02% which shows the good agreement between regression model and experiments as reported in Table 5.4.

Table 5.4 Validation of regression model along with optimum values

Time (min)	Tool rotation (rpm)	Workpiec e rotation (rpm)	Working gap (mm)	Current (A)	Tool reciprocation (mm/min)	Experimental $\% \Delta R_a$	Predicted $\% \Delta R_a$ (Eq.5.4)	% error
60	1100	100	0.6	2	300	88.09	90.83	3.02
60	1100	100	0.6	2	300	91.38	90.83	-0.61
60	1100	100	0.6	2	300	93.09	90.83	-2.49

Further, MR finishing was performed on the external surface of the roll 20 mm (L1) finishing length and a diameter of 60 mm (D) with the optimized parameters for 60 minutes. The surface roughness value was reduced to 18 nm from the initial value of 200 nm in 60 minutes of MR finishing as shown in Figs. 5.6(a) and (b). After 60 minutes of MR finishing over the external surface of the roll, there was no significant improvement is observed with the same mesh number of the abrasive particles in MR polishing fluid. So, the MR finishing time is taken 60 minutes for the total finishing time evaluation. The waviness (W_a) value of the initial ground surface was measured as 0.2110 μm and the final surface waviness (W_a) value is found to be 0.0717 μm as measured by using Tylor Hobson profilometer after 60 minutes of the MR

finishing on 20 mm length of the roll surface with optimized parametric conditions, as depicted in Figs. 5.7(a) and (b), respectively.

The initial values of waviness root mean square (W_q) and a total height of profile (W_t) are found to be $0.2912 \mu\text{m}$ and $1.2322 \mu\text{m}$ respectively.

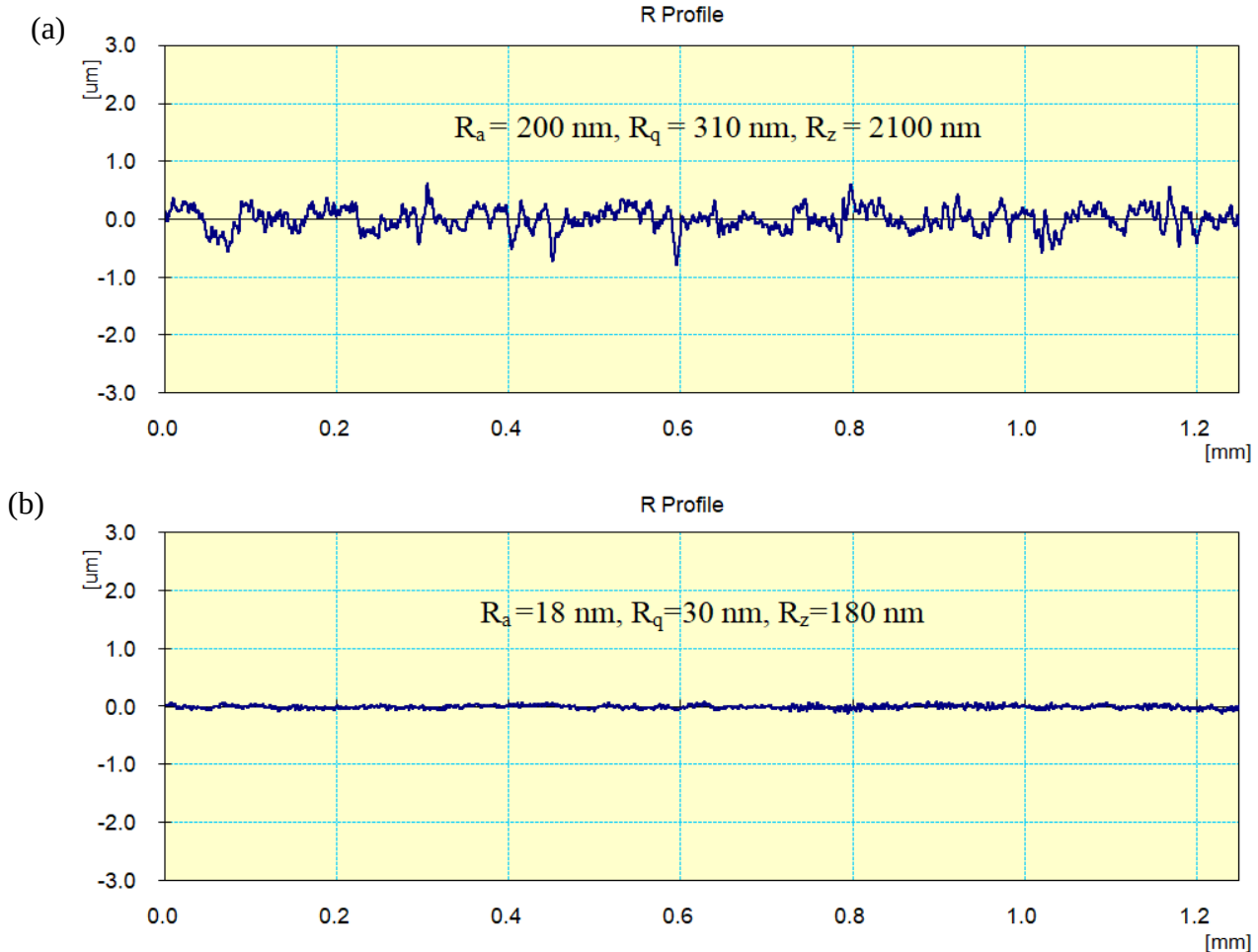


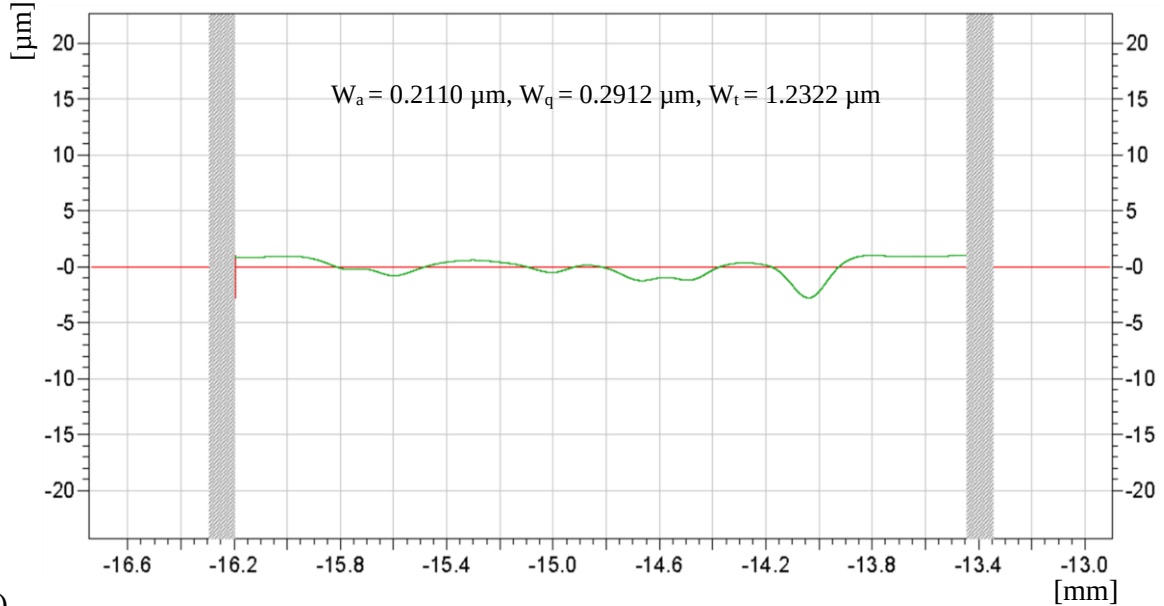
Fig. 5.6 Surface roughness profiles of roll workpiece (a) initial ground surface and (b) after 60 minutes of MR finishing with optimized parametric conditions on 20 mm length (L1) of the roll workpiece.

After 60 minutes of the MR finishing with optimized parameters, the final values of waviness root mean square (W_q) and a total height of profile (W_t) are found to be $0.0878 \mu\text{m}$ and $0.3204 \mu\text{m}$ respectively as shown in Figs. 5.7(a) and (b). Hence, the %age improvement in the W_a , W_q , and W_t was found as 66.01 %, 69.70%, and 73.99% after 60 minutes of MR finishing with optimized parameters on the external surface roll.

Scanning electron microscopy (SEM) images of cold rolling roll surface before and after the present MR finishing over 20 mm length are shown in Figs. 5.8(a) and (b). From Fig. 5.8(b) it can be seen that grinding lays has been removed and a smooth surface is obtained. The corresponding mirror images on the cold rolling roll surface before and after 60 minutes of MR

finishing over 20 mm length is shown in Fig.5.8(c) which shows better improvement in surface quality.

(a)



(b)

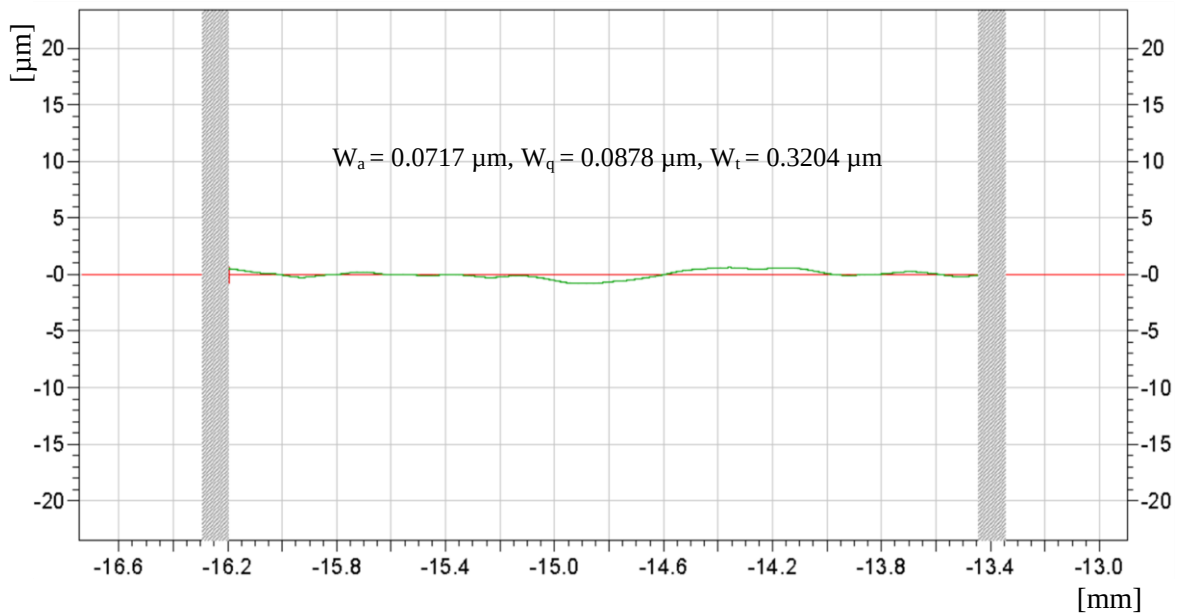


Fig. 5.7 Waviness profiles of roll workpiece (a) at initial ground surface and (b) after 60 minutes MR finishing operation with optimized parametric conditions on 20 mm length (L1) surface of the roll.

5.4.3 Industrial application for MR finished rolls surface in cold rolling process

Further, the optimized parameters were utilized to finish the entire external surface length (L₂) of the cold rolling rolls (Fig.5.1) for its industrial application. Main advantages of the cold

rolling process are to provide better dimensional correctness and superior surface finish on final squeezed products. The cold rolling process is dependent on the rolls.

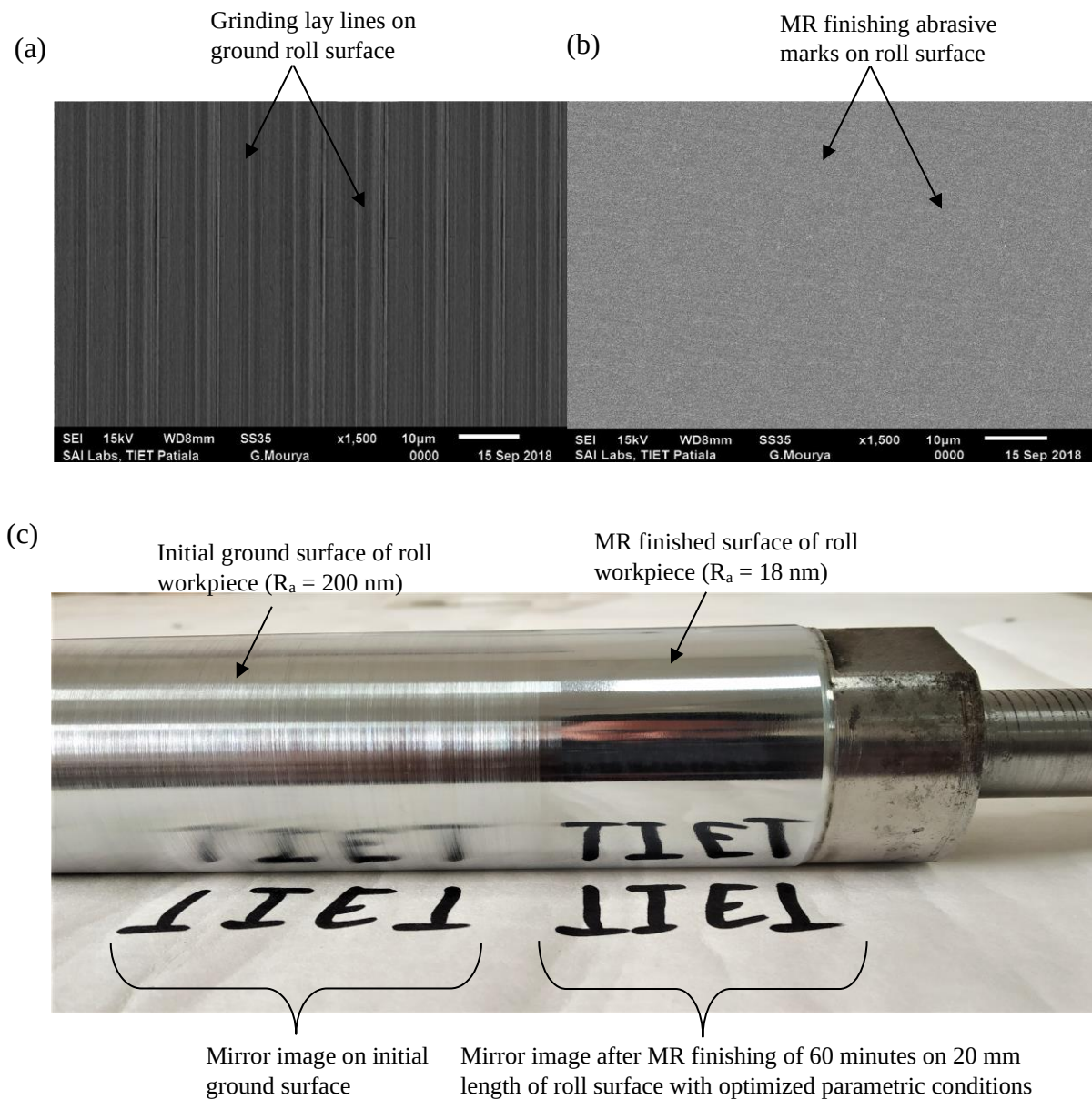


Fig. 5.8 Scanning electron microscopy (SEM) images of (a) initial ground roll surface, (b) MR finished roll surface and (c) mirror images of on the initial ground surface and after 60 minutes of the present MR finishing process over 20 mm length (L1) of the roll surface.

5.4.3.1 Calculation of time required to finish the entire surface of rolls with optimized parameters

The time required to finish the entire external surface of the industrial cold rolling roll is estimated by scaling out the time from the aforesaid experimentation over the 20 mm length of the cold rolling roll surface. The scaling of the time to finish the entire surface of the roll is

done with respect to the results of surface roughness as obtained 18 nm over 20 mm length in 60 minutes of the MR finishing with the optimized parameters. Fig. 5.8(c) shows the evaluated finish length of 20 mm (L_1) during experimentation with the optimized parameters in 60 minutes of the MR finishing. This has been taken as the reference to calculate the required MR finishing time for obtaining a R_a value of 18 nm over the entire roll surface length (L_2) with the optimized parameters. The evaluated reference finish surface area (A_1) of the cylindrical roll is calculated from Figs.5.1 and 5.8(c) using Eq. (5.6).

$$A_1 = \pi D L_1 \quad (5.6)$$

Where A_1 is the evaluated finish surface area of the cylindrical roll in mm^2 for R_a value of 18 nm in 60 minutes time with the optimized parameters, D is the diameter of cylindrical roll in mm and L_1 is the evaluated length of the cylindrical roll in mm. For $D = 60$ mm and $L_1 = 20$ mm, the of the surface area (A_1) of the roll is calculated as 1200 mm^2 . The MR finishing process has been taken 60 minutes to finish the cylindrical workpiece surface area (A_1) up to 18 nm with optimized parameters. Therefore, to finish the entire surface length of the industrial roll (L_2) (Fig. 5.1), the surface area (A_2) is calculated using Eq. (5.7).

$$A_2 = \pi D L_2 \quad (5.7)$$

Where A_2 is the full surface area of the industrial cylindrical roll to be finished in mm^2 , D is the diameter of cylindrical roll in mm and L_1 is the full length of the cylindrical roll in mm. For $D = 60$ mm and $L_2 = 240$ mm, the surface area (A_2) of the industrial cylindrical roll is calculated as $14,400 \text{ mm}^2$.

Total finishing time (T) required to finish the entire surface area (A_2) of the roll surface up to 18 nm is evaluated using the Eq. (5.8).

$$T = \frac{A_2}{A_1} \times \text{time taken to finish the surface area } A_1 \quad (5.8)$$

The time taken to finish the surface area A_1 up to 18 nm was 60 minutes with the optimized parameters. Therefore, to finish the entire surface area (A_2) of the cold rolling roll up to the roughness value of 18 nm with the optimized parameters, the finishing time using Eq. (5.8) was calculated as 12 hrs. So, again the present MR finishing was performed on the entire surface area of the two rolls surface for 12 hrs each with the optimized parametric conditions.

5.4.4 Improvement in functional application of MR finished cold rolls surface

The mirror images of the entire surface of the one of the rolls before and after the 12 hrs MR finishing are shown in Figs. 5.9(a) and (b). The results showed that uniform reflection of the letter ‘TIET’ over the entire MR finished roll surface ($R_a = 18$ nm).

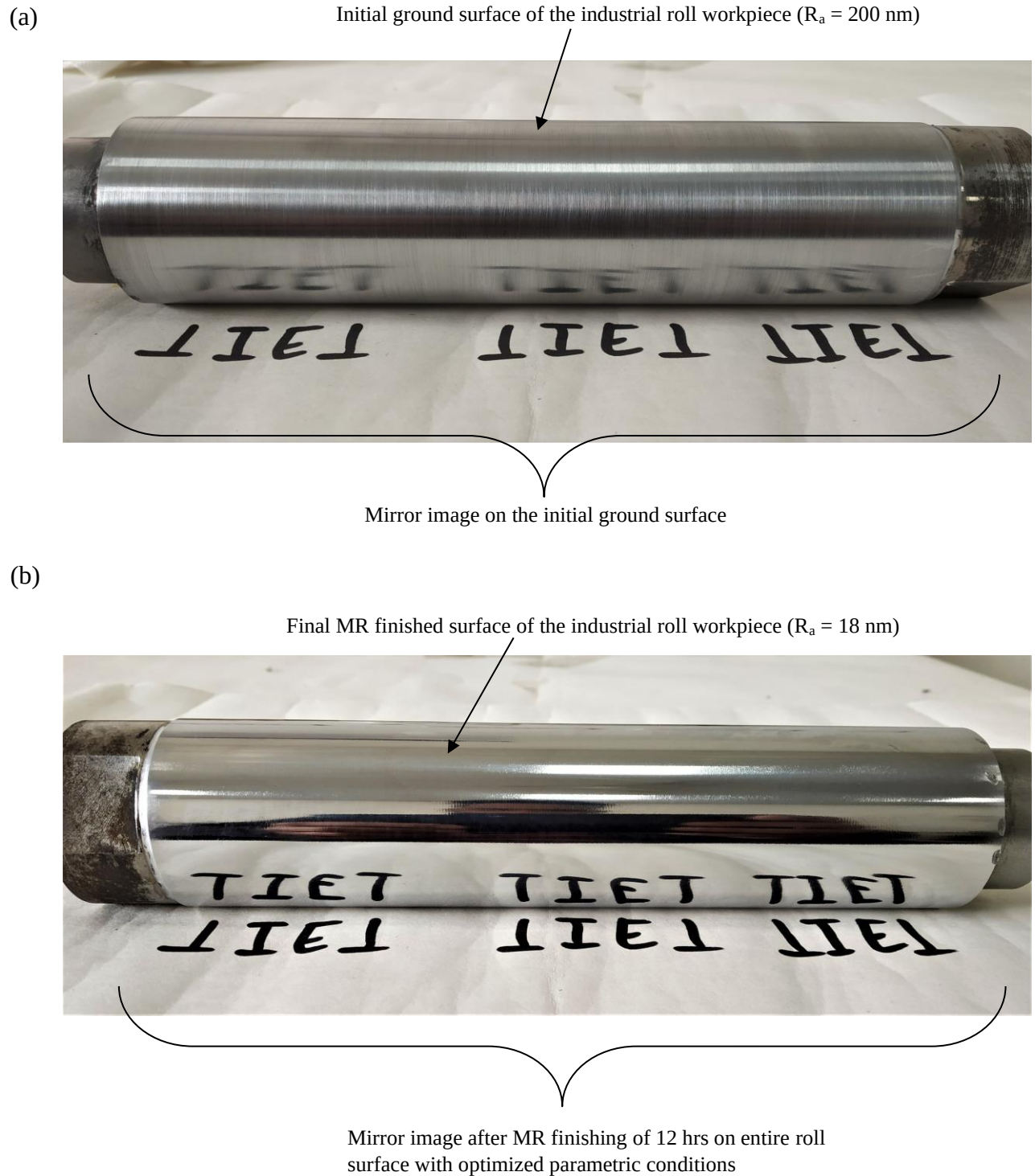


Fig. 5.9 Mirror images of the (a) initial ground roll surface and (b) after the MR finishing of 12hrs on the entire roll surface with optimized parameters.

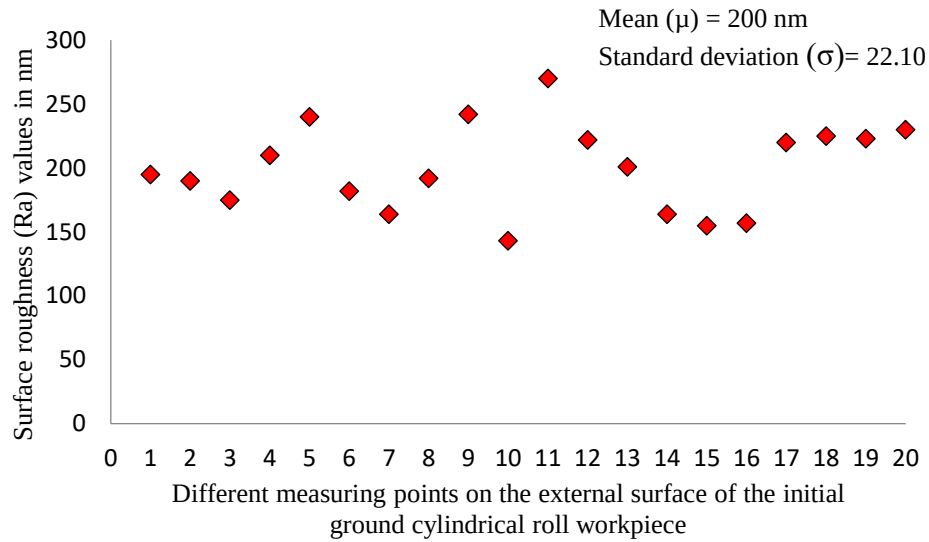
Also, the mean (μ) and standard deviation (σ) values of the 20 measured R_a values over the entire initial ground surface and MR finished external surface of the industrial cold roll workpiece are evaluated by the Eqs. (5.9) and (5.10).

$$\mu = \frac{y_1 + y_2 + y_3 \dots + y_n}{N} \quad (5.9)$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \mu)^2} \quad (5.10)$$

Where, μ is the mean of total measured R_a values of $y_1, y_2, y_3 \dots y_n$ on the external surface of the cold rolling roll. N is the number of measured R_a value readings (i.e. 20) on the external surface of the roll. σ be the standard derivation.

(a)



(b)

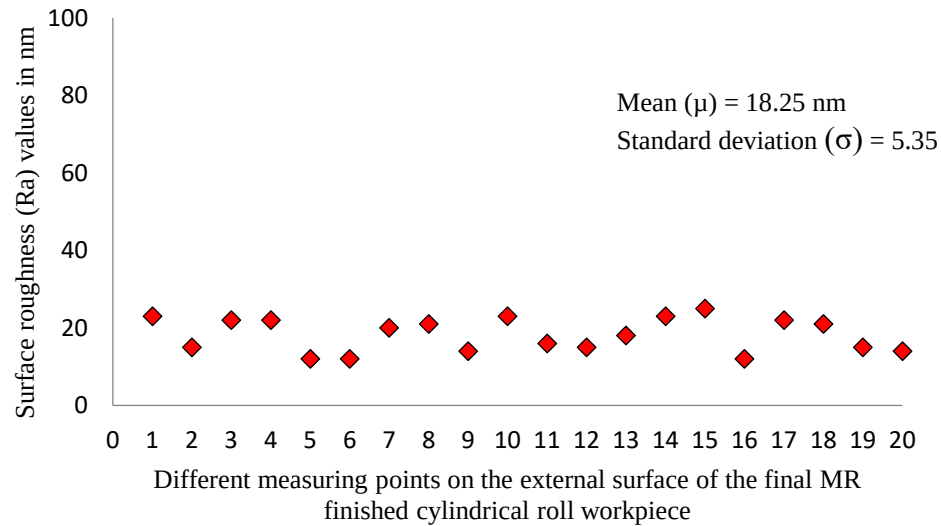


Fig. 5.10 Plot between the surface roughness values at different measuring points on entire length surface of the industrial roll workpiece to determine the mean (μ) and standard deviation (σ) (a) initial ground surface, and (b) after 12 hrs MR finished surface with optimized parametric conditions.

The surface roughness values on the initial and MR finished external surface of the roll workpiece is measured on 20 measuring points. The mean and standard deviation is evaluated

for 20 measured values. Putting these measured values from measuring points in Eq. (5.9) and the mean value is obtained as 200 nm for the initial ground roll surface.

The standard deviation value is evaluated from Eq. 5.10. The standard deviation for the initial ground external surface is found to be 22.10 as depicted in Fig. 5.10(a). After the present MR finishing, the mean and standard deviation values are found to be 18.25 nm and 5.35 respectively as depicted in Fig. 5.10(b). The mean and standard deviation values of the initial ground surface (200 nm and 22.10) and after the MR finishing of the external roll surface (18.25 nm and 5.35) proves more uniformity in MR finished surface has been achieved.

The cold rolling operation has been performed with before and after MR finished rolls. Before MR finished i.e. ground rolls surface which is already used in industry after the grinding operation. The MR finished rolls were used for the same rolling operation at the same working conditions. The cold rolling rolls after each 12 hrs MR finishing were taken to the industry Vaid Engineering New Delhi, India to check their functional performance in the cold rolling process. The parameters such as force, torque, and power consumption were analysed and compare the results for both before and after MR finished rolls surface.

The improvement in the surface characteristics of the rolls improves its functional life. When the surface characteristics of the rolls improve, the working force can decrease during the rolling operation. The surface roughness value directly affects the coefficient of friction factor. As the value of the coefficient of friction factor changes, the working forces are also changed. This affects the functional operation and efficiency of the rolling process.

The correlation between the roll force (P_r) and the frictional force (F_f) is given in Eq. (5.11) (Lenard, 2014).

$$\mu = \frac{F_f}{P_r} \quad (5.11)$$

Where μ is the friction coefficient factor between the roll surface and the flat strip surface, F_f is the frictional force in Newton and P_r is the roll separating or roll force in Newton. From the Eq. (5.11), it can be observed that when the value of the friction coefficient factor is reduced, the frictional force can also be reduced. The friction coefficient factor depends on the surface finish of the rolls. The coefficient of friction factor was measured with coefficient friction tester at the ground surface and MR finished surface. At the initial ground surface roughness value (200 nm), the coefficient of friction factor (μ) was measured as 0.075. After MR finishing, the R_a value was reduced to 18 nm and correspondingly the coefficient friction factor (μ) was measured as 0.010.

Average flow strength, σ_{fm} in Pa is obtained by Eq. (5.12) (Lenard, 2014).

$$\sigma_{fm} = \frac{1}{\varepsilon_{max}} \int_0^{\varepsilon_{max}} \sigma_r(\varepsilon_0) d\varepsilon_0 \quad (5.12)$$

Where ε_{max} is the maximum strain during the rolling pass, and σ_r and ε_0 is stress and strain during the rolling pass.

From the Schey's model, roll force (P_r) is obtained by Eq. (5.13) (Lenard, 2014).

$$P_r = 1.15 Q_p \sigma_{fm} L_c \quad (5.13)$$

Where Q_p is the pressure intensification factor, σ_{fm} is the average flow strength and L_c is the contact length of rolls in m.

At the measured coefficient of friction factors for the ground and MR finished surfaces, the roll force is calculated using the Eq. (5.13). The pressure intensification factor (Q_p) is dependent on shape factor and frictional force in the roll gap. As the coefficient of friction factor value increases, the frictional force is increased (Hausen and Egberts, 2018) between the roll surface and flat strip surface. On the basis of coefficient friction factor, the roll force (P_r) is found to be 6301.36 N at initial ground surface with the help of Eq. (5.13). On the MR finished surface, the roll force (P_r) is found to be 5388.12 N by using the Eq. (5.13).

The torque (M_a) to drive both rolls on per unit width of the flat rolling strip is calculated by Eq. (5.14) (Lenard, 2014).

$$M_a = \frac{P_r L_c}{2} \quad (5.14)$$

Where M_a is the torque per unit width in Nm and P_r is the roll force in N.

After calculating the rolling force, the rolling torque is calculated by putting the force values in the Eq. (5.14). For both ground and MR finished surfaces, the roll torque is calculated as 35.50 Nm and 29.50 Nm respectively. From the Eq. 5.14, it is clear that the torque is directly proportional to the roll force. As the roll force decreases, the torque is also reduced for MR finished rolls surface.

The essential power required for plastic deformation of the flat strip is calculated by using the Eq. (5.15) (Lenard, 2014).

$$P = 2 \pi N_r P_r L_c \quad (5.15)$$

Where P is the essential power required for plastic deforming the flat strip in J/s or W and N_r is the rolls rotational speed in rpm.

The essential power required for plastic deformation of the flat strip is evaluated as 12.13 kW and 10.27 kW for ground and MR finished surfaces, respectively.

To evaluate the driving power of the rolls, firstly calculate the power loss due to the friction induced in the two rolls neck bearings (P_n). The power loss due to the friction induced in the two rolls neck bearings is evaluated by Eq. (5.16) (Lenard, 2014).

$$P_n = \mu_n P_r w' d N_\theta \quad (5.16)$$

Where μ_n is the coefficient of friction factor which induced in the bearings roll, w' is the width of the flat strip in m. d is the bearing diameter in m, and N_θ is the rolls angular rotation in rpm. P_n is the power loss due to the friction in the two rolls neck bearings and evaluated for both ground and MR finished surfaces with the help of the Eq. (5.16). The values of power loss due to the friction in the bearings are found to be 9.117 kW and 7.796 kW for the ground and MR finished rolls surfaces, respectively.

The total power required to operate the rolls is evaluated by Eq. (5.17) (Lenard, 2014).

$$P_{total} = \frac{1}{\eta_m \eta_t} (2P + 2P_n) \quad (5.17)$$

Where P_{total} is the total power consumption to operate the rolls, η_m is the driving motor efficiency, η_t is the transmission efficiency, P is the essential power required for plastic deformation of the flat strip in kW, P_n is the power loss due to the friction in the bearings in kW. The calculated values of the essential power required for plastic deformation of the flat strip (P) and the frictional power loss in the supportive bearings (P_n) are used in Eq. (5.17). The efficiency of driving motor and the transmission are considered to be 0.87 and 0.85 respectively (Lenard, 2014). The total power required (P_{total}) is found to be 57.462 kW for driving the ground rolls surface and 49.130 kW for driving the MR finished rolls surface, respectively. From the power consumption of the rolling machine, the one-day consumption is calculated. Assume that the machine is working 12 hours per day.

$$\text{Electricity (Energy)} = \text{Power} \times \text{Time} \quad (5.18)$$

$$\text{Daily units} = \frac{(\text{Wattage} \times \text{usage hours per day})}{1000} \quad (5.19)$$

$$\text{Monthly units} = \text{Units} \times 30 \quad (5.20)$$

First, calculate the 1-unit energy consumption. 1-unit is represented in kWH or Kilowatt Hour. This is the actual electricity or energy is used. The one-day consumption is calculated for operating the ground rolls surface and the MR finished rolls surface. The consumption units are found in both the cases and calculated the per hours consumption in INR (Indian rupees) from the Eqs. (5.18) and (5.19). The INR 45 per hour power consumption is to be found for the ground rolls surface which is already used in the industry. The INR 36 per hour power consumption is to be found for the MR finished rolls surface. The total INR 9 per hour power

consumption is saved with the MR finished rolls surface in comparison to the ground rolls surface. The monthly consumption of units is calculated from the Eq. (5.20). The cost of monthly power consumption of the electricity is to be found as INR 16200 for operating the ground rolls surface in the cold rolling process. While with the MR finished rolls surface, the cost of monthly power consumption of the electricity is to be found as INR 12960. Therefore, in a month, the total saving is approximately estimated as INR 3240. The total saving in a year is approximately estimated as INR 38880.

After examining the cost-effectiveness with the use of MR finished rolls surface, the final product properties were examined as produced from the use of MR finished and ground rolls surface. The surface roughness value of the final products from the use of ground finished rolls surface was measured which lies in between the 340-365 nm. When MR finished rolls surface were used, the surface roughness value of the final products gets lies in between the 300-330 nm. Hence, the MR finishing of the external surface of the rolls in a cold rolling process improves the surface quality of the final products. The low surface roughness value improves the fits and tolerances. This helps in providing exact final dimensions of the products. Thus, MR finishing is extremely beneficial for industrial applications in cold rolling processes for improving their functional applications. The use of MR finished rolls surface helps in saving power consumption and also improves the functional life of the final products. Thus, the magnetorheological (MR) finishing of the external surface of rolls improves its functional life and save power consumption which makes the cold rolling process more economical and effective.

5.5 Conclusions

A rectangular-rotating tool core tip based magnetorheological (MR) finishing process is used to finish the industrial rolls (H13 die steel material) external surface which uses in the cold rolling process. Response surface methodology with the central composite statistically design the experiments and analyse the effect of influencing process parameters on the %age improvement in the surface finish. This further predicts the optimum process parameters for effectively finishing the H13 die steel rolls surface with the present MR finishing process. The improvement in function performance of the MR finished rolls surface in the cold rolling process confirms while it uses in industry in comparison with the ground rolls surface. The following conclusions show the effectiveness of the MR finished rolls surface in improving the efficacy of the cold rolling process.

- The regression analysis with response surface methodology reveals the effective improvement in the surface finish of the H13 die steel rolls surface with the optimized

parameters as current 2 A, working gap 0.6 mm, tool rotation 1100 rpm, roll workpiece rotation 100 rpm and tool reciprocating feed 300 mm/min. Also, MR polishing fluid realized its effectiveness with 30% carbonyl iron particles (600 mesh number), 15% SiC abrasives (800 mesh number) and 55% oil-based carrier fluid.

- The surface roughness of the MR finished industrial rolls gets significantly reduced to 18 nm from 200 nm. The surface waviness also gets reduced to 0.0717 μm from 0.2110 μm . The mean and standard deviation of the external surface of the rolls after the MR finishing gets significantly reduced. The surface characteristics of MR finished rolls show a great improvement in comparison to the ground rolls surface as the surface becomes smooth after the removal of grinding lays.
- The reduction in surface roughness value from 200 nm to 18 nm on rolls surface with the present MR finishing process confirms the reduction in roll force, roll torque and power consumption during their functional application in cold rolling process. The MR finished rolls surface with the present MR finishing process predicts the cost of power saves approximately INR 38,800 per year for their operation in the cold rolling process.
- The overall results reveal the more usefulness of the MR finished rolls surface for improving the efficacy of the industrial cold rolling process and enhancing the surface quality of the final products with the reduced cost.

5.6 Magnetorheological finishing of micro-punches for enhanced performance of micro-extrusion process

In modern industries, the demand for product miniaturization is increased significantly. In electronic and mechanical industries, the demands for minuscule metal parts have increased due to the product miniaturization. For the micro-extrusion process, the micro-punches are used. Micro-punch material has properties like good high toughness, wear and tear resistance, oxidation resistance, and good hardness. The micro-punch is fully penetrating into the billet and whole surface area is contact to the billet surface. The better surface characteristics of micro punches reduce the frictional forces and provides more uniform deformation of billet material. For micro extrusion, the achievable form accuracy is influenced by the grain size and its distribution in the blank that is to be extruded, and the friction conditions between the contact surfaces of the billet and micro-punch. The distortion of extruded micro parts is caused by irrational local deformation, spring back effect and interfacial friction between billet and micro-punch. The spring back effect, local deformation, and interfacial friction are size-dependent, so as the size of the billet is reduced the accuracy is decreased as expected.

The friction coefficient has important role in the extrusion process. The increase of friction coefficient significantly increases the required punch load (Olguner and Bozdana, 2016). It has been observed that the increase of friction coefficient from 0 to 0.25 results an increase in punch load 30% approximately (Olguner and Bozdana, 2016). The working of the micro extrusion operation is depicted in Fig. 5.11. Due to handling difficulties (small size of micro-punches), the micro punches are difficult to be finished. The nano-finishing of micro-extrusion punches is helpful in reducing frictional forces between the punch external surface and the billet material surface which is useful for the uniform deformation of the billet material.

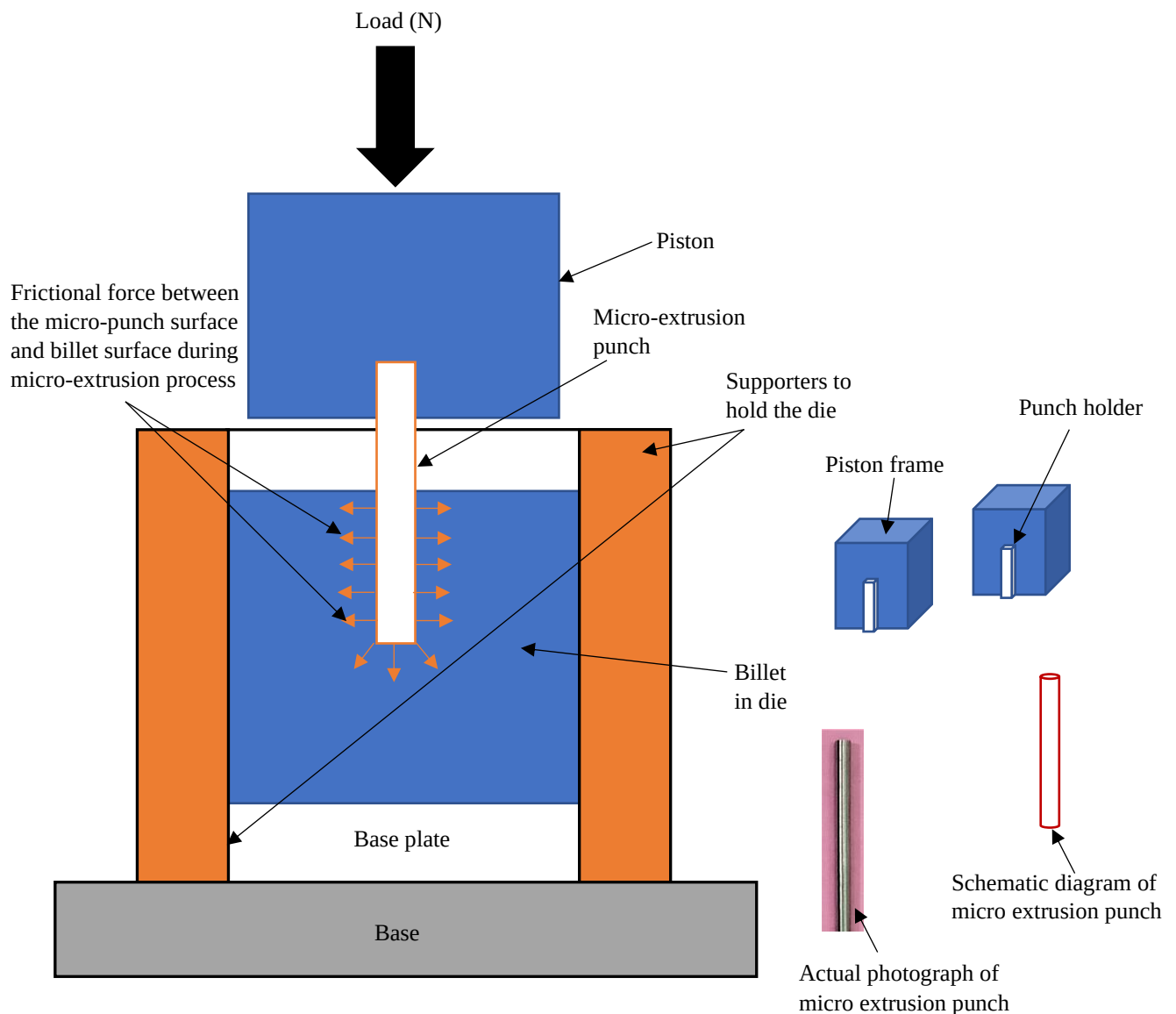


Fig. 5.11 Schematic diagram of working of extrusion process with micro extrusion punch.

The analysis is observed the performance effect of the fine finishing on the micro-punch and their effect of on extrusion force. Before and after MR finishing, the micro-extrusion punches are examined for its improved performance in the micro-extrusion process. Micro-extrusion

process has a various industrial application like micro fabrication of various shapes, micro die fabrication, and micro punching fabrication as depicted in Figs. 5.12(a), (b) and (c), respectively. The micro-die fabrication is useful for producing the minuscule components in the electronic and mechanical industries (McGeough, 2002).

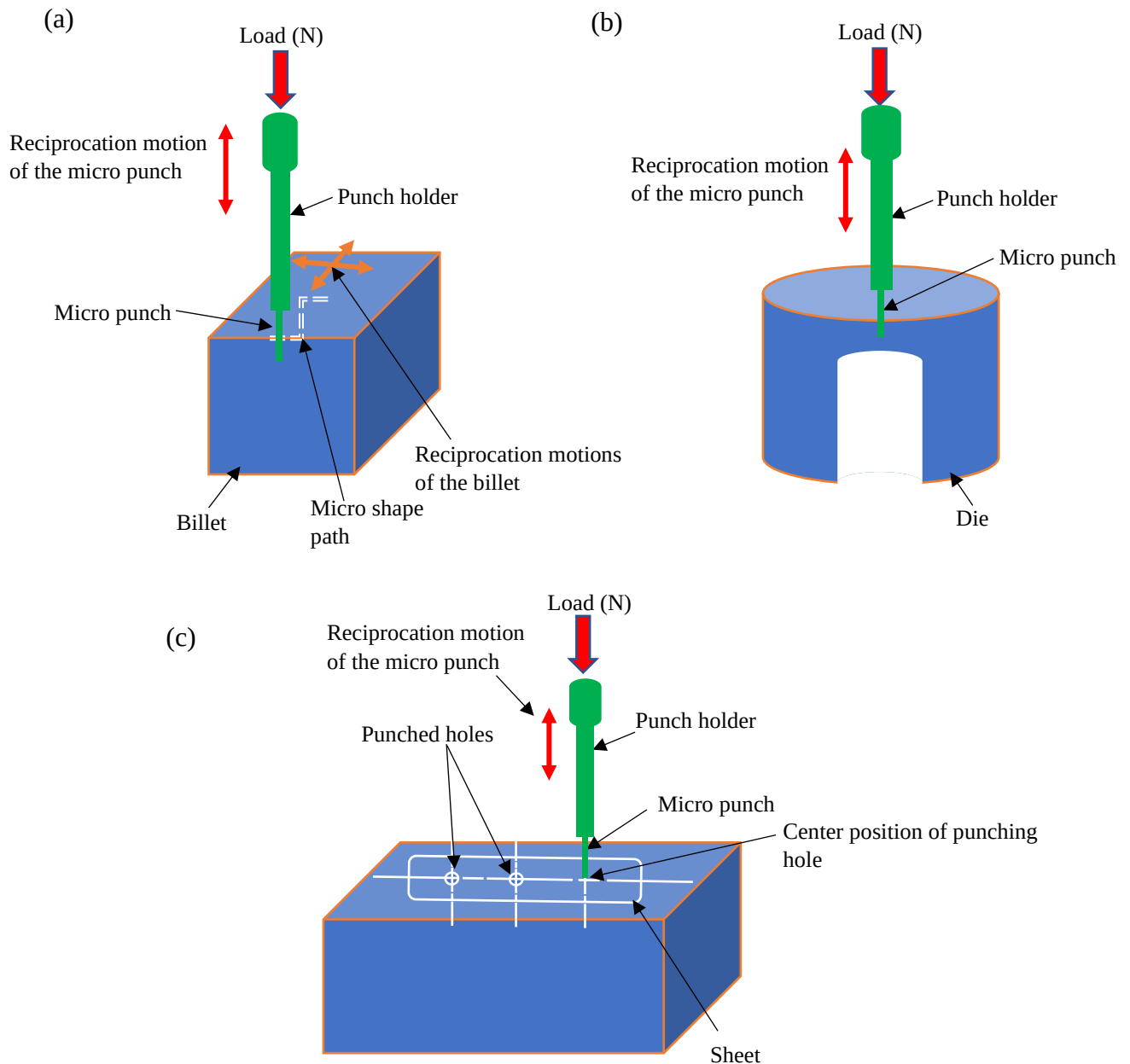


Fig. 5.12 Schematic diagram of the micro extrusion punch applications (a) micro shapes fabrication, (b) micro die fabrication, and (c) micro punching.

The micro punching is used in the electronic industries to produce the circuit boards and also useful for the mechanical industries. Improving the surface topography of the micro extrusion punches through the MR finishing process, help in reducing the extrusion frictional forces and also improving the dimensional accuracy of the final product.

5.7 Materials and methods

The deformation of the billet or raw material takes place with the help of micro-extrusion punch. The micro-extrusion punches are hard and tough in nature. The micro-extrusion punches are made of tungsten carbide. The tungsten carbide has impressive mechanical properties such as high hardness value at higher working temperature, good toughness, and good wear resistance. Different diameter micro-extrusion punches are utilized for different applications. These punches are fulfilling the various industrial applications. The four punches are taken from the metal forming industry and utilized as a workpiece for experimentation. The actual dimensions (diameter and length) and holding length of the micro-punches are shown in Fig. 5.13. These punches have diameters of 3.5 mm, 2 mm, 1.5 mm, and 1.2 mm (Fig. 5.13). The present process setup which is employed in nano-finishing the outer surface of the micro-extrusion punches as depicted in Fig. 5.14 (a). The micro-punch workpiece is held in a straight line with the help of drill chucks as depicted Fig. 5.14(b). For experimentation, the finishing process parameters were preferred on the basis of the previous research on the same setup and preliminary experimentation. The workpiece holding fixture is fabricated. The fixture has a wooden base, four plumber blocks, two cylindrical shafts to hold the drill chucks and nut and bolts to clamp the plumber blocks to the wooden base. The drill chucks are screwed with the cylindrical shafts and these shafts further locked to plumber blocks. The rotary motion is provided to the cylindrical shaft through the belt pulley drive as depicted in Fig.5.14(a).

The important parameters are the speed of both tool core and the micro-punch workpiece, reciprocatory movement of the tool core tip surface, and the working space between the tool core tip surface and outer surface of the micro-punch. Total finishing time for the experimentation is decided from the preliminary experimentation. The total finishing is carried out for 60 minutes. From the preliminary experimentation, it is clear that after the 60 minutes there is no significant improvement in the surface roughness with these selected parameters. The experiments are performed on the four micro-extrusion punches. These punches are collected directly from the industry. The finishing is performed on the 30 mm length of the punches. After 20 minutes, the MR polishing fluid is changed during the experimentation.

This was done due to that after the 20 minutes the active abrasives cutting edges are blunted. So, to get the fresh cutting edges the MR polishing fluid is changed after 20 minutes. Before and after finished outer surfaces of the micro punches are evaluated to know the parameters of the surface roughness (R_a , R_q , and R_z). These parameters of the surface roughness are evaluated by dealing with the surface roughness tester (surftest). To determine the surface topography of the micro punches external surfaces, the scanning electron microscopy (SEM)

and mirror image test were conducted. Further, after the MR finishing, the operative functionality of the micro-punch is examined in micro-extrusion process. The frictional force between the micro-punch surface and the billet with effect of decrease in the roughness values as well as improvement in the surface topography have been analysed. Fig. 5.15 shows the micro-extrusion process. The Fig. 5.15(a) shows the starting phase of the micro-extrusion process and Fig. 5.15(b) shows the final phase of the micro-extrusion process.

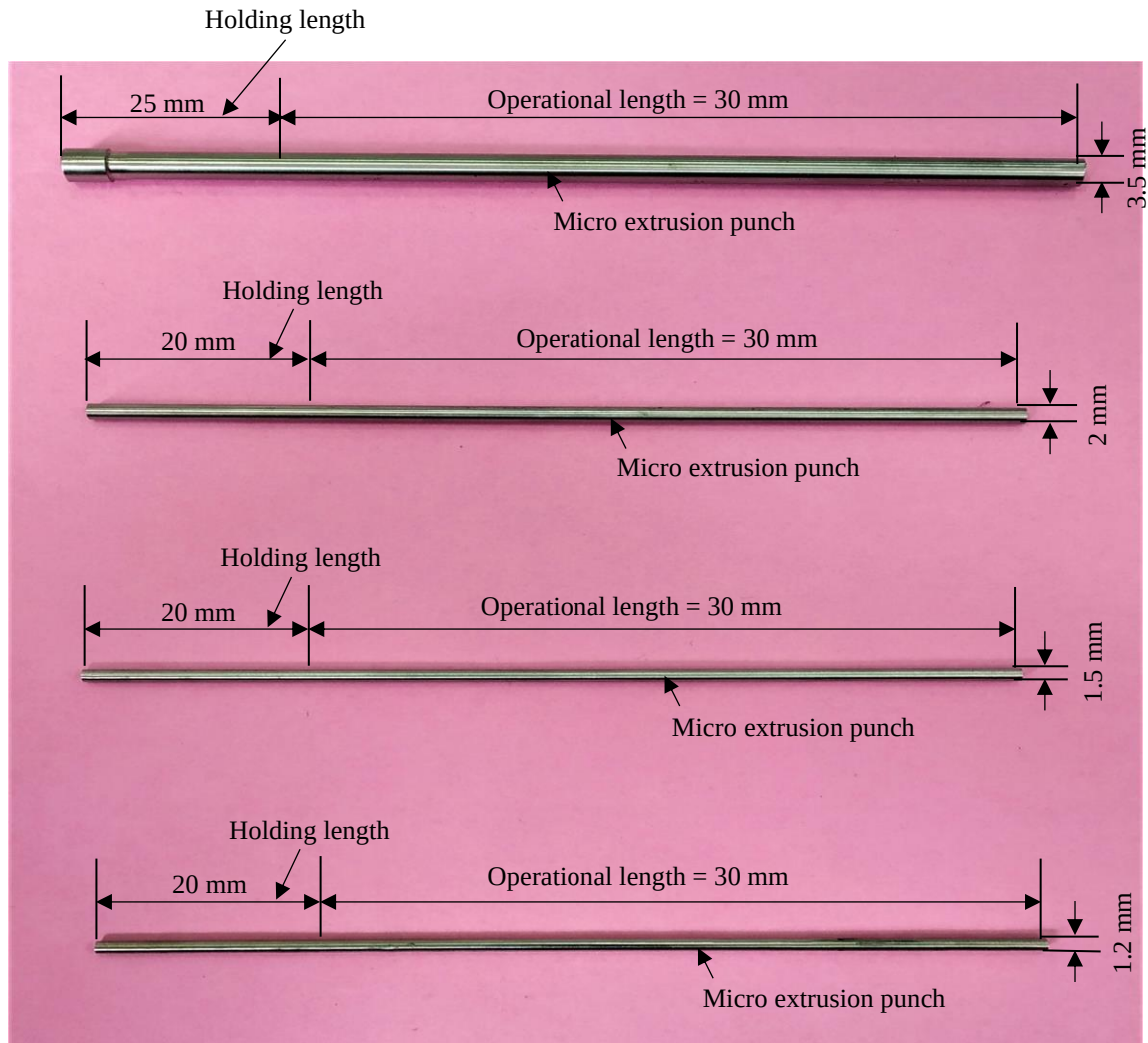


Fig. 5.13 Actual photographs of micro extrusion punches with actual dimensions.

5.8 Results and discussion

The surface roughness (R_a) values were reduced from the initial values of the four micro punches are 0.210, 0.230, 0.250 and 0.200 μm to the final finished values of 0.02, 0.02, 0.03, and 0.01 μm in 60 minutes of the MR finishing as shown in Fig. 5.16. The total finishing is done in three cycles, each cycle took 20 minutes.

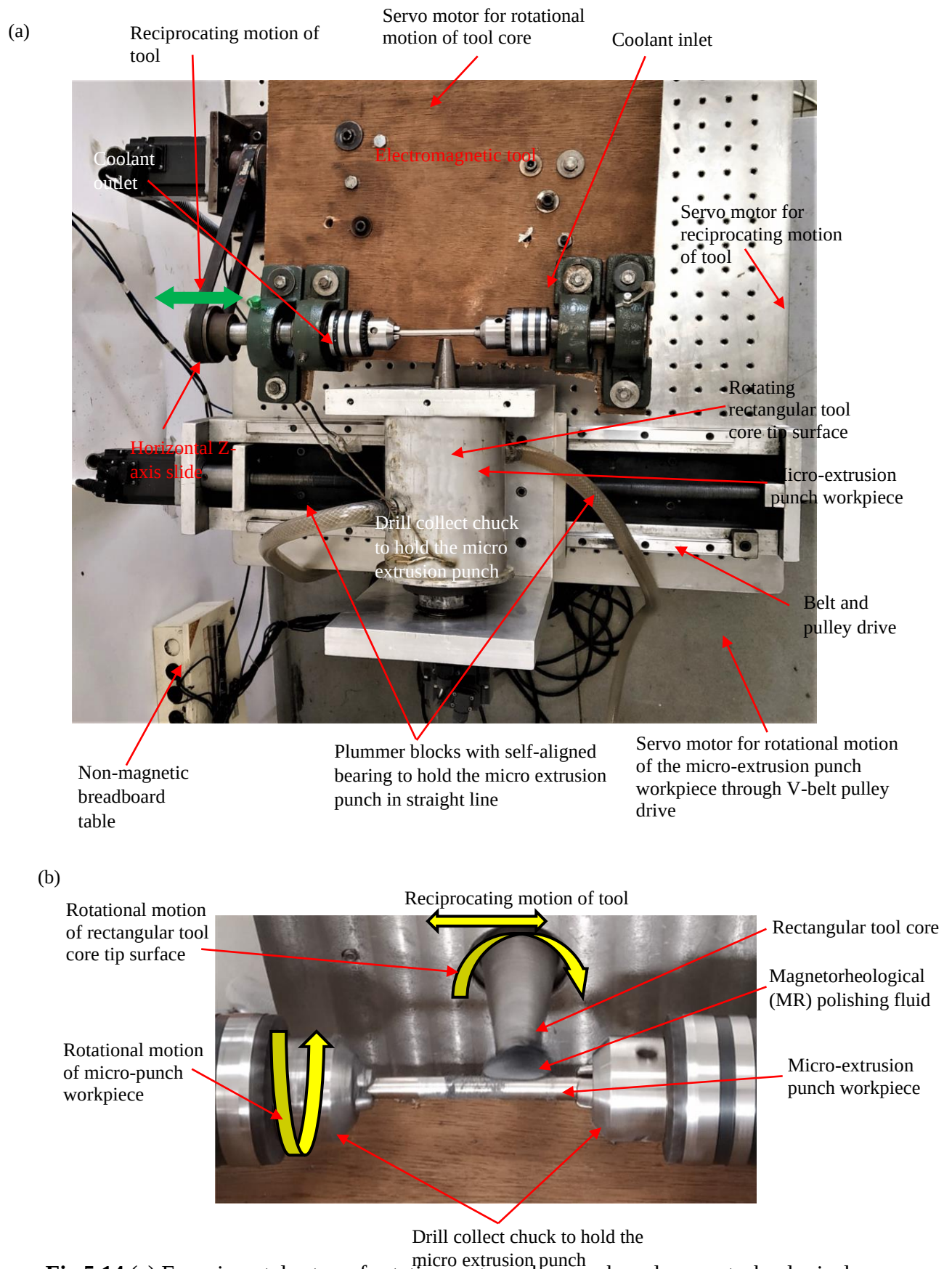


Fig.5.14 (a) Experimental setup of rotating rectangular core based magnetorheological finishing process with micro extrusion punch workpiece and (b) MR finishing of the micro-punch workpiece.

In the first finishing cycle, the R_a values were reduced from the initial values of 0.210, 0.230, 0.250, and 0.200 μm to 0.09, 0.09, 0.10, and 0.06 μm respectively. The R_a values are reduced in the second and third finishing cycle lesser compared to first finishing cycle. In second finishing cycle the R_a values were reduced from 0.09, 0.09, 0.10, and 0.06 μm to 0.04, 0.04, 0.05, and 0.02 μm . In third finishing cycle, the R_a values were reduced from 0.04, 0.04, 0.05, and 0.02 μm to 0.02, 0.02, 0.03, and 0.01 μm respectively.

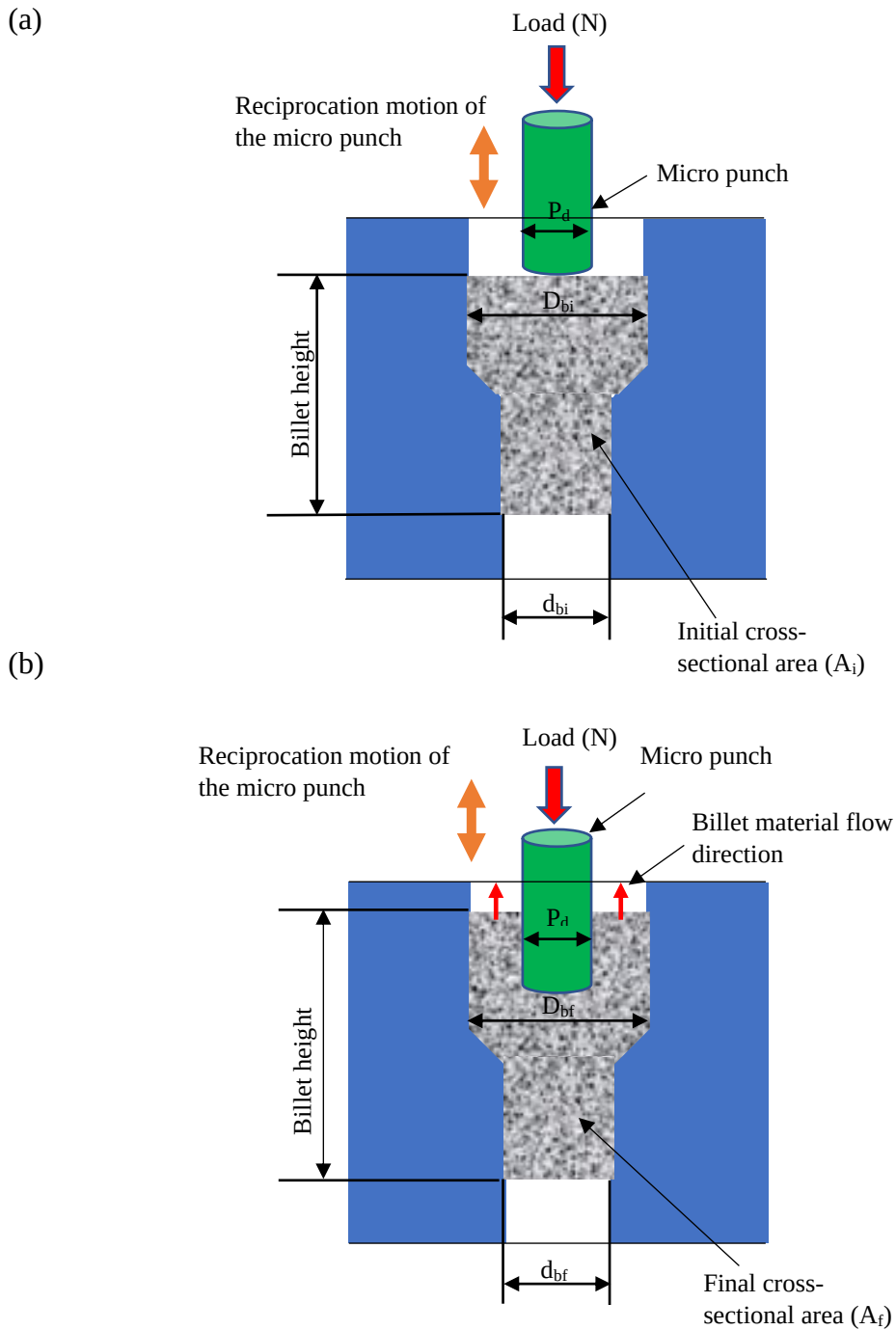


Fig. 5.15 (a) Position when micro-punch approaches the billet material and (b) deformation of billet material during micro-extrusion process.

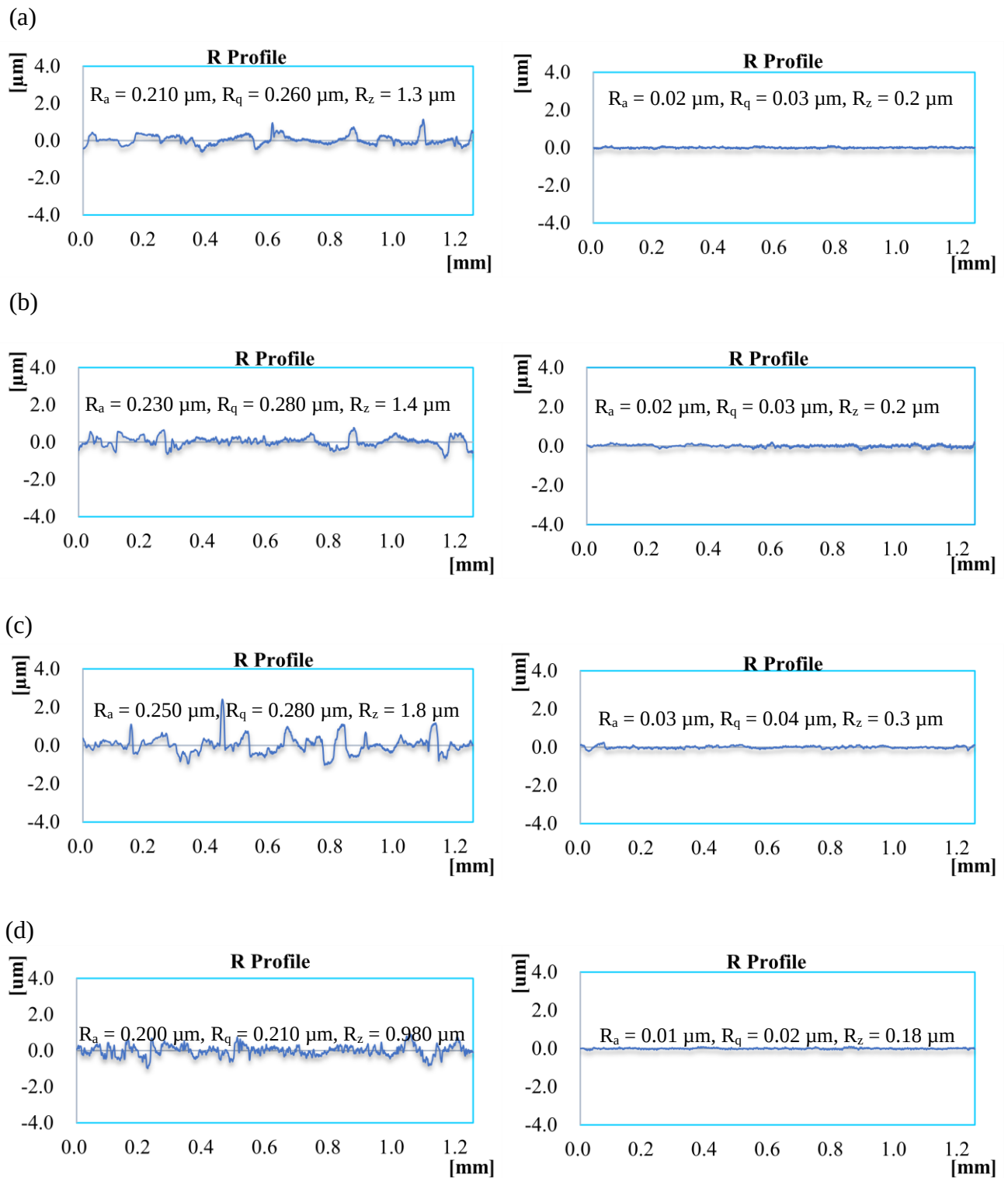


Fig. 5.16 Initial and final MR finished roughness profiles of the external surface of micro extrusion punches of (a) 3.5 mm diameter punch, (b) 2 mm diameter punch, (c) 1.5 mm diameter punch, and (d) 1.2 mm diameter punch.

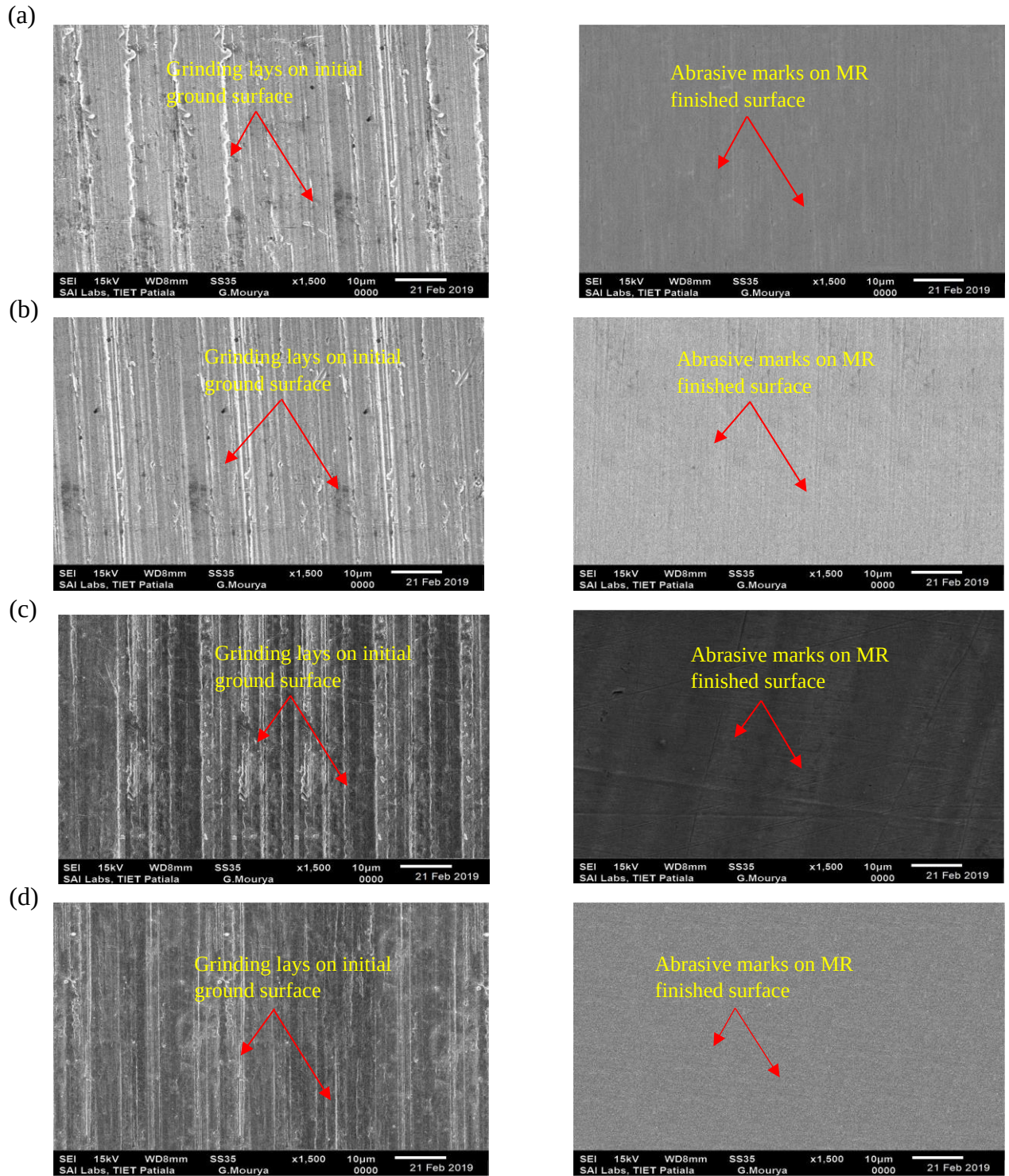


Fig. 5.17 Scanning electron microscopy (SEM) images of the initial surface of micro extrusion punches with grinding lays and final MR finished external surface of micro extrusion punches with abrasive marks (a) 3.5 mm diameter punch (initial $R_a = 0.210 \mu\text{m}$ and final $R_a = 0.02 \mu\text{m}$) (b) 2 mm diameter punch (initial $R_a = 0.230 \mu\text{m}$ and final $R_a = 0.02 \mu\text{m}$), (c) 1.5 mm diameter punch (initial $R_a = 0.250 \mu\text{m}$ and final $R_a = 0.03 \mu\text{m}$), and (d) 1.2 mm diameter punch (initial $R_a = 0.200 \mu\text{m}$ and final $R_a = 0.01 \mu\text{m}$).

The total %age improvement in surface roughness of the four micro-punches after the MR finishing were found as 90.47%, 91.30%, 88%, and 95% respectively. Usually in industry, the micro-punches finish through the belt grinder before its application. The initial ground surface roughness profiles of the four micro-punches after the belt grinder are depicted in Figs. 5.16(a-d). After the MR finishing, the surface roughness peaks were removed and fine finished external surface of the micro-punches were attained. The MR finished surface roughness profiles of the four micro-punches are depicted in Figs. 5.16(a-d). These surface roughness profiles reveal that the betterment in the surface finish of the outer surfaces of the micro-punches was attained. Scanning electron microscopy (SEM) pictures of the initial ground and MR finished outer surfaces of the micro-punches are shown in Figs. 5.17(a-d) and Figs. 5.17(a-d) respectively. From the Figs. 5.17(a-d), it can easily illustrate the grinding marks over the outer surface of the micro-punches. After the MR finishing, the grinding marks were removed and fine finished surface of the micro-punches were attained. After MR finishing, the smooth surfaces were obtained with some minor finishing marks as shown in Figs. 5.17(a-d). The reflection images of the initial ground and MR finished surfaces external surfaces of the four micro punches are depicted in Figs. 5.18(a-d). From the Figs. 5.18(a-d) it could be easily observed that the 'TIET' text is clearly visible on the MR finished surface of the micro-punches. But at initial ground surface the text 'TIET' is not visible easily as shown in Figs. 5.18(a-d). The SEM and reflection images of the MR finished micro punches were demonstrated the enhancement of the surface characteristics.

The micro-punches are the most important component of the micro-extrusion process. It is very beneficial to the minuscule manufacturing components in industries. The micro-extrusion punches are used in various applications like micro punching, micro die fabrication, and fabrication of the various micro shapes. The mechanical friction between the micro-punch and billet play an important role in the micro-extrusion operation. The frictional forces increase the power consumption, decreases the quality of the outcome product (roundness, surface roughness) and also generates various imprecation into the final product. The nano-finished micro-punches enhances the quality of the final product and also reduces the power consumption of the micro-extrusion process. The friction coefficient factor is playing an important role in the extrusion process. There are various frictional force models are used to evaluate the extrusion process forces. In the past years, the Coulomb friction model was utilized to evaluate the extrusion process. In the Coulomb model, the ratio of friction force to the normal reaction is termed as coefficient of friction.

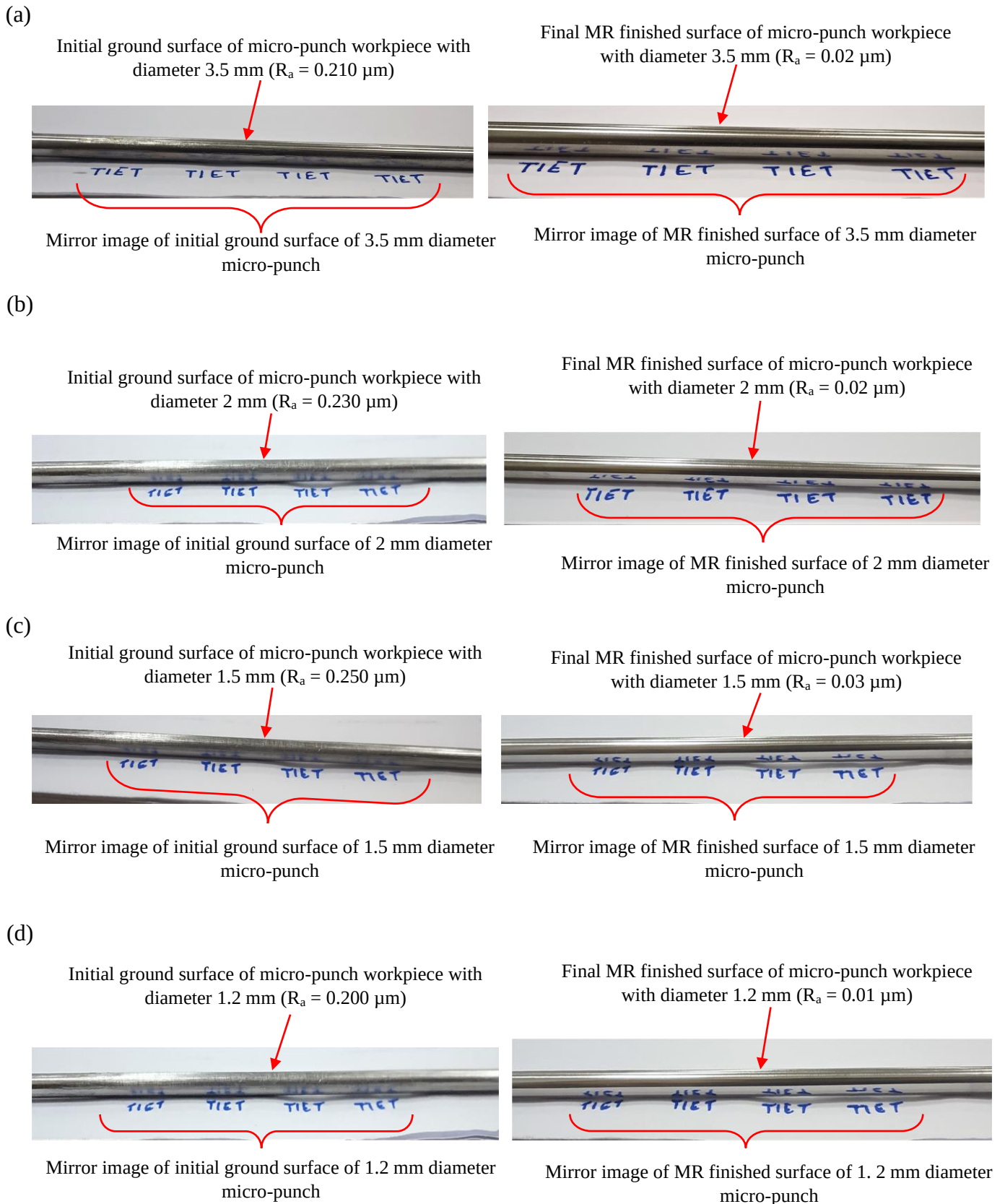


Fig. 5.18 Mirror images of the initial ground and final MR finished external surface of micro extrusion punches (a) with diameter of 3.5 mm, (b) with diameter of 2 mm, (c) with diameter of 1.5 mm, and (d) with diameter of 1.2 mm.

The frictional force (F) is evaluated by using the Eq. (5.21) (Tiesler, 2002).

$$F = \mu H_r \quad (5.21)$$

Where coefficient of friction is μ , and normal reaction is denoted as H in newton which acts on the punch or the ram in the extrusion process. From this model, it is clear that the force of friction is dependent on the coefficient of friction. In the micro-extrusion process, the high contact forces were usually produced between the billet and outer surface of the micro-punch. This model is in trends to calculate the frictional forces. But this model overestimated the friction stress in the extrusion process. To overcome this, the shear friction model is utilized for estimation the extrusion forces. The external load of the punch is depending upon the shear friction. Friction between the billet and micro-punch are evaluated by using the shear friction (σ_f) law can be expressed in Eq. (5.22) (Tiesler, 2002).

$$\sigma_f = k S_m \quad (5.22)$$

Where σ_f is the shear friction, S_m is the shear flow stress of the deformed material, and k is the factor of friction. The factor of friction (k) is ranges from 0 to 1. The 0 is refers to the frictionless condition and 1 is refers to the full sticking condition in the extrusion process. The friction coefficient factor (μ) and friction factor (k) relationship is expressed in Eq. (5.23) (Abeyrathna *et al.*, 2019).

$$\mu = \frac{k}{2\sqrt{3}} \quad (5.23)$$

The material of the billet is low carbon steel. The low carbon steel has good properties like good formability and lesser ductility. The AISI 1010 grade is used as a billet material in the application. In the micro-extrusion process, the extrusion ratio (e_x) is most important parameter. It is the ratio of the initial cross-sectional area (A_i) and final cross-sectional area (A_f) of the billet. Fig. 5.15 shows the deformation of the billet material during the extrusion process. Fig. 5.15(a) shows the initial position when micro-punch approaches the billet during the micro-extrusion process. The initial billet height (h_{bi}), initial billet bigger diameter (D_{bi}), and initial smaller diameter (d_{bi}) are used to calculate the A_i as depicted in Fig. 5.15(a). Fig. 5.15(b) depicts the deformation of the billet during the micro-extrusion operation. The micro-punch indent into the billet material and billet material flow outside the die as depicted in Fig. 5.15(b). The final cross-sectional area of the billet (A_f) is evaluated by using the micro-punch diameter (P_d), final billet height (h_{bf}), final billet bigger diameter (D_{bf}), and final smaller diameter (d_{bf}) as shown in Fig. 5.15(b). The extrusion ratio (e_x) is calculated by using the Eq. (5.24) (Xu *et al.*, 2011).

$$e_x = \frac{A_i}{A_f} \quad (5.24)$$

The cross-sectional area reduction or the extrusion ratio evaluate the strain rate of the extrusion process. The actual true strain (ϵ_x) is an important component to know the ram forces involved in the extrusion process. The actual true strain is evaluated by using Eq. (5.25) (Chen *et al.*, 2011).

$$\epsilon_x = a + b \times \ln e_x \quad (5.25)$$

Where ϵ_x is the true strain, a and b is empirical constants and the e_x is the extrusion ratio of the extrusion process. The value of the a and b constants are taken 0.8 and 1.2 respectively (Wang *et al.*, 2012).

The extrusion load is depending on the interface between the micro-punch and billet material. The extrusion load or force (F') is evaluated by using Eq. (5.26) (Chen *et al.*, 2011).

$$F' = A_f \times \sigma_f \times \epsilon_x \quad (5.26)$$

Where σ_f is the shear friction, and ϵ_x is the true strain during the extrusion process.

The true strain (ϵ_x) is depending on the extrusion ratio (e_x) and a further extrusion ratio is depending on the cross-sectional area of the initial and final deformation of billet. The shear friction (σ_f) directly affects the extrusion force as cleared from the Eq. (5.26). The shear friction (σ_f) is depending upon the coefficient friction factor (μ). When the coefficient friction factor (μ) is decreased, the shear friction (σ_f) is also decreased.

At the initial condition, the friction coefficient factor (μ) was found as 0.080. For measuring the coefficient friction factor (μ), the coefficient friction tester is utilized on the outer surfaces of the initial ground and MR finished micro-punches. After MR finishing, the friction coefficient factor (μ) was found as 0.010. These values are helped evaluate the value of the shear friction (σ_f) by using the Eqs. (5.22) and (5.23). The true strain value (ϵ_x) is the same for the cases when the extrusion process performed with existing ground micro-punch and with MR finished micro-punch. Because the initial (A_i) and final (A_f) cross-sectional area are found to be the same for both cases. The true strain (ϵ_x) is calculated for both cases by using the Eq. (5.25). For both the cases, the final cross-sectional area (A_f) is the same, because the punch diameter for both the cases is same. The factor which differs for both the cases that are shear friction (σ_f) value.

The shear friction is depending upon the friction coefficient factor (μ) (Bennewitz *et al.*, 2010) which is cleared from the Eq. (5.23). At initial surface roughness value (0.210 micrometer) of the micro-punch, the friction coefficient factor (μ) is found as 0.080 and at the MR finished surface roughness value of 0.020 micrometer of micro-punch, the friction coefficient factor (μ) is found as 0.010. After putting these values into the Eq. (5.26), the extrusion force (F') is

evaluated for both cases. The extrusion force (F') is calculated with existing micro-punch at initial ground surface roughness value of 0.210 micrometer is found as 650 N. But when the extrusion process is performed with the MR finished micro-punch at surface roughness value of 0.020 micrometer, the extrusion force (F') is found as 585 N. Thus, enhancement in the surface topographic of the outer surface of the micro-punch reduces the extrusion force. From the extrusion force analysis, it is cleared that the MR finished micro-punch has enhance the effectivity of the micro-extrusion process. This analysis is performed on an application with one of the micro-punches in the micro-extrusion process. Form this analysis, it is confirmed that the applications of the micro-punches like micro-punching, microfabrication die processes are also improved with the MR finished micro-punches. In these processes, the frictional forces are to be reduced due to the fine finished external surface of the micro-punches. The MR finished micro-punches reduces the extrusion force which further reduces the power consumption, enhances the final products quality in terms of roundness, surface roughness. So, MR finished micro-punches enhances the functional efficiency of the micro-extrusion process.

5.9 Conclusions

The rotating rectangular core based magnetorheological (MR) finishing process express the potential in various industrial applications through fine finishing and improves the functional operative performance. The micro-punches are fine finished by utilized the present finishing process for improving the effectiveness of the micro-extrusion process. The reduction in extrusion force demonstrates the effectiveness of the micro-extrusion process due to the reduction in coefficient friction factor after MR finishing on the micro-punches. The reduction in extrusion force is found beneficial in terms of improvement in the final products quality and economical the micro-extrusion process. The following conclusions are drawn.

- The magnetostatic finite element analysis reveals that the flux density gradient is uniformly spread in between the working space. This helps in the uniform clipping off the roughness peaks over the outer surface of the micro-punches. The surface roughness (R_a) values get reduced from the initial values of the four micro punches are 0.210, 0.230, 0.250, and 0.200 μm to the final finished values of 0.02, 0.02, 0.03, and 0.01 μm in 60 minutes the MR finishing.
- The reflection and scanning electron microscopy photographic results confirmed that the surface characteristics of the outer surface of the micro-punches workpieces get improved with the present process.

- The enhancement in the surface characteristics and the reduction in roughness values of the micro-punches reducing the frictional force between the outer surface of the micro-punch and billet material during the micro-extrusion process. This further reduces the extrusion force. The extrusion force gets reduced from the 650 N to 585 N when the MR finished micro-punch was utilized for the extrusion process instead of the ground micro-punch.
- The reduction in extrusion force after the MR finishing reduces the power consumption during the micro-extrusion process and enhances the final product quality in terms of roundness, and surface roughness. This enhances the overall efficiency of the micro-extrusion process.

5.10 Magnetorheological finishing of grooved drum surface and its performance analysis in winding process

The winding and unwinding, both are the most significant operations in the fabric manufacturing industries (Heitmann, 2011). The winding is a creation of larger thread (yarn) packages that could be effortlessly wound and unwound. Due to this, the yarn is easier to process and more economical for the industrial textile winding machines (Yan and Chen, 2010). The winding technique is far more than just transferring yarn from one package to another. The winding is performed using the grooved drums. The grooved winding drum is well recognized and verified technique. This technique is also used in automatic winding machines (Patil *et al.*, 2017). The grooved winding drums are made of various materials such as bakelite, aluminium, and steel on the basis of their uses (Heitmann, 2016), (Halimi *et al.*, 2007). The steel made winding drums owe the various qualitative attributes like corrosion resistance, high strength, and optimum finish. While using the grooved winding drum, the winding system is simpler and more cost effective (Wang and Miao, 1997), (Barella and Manich, 1988). The winding operation is usually wound the textile yarns into a suitable package which make ease to process the yarn. The majority of packages are obtained on the cylindrical or conical tubes by the grooved winding drum machines (Hasani and Tabatabaei, 2011), (Han *et al.*, 2018). The winding operation is a combination of two types of motions; one is a rotational motion of the cylindrical or conical tube to draw the yarn, and other is a traversing motion of the yarn in the axial direction of the cylindrical or conical tube (Ali *et al.*, 2015), (Nobauer and Baumeler, 1992). Due to these two types of motions, the yarn follows the helical path and upturned the yarn at each end of the package. This results in a cross-wound appearance of the yarn on the package (Osawa and Koyama, 1972). The MR finishing process improves

the geometric accuracy of the grooved in term of curvature of the yarn position on the package surface with the optimized grooved surface of the winding drum. The advanced finishing is not excessively material removal processes, these processes only remove surface asperities. This results in refining the geometric accuracy of the groove surface of the winding drum. The improved surface characteristics of the grooved drum surface increase the overall efficiency of the process which has been validated in this work. In the present work, the experiments are performed on the initial ground surface of the winding drum. In order to check the working performance of the MR finished grooved surface of the winding drum, the MR finished grooved drum has been used in the industry for winding operation. It has been found that the MR finished grooved surface of the winding drum improves the performance of the winding process and quality of the yarns and clothing products.

5.10.1 Selection of material for present work

The selection of material depends upon the operational conditions of the process. The grooved winding drum is made of the AISI 4140 steel alloy. AISI 4140 is a chromium-molybdenum alloy steel. The chromium content provides good hardness penetration, and the molybdenum content ensures uniform hardness and high strength.

The present grooved drum is taken from the industry and used as a workpiece with a hardness value of 21 HRC. The length and diameter of the grooved drum workpiece are 220 mm and 75 mm respectively.

Table 5.5 Mechanical properties of the AISI 4140 steel grooved winding drum

Mechanical properties	Metric
Hardness	21 HRC
Shear modulus	80 Gpa
Tensile strength	655Gpa
Yield strength	415Gpa

The grooved surface of the winding drum manufactured through various mechanical processes. After fabrication, the grooved winding drum is finished by using the belt grinder and the ground grooved surface of the winding drum is used in the textile industries. The mechanical properties of the AISI 4140 like hardness, shear modulus, tensile and yield strength is reported in Table 5.5. Fig. 5.19 shows the motions of the thread which governed by the grooved drum and wounded on the yarn package. During the rotational motion of the grooved drum, the yarn has experienced the two type of motions such as reciprocating and straight motion as depicted in Fig. 5.19. Due to these motions, the yarn is wounded on the yarn package.

The different components of the winding process are spinner package, yarn guide, tension device, yarn cleaner, and slow-motion feeler. These components help to wind the yarn on the package. These components are divided into different zones such as unwinding zone, tensioning and clearing zone, and winding zone as shown in Fig. 5.19.

5.11 Experimental setup

The experimental setup which is used for experimentation is shown in Fig. 5.20 (a). In the grooved drum, there is through hole has been provided to fix on the setup. The grooved drum is attached to the pillow blocks with the help of straight shaft and locked with the allen screws. The experimental setup with rectangular tool core tip surface (10 mm x 7.85 mm) is utilized for finishing the 6 mm width of the grooved surface of the winding drum as shown in Fig. 5.20 (a). The winding drum has three grooved openings which completes the total length of the yarn package. These three grooved surfaces are finished by using the present MR finishing process as shown in Fig. 5.20 (b). The same reciprocating motion is provided to the tool core tip surface as a transverse motion used to provide the grooved drum during the winding operation. Because of the transverse and rotational motions of the winding drum as well as the same transverse motion of the tool core tip surface, the tip surface of the tool core follows the grooved surface path of the winding drum during the MR finishing process as depicted in Fig. 5.20 (b). The grooved drum is a very important part of the winding machine in the textile industry.

5.12 Experimentation

The taguchi optimization tool was utilized to plan and analyse the effect of process parameters and maximize the response (%age improvement in surface roughness, (% ΔR_a)). The process parameters such as rotational speed of grooved drum workpiece (S) and rotational speed of the rectangular tool core tip surface (R), reciprocating speed of rectangular tool core tip surface (F) % concentration SiC abrasive particles by volume (C) and current (I) were examined. The surface roughness measurement was performed with the help of Mitutoyo surfest roughness tester. During measurement, the cut of length is considered to be 0.25 mm, and the measuring range was selected as 80 μm . The experimentation was evaluated between the two grooved surfaces of the winding drum. The surface characteristics of the grooved surface were examined with the help of scanning electron microscopy and mirror images. The experimentation was performed in three number of trails, and the average value of the %age improvement in surface roughness was taken for predicting the optimum process parameters.

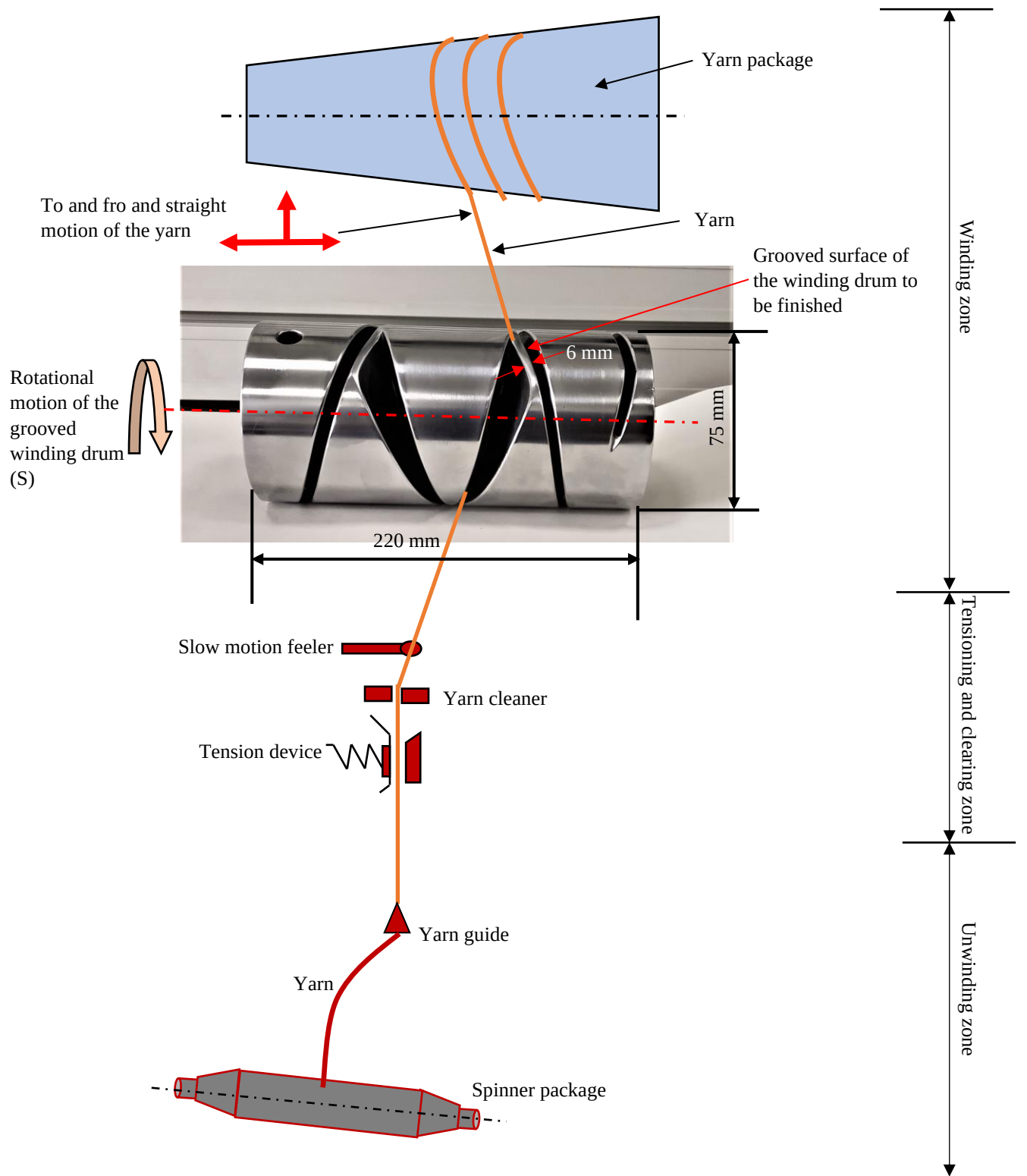


Fig. 5.19 Schematic diagram of the various zones of winding machine with actual winding grooved drum along with dimensions and representation of the motions.

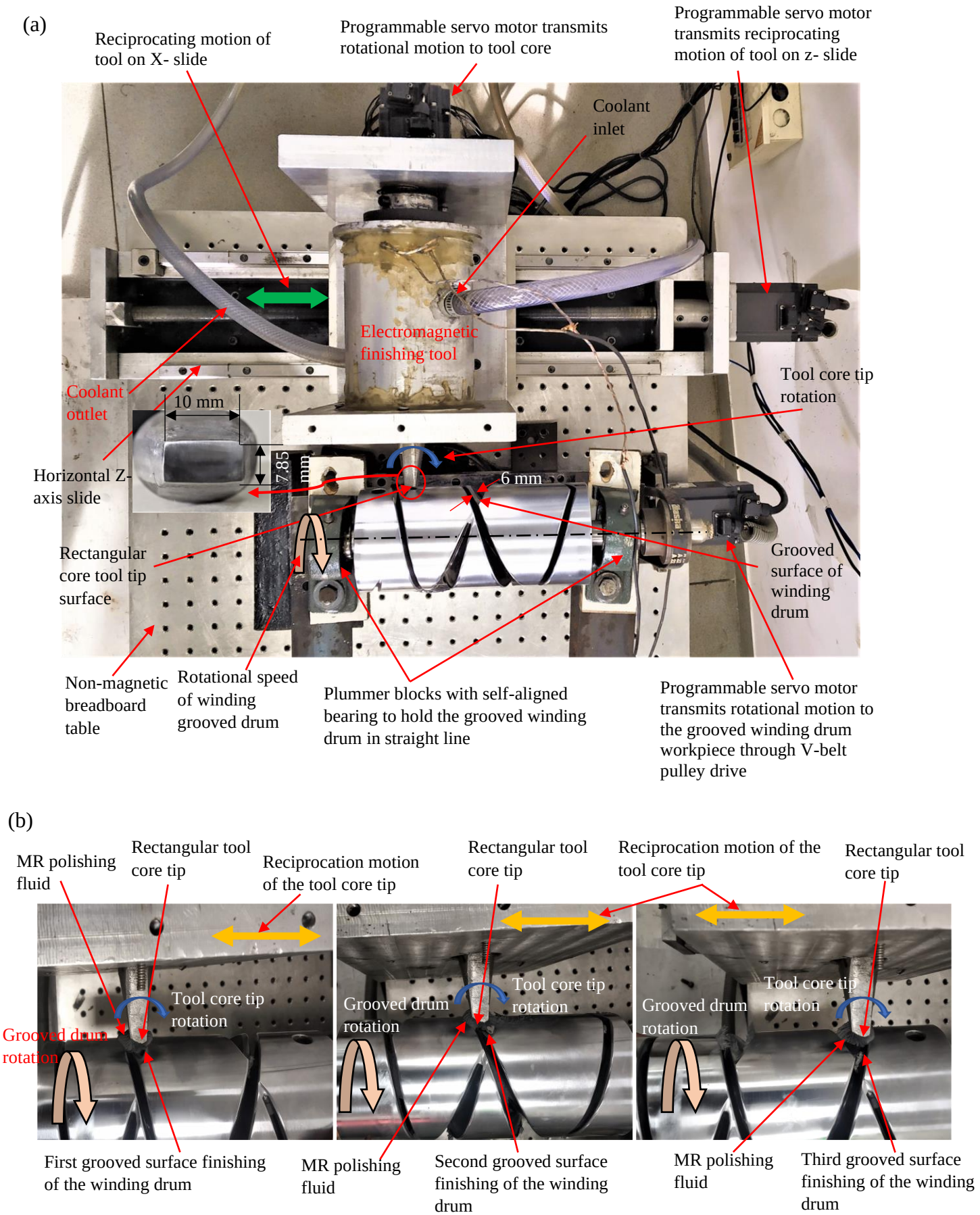


Fig. 5.20 (a) Top view of a rectangular rotating core magnetorheological finishing process with grooved winding drum, and (b) MR finishing of the entire all three grooved surfaces of the winding drum along with the helical motion over the surface

5.12.1 Selection of process parameters for present MR finishing on the grooved surface of the winding drum

The finishing parameters were analysed on the grooved surface of the winding drum AISI 4140 steel alloy grooved drum by using the taguchi optimization technique. The magnetizing force depends upon the current intensity. The rotational speed of the tool core tip surface and workpiece surface governs the tangential shear force (F_T) on the workpiece surface by the active abrasive particles. The reciprocating speed governs the axial force (F_A) by the active abrasive particles.

Table 5.6 Experimental process parameters and its range

S. No	Parameters	Units	Range		
1	Rotational speed of tool core tip surface (R)	rpm	500	1000	1500
2	Rotational speed of grooved drum workpiece (S)	rpm	50	100	150
3	Reciprocating speed of the tool core tip surface (F)	cm/min	10	30	50
4	Current (I)	A	1	2	3
5	%age concentration of SiC abrasive particles (C)	vol.%	10	15	20

For MR finishing of the AISI 52100 steel workpiece, the current and working gap was considered as 3 A and 0.6 mm respectively. The rotational speed and reciprocating speed of the tool core tip surface was taken as 1500 rpm and 30 mm/min, respectively. The abrasive particles also play a great role in MR finishing. The %age concentration of SiC abrasive (C) is also considered in the present work as a finishing parameter. The range of the C is lies between 10% to 20%. From these observations and on the basis of preliminary experimentation as well as transverse motion of the grooved drum provided during the winding operation, the process parameters are selected and reported in Table 5.6. Other process parameters like the working gap 0.6 mm, and each trail finishing cycle time 40 min was kept constant during the experimentation.

5.12.2 Design of experiment

The Taguchi method is an optimization technique. On the basis of orthogonal arrays which is a well-planned set of experiments in which all parameters of interest are varied over a specified range. Larger the better method was utilized to evaluate the best combination of the process parameters. In this method, the response ($\% \Delta R_a$) is maximized. The L27 orthogonal array is meant for understanding the effect of 5 process parameters where each parameter is having three level values. Signal-to-noise ratio (S/N) which are log functions of the desired output, serve as an objective function for optimization. It helps in data analysis and prediction of

optimum results. The S/N ratio for maximizing the response (%age improvement in surface roughness, % ΔR_a) is evaluated by using the Eq. (5.27).

$$\frac{S}{N} = -10 \log \left(\sum \left(\frac{1}{z^2} \right) / n \right) \quad (5.27)$$

Where z is the mean of sum squares, and n is the number of the experiments. From the S/N ratio with the help of larger the better technique, the plot between the mean of response and process parameters is obtained. The L27 orthogonal array generated the twenty-seven parametric combinations and each combination is performed in three trials (Y1, Y2, and Y3). The average %age improvement in surface roughness (% ΔR_a) value with respect to the three trials (Y1, Y2, and Y3) was taken as response and reported in Table 5.7. The experimentation was carried out for 40 min in each trial. After 20 min, the MR polishing fluid is renewed during the experimentation. The experimental plan and response values are reported in Table 5.7.

Table 5.7 Experimental plan and its response

S. No.	Rotational speed of tool core tip surface, R (rpm)	Rotational speed of grooved drum workpiece, S (rpm)	Reciprocating speed of the tool core tip surface, F (cm/min)	Current, I (A)	%age concentration of SiC abrasive, C (% by vol.)	%age reduction in surface roughness (% ΔR_a) value			
						Y1	Y2	Y3	Avg.
1	500	50	10	1	10	62	61	63	62
2	500	50	10	1	15	68	70	65	67.6
3	500	50	10	1	20	63	60	65	62.6
4	500	100	30	2	10	71	72	70	71
5	500	100	30	2	15	76	74	72	74
6	500	100	30	2	20	72	75	76	75.3
7	500	150	50	3	10	68	71	72	70.3
8	500	150	50	3	15	71	70	72	71
9	500	150	50	3	20	67	63	67	65.6
10	1000	50	30	3	10	77	78	75	76.6
11	1000	50	30	3	15	85	82	83	83.3
12	1000	50	30	3	20	75	73	71	73
13	1000	100	50	1	10	78	80	81	79.6
14	1000	100	50	1	15	82	81	83	82
15	1000	100	50	1	20	80	77	79	78.6
16	1000	150	10	2	10	78	75	79	77.3
17	1000	150	10	2	15	82	80	77	79.6
18	1000	150	10	2	20	71	74	71	72
19	1500	50	50	2	10	69	70	68	69
20	1500	50	50	2	15	75	72	71	72.6
21	1500	50	50	2	20	67	62	65	65.6
22	1500	100	10	3	10	72	70	74	72
23	1500	100	10	3	15	77	73	79	76.3
24	1500	100	10	3	20	73	71	67	70.3
25	1500	150	30	1	10	71	74	70	71.6

26	1500	150	30	1	15	74	71	74	73
27	1500	150	30	1	20	68	66	67	67

5.12.3 Calculation of transverse or reciprocation speed of the rectangular tool core tip surface along the yarn wind angle

The reciprocation speed of the rectangular tool core tip surface was calculated to finish the entire grooved surfaces over the winding drum. These grooved surfaces are made on a particular angle and thread passes through these grooved surfaces at a particular angle which is known as wind angle ($\emptyset$) or angle of wind as shown in Fig. 5.21.

The angle of wind ($\emptyset$) is made by the yarn with the side of the package surface. The coil angle (α) which is made by the thread with the axis of the package as shown in Fig. 5.21. The sum of the wind angle ($\emptyset$) and coil angle (α_c) is equal to the 90° . The industrial grooved winding drums are made on the basis of their use like which type of yarn or thread is wounded or unwounded, etc. In present work, the grooved surface of the winding drum used for experimentation has 17.5° of the wind angle as shown in Fig. 5.21. On the basis of the wind angle, the reciprocating speed of the tool core tip surface was evaluated. First, calculate the surface rotational velocity (V_s), and their transverse velocity (V_t) of the yarn over the grooved surface of the winding drum is assessed by using the Eqs. (5.28) and (5.29).

$$V_s = \pi d_d n_d \quad (5.28)$$

Where V_s is the surface velocity of the grooved drum in m/min, d_d is the diameter of the grooved drum in meter and n_d is the revolution of the grooved drum in rpm. The diameter and length of the grooved drum are 75 mm and 220 mm, respectively. On the basis of the different rotational speeds of the workpiece, the surface velocity is calculated. The diameter of the drum for all the surface velocities are the same. As per the rotational speed of the workpiece, the surface velocity values are varied.

The transverse velocity is evaluated by using the Eq. (5.29).

$$V_t = \frac{2L_g n_d}{S} \quad (5.29)$$

Where V_t is the transverse velocity of the yarn in m/min, $2L_g$ is the distance covered by the yarn in one revolution in m, S is the number of revolutions required for the drum for double traverse in m, n is the revolution of drum in rpm (Fig.5.21).

After calculating the transverse velocity and surface velocity of the drum, the reciprocating speed of the tool core tip surface is evaluated by using Eq. 5.30.

$$\tan \emptyset = \frac{V_t}{V_s} \quad (5.30)$$

Where $\emptyset$ is the angle of wind in degree. V_t and V_s are the transverse and surface velocities of the grooved drum.

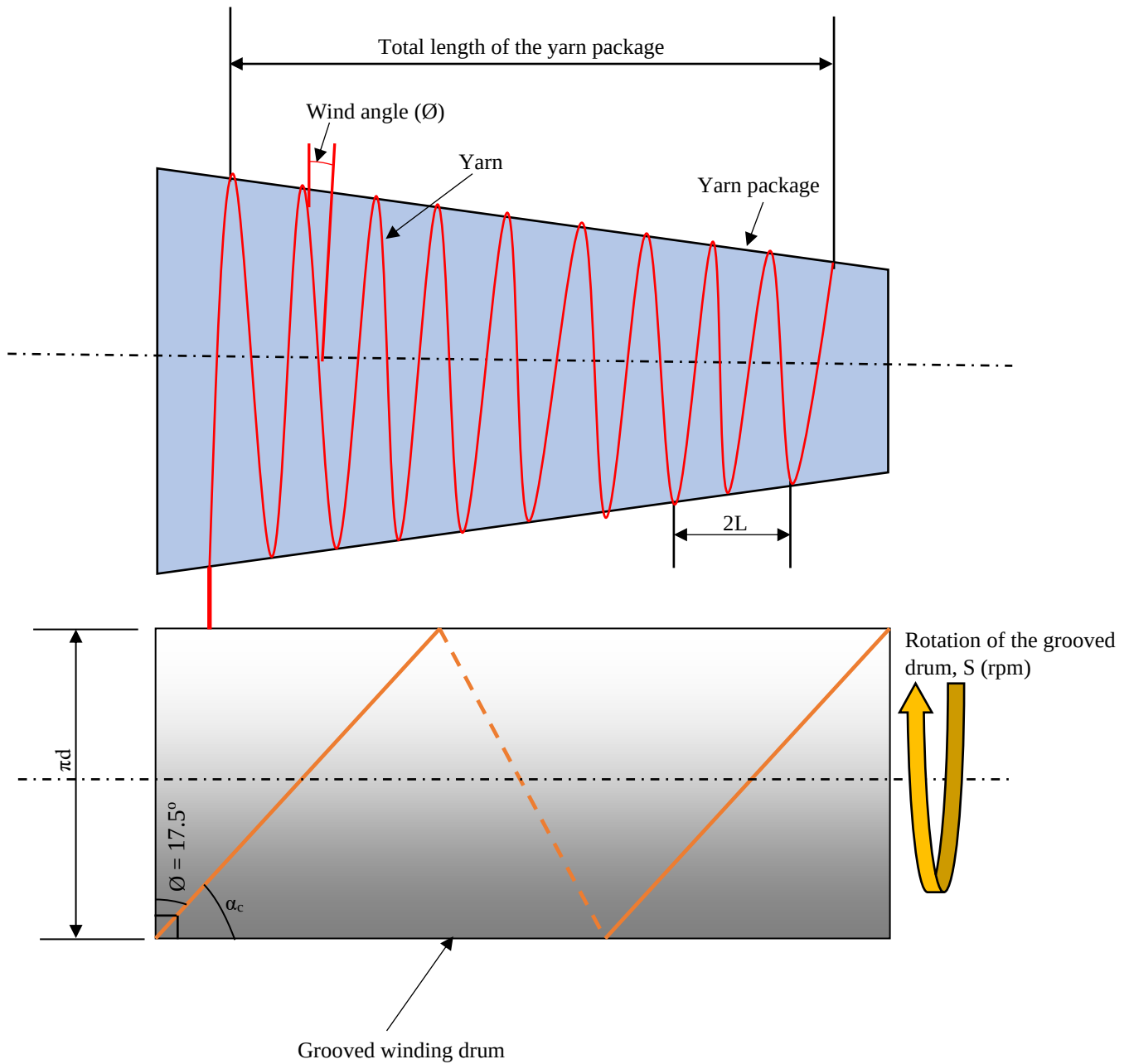


Fig. 5.21 Representation of the angles of the winding drum during the winding operation.

The transverse velocity of the yarn is calculated by using the Eq. (5.29). The transverse velocity is the most important factor to evaluate the reciprocating motion of the tool core tip surface. The yarn follows the grooved surface of the winding drum with the help of transverse velocity. To know the position of the grooved surface of the winding drum, the transverse velocity is assisted. It helps to calculate the reciprocating motion of the tool core tip surface. Hence, the reciprocating motion of the tool tip surface is maintained the same as the transverse velocity of

the yarn. In present experimentation, the reciprocating motion of the tool core tip surface is evaluated with the help of the Eqs. (5.28-5.30). On the basis of the transverse velocity, the reciprocating motion of the tool core tip surface is decided which is used in the experimentation as reported in Table 5.6.

5.13 Results and discussion

To finish the grooved surface of the winding drum with the MR finishing process, larger the better method was utilized to predict the best process parametric combination. Fig. 5.22 shows the mean of S/N ratio for each parameter condition and larger S/N ratio value parameters are selected for maximum response value. The larger value of the S/N ratio gives the maximum response (%age improvement in surface roughness) value.

5.13.1 Effect of finishing parameters

The effect of process parameters like rotational speed of rectangular tool core (R) and grooved drum (S), feed rate of tool core (F), current (I) and %age concentration of SiC abrasives (C). Each parameter has its own contribution in the MR finishing process. Fig. 5.22 shows the effect of each process parameter. The rotational speed of the tool core (R) and grooved drum (S) governs the relative motion of the active abrasives (AABs). At rotational speed of 500 rpm with 100 rpm of gives the lesser relative speed to the active abrasive (AAB) as compare to the combination of the 1000 rpm and 100 rpm as confirm from reported $\% \Delta R_a$ value. But when the rotational speed of tool core increases from 1000 rpm to 1500 rpm the value of response is decreased. This fact own that the higher speed of the tool core generates the centrifugal force which weak the strength of the iron particle chains. The combination of 1000 rpm of tool core and 100 rpm of grooved drum rotational speed gives the optimum relative speed of active abrasives with less effected centrifugal force. The tool feed rate influences the interaction time of the AABs with the roughness asperities. At lower feed rate 10 cm/min, the interaction time is lesser as compare to the feed rate of 30 cm/min which gives the less collision between the AABs and roughness asperities. But at higher feed rate the iron particle chains are disturbed because of the stresses are induced in the chains. This results in lesser reduction in surface roughness (R_a) value. The magnetic field intensity is directly dependent on the magnetization current as cleared from the expression in Eq. (5.31). As the value of the current is increased the value of the magnetic field intensity is increases (Ida., 2000).

$$B = \frac{\mu_o I}{2\pi R} \quad (5.31)$$

Where, B is the magnetic field intensity, μ_o is the free space magnetic permeability, I is the current and R is the distance from the conductor.

As the current is increased the stiffness of the MR polishing fluid is increased which results in higher magnetic normal force (F_m). As compared to the 1A current 2A gives the higher F_m which shear off the larger surface asperities than the 1 A current. But as the current is increased 2A to 3A which extremely increases the F_m which shear off the larger surface asperities but also affect the surface of the grooved drum. This effect reduces the %age improvement in average surface roughness. The %age concentration of the SiC abrasive particles is playing an important role in MR finishing. In Fig. 5.22 see that the 15% concentration of the SiC abrasives gives the maximum %age improvement in average surface roughness.

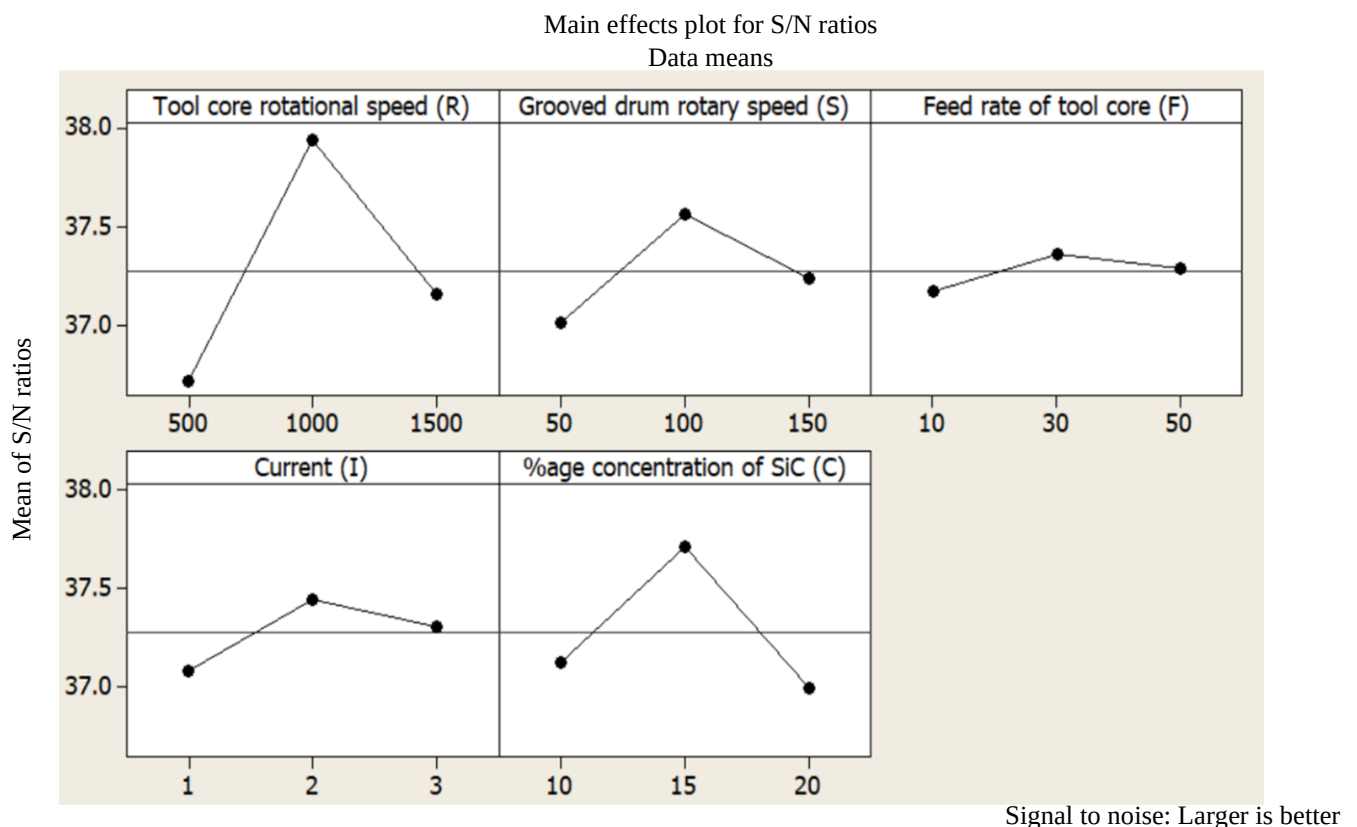


Fig. 5.22 2D plot of the mean of S/N ratio with the different finishing parameters using larger the better technique.

At the 10% concentration of the SiC abrasives (C) lesser active abrasive is projected the finishing area because of this the lesser improvement is observed in response. But at 20% C gives the lesser improvement in the response, the reason behind that at higher concentration of the SiC abrasives increase the number of active abrasives. But at same concentration of iron

particles, these active abrasives are not properly hold by the iron particle chains. This results in disruption of the active abrasives which results in lesser %age reduction in average surface roughness.

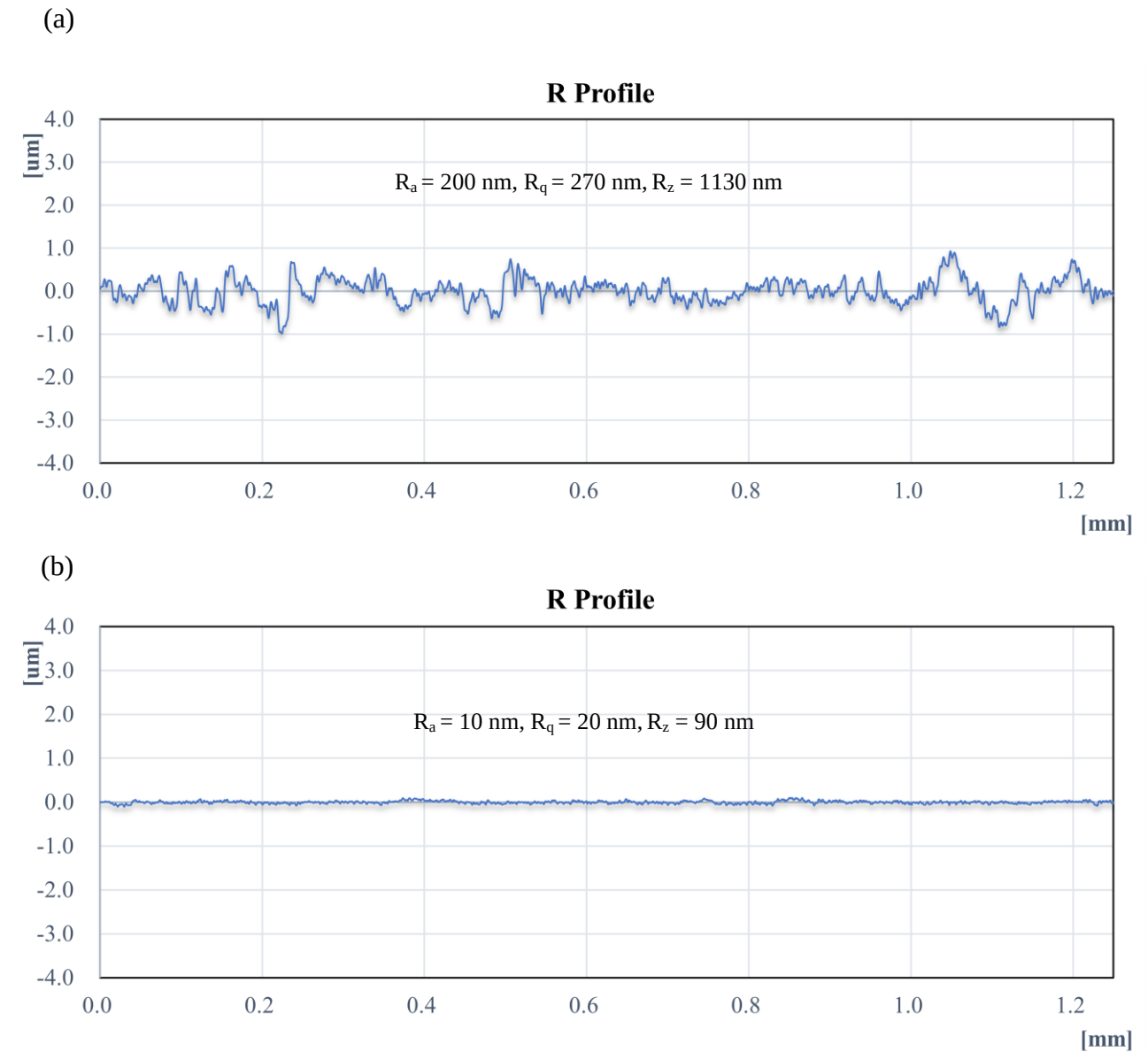
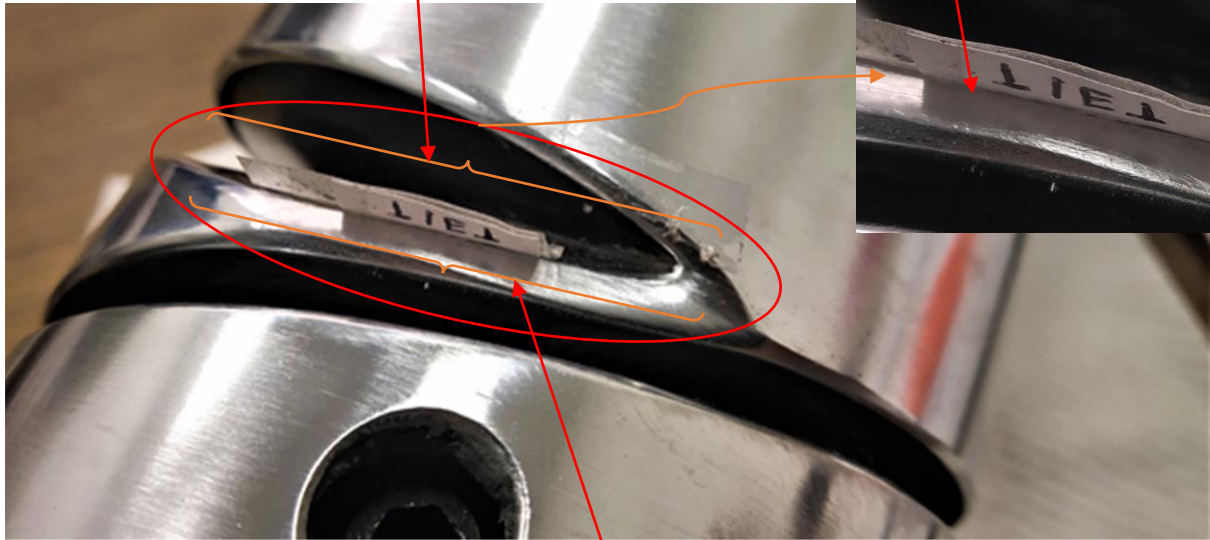


Fig. 5.23 Surface roughness profiles of the grooved surface of drum workpiece (a) at initial ground surface, (b) after 60 minutes of finishing with optimized parametric conditions using present MR finishing process.

(a)

Initial ground surface of grooved drum workpiece ($R_a = 200 \text{ nm}$)

Text 'TIET' is not visible at initial ground surface



Mirror image on the initial ground surface

(b)

Final MR finished surface of grooved drum workpiece ($R_a = 10 \text{ nm}$)

Text 'TIET' is easily visible at MR finished surface



Mirror image after finishing on the grooved surface of the winding drum with optimized parametric conditions

Fig. 5.24 Mirror images of the grooved surface of the winding drum (a) initial and (b) after 60 minutes of the MR finishing with optimized parametric conditions.

The average surface roughness value was reduced to 65 nm from an initial ground value of 200 nm in the first 20 minutes finishing cycle. In the second and third finishing cycle, the surface roughness values were reduced from 65 nm to 25 nm and from 25 to 10 nm respectively. Hence, the %age improvement in average surface roughness values in the first, second and third finishing cycle were 67.5 %, 61.53%, and 60% respectively. The best process parametric combination is found as the rotational speed of tool core tip 1000 rpm, the rotational speed of the grooved drum workpiece 100 rpm, the feed rate of the tool core tip surface 30 cm/min and current 2 A, respectively. The experimentation was carried out on the grooved surface of the winding drum with these selected best parametric conditions for 60 minutes finishing time. After 20 minutes of finishing, the surface roughness measurement was performed. The reduction in surface roughness value is more in the first finishing cycle comparatively to the second and third finishing cycles. This is because of that at the initial stage, the roughness peaks have sharpness in nature. Hence, a lesser shearing force is required to shear out the sharp roughness peaks. But in the second and third finishing cycle, the sharpness of the roughness peaks is reduced and shear area increased. Due to this, the greater amount of shearing force is required to shear out the roughness peaks. Further in order to precise the measurement, the average surface roughness (R_a) value is measured after every 5 minutes. The total time of MR finishing is 60 minutes. So, 13 times the measurement of average surface roughness (R_a) value is performed at MR finished groove surface after every 5 minutes. The measurement of R_a value is taken three random regions (Y1, Y2, and Y3) on the MR finished surface and the average value of that measurement is taken. The average surface roughness (R_a) value was reduced from an initial ground value of 200 nm to 10 nm in 60 minutes finishing time with present MR finishing process. The root mean square roughness value (R_q) and the maximum height of the roughness value (R_z) were reduced from the initial values of 270 nm, 1130 nm to 20 nm and 90 nm in 60 minutes finishing time with present MR finishing process. The roughness profiles of the initial ground and MR finished grooved surface of the winding drum are depicted in Figs. 5.23(a) and (b) respectively. This shows that roughness parameters of the grooved surface of the winding drum get reduced significantly after the MR finishing process. Mirror photographs of initial ground grooved surface and MR finished grooved surface of the winding drum are depicted in Figs. 5.24(a) and (b), respectively. From Fig. 5.24(b), it can be easily depicted that the grinding marks have been removed and a smooth surface is obtained. In Fig 5.24(a), it can easily depict that the text ‘TIET’ was not visible. But after the MR finishing of the grooved surface of the winding drum, the text ‘TIET’ was easily readable on its MR finished surface as depicted in Fig. 5.24(b).

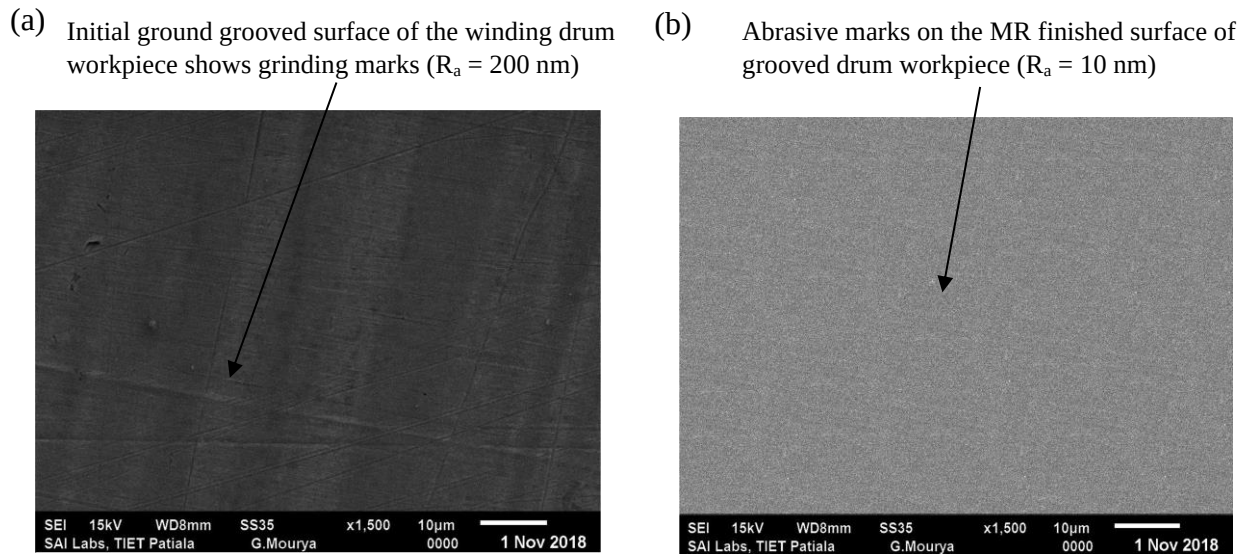


Fig. 5.25 Scanning electron microscopy images of the grooved surface of the winding drum at 1500 X focus (a) initial ground surface after the grinding operation, and (b) MR finished after 60 minutes with optimized parametric conditions.

For better understanding and visibility, the enlarge photographs of initial ground surface and MR finished surface is added in Fig. 5.24(a) and (b) respectively. These enlarge photographs reveal the enhancement in the surface texture after MR finishing of the groove surface. These results reveal the improvement in the surface topography of the grooved surface of the winding drum. Scanning electron microscopy (SEM) photographs of initial ground and MR finished grooved surface of the winding drum are depicted in Figs. 5.25(a) and (b), respectively. The SEM images show the surface texture of the initial and MR finished grooved surface of the winding drum. In Fig. 5.25(a), the grinding marks are depicted on the grooved surface of the winding drum. From Fig. 5.25(b), it is revealed that the MR finishing improves the surface texture of the grooved surface of the winding drum and uniform finishing on the whole grooved surface of the winding drum was taken place. The grinding marks were removed. The SEM and mirror images were revealed that the surface topography of the MR finished grooved surface was greatly improved. The SEM and mirror images also reveal the effectiveness of the present process to finish the grooved surface of the winding drum.

5.13.2 Industrial application for MR finished grooved surface of the winding drum in winding process

The optimized combination of process parameters was employed to nano-finish the entire grooved surfaces of the winding drum. The grooved drum is the most important component of the winding machine. This winding drum is utilized in textile industries to the wind and unwind the yarn and makes the yarn packages for further uses. The breakage and hairiness of the yarn

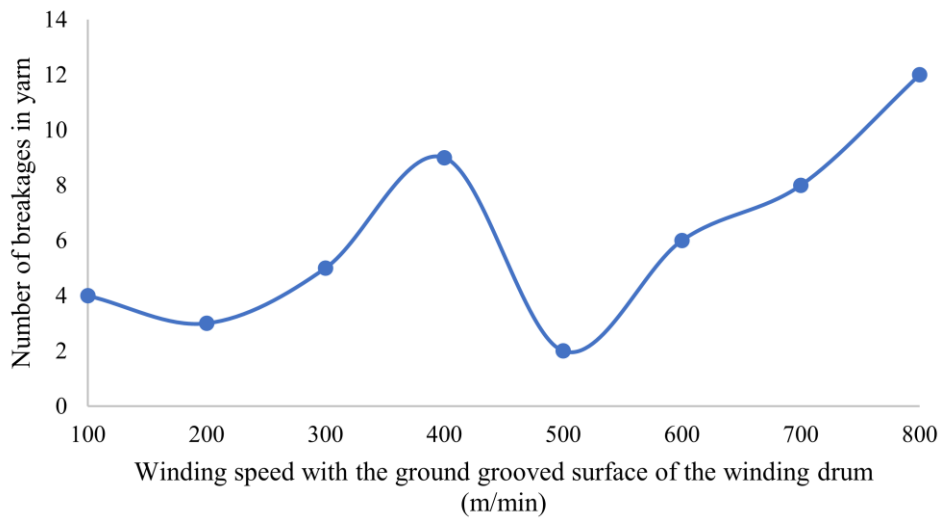
are the most undesirable issues in the textile industries. The hairiness is the quantity of the protruding of the fibres from the structure of the threads or yarns. The surface finish of the grooved surface of the winding drum is the most important factor to reduce the breakage and hairiness of the yarn.

5.13.3 Improvement in functional application of MR finished grooved surface of the winding drum in winding process

The functional improvement was checked by comparing the experimental results of the already used ground surface and the present MR finished grooved surface of the winding drum. The functional improvement was examined on the basis of the breakage of the yarn and the reduction in hairiness of the yarn. At the ground grooved surface of the winding drum, the surface roughness value is measured as 200 nm. Due to the higher surface roughness value (200 nm), the friction between the grooved surface and yarn is greater. Greater friction is the main reason to break the yarn during the winding process. To check the performance of the grooved winding drum, the winding operation is performed at different winding speeds. The winding speed is dependent on the rotational speed of the grooved winding drum. At the higher winding speed, the interaction between the yarn and grooved is lesser. But higher winding speed is generating the greater heat between yarn and the grooved surface of the winding drum. The experimentation was performed at eight different winding speeds (100-800 m/min) in the textile industry.

The functional performance of the winding grooved drum in terms of the number of breakages in yarn during the winding operation with already used ground grooved drum and with the present MR finished grooved drum surfaces at different winding speeds were analysed. The breakage of the yarn is the most undesirable issue in the winding process. The breakage of the yarn shut down the production line of the packages winding. The breakage of the yarn is consuming more time to run the production line. During the winding, when the yarn is broken, the yarn packages are not considered for the usage. These packages are shifted to the wastage centre. So, the breakage of the yarn during the winding of the package is a massive issue. To overcome this issue, the surface texture of the grooved surface of the winding drum is improved after MR finishing to reduce the sliding friction between the yarn and the grooved surface of the winding drum.

(a)



(b)

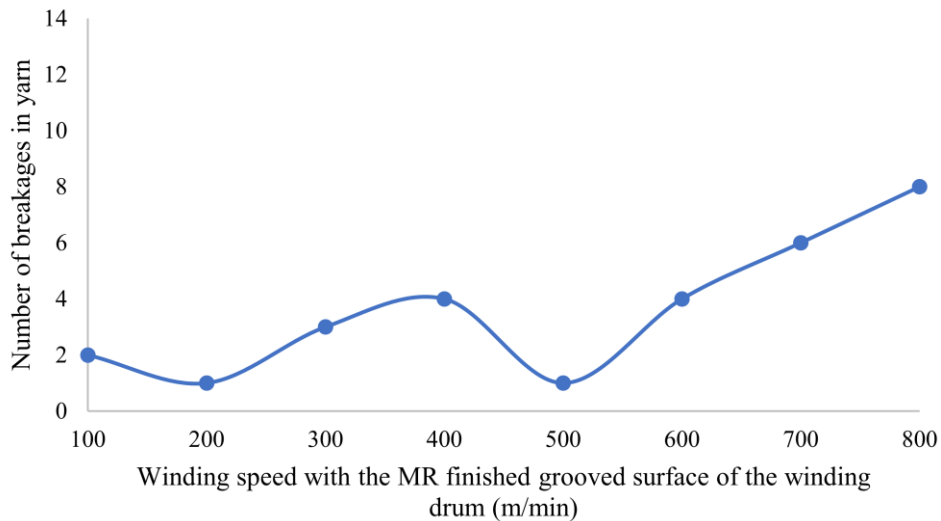


Fig. 5.26 Number of breakages in yarn at different winding speed with 3 hours sample time while using the (a) ground grooved drum surface and (b) MR finished grooved drum surface.

As the sliding friction between the yarn and grooved surface is reduced the breakage of the yarn is reduced. At different winding speeds, the breakage of the yarn was counted. Eight different winding speeds (100-800 m/min) are utilized for experimentation as shown in Fig. 5.26. The 3 hours operation time was taken for all the trails. The 30 Tex (linear density in g/km) yarn was used for the investigation. From Fig. 5.26(a) it is observed that a greater number of breakages occur in the yarn when the winding operation is performed with the existing ground grooved drum surfaces which are mainly used in the industry. But when MR finished grooved drum surface was utilized in the winding operation, the lesser number of breakages was observed in the yarn as shown in Fig. 5.26(b). This happens due to the fine finishing of the grooved surface of the winding drum which reduces the sliding friction force between the

winding drum surface and the yarn. The average breakage of the yarn with the already used ground grooved surface of the winding drum in industry and the MR finished grooved surface of the winding drum is observed as 11 and 6, respectively.

Hairiness is characterized by the quantity of freely moving fibre ends or fibre loops projecting from yarn or textile fabric. Yarn hairiness significantly influences the characteristics of yarn and fabric appearance. Hairiness is influenced by the drum winding speed, winding yarn tension and winding drum grooved surface texture. Hairiness is the most important factor for the clothing industries. It affects the various factor of the fibres like fine designs, pilling in knitted fibres, shade variation in the fabric, and governs the quality of the fluff yarn. High level of hairiness is creating difficulties while making a fine level of designs in clothing industries. It also results in difficulties in printing. The higher value of the hairiness is undesirable, while a smaller value of the hairiness is desirable for the soft feel of the fabric. High level hairiness reduces the life of the machine parts. The hairiness index is distinct the level of the yarn hairiness. The hairiness index is evaluated by using Eq. (5.32).

$$\text{Hairiness index} = \frac{\text{Total length of Protruding fibres (in mm)}}{\text{Total length of evaluating yarn (in mm)}} \quad (5.32)$$

The hairiness index is tested by the OH sensor with Evenness Tester. This tester works on the monochrome light source shines. The test is performed on the yarn which is processed through the present MR finished grooved drum and the already used ground grooved drum. The tester is provided the average of all protruding fibre length in the one-centimeter length of the yarn. The hairiness index of the yarn which was used for the processing of the packages was 6.40. To check the hairiness index with the already used ground grooved drum surface in industry and present MR finished grooved drum, the winding speed set at a constant value of 500 m/min. This value of winding speed was taken on the basis of the previous results. At the 500 m/min winding speed, the minimum breakage of yarn was observed by using the MR finished drum. The hairiness index value was observed as 8.80 with the already used ground grooved drum and 6.60 with the present MR finished grooved drum. This reduction in the hairiness index value is beneficial for the textile industries. This results in fine designs, reduces pilling in knitted fibres, reduces the shade variation in the fabric, and reduces the breaks at knitting. The fine MR finishing of the grooved surface of the winding drum results in a reduction in the hairiness index value and reduces the breakage of the yarn. Fine finishing of the grooved surface of the winding drum is very helpful to improve the efficiency of the winding operation and enhances the fabric quality in the textile industries. This improves the life span of the machine parts and improves the quality of the clothing products.

5.14 Conclusions

In the taguchi technique, larger the better method is used to optimized the process parameters. The optimized combination of parameters was utilized to fine finishing the grooved surface of the winding drum using the present MR finishing setup. After the MR finishing, the winding grooved drum surface characteristics were compared to the initial ground surface. Further, the MR finished grooved drum was examined its functional improvement in the winding process in the industry. The following specific conclusions are drawn.

- The analysis reveals the effective improvement in the grooved surface of the winding drum with optimized parametric combination as tool core rotational speed 1000 rpm, the workpiece rotational speed 100 rpm, feed rate 30 cm/min and current 2 A for fine finishing the grooved surface of the winding drum with the present MR finishing process.
- The average surface roughness of the grooved surface of the winding drum gets reduced from the initial ground value of 200 nm to 10 nm in 60 minutes with the optimized parametric combination. The surface characteristics of MR finished grooved surface show a great improvement in comparison to the ground grooved surface of the winding drum.
- The improvement in surface characteristics of the grooved surface of the winding drum with the present MR finishing process confirms the reduction in breakage of the yarn. Because the average breakage of yarn before and after MR finishing of the grooved surface of the winding drum found as 11 and 6 respectively.
- The hairiness index value of the yarn with the existing ground grooved surface and with the MR finished grooved surface of the winding drum gets reduced to 8.80 and 6.60. This reduction in hairiness confirms beneficial for the fine designs, reduces pilling in knitted fibres, reduces the shade variation in the fabric, reduces the breaks at knitting and reduces the fluff of the yarn.
- The overall results reveal the reduction in the breakage of the yarn and in the hairiness index value of the yarn improves the design of the product and quality and also improves the life span of the machine parts.

5.15 Magnetorheological finishing of spline shaft for performance enhancement

Spline couplings are commonly utilized to transport the rotary motion or torque in the mechanical system (Ratsimba *et al.*, 2004). It has various advantages like greater linking strength, higher reliability, compact structure, flexible and convenient assembly of the connection (Tatur and Vygonyi, 1969). Due to these advantages, spline couplings are used in

several industries like marine, aerospace, automobile and engineering machines (Barrot *et al.*, 2009). In the automobiles, spline shafts have used in a various system like in clutch, gearbox, differential, etc (Gamez-Montero *et al.*, 2009). Due to the greater necessity of spline shaft, the performance of the spline shaft is put forward in the modern engineering (Volfson, 1982), (Adey *et al.*, 2000). These shafts carry high specific power. Due to this, spline shafts need accurate design to reduce the weight and reduces the wear and fatigue losses. The most significant factor which influences the wear rate and fatigue of the spline teeth is pressure or force distribution on the spline faces (Leen *et al.*, 2000). The pressure or force distribution on the spline faces depends on the design, manufacturing processes, material, surface contact and surface characteristics of the spline faces (Barrot *et al.*, 2000), (Tatur and Vygonnyi, 1969). The uniform fine finishing of the spline teeth surface is highly beneficial for the uniform distribution of the pressure. This helps to overcome the stress localization which generally decreases the life span of the spline shaft.

Further, to predict the optimum parameters for the better process performance, the parametric evaluation of the MR finishing of the spline shaft workpiece (440C stainless steel) has been performed. So, to get uniform and effective fine finishing of the spline shaft, the finishing parameters of the present process has been optimized and validated. The tooth surfaces quality of the spline shaft is studied with the help of the scanning electron microscopy, and standard deviation. Also, the improvement in the mechanical property (micro-hardness) has been investigated. Because, hardness directly effects the volumetric wear rate of the material. Hardness is quite often used as the criteria for judging alloys, castings, hard facings, and overlays in the field of wear resistance. The premise is that the harder the material, the greater the resistance to wear (Archard, 1953). As the value of the hardness varies which influences the volumetric wear rate of the components (Archard, 1953). Enhancement in the hardness value improves the volumetric wear rate of the work-part. Fine finishing of the spline shaft surfaces is beneficial for the pressure distribution on the spline inner and outer teeth surface. The MR finishing of the teeth surfaces (external, face and bottom land) of the spline shaft help to improve the pressure distribution on the teeth surfaces, resistance to wear rate, and micro-hardness which has been confirmed in the present work. This leads to an increase the functional performance of the spline shafts in various industrial applications such as in transmission systems of the marine, aerospace, automobile and for high specific power transmission couplings.

Spline shaft material has good mechanical properties like higher strength, good hardness, and great wear resistance. For the experimental plan, the finishing parameters are nominated on the

basis of machine ability and available literature review (Maan and Singh., 2018). There are four most influencing process parameters which are taken as the rotary speed of rectangular tool core (S), rotary speed of the spline shaft workpiece (W), current (I) and the reciprocatory movement of the rectangular tool core (R). Current governs the flux intensity to control the degree of stiffness of MR polishing fluid in the working gap, which helps to remove the surface roughness asperities.

The level of the current was varied from 1 to 3 A in present experimentation. Other three process parameters are governed the relative motion amid the work-part and rectangular tool core end surface. The rotary speed of the rectangular tool core and spline shaft directs the tangential force (F_t) of the active abrasives. The level of the rotary speed of the rectangular tool and spline shaft is varied from 800 to 2800 rpm and 50 to 170 rpm respectively. The feed rate of the tool core influencing the axial force (F_a) of the active abrasives. The level of the feed rate varied from 10 to 50 cm/min in present experimentation. The process parameters and their level are given in Table 5.8.

Table 5.8 Experimental process parameters and its range

S. No	Parameters	Units	Range				
1	Rotational speed of tool core tip surface (S)	rpm	800	1300	1800	2300	2800
2	Rotational speed of cylindrical spline shaft workpiece (W)	rpm	50	80	110	140	170
3	Reciprocating speed of the tool core tip surface (R)	cm/min	10	20	30	40	50
4	Current (I)	A	1	1.5	2	2.5	3

For finishing the spline profile surfaces (face and bottom land) of the spline shaft, two motions are required one is rotational speed of spline profiled finishing tool (T) and second one is reciprocation speed of spline profiled finishing tool (P) to cover the whole profile surfaces of the spline shaft. The range of the rotational and reciprocation speed is varied from 400 to 2000 rpm and 5 to 25 cm/min respectively. The process parameters and their levels are given in Table 5.9.

Table 5.9 Experimental process parameters and its range for inner grooved (face and bottom land) surfaces of spline shaft

S. No	Parameters	Units	Range				
1	Rotational speed of spline profiled finishing tool (T)	rpm	400	800	1200	1600	2000
2	Reciprocating speed of the spline profiled finishing tool (P)	cm/min	5	10	15	20	25

The central composite design (CCD) technique is utilized to construct the experimental combination. The four process parameters with five-level are constructed the 30 experimental combinations. Each experimental combination is performed on 20 mm length and 45 mm diameter of the spline shaft for 40 min finishing time. The experimental setup which is used for experimentation is shown in Fig. 5.27.

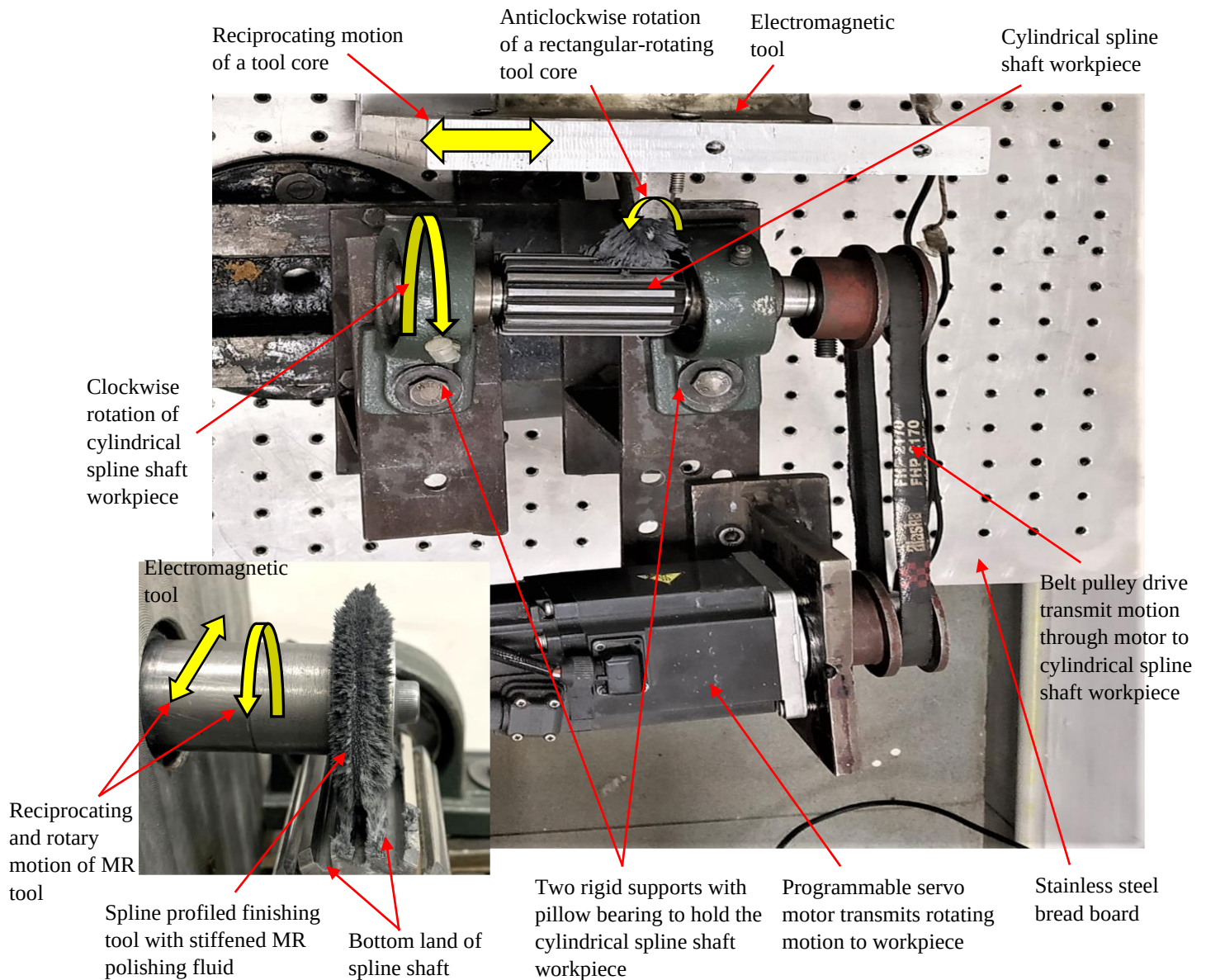


Fig. 5.27 Setup of rectangular-rotating core based magnetorheological finishing process during MR finishing of external (topland) surface and profile (face and bottom land) surfaces of the spline shaft workpiece.

After performing MR finishing with each experimental combination, the response % improvement in surface roughness ($\%\Delta Ra$) is evaluated. The initial ground surface roughness on each tooth face of the spline shaft is measured at 6 different locations and the average value

of the initial surface roughness value is calculated. After MR finishing, the final Ra values are also measured at 6 different locations on the tooth face of the spline shaft at each experimental trial and average final Ra value is calculated, and then %ΔRa is evaluated. Similar steps were taken for the profile surfaces of the spline shaft which were taken for external teeth surface. The initial and final surface roughness values of face surface and bottom land were measured at 6 different locations on the both face and bottom land surfaces and average values of initial and final surface roughness were taken as outcome. Surftest SJ-410 (Mitutoyo) was used to measure surface roughness values. In the present work, the surface roughness measurement is performed with 0.25 mm cut off length and 80μm resolution range. After surfaces finishing achieved by the present process, the scanning electron microscopy (SEM) was performed to analyse the finished surface characteristics. Also, the mechanical property (micro-hardness) and standard deviation were investigated of the finished surface after the experimentation.

5.16 Results and discussion

The % involvement of individually and interaction of the process parameter on the outcome is analysed. The % contribution of the process parameters indicates the impact of each parameter on the process performance. Individually maximum contributing parameters are found as current (I) and tool core speed (S) which contributes 26.77% and 16.07% respectively in reduction in Ra value. The square of the current (I) value and feed rate (R) value is a significant effect on the outcome with contribution of 18.69% and 12.59% respectively. It is cleared that the two individuals i.e. current (I) and tool core speed (S) and two squared terms i.e. current (I) and feed rate (R) significantly affect the process performance with the overall %age contribution of 74.12%. These parameters significantly impact the process performance during MR finishing of spline shaft. The regression model helped to predict the optimum process parameters, which maximized the % improvement in Ra for external teeth surface of the spline shaft. The R-squared value of the regression model was found as 94%. The regression model is given from the experimental analysis is expressed in Eq. (5.33).

$$\begin{aligned} \% \text{ improvement in Ra } (\% \Delta \text{Ra}) \text{ for external teeth surface of spline shaft} = & -202.77 + 0.0711 S \\ & + 0.737 W + 2.663 R + 93.58 I - 2.9 \times 10^{-5} S^2 - 3.29 \times 10^{-3} W^2 - 0.027 R^2 - 19.33 I^2 - 2.3 \times 10^{-4} \\ & SW - 2.3 \times 10^{-4} SR - 0.325 RI \end{aligned} \quad (5.33)$$

Where, S is rotational speed of tool core in rpm, W is rotational speed of the cylindrical spline shaft workpiece in rpm, R is the reciprocating speed of the tool core in cm/min and I is current in Ampere. The optimum process parameters were found as current 2 A, the feed rate of the rectangular tool core 30 cm/min, the rotary speed of the rectangular tool core 1800 rpm, and workpiece rotation of 110 rpm at 0.6 mm working gap to achieve the maximum %ΔRa. The

validation test experiment is performed to check the accuracy of the regression model. To check the accuracy of the model, three trial experiments were performed at optimum process parameters and compare the outcome to the regression model outcome (Eq. (5.33)). The value of the theoretical outcome ($\% \Delta Ra$) was obtained by using the Eq. (5.33).

In the fine finishing of profile surfaces, the individual maximum contributing parameter is found as rotational speed of spline profiled finishing tool (T) which contributes 39.04% in reduction in Ra value of profile surfaces of spline surface. The square of the rotational speed of spline profiled finishing tool (T) value is a significant effect on the outcome with contribution of 18.89%. It is cleared that the individual i.e. rotational speed of spline profiled finishing tool (T) and squared term of it significantly affect the process performance with the overall %age contribution of 57.93%. The regression model helped to predict the optimum process parameters, which maximized the % improvement in Ra for profile surfaces of the spline shaft. The R-squared value of the regression model was found as 91%. The regression model is given from the experimental analysis is expressed in Eq. (5.34).

$$\% \text{ improvement in Ra } (\% \Delta Ra) \text{ for profile (face and bottom land) surfaces of spline shaft} = 72.33 + 9.06 \times 10^{-3} T + 8.01 \times 10^{-4} P + 5.06 \times 10^{-6} T^2 + 2.97 \times 10^{-7} P^2 + 7.56 \times 10^{-6} TP \quad (5.34)$$

The % error was evaluated between experimental and theoretical outcome to check the accuracy of the regression model. The % error value was lies in the range between -5.10 % to 3.37 %. The optimum parameters for internal grooved surface finishing were found as rotational speed of spline profiled finishing tool 1200 rpm and reciprocation speed of spline profiled finishing tool 20 cm/min to attain the maximum $\% \Delta Ra$. This % error range reveals a good agreement between the experimental and theoretical outcome. To check the accuracy of the model for spline profile surfaces of spline shaft, three trial experiments were performed at optimum process parameters and compare the outcome to the regression model outcome (Eq. (5.34)). The value of the theoretical outcome ($\% \Delta Ra$) was obtained by using the Eq. (5.34). The % error value was lies in the range between -5.02 % to 3.95 %. This % error range reveals a good agreement between the experimental and theoretical outcome. This signifies that this optimization of process parameters for external and inner profile surfaces are highly beneficial for the MR finishing of the 440C material industrial applications.

The interaction effect of the rotary speed of the rectangular tool core (S) and the spline shaft workpiece (W) on %age reduction in the Ra ($\% \Delta Ra$) while other finishing parameters are taken at constant values as depicted in Fig. 5.28(a). The rotary speed of both rectangular tool core and spline workpiece influencing the tangential force (F_{tt}) of the active abrasive particles. At the 800 rpm speed of tool core with different speeds of workpieces, the lesser relative motion

between the workpiece surface and active abrasives in MR polishing fluid at tool tip end surface is obtained.

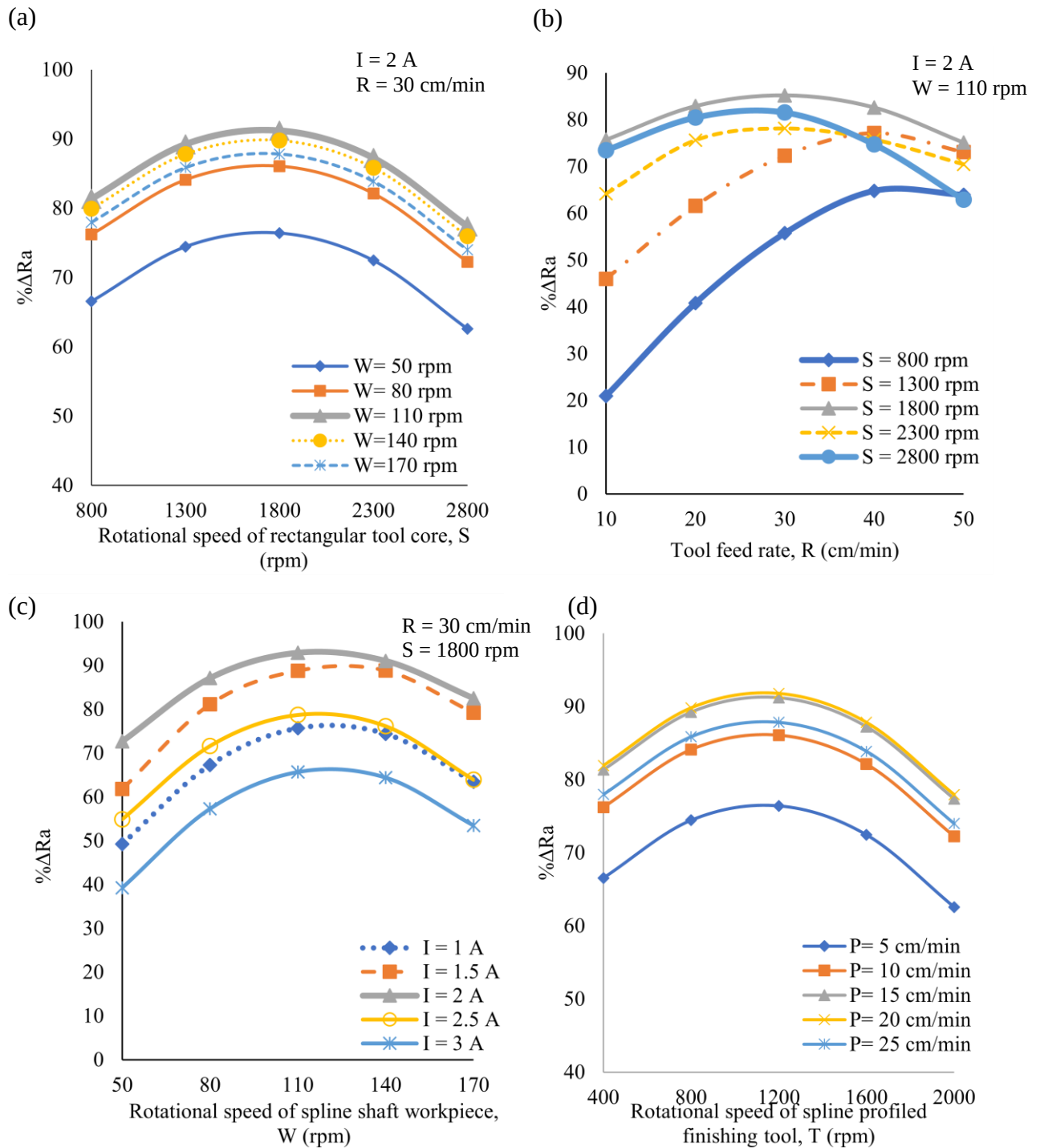


Fig. 5.28. (a) Effect of rectangular tool core speeds (T) at different spline shaft workpiece speed (W) on $\% \Delta R_a$, (b) effect of feed rate (R) at different tool core speeds (S) on $\% \Delta R_a$, (c) effect of spline shaft workpiece speed (W) at different current (I) values on $\% \Delta R_a$ and (d) effect of rotational speed of spline profiled finishing tool (T) at different feed rate of spline profiled finishing tool (P) on $\% \Delta R_a$.

Due to this lesser tangential force generates which leads to reduces the %age reduction in Ra. When the rotary speed of the rectangular tool core increases, the relative motion between the workpiece surface and the polishing fluid at the tool tip end surface is increased. At the 1800 rpm, speed of tool core with different speeds of workpiece maximum % Δ Ra is observed. But after 1800 rpm speed of tool core, the % Δ Ra is decreasing. Because of the rotary speed of the rectangular tool tip, a centrifugal force (F_c) also acts over the active abrasive particle that can be calculated by using the Eq. (5.35).

$$F_c = m_a r \omega^2 \quad (5.35)$$

where, the radius of the active abrasive is denoted as r in m.

This happens because of the higher speed of the tool core, the centrifugal force (F_c) is also started to participate in the finishing forces. From Eq. (5.35) it is cleared that the mass of the active abrasive (m_a) and angular velocity (ω) governs the centrifugal force (F_c). At higher tool speed, the value of the ω is increased which increases the centrifugal force (F_c) on the active abrasives as expressed in Eq. (5.35). As the centrifugal force (F_c) increases, the active abrasives trends to moves in a radial direction. Due to this chain structure of the iron particles are disturbs, which leads to decreases the % Δ Ra. As the speed of tool core, further increases from 1800 rpm to 2300 rpm and further 2300 rpm to 2800 rpm the % Δ Ra is decreased. The best combination of the rotary speed of the rectangular tool core and spline shaft is predicted as 1800 rpm and 110 rpm which provides the maximum % Δ Ra as depicted in Fig. 5.28(a). The interaction effect of the rotary speed of the rectangular tool core (S) and the reciprocation speed of the tool core (R) on %age reduction in Ra (% Δ Ra) while other finishing parameters are taken at constant values as depicted in Fig. 5.28(b). The reciprocation tool core speed is governing the axial force (F_a) of the active abrasive. In Fig. 5.28(b) shows that as the value of the feed rate increases, the % Δ Ra decreases. As the tool feed rate increase, the value of the axial force (F_a) rises which results in a rise of the shear stress in the iron particle chains. Due to this excessive shear stress, the breakage of the iron particle chains takes place. At the rotational speed of 800 rpm and 1300 rpm of tool core, lesser %age reduction in Ra is observed because of the lesser collusion between the active abrasives and roughness peaks is takes places. But at a higher speed of the tool core at 2300 rpm and 2800 rpm, the centrifugal force (F_c) is starting to disturbing the iron chains which decreases the %age reduction in Ra. The maximum % Δ Ra is obtained at the interaction value of the reciprocation speed of the rectangular tool core (R) and rotary speed of rectangular tool core (S) is 30 cm/min and 1800 rpm respectively.

The interaction effect of the rotational speed of spline shaft workpiece (W) and current (I) on %age reduction in Ra (% Δ Ra) while other finishing parameters are taken at constant values is

depicted in Fig. 5.28(c). The magnetizing current is governing the iron particles chains rigidness and workpiece rotational speed govern the collision of the roughness peaks to the active abrasives. In Fig. 5.28(c) it shows that at a rotational speed of the workpiece 50 rpm and 80 rpm, lesser %age reduction in Ra value is observed because of the lesser striking among the active abrasives and the roughness crests. But at a higher speed of workpiece at 140 rpm and 170 rpm, the breaks of the iron particles chains take place because of the fast striking among the active abrasives and the roughness crests. At the current value of 1 A and 3 A, lesser %age reduction in Ra observed. At 1 A current, the iron particles chains are not that strong to clip off the roughness peaks. But at 3 A current, the iron particles chains have excessively strong which clip off the excess material. Due to this $\% \Delta Ra$ is decreased. At the combination of 2 A current and 110 rpm of the workpiece, the optimum collision and strength to iron particle chains are provided. Due to this the maximum $\% \Delta Ra$ is observed at that combination as depicted in Fig. 5.28(c).

The interaction effect of rotational speed of spline profiled finishing tool (T) at different feed rate of spline profiled finishing tool (P) on %age reduction in Ra ($\% \Delta Ra$) while other finishing parameters are taken at constant values as depicted in Fig. 5.28(d). The rotational speed of spline profiled finishing tool influencing the tangential force (F_{tt}) of the active abrasive particles. At the rotational speeds of spline profiled finishing tool 400 and 800 rpm with different feed rate of spline profiled finishing tool, the lesser relative motion between the workpiece surface and active abrasives in MR polishing fluid at spline profiled finishing tool surface is obtained. Due to this lesser tangential force generates which leads to reduces the %age reduction in Ra. When the rotary speed of the spline profiled finishing tool increases, the relative motion between the workpiece surface and the polishing fluid at the spline profiled finishing tool surface is increased. At the rotational speed of spline profiled finishing tool 1200 rpm with different feed rate of spline profiled finishing tool maximum $\% \Delta Ra$ is observed. But after 1200 rpm of rotational speed of spline profiled finishing tool, the $\% \Delta Ra$ is decreasing. This happens because of the higher speed of the tool core; the centrifugal force is also started to participate in the finishing forces. From Eq. (5.35) it is cleared that the mass of the active abrasive (m_a) and angular velocity (ω) governs the centrifugal force (F_c). At higher spline profiled finishing tool speed, the value of the ω is increased which increases the centrifugal force (F_c) on the active abrasives as expressed in Eq. (5.35). As the centrifugal force (F_c) increases, the active abrasives trends to moves in a radial direction. Due to this chain structure of the iron particles are disturbs, which leads to decreases the $\% \Delta Ra$. As the rotational speed of spline profiled finishing tool, further increases from 1200 rpm to 1600 rpm and further 2000

rpm the $\% \Delta Ra$ is decreased. The best combination of the rotational speed of spline profiled finishing tool and feed rate of spline profiled finishing tool is predicted as 1200 rpm and 20 cm/min which provides the maximum $\% \Delta Ra$ as depicted in Fig. 5.28(d).

After optimization of the process parameters, the whole surface of the spline shaft is finished with optimized parameters. The length and diameter of the spline shaft were 80 mm and 45 mm during the whole surface finishing of the spline shaft's inner and external teeth. The total time was taken 6 hrs for the MR finishing of the whole surface of the spline shaft teeth. The surface roughness parameters (Ra , Rq , Rz) measurement was performed on the total length of the teeth surface in every 2 hrs of MR finishing. The total 9 measurements of the roughness parameters were taken at each MR finished external (top land) tooth surface of the spline shaft and average of the measured surface roughness parameters are evaluated. The total change in the surface roughness parameters in 6 hrs is depicted in Fig. 5.29(a). The average initial ground surface roughness at spline shaft external teeth was found as $0.27 \mu m$ as depicted in Fig. 5.29(b). After the 6 hrs MR finishing on the whole surface, the average final surface roughness at spline shaft external teeth was found as $0.02 \mu m$ as depicted in Fig. 5.29(c). This surface roughness reduction is observed in three cycles each got 2 hrs finishing time. In the first 2 hrs finishing cycle, the surface roughness reduction was observed as $0.09 \mu m$ (Fig. 5.29(a)). In the second and third finishing cycle, the surface roughness reduction was observed as $0.04 \mu m$ and $0.02 \mu m$ (Fig. 5.29(a)), respectively. The % improvement in surface roughness in these three finishing cycles was observed as 66.66%, 55.55%, and 50% respectively. From Fig. 5.29(a), it is easily observed that the % improvement in Ra is greater in the first finishing cycle compare than the second and third. The maximum change in Ra value is observed in the first finishing cycle on the low cutting (shear) area of the roughness peaks at its uppermost part. Due to this, the smaller magnitude of the shear force is required to shear off the roughness asperities. However, during the second and third finishing cycle, no significant change was observed in the reduction of Ra value in comparison to the first finishing cycle. Same procedures were taken for the spline shaft's profile surfaces, overall, 6 hours MR finishing of the spline shaft teeth's profile surfaces were carried out. The total reduction in parameters of surface roughness within 6 hours as seen in Fig. 5.30(a). The average initial ground surface roughness at spline shaft profile surface was found as $0.30 \mu m$ as depicted in Fig. 5.30(b). The average final surface roughness at spline shaft profile surface was found as $0.03 \mu m$ as depicted in Fig. 5.30(c). To know the surface topography of the teeth surface of the spline shaft, the scanning electron microscopy (SEM) test is performed.

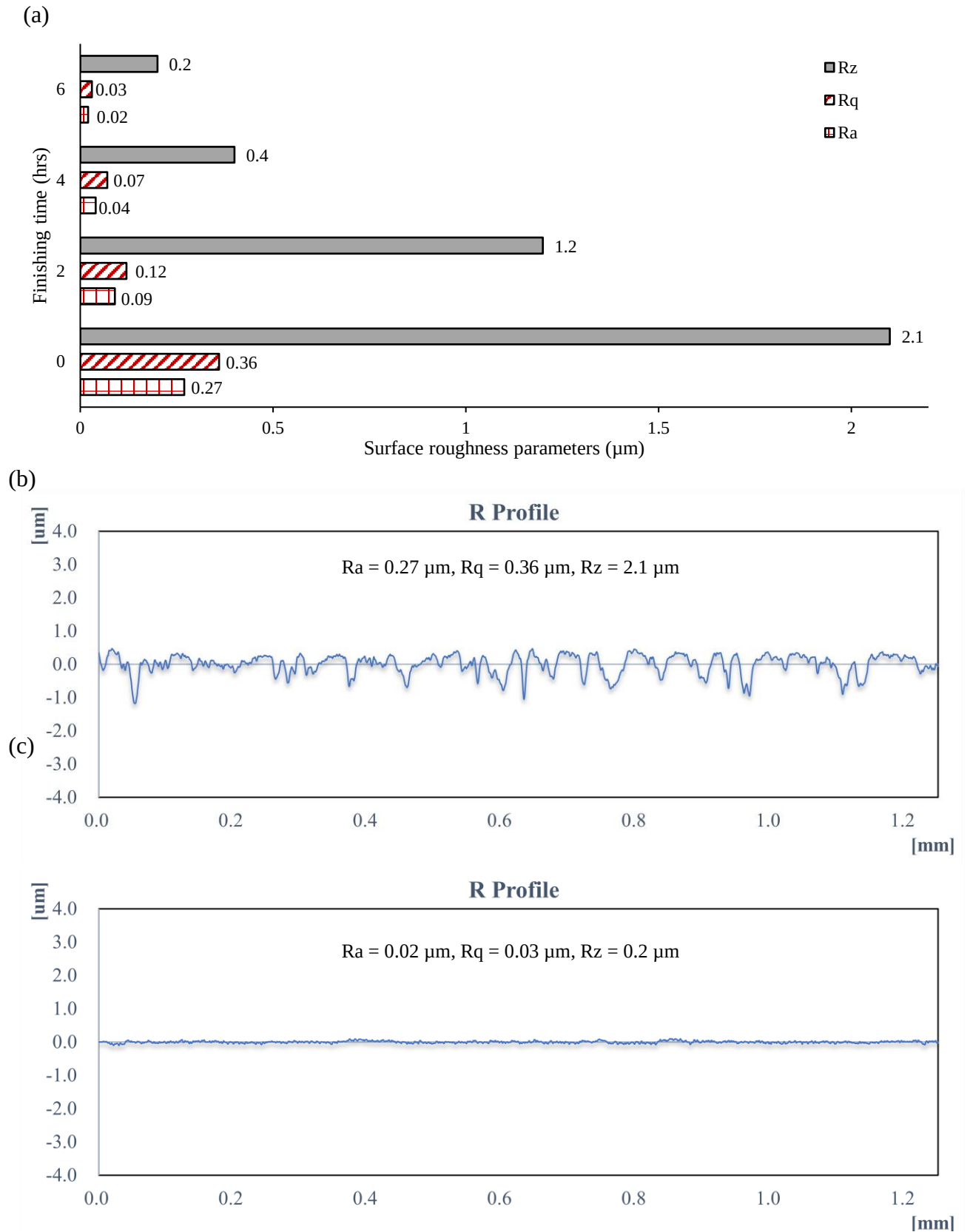


Fig. 5.29 (a) Change in surface roughness parameters at different finishing time on entire external (top land) surface of the spline shaft workpiece, surface roughness profiles of the tooth external (top land) surface of the spline shaft workpiece (b) initial ground surface, (c) after 90 min MR finishing with optimized process parameters.

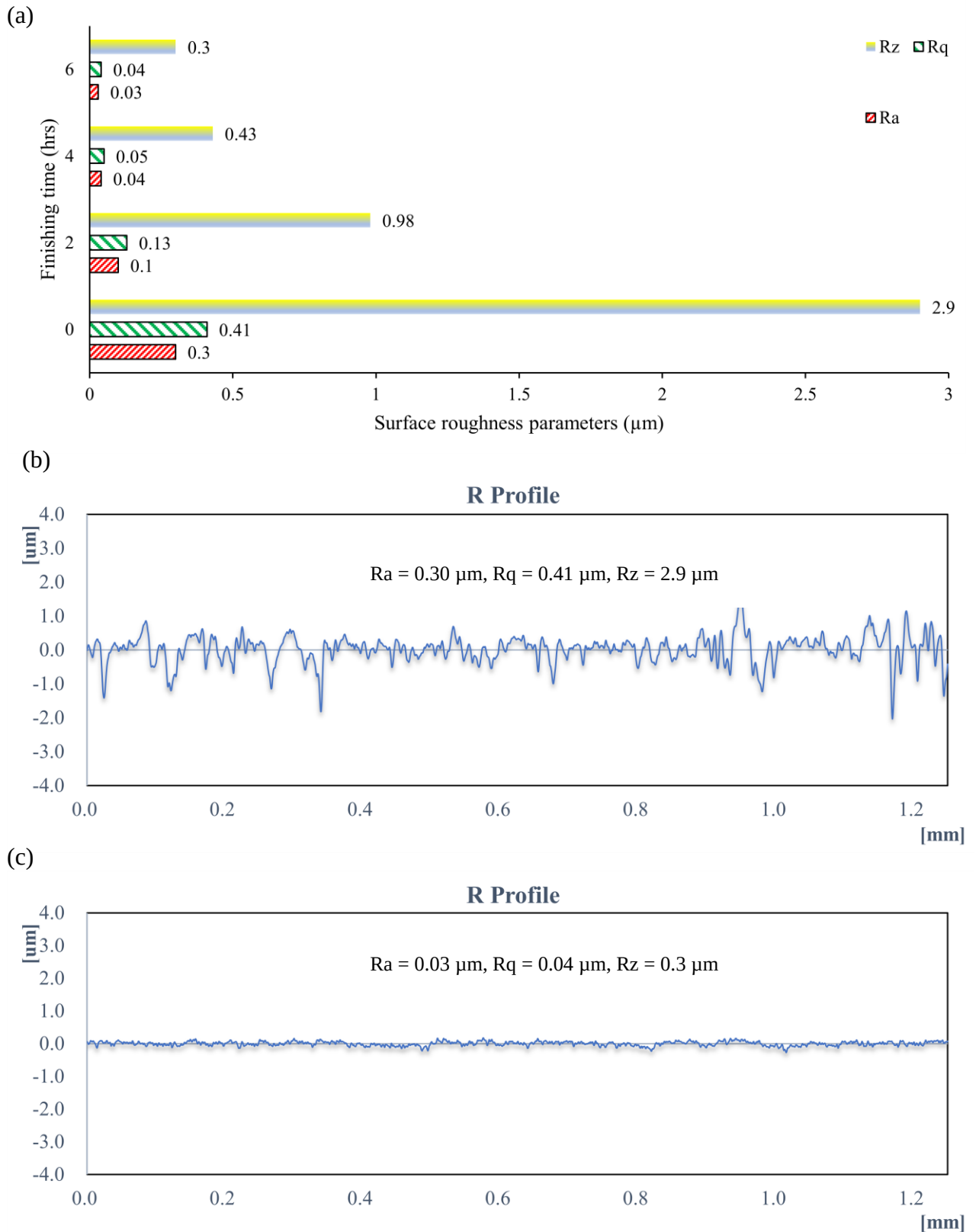


Fig. 5.30 (a) Change in surface roughness parameters at different finishing time on entire profile (face and bottom land) surfaces of the spline shaft workpiece, surface roughness profiles of the profile (face and bottom land) surfaces of the spline shaft workpiece (b) initial ground surfaces, (c) after 90 min MR finishing with optimized process parameters.

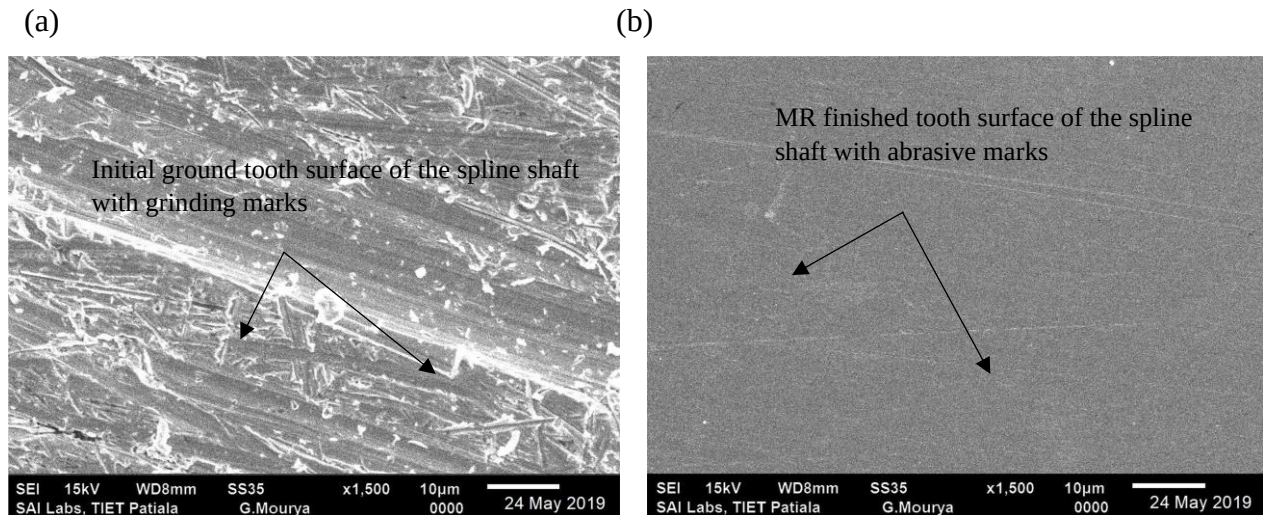


Fig. 5.31 SEM images of the tooth external (top land) surface of the spline shaft workpiece at 1500X (a) initial ground surface, (b) after 90 min of MR finishing with optimized process parameters.

In this test, amplify the optical zoom of the instrument and check the surface topography of the workpiece surface. In the present test, the optical zoom is set at 1500 X. The SEM test photographs of before and after MR finish spline shaft tooth surface are depicted in Fig. 5.31. Fig. 5.31 (a) shows the initial ground surface photograph of the tooth surface of the spline shaft workpiece.

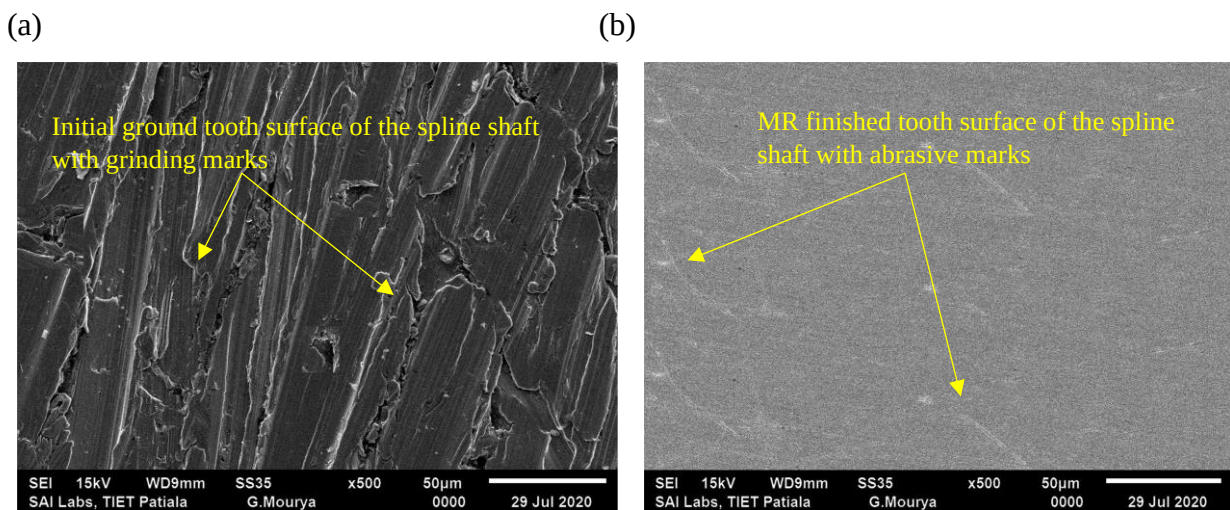


Fig. 5.32 SEM images of the profile (face and bottom land) surfaces of the spline shaft workpiece at 500X (a) initial ground surface, (b) after 90 min of MR finishing with optimized process parameters.

The grinding marks are easily depicted on the initial ground tooth surface of the spline shaft workpiece. Fig. 5.31 (b), it is shown that the MR finished surface photograph tooth surface of the spline shaft workpiece. Fig. 5.31 (b) easily depicted that the all grinding marks are removed

and smooth surface of the spline shaft teeth was obtained. The SEM test photographs of before and after MR finish spline shaft profile surfaces are depicted in Fig. 5.32. Fig. 5.32 (a) shows the initial ground surface photograph of the profile surfaces of the spline shaft workpiece. The grinding marks are easily depicted on the initial ground profile surface of the spline shaft workpiece. These grinding marks increase localization of the pressure on particular locations where grinding marks are deeper or shallow that increases the failure rate and wear rate of the spline shaft. Fig. 5.32(b), it is shown that the MR finished surface photograph profile surface of the spline shaft workpiece. Fig. 5.32(b) easily depicted that all grinding marks are removed and the smooth profile surface of the spline shaft was obtained. Figs. 5.31(b) and 5.32 (b) show the capability of the MR finishing process which remove all grinding marks and fine finished surface is obtained. The fine finished surface of the spline shaft helpful for the uniform pressure distribution and reduces the wear rate of the spline shaft's tooth surface. The SEM test and roughness profiles of external and profile surfaces prove the significant enhancement in the spline shaft.

5.16.1 Application of magnetorheological (MR) finished spline shaft for the enhanced performance

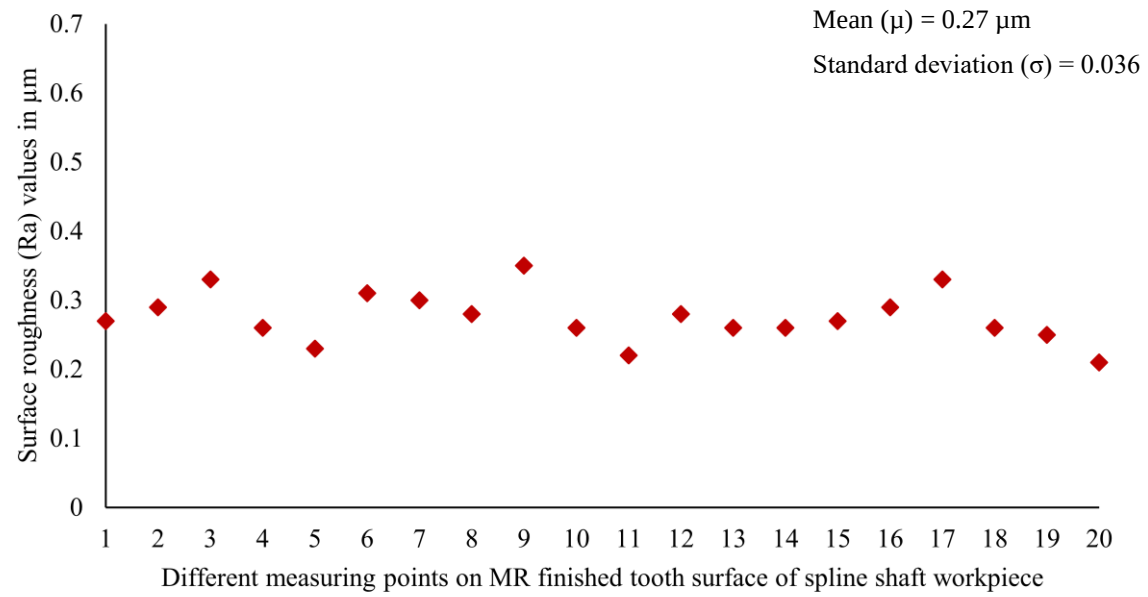
The spline shaft has various applications in the transmission system, in the marine industry, aerospace industry, automobile, and engineering machines. The main factor which influences the performance of the spline shaft is pressure distribution along the tooth surface. The MR finishing of the tooth surface enhances the performance of the spline shaft in the transmission system. The influencing factor in the spline shaft is pressure distribution on the tooth surface. To know the uniformity of fine finishing on the tooth surface of the spline shaft, the standard deviation (σ) and mean (μ) values are calculated on the tooth surface. To perform the standard deviation (σ) and mean (μ) test, 20 different Ra value measurements was taken on the whole tooth surface of the spline shaft to evaluate the uniformity of the finishing. The 20 measurements of the Ra value are measured on the initial ground surface and MR finished surface of the tooth surface of the spline shaft. The value of the mean (μ) and standard deviation (σ) is calculated by using Eqs. (5.36) and (5.37).

$$\mu = \frac{m_1 + m_2 + m_3 \dots + m_n}{N} \quad (5.36)$$

Where $m_1, m_2, m_3 \dots m_n$ are the measured Ra values on the initial ground surface and final MR finished surface. N is the total number of measurements on the tooth surface of the spline shaft workpiece.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^n (m_i - \mu)^2} \quad (5.37)$$

(a)



(b)

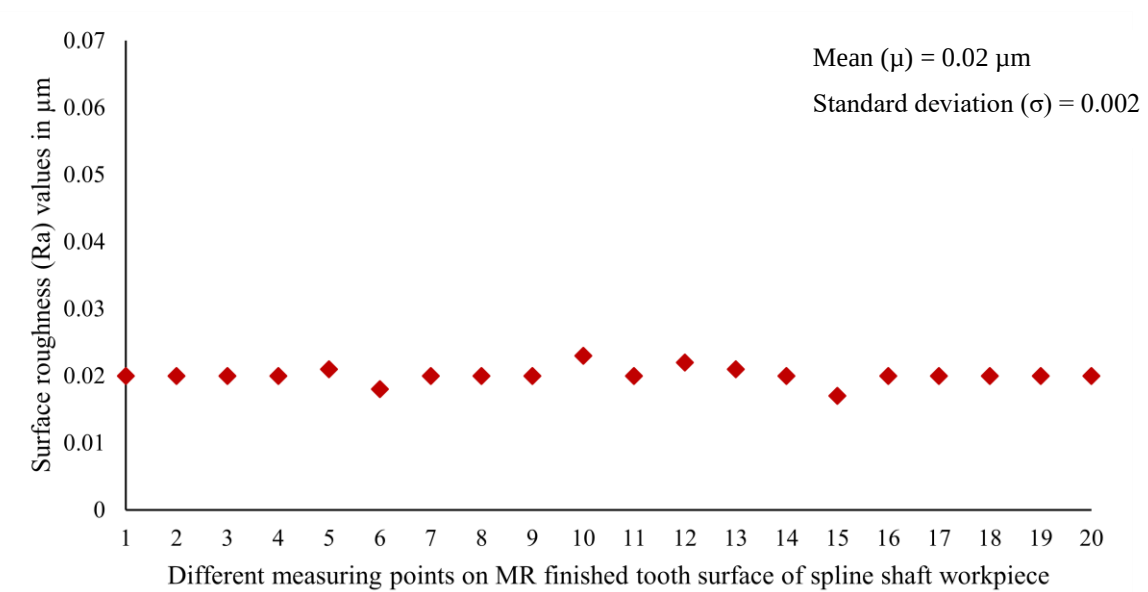
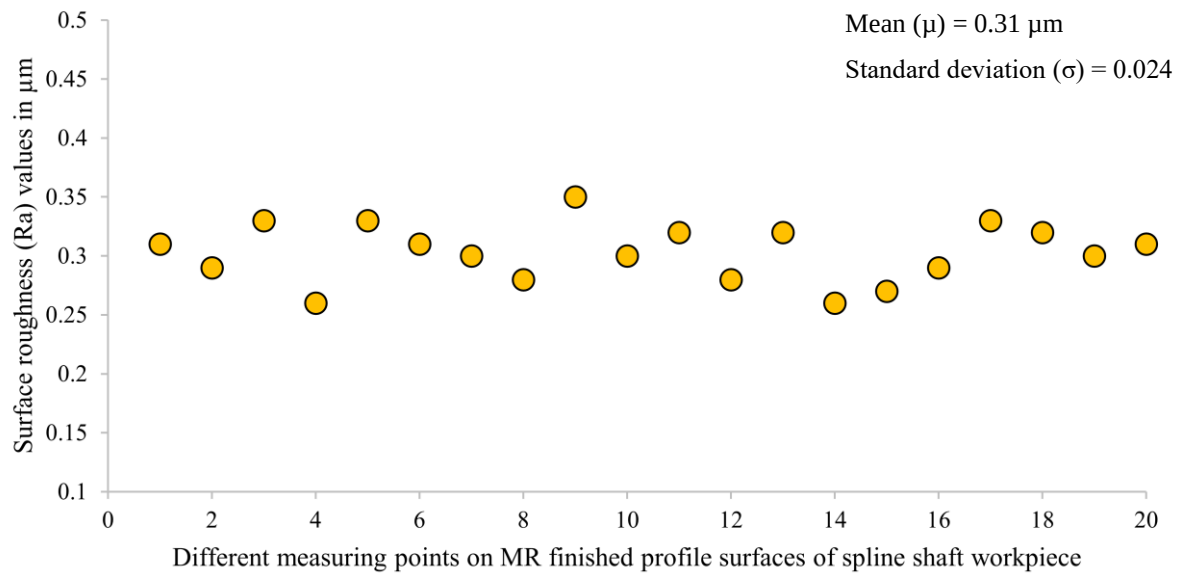


Fig. 5.33 Plot between the surface roughness values and different measuring points on the tooth external (top land) surface of the spline shaft workpiece for mean and standard deviation values at (a) initial ground surface, (b) after 90 min of MR finishing with optimized process parameters.

The measured values of Ra on the initial ground surface and MR finished surfaces are put into Eqs. (5.36) and (5.37) and evaluated the values of the mean (μ) and standard deviation (σ). The

20 measured values of the before and after MR finishing of external (top land) surface of spline shaft is plotted as depicted in Figs. 5.33(a) and (b).

(a)



(b)

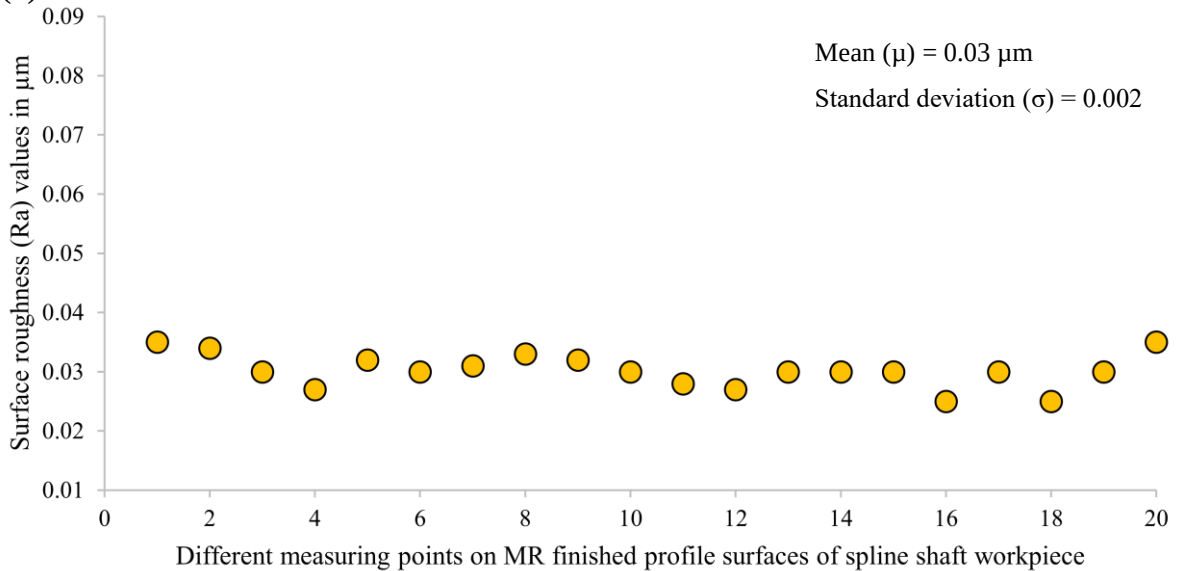


Fig. 5.34 Plot between the surface roughness values and different measuring points on the profile (face and bottom land) surfaces of the spline shaft workpiece for mean and standard deviation values at (a) initial ground surface, (b) after 90 min of MR finishing with optimized process parameters.

The value of the mean (μ) at before and after MR finished external surface was found as 0.27 μm and 0.02 μm . The standard deviation (σ) value of the before and after MR finished

tooth surface was found as 0.036 and 0.002 as depicted in Figs. 5.33(a) and (b). The localization of the stresses is mainly occurred due to the uneven or non-uniformity of the surface finish along the tooth surface. The 20 measured values of the before and after MR finishing of profile (face and bottom land) surfaces are plotted as depicted in Figs. 5.34(a) and (b). The value of the mean (μ) at before and after MR finished of profile surfaces were found as 0.30 μm and 0.03 μm . The standard deviation (σ) value of the before and after MR finished profile surfaces were found as 0.024 and 0.002 as depicted in Figs. 5.34(a) and (b). The standard deviation (σ) value of the final MR finished surface proves that the whole surfaces of the profile and external surface is uniformly fine finished.

The uniformly fine finishing of the tooth surface of the spline surface helps to uniformly distribute the pressure along the tooth surface. This help to reduces the localization of the stresses on the tooth surface of the spline shaft. The localization of the stresses leads to increase the fatigue load which generates the micro-cracks on the tooth surface of the spline shaft. This leads to breakage of the spline tooth and degrades the life span of the tooth of the spline shaft. The uniformly MR finishing of the spline shaft tooth surfaces reduce the fatigue load and enhance the life span of the spline shafts. The micro-hardness test is also performed on the profile and external surfaces of the spline shaft before and after MR finishing. The micro-hardness is performed using the Mitutoyo HM-210 model. The diamond indenter is utilized to measure the micro-hardness on the before and after MR finished spline shaft tooth surface. The 500 N load is applied to the diamond indenter during the testing. The hardness value is obtained by the test in Vickers Pyramid Number (HV). The 6 measurements of micro-hardness values are performed on the before and after MR finished spline shaft profile and external surface and the average value of HV number is calculated. The avg. value of HV number on the initial ground surfaces were found as 649. The average HV number on the final MR finished surfaces were found as 746. From the micro-hardness test, it proves that the hardness value is increased after the MR finishing. The reason behind that when the surface roughness value is higher, the height of peaks and the depth of the valleys are higher. When the height of the peaks is higher (Ra value of 0.27 μm (external) and 0.30 μm (profile)) after the grinding on the spline shaft, the sharp roughness peaks lead to stress concentration and lesser loading capacity on the inner and external surface of the spline shaft. But, when the external and profile surfaces of the spline shaft get fine finished (Ra value of 0.02 μm and 0.03 μm) using the present MR finishing process, the height of the roughness peaks get further reduced uniformly. This leads to reduce the stress concentration and gives a good loading capacity on the tooth surfaces of the spline shaft. This results in the improvement of the hardness of the MR finished teeth surfaces of the

spline shaft. The higher hardness value of the spline teeth resists the wear by either due to friction or erosion. The hardness value directly impacts on the volumetric wear of the workpiece. According to the classical Archard sliding wear theory (Archard, 1953), total volume of the material removal due to the wear (V_q) can be calculated using Eq. (5.38).

$$\frac{V_q}{L_s} = C_A \frac{W_L}{H} \quad (5.38)$$

Here, C_A is the wear coefficient of the workpiece material, W_L is the total normal load in kg, L_s is the total sliding distance in mm, and H is the Brinell hardness number of the workpiece material in N/mm^2 . From the classical Archard sliding wear theory, it is cleared that the hardness is inversely proportional to the total volumetric removal of material due to wear (V_q) that verified, as the value of the hardness is increased the V_q is decreased. As seen the micro hardness results of the spline shaft after MR finishing cleared that the hardness value is increased. This signifies that the after the MR finishing of the spline shaft, the wear rate of it is decreases. Suppose, the working spline shaft (before MR finishing) is work on the particular load with HV hardness value of 649. But after the MR finishing the hardness number HV is enhanced and it is 746. This signifies that MR finished spline shaft at that working load gives the lesser wear of material which increases the life span of the spline shaft. So, MR finishing of the spline shaft teeth surface can help to enhance the functional performance of the spline shaft in various industrial applications. The MR finishing provides the exact fits and good tolerances between the mating parts of the spline shaft during the transmission coupling.

5.17 Conclusions

The optimization study of the process parameters was performed on the 440C stainless steel spline shaft workpiece. After fine finishing, the surface characteristics and micro-hardness value get increased as compared to the initial ground teeth surfaces of the spline shaft. The results from the present work are made as to the following conclusions.

- Process performance mechanism found better when spline shaft workpiece rotates clockwise with an anticlockwise rotation of the rectangular tool core as surface roughness value gets reduced more in this combination for the same parametric conditions and finishing time. This signifies the direction of motions of tool core and workpiece influences process performance.
- The regression model analysis signifies that the present process performance in fine finishing the external (top land) surface of spline shafts are highly contributed by the magnetizing current as 26.77% followed by the rotary speed of rectangular tool core as

16.07%, the rotary speed of the spline shaft as 9.43% and the tool core feed rate as 3.98% in total % improvement in the Ra value. The regression model analysis for profile (face and bottom land) surfaces of the spline shaft workpiece reveals that the maximum contributed parameter is tool core rotating speed with percentage of 39.04.

- The reduction in Ra value from 0.27 μm to 0.02 μm after MR finished on the spline shaft 's external teeth surface and the profile surfaces reduction in Ra value from 0.30 μm to 0.03 μm is observed with the optimum process parameters expected to show that the spline shaft surface is fine finished and helps increase performance as it is used for practical applications.
- Uniform fine finishing of the teeth surface of the spline shaft confirms the reduction in the localization of the stresses on its surface because of the negligible height of the roughness peaks. Also, it improves the uniform distribution of the pressure over the teeth surface of the spline shaft which further, improve the life span of the spline shaft.
- Improvement in the micro-hardness number from 649 HV to 746 HV after MR finishing of teeth surface of the spline shaft reveals the enhancement in wear resistance and the life span of the MR finished spline shaft. The overall results signify that the MR finishing of the spline shaft can facilitate better functional conditions.

5.18 Magnetorheological finishing of copper cylindrical roller for its improved performance in printing applications

Copper and its alloy are the most versatile engineering materials which are used for various industrial applications (Li, 2008), (Murarka *et al.*, 2000), (Ein-Eli and Starosvetsky, 2007). These materials have good mechanical and physical properties such as strength, conductivity, corrosion resistance, machinability, and ductility which make these materials suitable for a wide range of applications (Wagal, 1996). Therefore, these are widely used in the energy, electrical power, electronics, transportation, petrochemicals, metallurgy, machinery, light, and other new industries. Copper material also used in the automotive industry for various applications like in brake linings, hydraulic equipment, bearings, gears, power distribution and power systems, braking systems, gaskets, fittings and all kinds of joints, and accessories, etc. The rectangular rotating magnetorheological (MR) finishing process fulfills the uniform and fine finishing requirements of the various industrial applications of the ferromagnetic cylindrical workpieces. But non-ferromagnetic material such as diamagnetic copper cylindrical work-part is not yet finished with the rectangular rotating magnetorheological (MR) finishing process. In this work, initially the suitable composition of the magnetorheological polishing

fluid (electrolytic iron particles (EIPs), aluminium oxide abrasive particles and base fluid.) is analysis and found out the better performance. The preliminary experimentation is performed with different MR polishing fluid compositions. From preliminary experimentation, which combination of the abrasive and iron particles is found with maximum reduction in surface roughness is utilized for further experimentation. Furthermore, the design of experiments is performed to optimize the process parameters like rotary motion of the rectangular core and the copper cylindrical work-part, to and fro motion of the core and current of the electromagnet. Furthermore, the experimentation is performed using optimized MR polishing fluid with optimized process parameters to obtain the fine and uniform finishing over the external surface of the copper cylindrical roller as used in printing process. Furthermore, after MR finishing, the mechanical property like micro hardness test is performed on the copper cylindrical roller to know change in the mechanical property. The circularity (C) and straightness (S) tests of the initial and final MR finished copper cylindrical roller is performed to verify the cylindricity of the work-part. Cylindricity tolerance is used when cylindrical part features must have good circularity (C) and straightness (S). Cylindricity is a merger of circularity and surface straightness. The circularity applies only to uniformity in cross-sections, while cylindricity applies to the entire surface of the cylindrical work-part along its length. If the circularity and straightness are improved after the MR finishing of the cylindrical work-part, the better cylindricity tolerances can be achieved.

5.18.1 Copper roller material and its properties

The copper roller material is nominated based on the industrial need and material functional conditions. Copper and the copper alloy have various industrial applications in automobile, manufacturing and in printing industries. The printing industries require fine and uniform finished cylindrical copper rollers. The copper has good mechanical and physical properties which put the copper and copper alloys in the most versatile engineering materials category. This material has good conductivity, strength, machinability, corrosion resistance, and ductility. So, these properties make the copper material more appropriate for a wider range of industrial applications.

A typical copper cylindrical roller as uses printing is utilized for experimentation with dimensions of 120 × 25 mm as depicted in Fig. 5.35. The prototype typical copper cylindrical work-part is scaled down with a scale of 10:1 that means actual copper roller dimensions are used in printing as 1200 mm long and 250 mm diameter respectively. The hardness value of the copper cylindrical workpiece is found as 85 HRB.

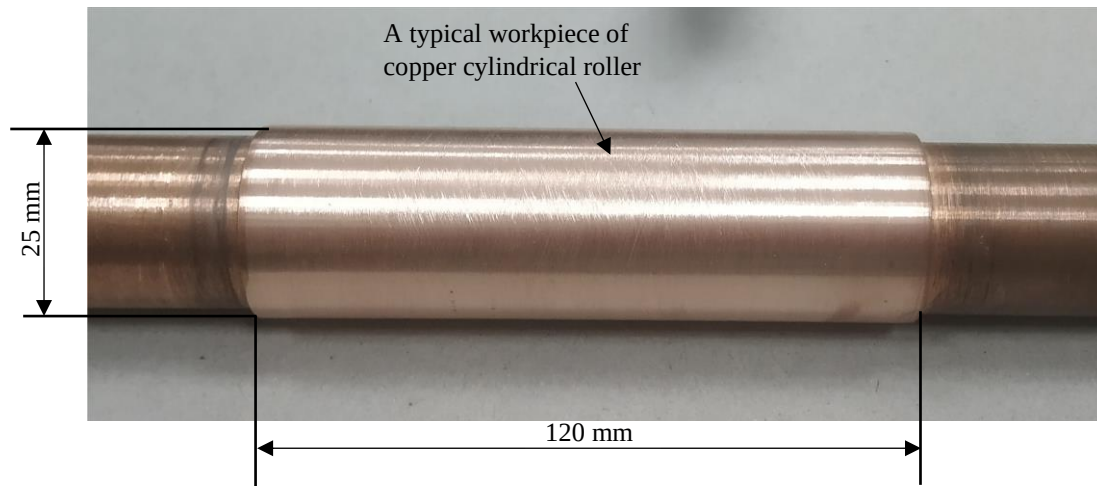


Fig. 5.35 A typical workpiece of copper cylindrical roller with actual dimensions.

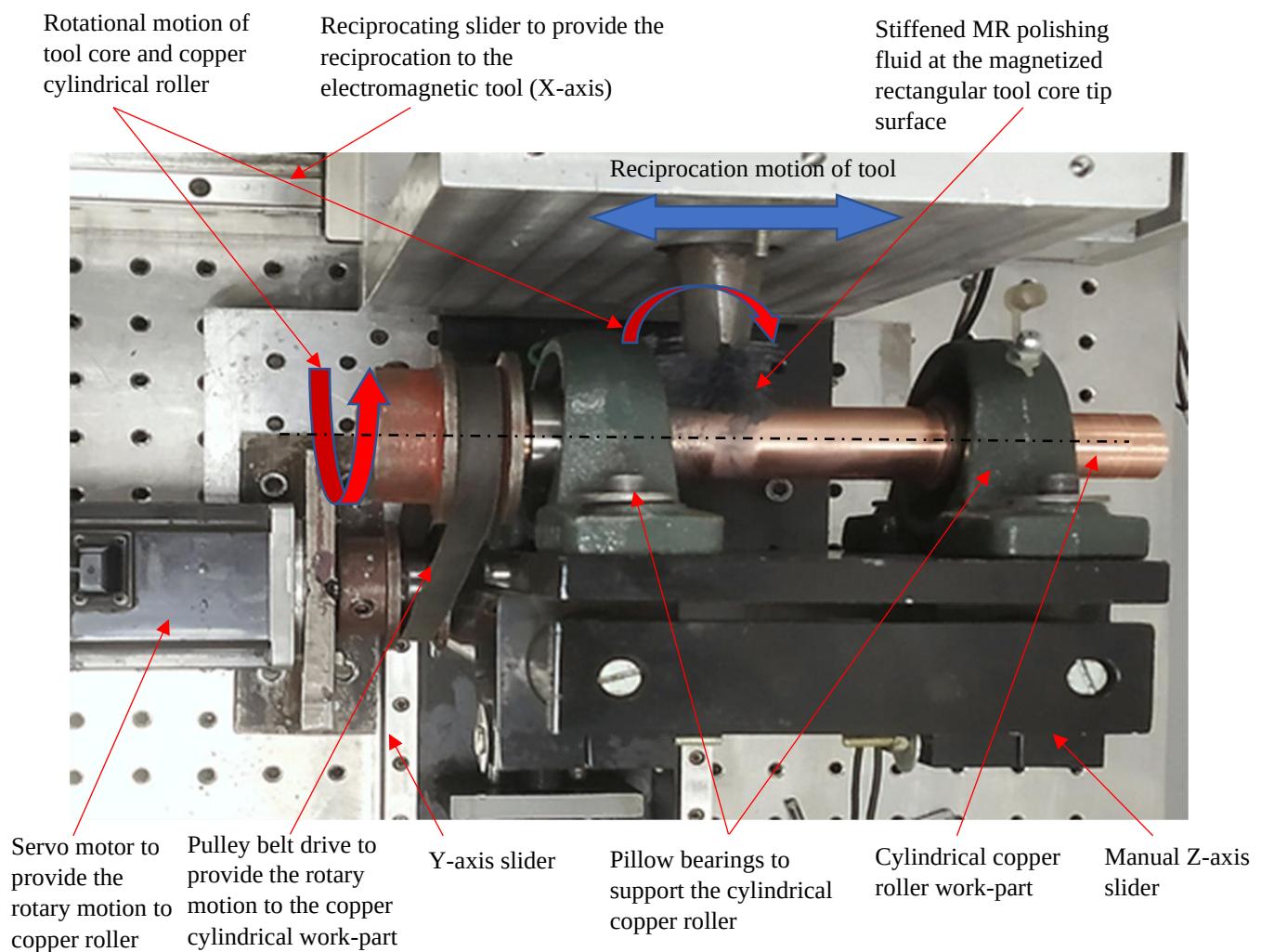


Fig. 5.36 Experimental setup with for MR finishing of the copper cylindrical roller workpiece.

The initial surface roughness of the cylindrical copper workpiece is measured 190 nm. The rectangular-rotary core MR finishing setup is utilized for fine finishing of the cylindrical copper workpiece as depicted in Fig. 5.36.

5.19 Experimentation

The design of experiments is employed to design and investigate the effect of process parameters. The central composite design (CCD) is utilized to design the combination of process parameters with 4 factors and 5 levels. Initially, the optimum magnetorheological (MR) polishing fluid composition required for finishing the copper cylindrical is found out. Furthermore, the finishing process parameters like rotary motion of the tool core (R) and copper cylindrical workpiece (C), feed rate of tool core (F) and current of electromagnet (I) are selected for optimizing these finishing parameters in the MR finishing of the copper cylindrical rollers for better performance.

5.19.1 Magnetorheological (MR) polishing fluid

The magnetorheological (MR) polishing fluid is constituted of the electrolyte iron particles (EIPs), aluminium oxide abrasives and base fluid with 80% paraffin oil and 20% grease in present experimentation. On the basis of the previous literature review, the different compositions of the MR polishing fluid are used for preliminary experimentation as reported in Table 5.10. The aluminium oxide abrasives composition (4% to 16%) are selected for preliminary experimentation as reported in Table 5.10. The base fluid (80% paraffin oil + 20% grease) is kept constant at 60 % by volume. The %age concentration of the EIPs and aluminium oxide abrasives by volume are varied from 24% to 36% and 4% to 16% respectively. The five different composition combinations of the EIP and aluminium oxide abrasives are reported in Table 5.10. In the preliminary experimentation, both SiC and aluminium oxide (Al_2O_3) abrasives were used and it cleared from the experimentation that the Al_2O_3 gives better finishing results. The reason beyond that the SiC abrasives are harder in nature which may embed into the surface of the copper cylindrical workpiece during the finishing operation and likely unable to produce a smooth surface (Khan and Jha, 2018). But the Al_2O_3 is softer as compared to the SiC abrasives which help to finish the soft materials. The experimentation is performed three times with each MR polishing fluid composition for 40 minutes finishing time as reported in Table 5.10.

Table 5.10 Effect of different magnetorheological (MR) polishing fluids on process performance

S.No.	%age concentration of base fluid (Paraffin oil 60% and grease 20%)	%age concentration of aluminium oxide abrasive particles (800 mesh)	%age concentration of electrolyte iron particles (500 mesh)	%age reduction in R_a value			
				Z1	Z2	Z3	Avg.
1	60	4	36	40	44	42	42
2	60	7	33	64	66	69	66.3
3	60	10	30	78	75	72	72
4	60	13	27	82	84	80	82
5	60	16	24	65	72	68	68.3

5.19.2 Selection of finishing machine process parameters

The finishing machine process parameters are nominated on the basis of the literature review (Khan and Jha., 2019), (Alam *et al.*, 2019) and preliminary experimentation. The main finishing machine parameters are rotary motion of the tool core and copper cylindrical workpiece, reciprocating motion of tool core and electromagnetic current to magnetize the tool core. The electromagnet current supply is very important factor because the magnitude of the magnetization is dependent on it. The magnetic normal force (F_n) directly depends on the magnetization of the tool tip surface. The electromagnet current level is decided on the basis of the preliminary experimentation and previous literature review which decided that the level of current lies between the 1 to 5 A. The rotary motion of copper cylindrical workpiece and tool core is responsible for the improvement of relative motion of active abrasives in finishing mechanism which further improves the active abrasive's cutting shear forces. Because the net tangential force of the active abrasive is increased due to the rotary motion of the copper cylindrical work-part and tool core. The level of the rotary motion of tool core and copper cylindrical workpiece lies between the 100 to 1300 rpm and 10 to 90 rpm respectively. The feed rate of the tool core also contributed in the cutting of roughness peaks through the axial shear force (F_a). The level of the tool feed rate lies between the 5 to 25 cm/min. Thus, the level of the finishing machine parameters is decided for the present experimentation as given in Table 5.11.

Table 5.11 Finishing process parameters and their levels

Finishing process parameters		Levels of finishing process parameters				
Representation	Description					
R	Tool core rotary speed (rpm)	100	400	700	1000	1300
C	Copper cylindrical workpiece rotary speed (rpm)	10	30	50	70	90
I	Current (A)	1	2	3	4	5
F	Feed rate of tool core (cm/min)	5	10	15	20	25

5.19.3 Plan of experimentation

The design of the finishing process parameters is done through the central composite design technique and for four process parameters with five levels, total 30 experimental combinations are designed. The design expert version 6.0.8. is employed to design the experimental combinations. The response of these experimental combination is taken as %age reduction in the roughness value ($\% \Delta R_a$). Each experimental parametric combination is performed three times to confirm the reduction in R_a value and take the average R_a value of these three obtained R_a values for the response ($\% \Delta R_a$). The three values of R_a are obtained as Z1, Z2 and Z3 respectively. Each experimental combination is performed for 40 minutes on 20 mm length of the copper cylindrical workpiece (diameter 25 mm) using the experimental setup (Fig.5.35). Each experimentation on the surface of the copper roller was performed at a working gap of 0.6 mm using the aforesaid selected suitable MR polishing fluid. Each experimental parametric combination was performed repeatedly 3 times and took the average of all the R_a values as obtained after each experimentation for ensuring more accuracy in response result. Further, the final average R_a value was used in calculating the %age reduction in R_a value as each experimental response. The R_a value measurement is performed by Mitutoyo SJ-400 surf test after each experiment at the end of 40 minutes of finishing cycle. During measurement of the R_a value, the 0.25 mm cut off length is considered. F value analysis of variance (ANOVA) is performed on the process parameters and found out the %age contribution (%S) of each finishing process parameter. The F value test is performed with 95% confidence level. The response ($\% \Delta R_a$) is evaluated using Eq. (5.39).

$$\% \Delta R_a = \frac{\text{Initial average } R_a \text{ value} - \text{Final average } R_a \text{ value}}{\text{Initial average } R_a \text{ value}} \times 100 \quad (5.39)$$

The experimental combinations of the finishing parameters which are designed by the central composite design and their responses are given in Table 5.12.

Table 5.12 Experimental combinations with their responses

S.No.	Finishing process parameters				Initial Ra value (nm)	Final Ra value (nm)				%ΔR _a
	R (rpm)	C (rpm)	I (A)	F (cm/min)		Z1	Z2	Z3	Avg.	
1	700	50	5	30	200	104	100	102	102	49
2	400	70	4	40	190	90	95	94	93	51
3	700	50	3	30	195	30	33	32	31.6	85
4	700	50	3	30	198	28	26	25	26.3	87
5	700	50	3	10	200	35	38	33	35.3	82
6	700	50	1	30	205	86	83	80	83	59
7	100	50	3	30	200	104	100	102	102	49
8	1000	30	2	40	190	73	77	75	75	61
9	400	70	2	20	195	73	75	77	75	62
10	400	70	2	40	188	77	79	75	77	59
11	700	50	3	30	190	30	28	26	28	85
12	700	50	3	50	200	40	42	36	39.3	81
13	1000	70	2	20	207	79	80	81	80	61
14	700	50	3	30	202	34	30	32	32	84
15	400	30	2	20	205	90	94	91	91.6	55
16	1000	30	4	40	200	75	72	76	75.3	63
17	700	50	3	30	190	38	40	37	38.3	80
18	400	30	4	20	195	94	92	90	92	52
19	1000	30	4	20	190	78	79	81	79.3	58
20	400	70	4	20	185	75	77	75	75.6	59
21	700	10	3	30	190	47	49	45	47	75
22	700	90	3	30	200	69	71	72	70.6	65
23	1000	30	2	20	190	76	77	71	75.6	61
24	1300	50	3	30	195	94	92	90	92	52
25	400	30	4	40	190	98	97	94	96.3	49
26	1000	70	4	40	195	95	93	90	92.6	52
27	1000	70	2	40	200	82	84	86	84	58
28	1000	70	4	20	200	70	72	73	71.6	64
29	700	50	3	30	210	29	25	27	27	88
30	400	30	2	40	190	85	88	82	85	55

5.20 Results and discussion

The %age contribution (%S) of the individual and interaction finishing process parameters are evaluated using the ANOVA. The model is performed on 95% confidence level. The process parameters on which p value of less than 0.05 are significant parameters and the parameters which have p value greater than 0.05 are insignificant parameters. The insignificant parameters are neglected and ANOVA is reported in Table 5.13.

Table 5.13 ANOVA for %age surface roughness reduction with contribution of the finishing process parameters

	Sum of squares	Degree of freedom	Mean sum of squares	F value	Prob>F		% contribution (%S)
Model	7812.12	10	673.42	37.35	< 0.0001	significant	
R	756.62	1	756.62	41.97	< 0.0001		9.68
C	595.16	1	595.16	32.96	< 0.0001		7.60
F	235.38	1	235.38	13.00	0.0019		3.00
I	100.04	1	100.04	5.55	0.0294		1.28
RR	2792.61	1	2792.61	155.90	< 0.0001		35.74
CC	952.66	1	952.66	52.84	< 0.0001		12.19
FF	1850.58	1	1850.58	102.65	< 0.0001		23.68
RC	175.56	1	175.56	9.74	0.0056		2.24
RI	217.56	1	217.56	12.07	0.0025		2.78
FR	138.06	1	138.06	7.66	0.0123		1.76
Residual	342.55	19	18.03			not significant	
Lack of fit	296.55	14	21.18	2.30	0.1827		
Pure error	46.00	5	9.20				
Cor total	8497.33	29					

The impact of each process parameter individually and with interaction is important to determine the process performance. The impact of each process parameter is evaluated through %age contribution of each parameter in process performance. The %age contribution (%S) of the process parameters is very important factor to decide the process performance. %S is calculated using Eq. (5.40). $\% \Delta R_a$

$$\%S = \frac{\text{Each parameters sum of square}}{\text{Total model sum of square}} \times 100 \quad (5.40)$$

Fig. 5.37 shows the %age contribution (%S) of each process parameters through the bar chart. The maximum %S is found with 35.74% of square of the tool core rotary motion as depicted in Fig. 5.37. The individual process parameter maximum contribution is played by rotary motion of tool core (R) with 9.68% and copper workpiece rotary speed 7.60% respectively. The insignificant parameters are neglected and the significant parameters are found as namely R, C, F, I, R^2 , C^2 , F^2 , RC, RI and FR. The model has R square value of 95% which relates the accuracy of the model with the practical results. From the model, the quadratic expression is generated and given in Eq. (5.41).

$$\% \Delta R_a = -39.27 + 0.0944R + 0.617C + 55.008F - 0.517I - 7.455 \times 10^{-5}R - 8.068 \times 10^{-3}C - 8.053F + 8.281 \times 10^{-4}RC + 1.229 \times 10^{-2}RI - 0.293FR \quad (5.41)$$

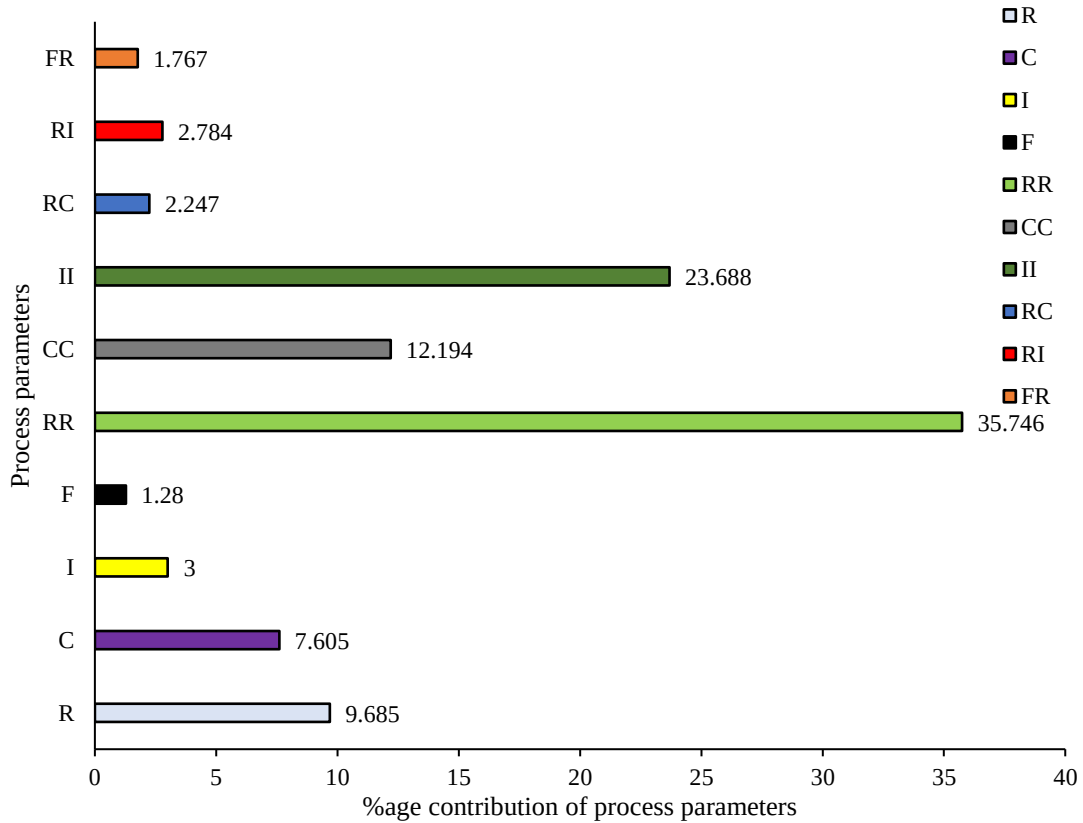


Fig. 5.37 %age contribution (%S) of individual and interaction of the finishing process parameters.

5.20.1 Effect of finishing process parameters

The interactional effect of the finishing process parameters is analysed through the 2D interaction plots. The 2D interaction plots are generated with the help of quadric expression. The interaction effect of finishing process parameters is discussed on the process performance i.e. %age reduction in R_a value ($\% \Delta R_a$). Fig. 5.38(a) shows the interaction between the core rotary motion (R) and copper cylindrical work-part rotary motion (C) at constant values of tool feed rate (F) 30 cm/min, electromagnet current (I) of 3A and working gap of 0.6 mm. The interaction plot trend shows that at the 100 rpm and 400 rpm motion of tool core with different motions of copper cylindrical workpiece, the lesser relative motion between the copper workpiece surface and aluminium oxide active abrasives are obtained which leads to reduce the %age reduction in R_a as depicted in Fig. 5.38(a). When the rotary motion of the tool core increases up to 700 rpm, the relative motion between the workpiece surface and the aluminium

oxide active abrasives is increased which leads to increases the %age reduction in R_a . As the rotary motion of the tool core increases up to 700 rpm, with different rotational motions of the copper cylindrical roller the %age reduction in R_a value ($\% \Delta R_a$) is increased. But further increase in tool core motion, decreases the $\% \Delta R_a$ as shown in Fig. 5.38(a). This is owing to the fact that greater the motion of tool core with the attached MR polishing fluid increases the centrifugal force. This centrifugal force weakens the magnetization force between the electrolyte iron particle (EIP) chains. Because of this, the indentation force of the aluminium oxide abrasive decreases which results in decrease the response ($\% \Delta R_a$). The copper cylindrical workpiece rotary motion increases the interaction between the aluminium oxide abrasives and roughness crests. But higher rotary motion of the copper cylindrical workpiece increases the stresses on the EIP chains which holds the aluminium oxide abrasive. Fig. 5.38(a) shows that the maximum $\% \Delta R_a$ gives at the rotary motion of 700 rpm and 70 rpm of the tool core and copper cylindrical workpiece, respectively. This combination of rotary motion of the tool core and the copper cylindrical workpiece also gives the optimum relative motion between the aluminium oxide abrasives and roughness crests which gives the maximum $\% \Delta R_a$.

Fig. 5.38(b) shows the interaction between the electromagnet current (I) and tool core rotary motion (R) at constant values of tool feed rate (F) 30 cm/min, copper workpiece rotary motion 70 rpm, and working gap of 0.6 mm. The electromagnet current directs the magnetic strength of the EIPs chains. As the value of the electromagnet current (I) increases, the value of magnetic strength of the EIPs chains increases. This EIPs chains magnetic strength increases the indentation force of the aluminium oxide abrasives which results in increase the %age reduction in R_a value. As shown in Fig. 5.38(b), the plot trend increases with 700 rpm of tool core rotary motion as current value increases up to 3 A. Further increase in current (I) as 4 A and 5 A with different tool core motion, the value of the response ($\% \Delta R_a$) decreases. This is owing to the fact that, the greater indentation force of aluminium oxide abrasives does not only remove the roughness crests but also it may scratch the workpiece surface as well, which result in decreases the %age reduction in R_a value. Also, as the tool core rotary motion is increased after 700 rpm, the magnetization of the EIP chains is weakened due to centrifugal force. From Fig. 5.38(b) reveals that the maximum %age reduction in R_a value is obtained at electromagnet current of 3A and tool core rotary motion of 700 rpm. Fig. 5.38(c) shows the interaction between the feed rate of tool core (F) and rotary motion of the tool core (R) at constant values of copper workpiece rotary motion of 70 rpm, electromagnet current (I) of 3A and working gap of 0.6 mm. F governs the axial force (F_a) of the active aluminium oxide

abrasives. This axial force enhances the interaction between the active abrasives and roughness crests.

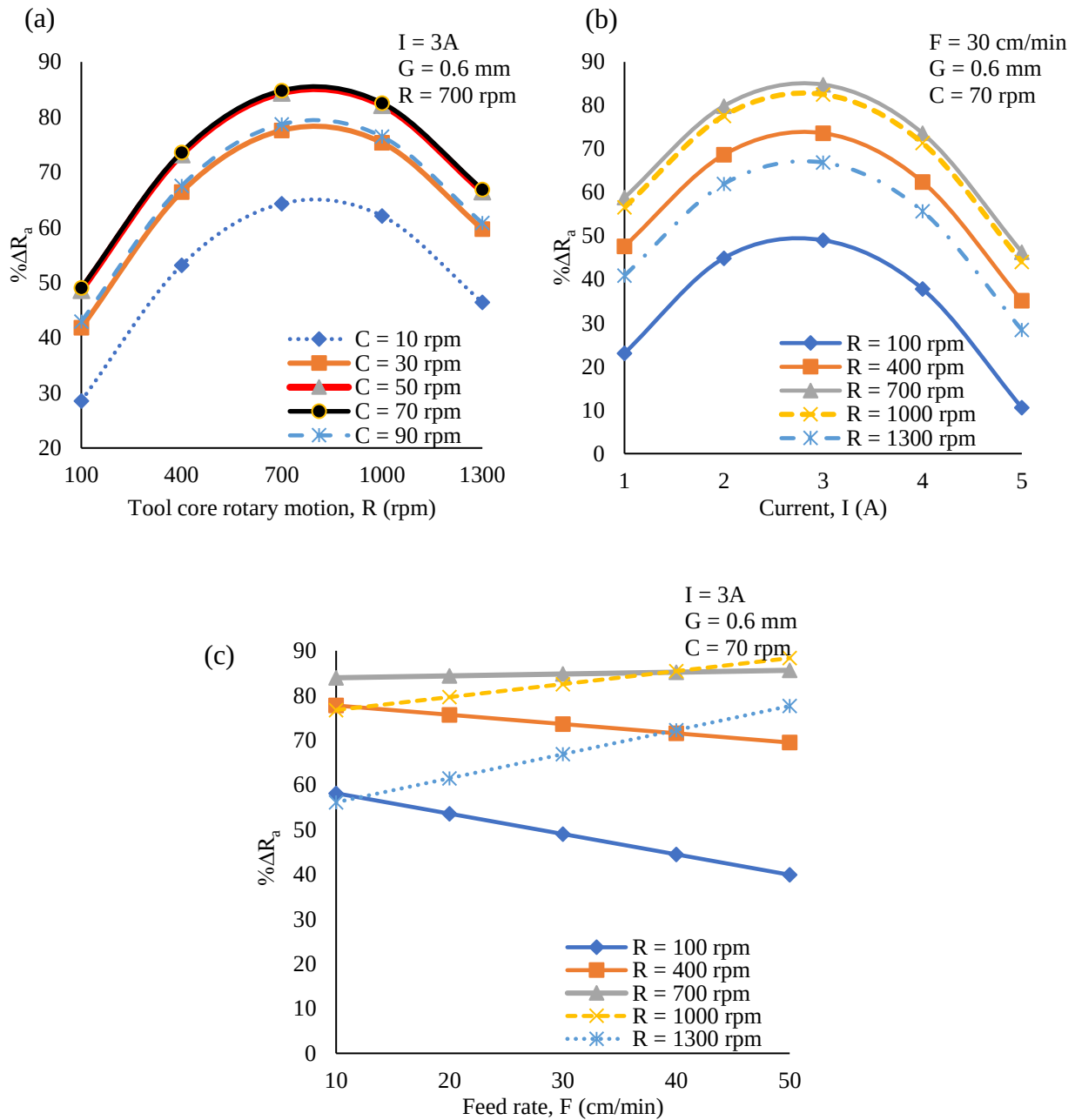


Fig. 5.38 (a) Interaction effect of tool core rotary motion (R) and copper cylindrical workpiece rotary motion (C) on $\% \Delta R_a$, (b) interaction effect of current (I) and tool core rotary motion (R) on $\% \Delta R_a$ and (c) interaction effect of feed rate of tool core (F) and tool core rotary motion (R) on $\% \Delta R_a$.

This result in increased the %age reduction in R_a value. In Fig. 5.38(c), plot of trends shows that the as the feed rate of tool core increases, the response value ($\% \Delta R_a$) decreases, but at rotary motion of tool core at 1000 rpm and 1300 rpm, the value of response increases. This is owing to the fact that at higher rotary motion of the tool core, the upsurges the interaction

between the active abrasives and surface asperities which compensate by the enhancing the collision at higher feed rate of tool core. The opposite trend is followed at the rotary motion 400 rpm and 100 rpm of tool core. This is due to that at lesser rotary motion of tool core, the interaction rate is low. So, as the feed rate increases, the collision rate between the active abrasives and surface asperities is lesser which result in decreased %age reduction in R_a value. The rotary motion of tool core at 700 rpm and 30 mm/min feed rate gives the highest %age reduction in R_a value.

5.20.2 Optimization and validation of finishing process parameters

The optimized machining process parameters were predicted on the basis of interaction effect of the finishing process parameters on the %age reduction in R_a value. Also, at these optimum parameters, the quadratic expression of the regression model gives the maximum %age reduction in R_a value ($\% \Delta R_a$).

Maximize %age reduction in R_a values are subjected to

$$100 \text{ rpm} \leq R \leq 1300 \text{ rpm}$$

$$10 \text{ rpm} \leq C \leq 90 \text{ rpm}$$

$$10 \text{ cm/min} \leq F \leq 50 \text{ cm/min}$$

$$1 \text{ A} \leq I \leq 5 \text{ A}$$

The optimum finishing process parameters are obtained as 700 rpm of tool core rotary motion, 70 rpm of copper cylindrical workpiece rotary motion, electromagnet current of 3A and 30 cm/min core of feed rate give the highest %age reduction in R_a value. The validation test is performed to confirm the accuracy of quadratic expression of the regression model. The experimental trials are performed at optimum finishing process parameters. The four experimental trial are performed as reported in Table 5.14. The %age error between the experimental and theoretical %age reduction in R_a value is calculated using the Eq. 5.42.

$$\%error = \left(\frac{\text{Experimental } \% \Delta R_a - \text{theoretical } \% \Delta R_a}{\text{Experimental } \% \Delta R_a} \right) \times 100 \quad (5.42)$$

From Eq. (5.42), the %error is calculated and it is found in range of -1.24% to 3.57% as reported in Table 5.14. This %error between the experimental and theoretical response reveals the good agreement which expresses that the quadratic expression gives the response value close to the experimental response as given in Table 5.14. The optimized process parameters were used to finish the whole copper printing roller surface. The whole length of the workpiece is divided into three equal sections and each section has 30 mm length with diameter of 25 mm. Each section takes 60 minutes to fine finish the external surface of copper cylindrical roller. After

60 minutes of MR finishing of the 30 mm length of the copper cylindrical roller (diameter 25 mm), the surface roughness (R_a) value is reduced from 190 nm to 25 nm with the optimized finishing process parameters.

Table 5.14 Validation test between the theoretical and experimental responses

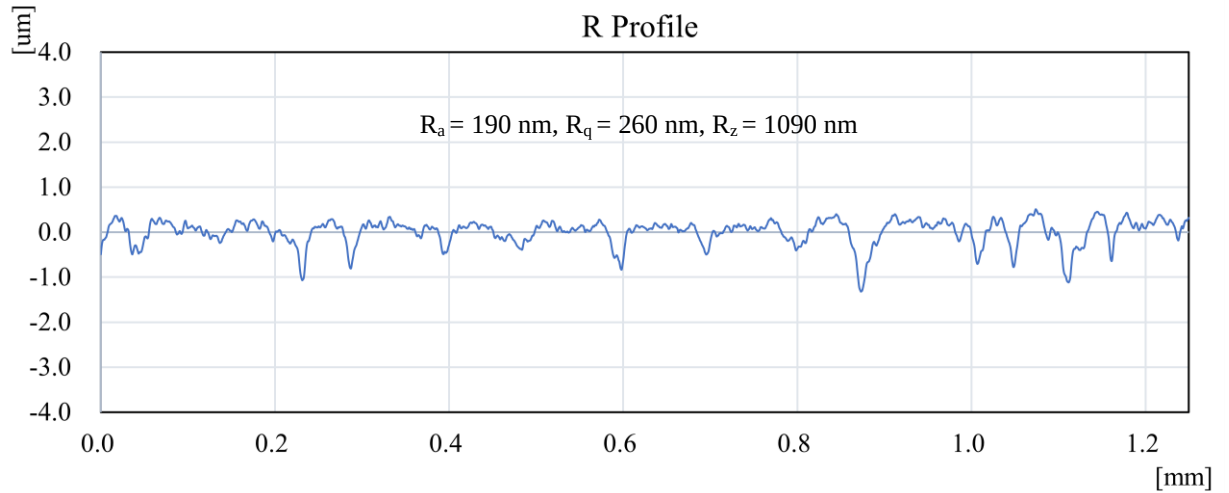
Time (min)	R (rpm)	C (rpm)	G (mm)	I (A)	F (cm/min)	Experimental % ΔR_a	Predicted % ΔR_a (Eq.5.41)	%error
60	700	70	0.6	3	30	86.84	88.35	1.70
60	700	70	0.6	3	30	87.38	88.35	1.09
60	700	70	0.6	3	30	89.45	88.35	-1.24
60	700	70	0.6	3	30	85.19	88.35	3.57

There was no further significant enhancement in the surface finish after 60 minutes. After scaling of the time span it is found that the total length of 120 mm of the copper roller (diameter 25 mm) takes the 4 hrs for whole external surface finishing. The actual copper roller (used in printing) with dimensions of 1200 mm long and 250 mm diameter can take the 40 hrs for whole surface finishing. Furthermore, the surface roughness and topography of the MR finished copper roller surface as well as ground initial surface is judged through surface roughness profiles, scanning electron microscopy (SEM) and reflection tests.

To check the uniformity of the surface roughness value over the whole external surface of the copper roller, the standard deviation (σ) test was performed. The initial R_a profile is measured at initial ground surface of the cylindrical copper roller. The R_a profile reveals the highest peaks and deepest valleys over the initial surface of the copper roller. The initial ground surface R_a profile with R_a value of 190 nm is depicted in Fig. 5.39(a). After MR finishing of the whole surface of the copper cylindrical roller, the R_a profile measured with the R_a value of 25 nm as shown in Fig. 5.39(b). The MR finished R_a profile reveals that the peaks and valleys are shortened and surface of the copper roller is fine finished. The waviness test is also performed to check the straightness of cylindrical copper roller. The waviness test is carried out over the initial ground and MR finished surface of the cylindrical copper roller. Straightness is a measured of the linear uniformity of work surface from an external reference line. The waviness has long sample length than the roughness profiles which gives the detail about the linear surface. The waviness test is carried out by the Taylor Hobson profilometer. The arithmetic mean waviness (W_a) is obtained 200 nm at initial ground surface of the copper roller (Fig. 5.40(a)). After MR finishing of copper cylindrical roller, the arithmetic mean waviness (W_a) is obtained as 30 nm (Fig. 5.40(b)). These values reveal that the straightness of the

cylindrical copper roller gets enhanced after performing the MR finishing on its external surface which leads to beneficial for the end product quality and geometrical accuracy.

(a)



(b)

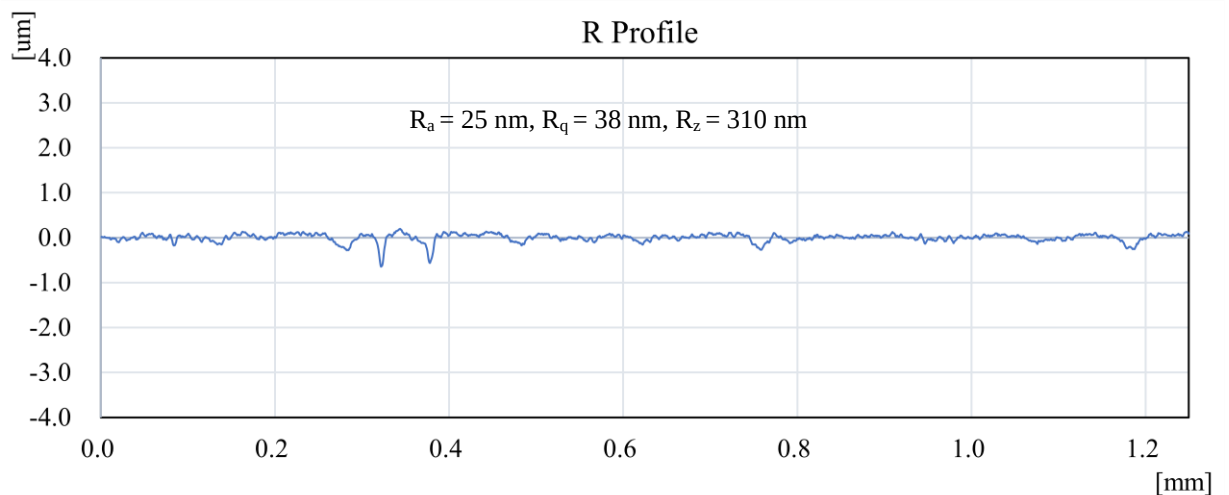
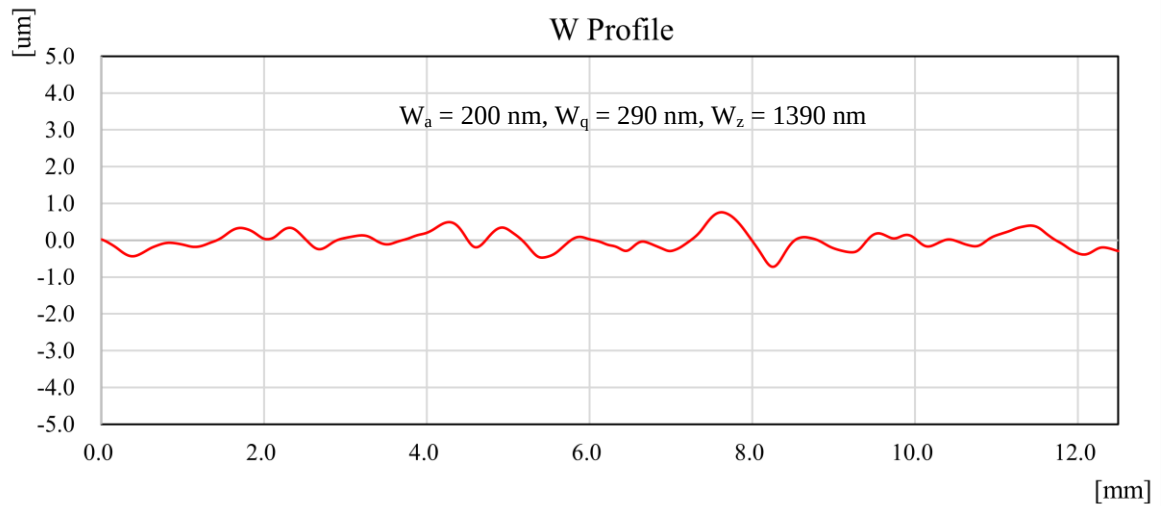


Fig. 5.39 Surface roughness profiles of copper cylindrical roller over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4 hrs MR finished with optimized finishing process parameters.

The SEM test is achieved on the initial ground surface of the copper roller work-part and the MR finished surface. SEM reveals the surface topography through the highly zoomed photographs of the outer surface of the copper roller before and after the MR finishing. In initial surface SEM photograph, the grinding marks are easily depicted at the zoom scale of 500X as shown in Fig. 5.41(a). The MR finished surface's SEM photograph reveals that the grinding marks are removed and smooth finished surface of the copper roller is obtained as shown in Fig. 5.41(b). The appearance of the copper roller surface is evaluated by reflection test. This

test reveals the appearance of the copper roller surface before and after MR finishing. Figs. 5.42(a) and (b) shows the reflection test photographs of the initial ground surface and MR finished surface of the copper roller, respectively.

(a)



(b)

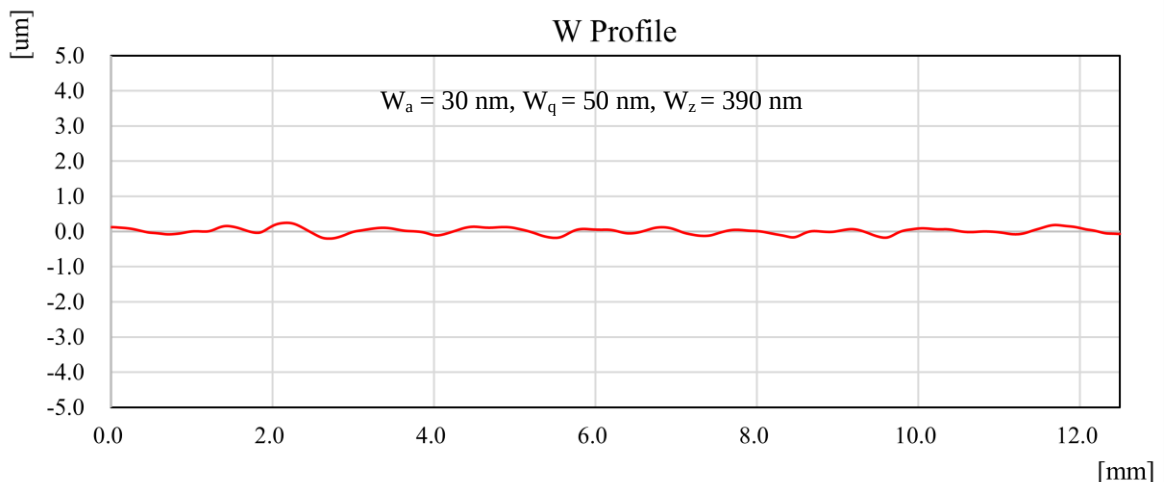
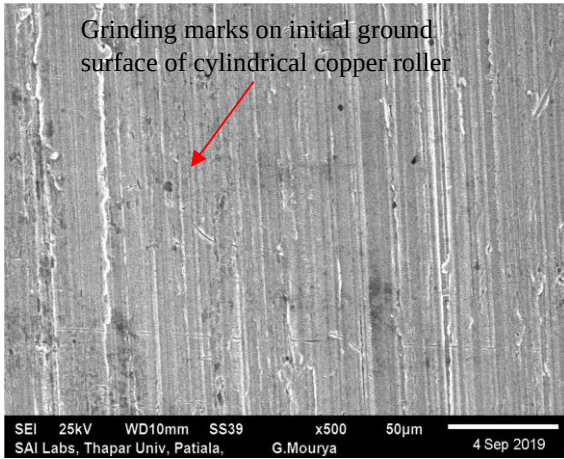


Fig. 5.40 Waviness profiles of copper cylindrical roller over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4hrs MR finished with optimized finishing process parameters.

For reflection test, the text ‘TIET’ is written on the white sheet and place in front of the external surface of copper roller. In Fig. 5.42(a), it is seen that at initial ground surface the text ‘TIET’ is not readable due to the grinding lays. But after the MR finishing the grinding lays are removed and smooth surface is attained. As it is seen in Fig. 5.42(b), the text ‘TIET’ is easily readable due to the fine finished surface of the copper roller. So, the R_a profile, SEM and reflection test reveal that the surface fine finish and the characteristics get significantly improved after the MR finishing on external surface of the copper cylindrical roller.

(a)



(b)

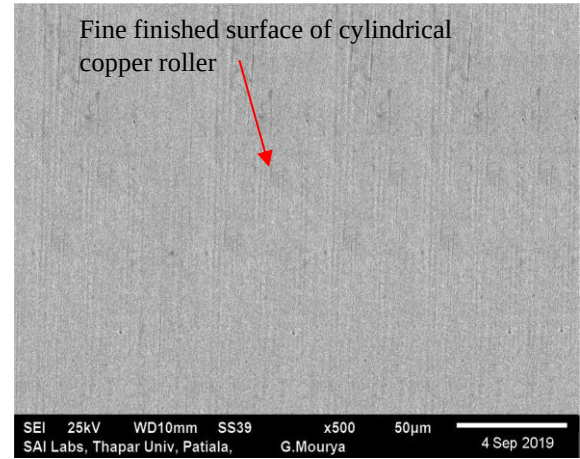
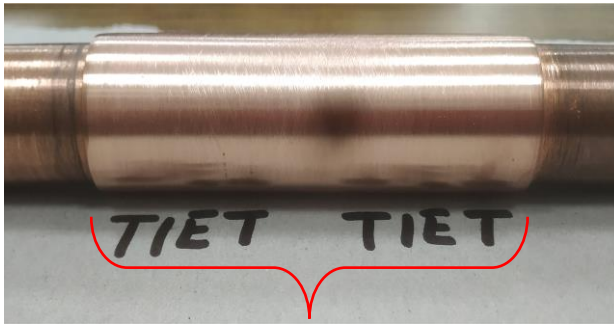


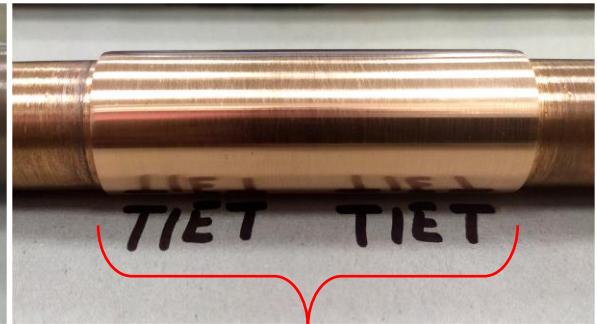
Fig. 5.41 Scanning electron microscopic photographs of copper cylindrical roller over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4hrs MR finished with optimized finishing process parameters.

(a)



Mirror image of the initial ground surface of the copper cylindrical roller ($R_a = 190$ nm)

(b)



Mirror image of the MR finished surface of the copper cylindrical roller ($R_a = 25$ nm)

Fig.5.42 Reflection photographs of copper cylindrical roller over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4hrs MR finished with optimized finishing process parameters.

The circularity test is described how close a work-part should be to a true circle. The circularity is a 2-dimensional tolerance that controls the overall form of a circle. Circularity is defined as the degree of roundness of a circular cylinder. The circularity (C) is given by four times pi times the circle area divided by the circle perimeter squared as expressed by Eq. (5.43).

$$C = 4\pi \times \frac{\text{Area of the circle } (\pi r^2)}{[\text{Perimeter of the circle } (2\pi r)]^2} \quad (5.43)$$

The coordinate measuring machine (CMM) is used to evaluate the circularity of the initial ground and MR finished surface of the copper cylindrical roller. Figs. 5.43(a) and (b) shows

the circularity (C) of the initial ground and MR finished surface of the copper cylindrical roller. The CMM probe traces the surface of the copper cylindrical roller at 13 measuring points in both the cases.

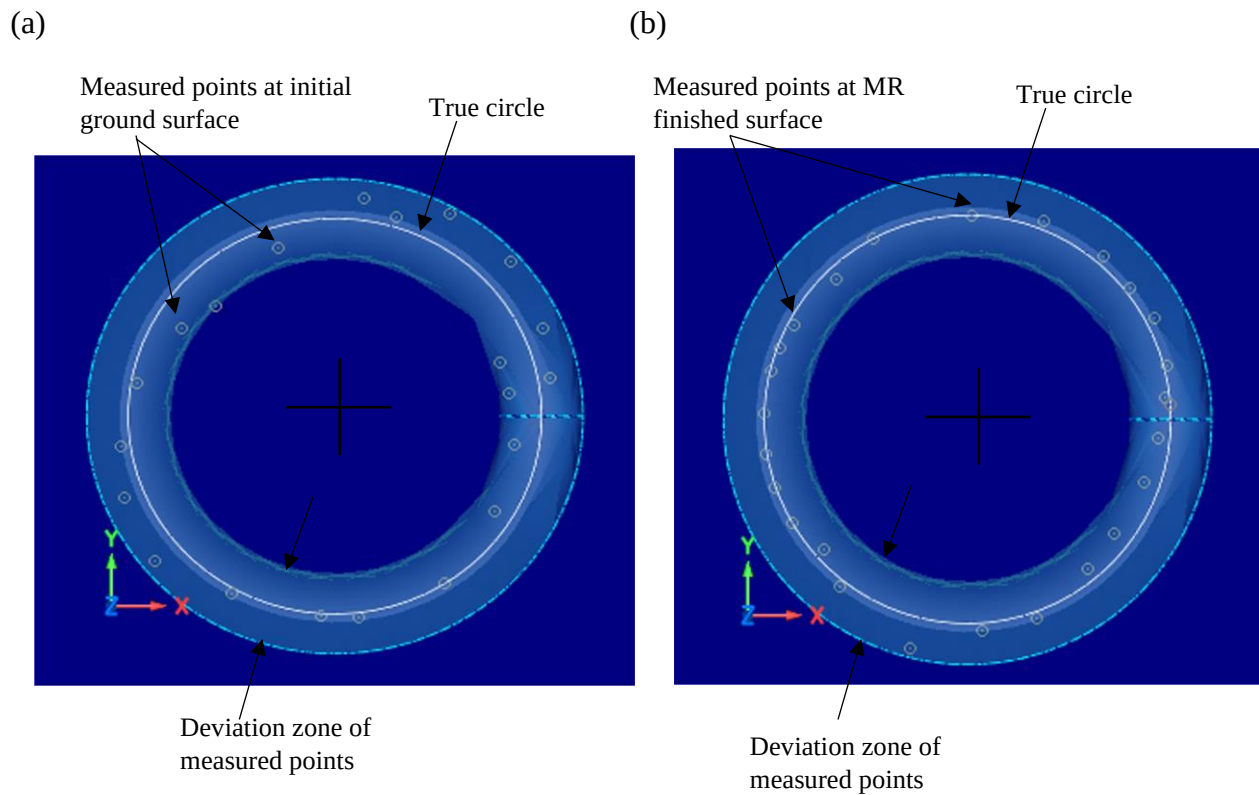


Fig. 5.43 Circularity photographs of copper cylindrical roller over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4hrs MR finished with optimized finishing process parameters.

Table 5.15 Comparison of circularity of the copper cylindrical workpiece at initial surface and after MR finishing

Parameters	Copper cylindrical workpiece at initial surface			Circularity of the copper cylindrical workpiece after MR finishing		
	Mean	Nominal	Deviation	Mean	Nominal	Deviation
X(mm)	161.9564	161.9564	0.0000	161.3567	161.3567	0.0000
Y(mm)	106.3118	106.3118	0.0000	106.1123	106.1123	0.0000
Z(mm)	184.5492	184.5492	0.0000	184.5492	184.5492	0.0000
Diameter (mm)	25.3435	25.3435	0.0000	25.3435	25.3435	0.0000
Circularity (μm)	0.0249	0.0000	0.0249	0.0130	0.0000	0.0130
Sigma	0.0199	0.0000	0.0199	0.0015	0.0000	0.0015

The deviation in the circularity was found out at initial ground surface of the copper roller as 0.0249 and after 4 hrs of magnetorheological (MR) finishing of whole surface (120 mm $\times$ 25 mm) with optimum finishing parameters, the deviation in the circularity was observed as 0.0130 as reported in Table 5.15. At the initial surface of the copper cylindrical roller have

surface asperities which disturbs the circularity. As seen in Fig. 5.43(a), the measuring points deviate from each other much near to the true circle. But after the MR finishing, the measuring points are found near to the true circle as shown in Fig. 5.43(b).

After testing of the straightness through waviness and circularity through CMM proves that the circularity and straightness of the copper cylindrical roller get improved after performing the MR finishing process over its external surface. These results show the improvement in the cylindricity of the copper cylindrical work-part because the cylindricity is a merger of circularity and surface straightness. This enhancement may improve the close tolerances between the cylindrical copper work-part and die work-part or any other relative work-part which has fit to the cylindrical work-part. So, the MR finishing is beneficial for the copper cylindrical work-parts to improve its surface characterises and dimensional accuracy which helpful in functional performance of the work-part.

5.20.3 Enhancement in functional application of MR finished copper cylindrical rollers in printing industry

Copper is a ductile material which is difficult to finish at fine level. The copper cylindrical roller is required uniform fine finishing for uniform pressure distribution on the PVC printing poster or other printing products in printing operation. So, the factor influence in the copper roller is pressure distribution on the printing products. To know the uniformity of fine finishing on the copper roller surface, the standard deviation (σ) and mean (μ) values are calculated on the external surface of the copper roller. To perform the standard deviation (σ) and mean (μ) test, 25 different R_a values measurements were measured on the whole external surface of the copper roller to evaluate the uniformity of the finishing. The 25 measurements of the R_a values are measured on the initial ground surface and MR finished surface of the copper roller (length = 120 mm and diameter = 25 mm) external surface. The value of the mean (μ) and standard deviation (σ) is calculated using equations (5.43) and (5.44).

$$\mu = \frac{p_1 + p_2 + p_3 \dots + p_n}{Q} \quad (5.43)$$

Where $p_1, p_2, p_3 \dots p_n$ are the measured R_a values on the initial ground surface and final MR finished surface. Q is the total number of measurements on the copper roller external surface.

$$\sigma = \sqrt{\frac{1}{Q} \sum_{i=1}^n (p_i - \mu)^2} \quad (5.44)$$

The measured values of R_a on the initial ground surface and the MR finished surface are put into the equations (5.43) and (5.44) and evaluated the values of the mean (μ) and standard deviation (σ). The 20 measured values of before and after the MR finishing are plotted as shown

in Figs. 5.44(a) and 5.44(b). The values of the mean (μ) at before and after MR finished surface were found as 190 nm and 25 nm. The standard deviation (σ) value of the before and after MR finished surface were found as 18.24 and 3.75 as depicted in Figs. 5.44(a) and 5.44(b).

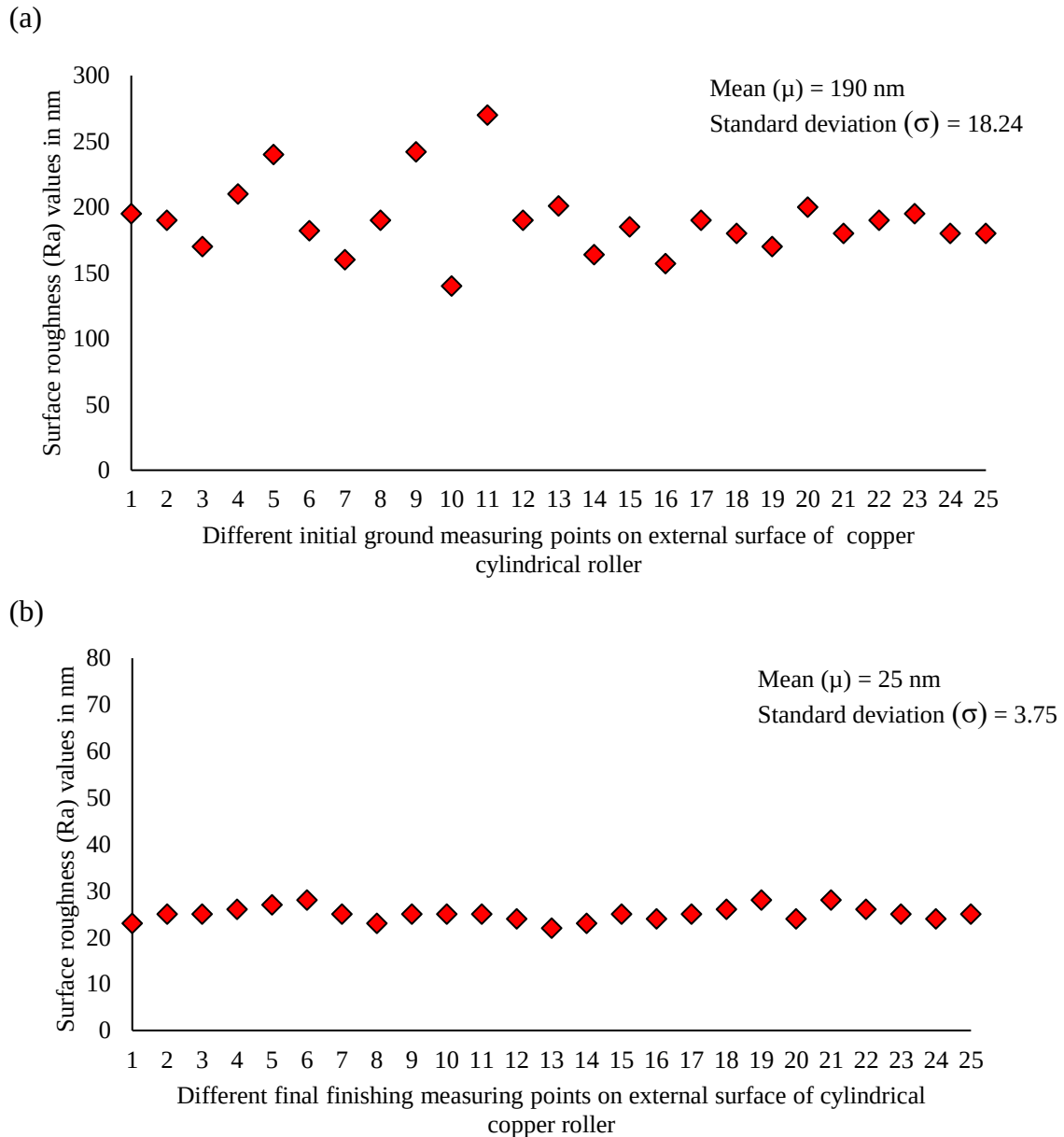


Fig. 5.44 Mean (μ) and standard deviation (σ) over the length of 120 mm and diameter of 25 mm (a) initial and (b) after 4hrs MR finished with optimized finishing process parameters.

The standard deviation (σ) value of the final MR finished surface proves that the whole surface of the copper roller is uniformly fine finished. The uniformly fine finishing of the copper roller external surface helps to uniformly distribution of the pressure along the width of working fluid during the printing operation.

The micro-hardness test is also performed on the external surface of the copper roller before and after the MR finishing. Hardness is the property of a material that enables it to resist plastic deformation, penetration, indentation, and scratching. Therefore, hardness is important from an engineering standpoint because resistance to wear by either friction or erosion (Gosvami et al., 2009). The micro-hardness is performed using the Mitutoyo HM-210 model. The diamond indenter is utilized to measure the micro-hardness on the before and after MR finished copper roller external surface. The 100 N load is applied to the diamond indenter during the testing. The hardness value is obtained after the test in Vickers Pyramid Number (HV). The 6 measurements of micro-hardness values are performed on the before and after MR finished copper roller external surface and average value of HV number is calculated. The avg. value of HV number on the initial ground surface was found as 85. The avg. HV number on the final MR finished surface was found as 90.

The results of micro-hardness test prove that the hardness value gets increased after the MR finishing. The higher hardness value with uniform fine finishing on copper roller external surface can give a better performance during its functional applications. The higher hardness value of the copper roller surface resists the wear by either due to friction or erosion. The higher value of hardness can increase the life of the copper roller. So, MR finishing of the copper cylindrical roller enhances the functional performance in the printing industry.

5.21 Conclusions

The optimum finishing parameters was predicted for fine finishing the copper cylindrical roller. After fine finishing, the improvement in surface characteristics and function performance of the copper cylindrical roller in printing application confirmed the efficacy of the present magnetorheological finishing process as compared to the initial ground surface of the copper cylindrical roller. The results from the present work are made as to the following conclusions.

- The maximum outcome as %age reduction in the Ra value is obtained at optimum finishing parameters which are the rotary speed of copper cylindrical roller workpiece 70 rpm, current 3 A, the rotary speed of the rectangular tool core 700 rpm, working gap 0.6 mm, and feed rate of tool is 30 cm/min. The MR polishing fluid composition of 27% of electrolytic iron particles by volume (500 mesh) and 13% of aluminium oxide abrasives (800 mesh) by volume with 60 % of base fluid by volume is found as best polishing fluid for the maximum %age reduction in surface roughness of copper cylindrical workpiece.

- The surface roughness of copper cylindrical roller is reduced from 190 nm to 25 nm after the MR finishing with the optimum parameters in 4 hrs on its length 120 mm and diameter 25 mm. This signifies that reduced surface roughness typically reduces friction which can be critical to reduce wear and increasing efficiency of the printing operation. The uniform fine finishing of the copper roller reduces the localization of the stresses because of the uniform distribution of the pressure over the surface and also uniformly distributes the colours and ingot material.
- The deviation in the circularity is found out at initial ground surface of the copper roller is 0.0249 and after 4 hrs of MR finishing with optimum finishing process parameters the deviation in the circularity is obtained as 0.0130. After MR finishing, the circularity and straightness of the copper cylindrical roller is improved which improve the cylindricity of the copper cylindrical work-part. This beneficial for close tolerances, less friction and less power consumption.
- The micro-hardness number is increased from initial ground surface 85 HV to 90 HV after MR finishing of the copper cylindrical roller. This enhancement in the hardness value improves the life span, provider better resistance to wear and improves the functional performance of the copper cylindrical work-part in various industrial applications.

Table 5.16 A comprehensive experimental overview result of all the industrial applications

Industrial application	Workpiece material	Dimensions of workpiece	Optimized finishing process parameters	Optimized composition of MR polishing fluid	Initial surface features	Final surface features
Cold rolling roll [Fig. 5.2] used in the sheet metal industries	H13 steel (Fe = 89.8, Cr = 5.25, Mo = 1.55, Si = 1.10, V = 0.95, C = 0.41, Ni = 0.3, Cu = 0.25 Mn = 0.35, P = 0.03, S = 0.03)	Diameter, D = 60 mm and length, L = 240 mm	Tool rotation = 1100 rpm, workpiece rotation = 100 rpm, working gap = 0.6 mm, Current = 2A and feed rate = 300 mm/min	30% by volume CIPs, 15% by volume SiC abrasives and 55% by volume carrier fluid (80% heavy paraffin and 20 % AP3 grease by weight).	Ra = 200 nm Wa = 0.2110 μ m μ = 200 nm σ = 22.10	Ra = 18 nm Wa = 0.0717 μ m μ = 18.25 nm σ = 5.35
Micro-punches [Fig. 5.14] used in the micro-	Tungsten carbide	L ₁ = 55 mm, D ₁ = 3.5 mm, L ₂ = 50 mm, D ₂ = 2 mm, L ₃ = 50 mm, D ₃ =	Tool rotation = 1100 rpm, workpiece rotation = 60 rpm, working	55% volume (80% paraffin oil + 20% grease), 15% volume of the	Ra ₁ = 0.210 μ m Ra ₂ = 0.230 μ m,	Ra ₁ = 0.02 μ m Ra ₂ = 0.02 μ m,

extrusion process		1.5 mm and $L_4 = 50$ mm, $D_4 = 1.2$ mm	gap = 0.6 mm, Current = 2A and feed rate = 300 mm/min	SiC abrasives and 30% iron particles	$Ra_3 = 0.250$ μm and $Ra_4 = 0.200$ μm	$Ra_3 = 0.03$ μm and $Ra_4 = 0.01$ μm
Winding grooved drum [Fig. 5.20] used in the winding machines in textile industries	AISI4140 (Fe = 97.11, Cr = 0.985, Mo = 0.22, Si = 0.29, C = 0.44, Mn = 0.88, Mo = 0.22, P = 0.035, S = 0.04)	Diameter, D = 75 mm and length, L = 220 mm and grooved surface thickness = 6 mm	Tool rotation = 1000 rpm, workpiece rotation = 100 rpm, working gap = 0.6 mm, Current = 2A and feed rate = 30 cm/min	55% of the base fluid, 15% of silicon carbide abrasive particles and 30% of the iron particles by volume	$Ra = 200$ nm	$Ra = 10$ nm
Spline shaft [Fig. 5.27] used in transmission couplings	440C (Fe = 80.9, Cr = 16.4, Mo = 0.02, C = 0.98, Mn = 0.76, P = 0.003, S = 0.05, Ni = 0.85)	Diameter, D = 20 mm and length, L = 45 mm	External tooth surface (Tool rotation = 1800 rpm, workpiece rotation = 110 rpm, working gap = 0.6 mm, Current = 2A and feed rate = 30 cm/min) and internal profile surfaces (tool rotation = 1200 rpm and feed rate = 20 cm/min)	55% carrier fluid, 15% of the SiC abrasive particles (800 mesh number) and 30% of the magnetic iron particles (500 mesh number) by volume	External surface ($Ra = 0.270$ μm) Internal profile surfaces average value ($Ra = 0.300$ μm) External surface ($\mu = 0.27$ μm $\sigma = 0.036$) Internal profile ($\mu = 0.31$ μm $\sigma = 0.024$)	External surface ($Ra = 0.02$ μm) Internal profile surfaces average value ($Ra = 0.03$ μm) External surface ($\mu = 0.02$ μm $\sigma = 0.002$) Internal profile ($\mu = 0.03$ μm $\sigma = 0.002$)
Copper cylindrical roller [Fig. 5.36] used in the printing industries	Copper	Diameter, D = 25 mm and length, L = 120 mm	Tool rotation = 700 rpm, workpiece rotation = 70 rpm, working gap = 0.6 mm, Current = 3A and feed rate = 30 cm/min	27% of EIPs by volume (500 mesh) and 13% of aluminium oxide abrasives (800 mesh) by volume with 60 % of base fluid	$Ra = 190$ nm $Wa = 200$ nm Circularity (C) = 0.0249, $\mu = 190$ nm $\sigma = 18.24$	$Ra = 25$ nm $Wa = 30$ nm Circularity (C) = 0.0130 $\mu = 25$ nm $\sigma = 3.75$

CHAPTER 6

MODELING OF SURFACE ROUGHNESS IN A ROTARY RECTANGULAR CORE MAGNETORHEOLOGICAL FINISHING PROCESS

To understand in-depth material removal and process performance, the mathematical model of the reduction in surface roughness is developed for the rotary rectangular core magnetorheological (MR) finishing process. In this chapter, the material removal mechanism is analysed through the development of surface roughness model. The efficiency of the process in term of the surface roughness reduction and finishing cycle time with the effect of process parameters are analysed. The number of active abrasives is dependent on the work-part surface area which is covered by the projected area of the rotary speed of the rectangular tool core tip surface and its feed rate. The shear force of the active abrasives depends on rotary as well as the reciprocating movement of the rectangular tool core and work-part which further governs the process performance. The indentation force on the active abrasives induced by magnetic field in the magnetorheological (MR) polishing fluid. The MR polishing fluid is an important component of the magnetic fluid-based finishing process. The magnetic flux concentration in the working space amid the rectangular tool tip and the cylindrical work-part is predicted with finite element analysis (FEA). Numerically it is calculated through the theoretical analysis performed in the present study and it is validated through the values obtained from the experimental measurement with gauss meter at the respective location. With the use of the developed theoretical analysis for magnetic flux density the roughness model is developed. Further for validation of the developed roughness model, the experiments were performed. Percentage error was calculated for the difference in the experimental and theoretical results. This theoretical analysis unveils the enhancement of process performance through the participating process parameters. The present developed model can be useful to predict the reduction in roughness value for the precise MR finishing of the different external cylindrical surfaces with the rotary rectangular tool core tip. The theoretical model of the present process is useful for precise finishing of the various industrial application where precise finishing is an important factor. In micro-punches and cold rolling rolls precise finishing is required for uniform flowability of the billet material and close tolerances between the punch and billet material.

6.1 Material removal mechanism of external surface with the present MR finishing process

The rheological behaviour of the magnetorheological (MR) polishing fluid is governed by the magnetic flux concentration within the working space. The working space is the distance maintained within the rectangular tool core tip surface and the cylindrical work-part. The rheological property of the MR polishing fluid alters suddenly with the effect of the magnetic field. This is due to the fact that the iron particles create dipoles owing to the impact of the magnetic field. In the flux density region, the interaction of the dipole of the iron particles forms the chain like structure which holds the abrasive particles. The finishing medium (MR polishing fluid) is applied in the working space. In the influence of the magnetic flux concentration, the MR polishing fluid makes the chain like arrangement and build a flexible rigid polishing fluid. During the MR finishing operation, the rectangular tool core is given a rotary as well as a reciprocatory motion which are transferred to the active abrasives. The removal of material is due to the relative motion in between the rigidly retained MR polishing fluid on the magnetized rectangular tool tip and the cylindrical work-part surface. This relative motion of the active abrasive leads the shearing action on the work-part surface. The shear action on the work-part surface with MR polishing fluid helps to clip off the roughness crests in the form of micro-chips. To understand the material removal mechanism, the in-depth study of the forces imposed on the active abrasives is studied. In this work, the iron particles organized themselves in the chains due to the influence of the magnetic field. The iron particles are attracted towards the high magnetic field region whereas abrasives are moved towards lower magnetic field region. The particles owing to taking part in material removal from the work-part surface are known as active abrasives.

In the present work, the magnetic normal force (F_n), the tangential force due to work-part rotation (F_{tw}), as well as tool core rotation (F_{tt}) and axial force (F_a) due to reciprocating speed are responsible for the material removal. Iron particles push the active abrasives towards the cylindrical work-part surface due to the F_n . The rotary movement of the rectangular tool core tip and rotary motion of the cylindrical work-part creates the net tangential shear force ($F_{Rt} = F_{tt} + F_{tw}$) as depicted in Fig. 6.1(a). The reciprocatory movement of the rectangular tool tip with the rigidly retained MR polishing fluid creates the axial shear force (F_a) on the work-part surface as depicted in Fig. 6.1(a). The F_n is accountable to indent the active abrasive particle into the roughness crests. Whereas, the resultant shear (F_c) of the net tangential shear force (F_{Rt}) and axial shear force (F_a) is accountable for clipping off the roughness crests from the cylindrical work-part surface. This happens when the resultant of the shear force (F_c) applied

by the active abrasives gets larger than the resisting shear force offered by the roughness peaks of the work-part material (Yadav and Singh, 2019).

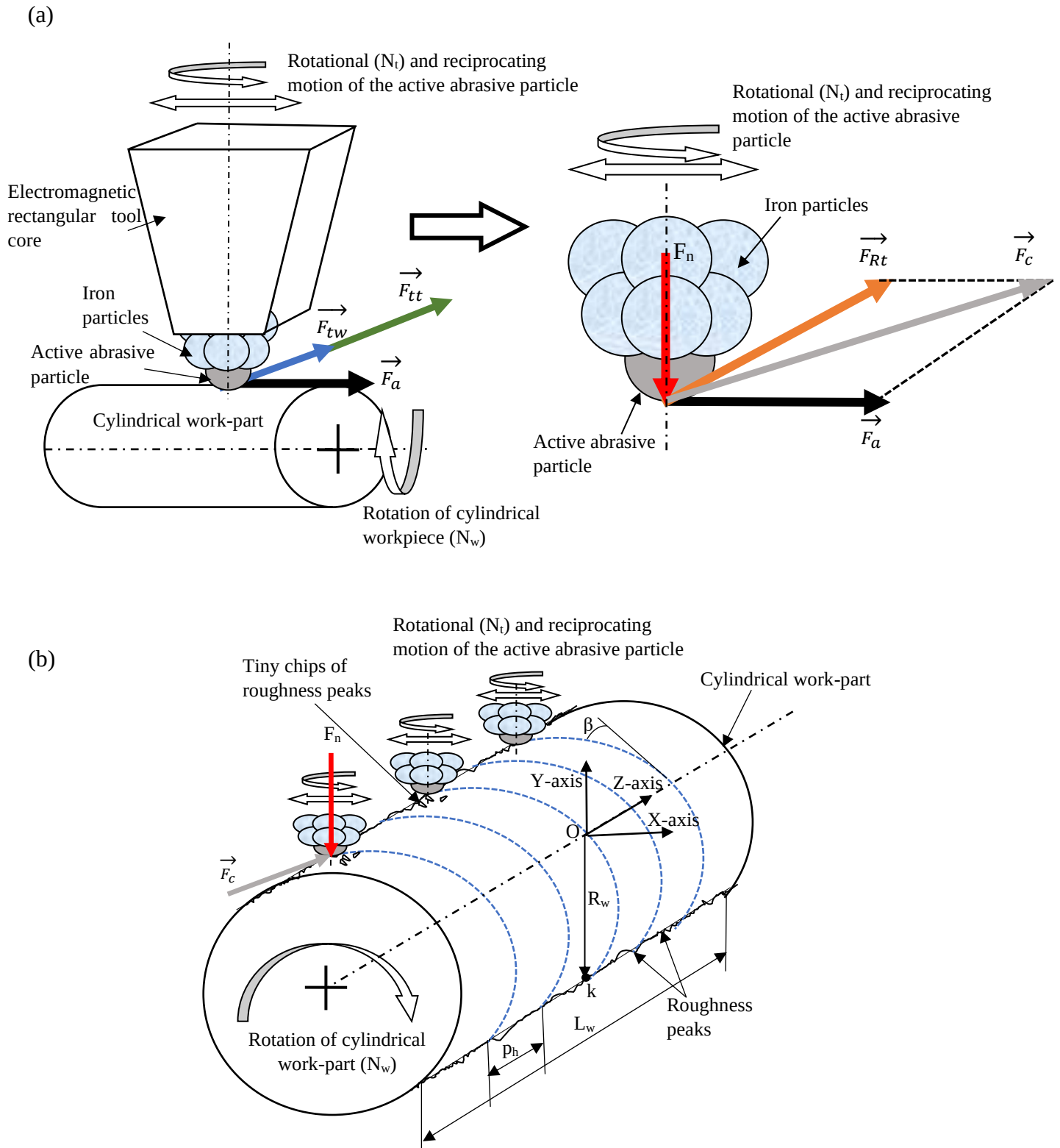


Fig.6.1 (a) Representation of the forces imposed on active abrasive particle during the MR finishing of cylindrical work-part and (b) mechanism of material removal along helical path.

Because of the concurrent rotary and reciprocatory motion of the tool core, the active abrasive particle forms a helical path on the work-part surface. It can be seen in Fig. 6.1(b) that the surface finishing is taken place due to the material removal in the helical path. Due to these motions, the active abrasives get axial and tangential forces which help to clip off the roughness crests from the cylindrical work-part surface. The cylindrical coordinate system is utilized to evaluate the parameters of helical path which is tracked by an active abrasive with origin point O as depicted in Fig. 6.1(b).

On the helical path, a random point (k) is taken. The positional coordinates of a point, k is evaluated using the Eq. (6.1).

$$x = R_w \sin(\omega_R T_a), y = R_w \cos(\omega_R T_a) \text{ and } z = z \quad (6.1)$$

Where, R_w is the radius of the cylindrical work-part. The coordinates of the random position, k on the helical path are x, y, and z. The net angular velocity of the active abrasive particle (AAP) due to the rotary motion of the rectangular tool tip and cylindrical work-part is denoted as ω_R . The time is taken by an AAP to trace one helical path over the external rotating cylindrical surface is denoted as T_a .

The resultant relative angular velocity of the AAP (ω_R) due to the rotary motion of rectangular tool core (N_t) and the cylindrical work-part (N_w) is an important factor to calculate the helix angle (β). The angular velocity of the active abrasive particle (ω_t) is due to the rotary motion of the rectangular tool core (N_t). The angular velocity of the AAP (ω_w) is owned to the rotary motion of the cylindrical work-part (N_w). Therefore, the resultant relative angular velocity of the AAP (ω_R) is calculated using Eq. (6.2).

$$\omega_R = \omega_t + \omega_w \quad (6.2)$$

The important parameters of the helical path are helix angle (β), helical path length (L_h) and helical path pitch (p_h). The helical path pitch (p_h) is the axial length trailed by an active abrasive on the external cylindrical work-part surface with one rotation of the work-part (2π) as depicted in Fig.6.1(b). The helical path pitch (p_h) is calculated using Eq. (6.3).

$$\text{Helical path pitch}(p_h) = \frac{2\pi \times \text{Axial velocity of an active abrasive particle}(v_a)}{\text{Net angular velocity of an active abrasive particle}(\omega_R)} \quad (6.3)$$

During the MR finishing of external cylindrical work-part surface, the active abrasive traces helical path with helix angle (β) on it and this angle is calculated using Eq. (6.4) (Yadav and Singh, 2019).

$$\beta = \tan^{-1} \frac{v_a}{R_w \omega_R} \quad (6.4)$$

Where the axial velocity of the rectangular tool core tip is denoted as v_a and R_w is the radius of the cylindrical work-part. In the present study, the value of v_a and R_w are taken as 30 cm/min

and 30 mm respectively. As the resultant relative angular speed of the AAP (ω_R) increases due to the work-part rotation, the helix angle (β) and helical pitch (p_h) decrease which can be observed from Eqs. (6.3) and (6.4). As the value of p_h is decreasing, the number of helical path turn gets increased on the external surface of the cylindrical work-part for the same axial velocity of the rotary rectangular tool core and becomes closed to each other. This helps in uniform removal of material from the external surface of the cylindrical work-part which leads to reduce the finishing time. Using Eq. (6.4), the helix angle (β) is found as 0.07599° . The helical path length (L_h) travelled by an active abrasive particle (AAP) along the helical path is evaluated using Eq. (6.5) (Jain *et al.*, 1999).

$$L_h = \frac{v_a T_a}{\sin \beta} \quad (6.5)$$

where, the time consumed by AAP to trace one helical path on the external rotating cylindrical surface is denoted T_a and it evaluated using the Eq. (6.6) (Paswan *et al.*, 2017).

$$T_a = \frac{\text{length of the cylindrical workpiece } (L_w)}{\text{Axial velocity of rectangular tool tip } (v_a)} \quad (6.6)$$

The motion of the active abrasives plays a significant role in the MR finishing of the cylindrical work-parts. The rotary motion of the rectangular tool core and cylindrical work-part enhances the relative motion of the AAP. Because of the rotary movement of the rectangular tool core tip along with the rotary motion of the cylindrical work-part, the net relative speed of the AAP gets enhanced. This enhancement in the relative motion of AAP decreases the pitch (p_h) and helix angle (β) which leads to an increase in the helical path length (L_h). This results in increase in the no. of turns of the helical path which causes the uniform fine finishing of the cylindrical work-parts in lesser time. This further improves the performance of the present process. In the present study, using length of the finishing surface of the cylindrical workpiece (L_w) as 15 mm and axial velocity of rectangular tool tip (v_a) as 30 cm/min into the Eq. (6.6), the time taken by an active abrasive particle (AAP) to trace one helical path on the external rotating cylindrical surface (T_a) is found as 0.05 min. Furthermore, using the value T_a in Eq. (6.5), the helical path length (L_h) travelled by an AAP along the helical path is found as 11.309 m.

6.2 Evaluation of the shear force acting in MR finishing of cylindrical external surface with the rotary rectangular tool core

Due to the rotary and reciprocating motion of the rectangular tool core, the active abrasive experiences the tangential shear force (F_{tt}) and axial shear force (F_a) respectively. Figure 2(a) shows the direction of the tangential cutting force (F_{tt}) which is tangential to the rotary speed of the active abrasive. Due to the rectangular tool core rotation, the position of active abrasives is changing from 0 to 6.35 mm radially as depicted in Fig. 6.2. The tangential shear force (F_{tt})

of the active abrasive is zero at the central portion of the rectangular tip since the radius is zero at the centre and maximum at the end corner of the rectangular tool tip as depicted in Fig. 6.2. The F_{tt} is evaluated using the Eq. (6.7).

$$F_{tt} = m_{sic} \left(\frac{\pi N_t}{30} \right)^2 \int_{r=0}^{r=6.35} dr_t \quad (6.7)$$

Where, the mass of the single abrasive particle is denoted as m_{sic} . The rotary speed of the rectangular tool core is denoted as N_t and dr_t is a variable radial distance of the AAP due to the rotary motion of the rectangular tool core as depicted in Fig. 6.2.

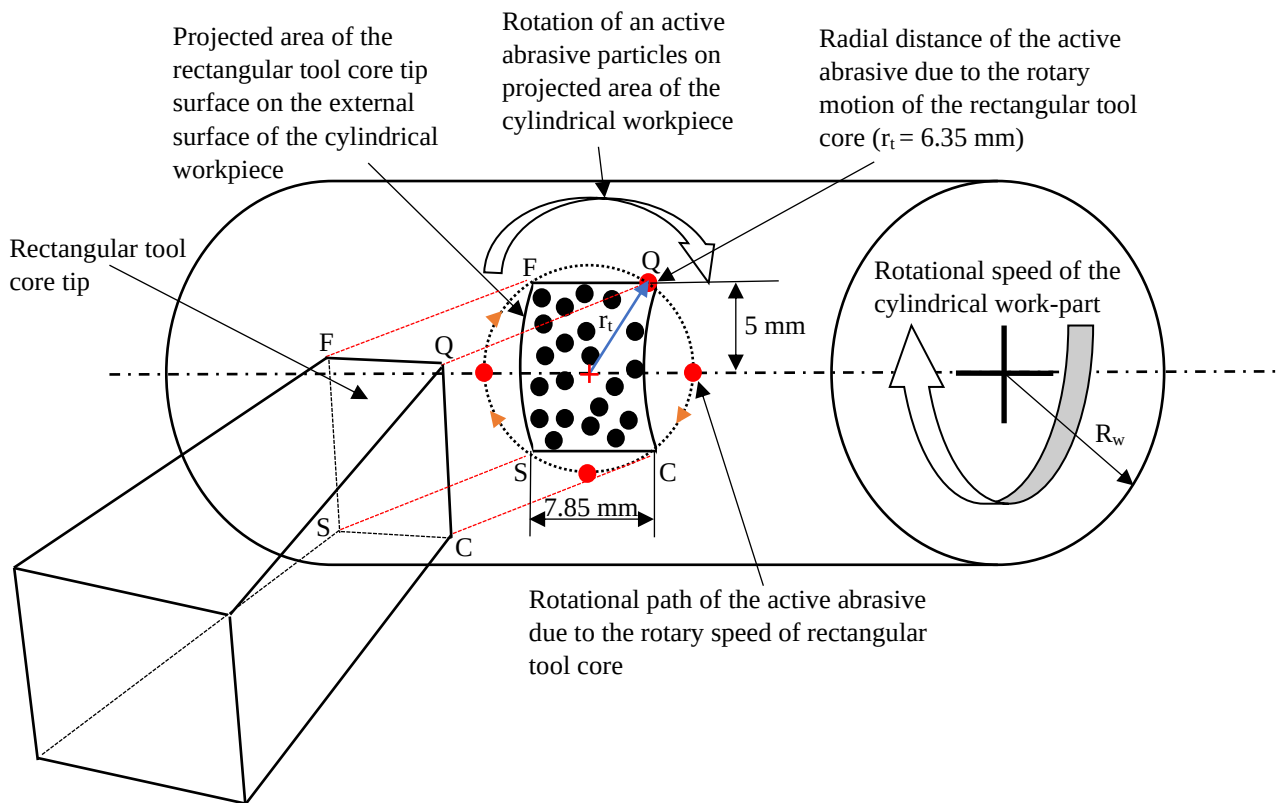


Fig. 6.2 Schematic of projected area of rectangular tool tip on cylindrical workpiece (work-part) with active abrasive particles.

The active abrasive also experiences the tangential cutting force (F_{tw}) because of the rotary speed of the cylindrical work-part. The F_{tw} is evaluated using the Eq. (6.8).

$$F_{tw} = m_{sic} R_w \left(\frac{\pi N_w}{30} \right)^2 \quad (6.8)$$

Where, the radius of the cylindrical work-part is denoted as R_w and the rotary speed of the cylindrical work-part is denoted by N_w .

In this work, the cylindrical work-part rotates in the clockwise direction and the rectangular tool core rotates in the anticlockwise directions. The tangential shear force is owned to the tool

core rotation (F_{tt}) and the tangential force due to work-part rotation (F_{tw}) act over the external surface of work-part through the active abrasive in the same direction as depicted in Fig. 6.1(a). These two forces get added to result in net tangential finishing force (F_{Rt}) and it can be calculated by using Eq. (6.9).

$$F_{Rt} = F_{tt} + F_{tw} \quad (6.9)$$

During the reciprocatory movement of the rectangular tool core tip, the AAP exerts an axial force (F_a) over the external cylindrical work-part surface. This F_a is acting in the parallel direction of the reciprocatory movement of the rectangular tool core tip and calculated by Eq. (6.10) (Gregory, 2006).

$$F_a = \tau_s \times (A_{sic} - A_h) \quad (6.10)$$

Where, the shear strength of the cylindrical work-part is denoted as τ_s in N/m^2 . The area of the single active abrasive is denoted as A_{sic} . The area of cross-section of indented AAP following the helical path is denoted as A_h .

The resultant of these two forces gives the cutting shear force (F_c) as given in Eq. (6.11). This cutting shear force (F_c) clip off the roughness crests in the form of tiny chips (Fig. 6.1 (b)).

$$F_c = \sqrt{F_{Rt}^2 + F_a^2} \quad (6.11)$$

The rotary motion of the rectangular tool core and cylindrical work-part enhance the relative velocity of the active abrasive particles (AAPs) on the cylindrical work-part surface. This upsurges in the relative velocity of the AAPs which further enhances the shear rate. The increased shear rate increases the resultant cutting shear force (F_c). This resultant cutting force increases the abrasion rate during the MR finishing of the cylindrical work-part.

6.3 Magnetostatically finite element analysis (FEA) of flux density in working space

The magnetic field (MF) variation in working space was inspected by performing the magnetostatic finite element analysis (FEA) with the assistance of Maxwell Ansoft V13 as depicted in Fig. 6.3(a-d).

To check the MF in the working space, the CAD model was created in the Creo 3.0 and saved as IGES file. The IGES file of the CAD model of the rectangular tool core, cylindrical work-part and MR polishing fluid in the working space was imported in Maxwell Ansoft. The material and their magnetic properties (magnetic permeability, magnetic mass susceptibility) were assigned to each component of the MR finishing process as reported in Table 6.1. To make a realistic analysis the environment is also considered around the model during magnetostatic FEA. The FEA analysis automatically runs for 10 iterations in the software. Fig. 6.3(b-d) represents the result of FEA of magnetic field variation in the working space at the

regions 1,2 and 3 respectively as shown in Fig. 6.3 (a). Fig. 6.3(a) shows that the negligible variation in magnetic flux density is observed at the end surface of the rectangular tool tip to the cylindrical work-part surface in variable working space. The magnetic flux density variation is checked at the central region 1 in working space of 0.6 mm, region 2 in working space of 0.8 mm and 3 in working space of 1 mm as shown in Fig. 6.3(b-d).

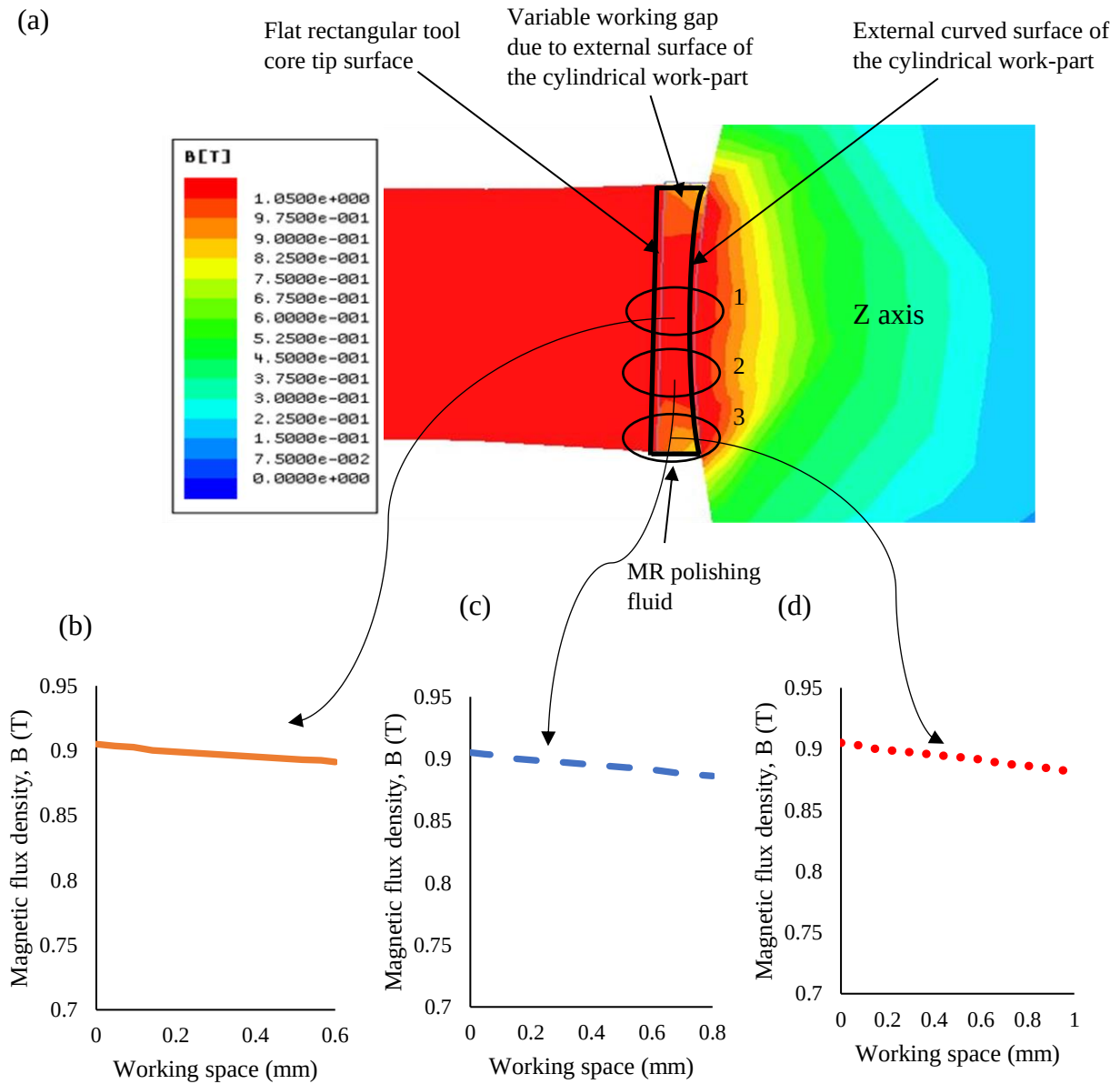


Fig. 6.3 (a) Magnetostatic finite element analysis in the variable working gap (space) in between the flat rectangular tool tip surface and external curved surface of the ferromagnetic cylindrical work-part and (b-d) 2D plot in variable working gap at the 3 different regions between the flat rectangular tool core tip surface and ferromagnetic cylindrical workpiece.

Fig. 6.3(a) shows that the negligible variation in magnetic flux density is observed at the end surface of the rectangular tool tip to the cylindrical work-part surface in variable working space. The magnetic flux density variation is checked at the central region 1 in working space of 0.6 mm, region 2 in working space of 0.8 mm and 3 in working space of 1 mm as shown in Fig. 6.3(b-d). It reveals that there is a negligible variation in magnetic flux concentration within the variable working space (0.6 mm to 1 mm) due to the effect of the curved external surface of the cylindrical work-part.

Table 6.1 Assigned parameters to the finite element analysis model

Component	Material	Relative permeability
Tool body	Aluminium	1
Rectangular tool core	Mild steel	600
Electromagnetic coil	Copper	0.99
Finishing medium	MR polishing fluid	5
Ferromagnetic cylindrical workpiece	H13 die steel	400

Therefore, it depicts that the strength of the magnetorheological (MR) polishing fluid does not vary much in the working space due to the external curved surface of the cylindrical work-part. Hence, the shearing off the roughness asperities from the external cylindrical work-part surface takes place almost uniformly. However, little variation in the magnetic field in variable working space may help to shuffle the active abrasives during rotation of the tool core in the variable working space. This helps to provide the fresh cutting edged active abrasives in MR polishing fluid on the external cylindrical surface from lower MF to the higher MF which may improve the finishing rate.

6.4 Surface roughness theoretical model for magnetorheological fine finishing of the cylindrical work-part

The surface asperities model is developed to understand in-depth process mechanism and process performance for fine finishing of the cylindrical external surface. To develop this model, initially, the magnetic flux concentration in the working space is calculated using the theoretical model developed for evaluation of flux concentration. The theoretical flux density is used to calculate the magnetic normal force. After that, the total number of active abrasive particles (AAPs) is calculated in the volume of MR polishing fluid. Further, the material removal by the AAPs in the helical path is calculated. This developed model helps to find out the reduction in surface roughness in a given number of finishing cycles or time. To simplified the surface roughness model, the following assumptions are taken into account as discussed below.

- The shape of the iron and abrasive particles is considered as spherical in nature (Alam and Jha, 2017).
- It is considered that the distribution of abrasives and iron particles is uniform throughout the working space.
- Magnetic leakage or losses are not considered in the calculation of normal magnetic force.
- For surface roughness model, calculations are done assuming uniform surface roughness throughout the cylindrical surface.
- MR polishing fluid characteristics are not changed by mixing of removed material, because of the very lesser material removal.
- Abrasive particles are embedded in the iron particles chain structure and chains are continuous in the working space.
- The effect of the external circular curved surface of the cylindrical work-part in working space with the flat end surface of the rectangular tool core tip surface is neglected while calculating the magnetic flux concentration in the working space as this effect is found very less in the working space (Fig.6.3).

6.4.1 Modeling of magnetic flux density in working space

The iron particles generate the chain-like structure due to the magnetic field in the working space. The magnetic field present in the working space is responsible for the magnetization of ferromagnetic particles. Fig. 6.4 shows the electromagnet which produces the magnetic flux concentration in the z-axis direction. The circular copper coil is utilized in the stationary electromagnet, 2100 turns of the copper coil are bounded over the bobbin and soft iron tool core is placed concentrically inside the bobbin as depicted in Fig. 6.4. The magnetic strength (H) in the working space on any point (P) has been evaluated using the Biot- Savarts Law. This law provides an expression which helps to find out the magnetic field using the current segment.

In Fig. 6.4, a single circular copper coil is considered with the current segment (Idl), where dl is the unit length of the segment. This segment generates the magnetic field (MF) intensity perpendicular to the radius of the circular coil (r). The MF intensity has an axial and perpendicular component to the axis. The X and Y components of magnetic field intensity get cancelled due to the symmetry of the current segment at point P. Hence there is only one non-zero field intensity (dH_z) in the Z-axis direction and evaluated using Biot-Savarts law as expressed in Eq. (6.12) (Ida, 2000).

$$dH = \frac{Idl \times R}{4\pi R^3} \quad (6.12)$$

Where R is the resultant distance of the radius of the circular copper coil (r) and axial distance (q) in the z direction of the point P . The intensity of the dH_z is directly proportional to the segment length (dl) and current (I). As the Idl and R in cross product relation to each other in Eq. (6.12), then this can be rewritten as in Eq. (6.13) (Ida, 2000).

$$dH = \frac{Idl}{4\pi R^2} \sin \gamma \quad (6.13)$$

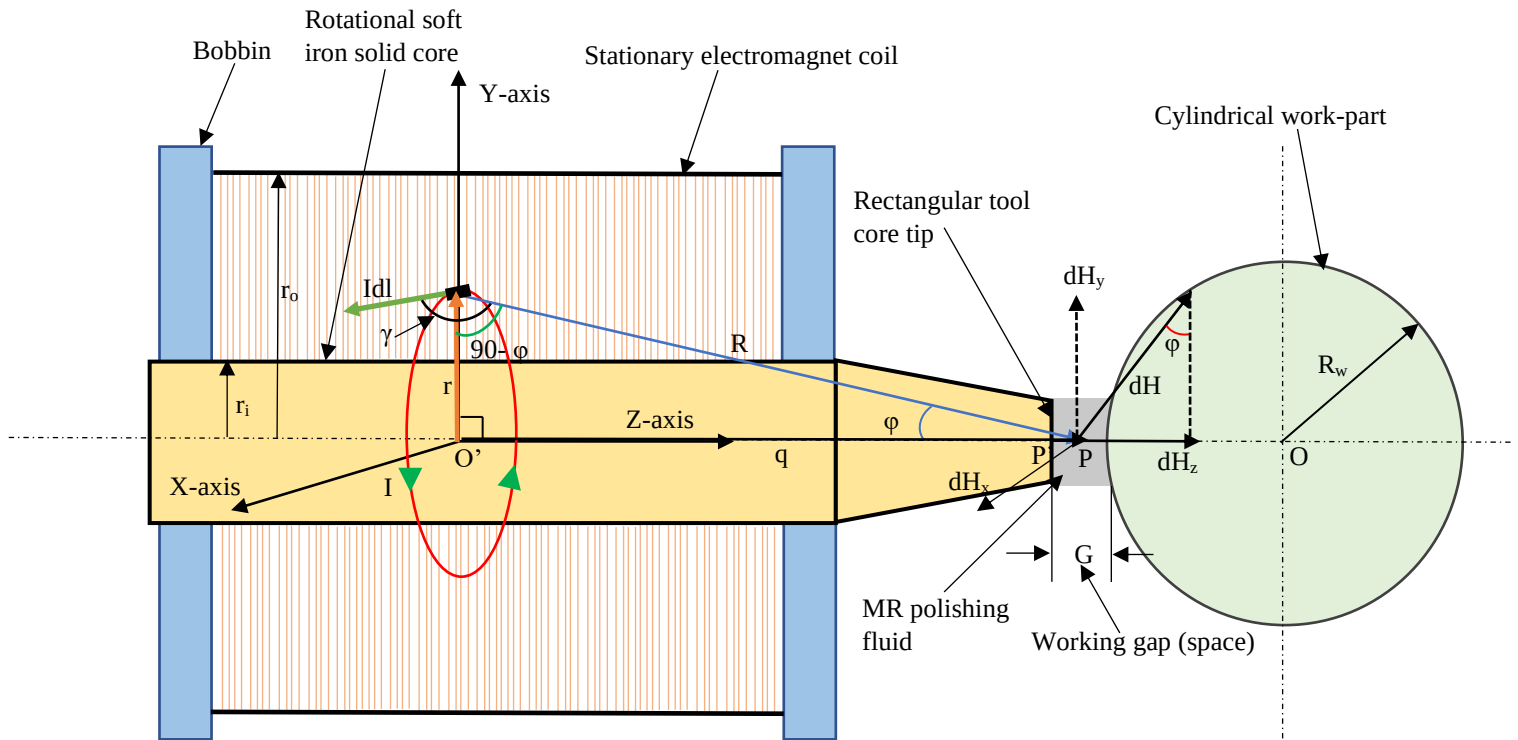


Fig. 6.4 Schematic of the electromagnet of the rotary rectangular core magnetorheological finishing process with magnetic field coordinates at measuring point.

Where, γ is the angle between current segment length dl and R . In this case, $\gamma = 90^\circ$. The ϕ is the angle between the resultant component of the magnetic field intensity (dH) and horizontal component of the magnetic flux density (dH_z) as shown in Fig. 6.4. The component dH_z is expressed as in Eq. (6.14).

$$dH_z = \frac{Idl}{4\pi R^2} \sin \phi \quad (6.14)$$

From Fig. 6.4 using the Pythagorean theorem the value of the R is calculated using Eq. (6.15).

$$R = \sqrt{r^2 + q^2} \quad (6.15)$$

The angle ϕ is the angle between electric current segment length (Idl) and the resultant component of the magnetic flux density (R). It is constant for any position on the single circular coil turn and equals as expressed in Eq. (6.16).

$$\sin \phi = \frac{r}{\sqrt{r^2 + q^2}} \quad (6.16)$$

After putting the values of R and $\sin \phi$ into the Eq. (6.14), the modified expression is obtained as express in Eq. (6.17).

$$dH_z = \frac{1}{4\pi} \frac{Idl}{r^2 + q^2} \frac{r}{\sqrt{r^2 + q^2}} \quad (6.17)$$

After substituting for dl and integrating over the single circular coil turn as expressed in Eq. (6.18).

$$H_z = \frac{1}{4\pi} \frac{Ir}{(r^2 + q^2)^{3/2}} \int_{l=0}^{l=2\pi r} dl \quad (6.18)$$

After completing the integration in Eq. (6.18), the final expression of magnetic field intensity along the z axis direction due to the single turn of copper coil is expressed as in Eq. (6.19).

$$H_z = \frac{1}{4\pi} \frac{I2\pi r^2}{(r^2 + q^2)^{3/2}} \quad (6.19)$$

Thus, the magnitude of the magnetic field (MF) intensity (H_z) because of a single circular copper coil along the z -axis can be evaluated using Eq. (6.19). The total MF intensity magnitude in the z -axis (H'_z) can be calculated by multiplying the total no. of copper circular coil turns (n) in the electromagnet as given in Eq. (6.20).

$$H'_z = \frac{nIr^2}{2(r^2 + q^2)^{3/2}} \quad (6.20)$$

Where, r is the variable radius for any number of copper coil turns in the electromagnet which varies between the inner radius(r_i) and the outer radius (r_o) of the electromagnet as depicted in Fig. 6.4. In present case, $r = r_o = 37.5$ mm for a total number of copper coil turns (n). q is also variable which depends upon the length of the electromagnet for total no of copper coil turns (n). In present case, $q = O'P' + P'P$. The number of turns (n) is taken as 2100. The $O'P'$ length is 130 mm in present magnetic tool. The value of the $P'P$ is the variable in the working space which is measured up to 0.6 mm in the present analysis. According to the value of the q is changed, the value of the H'_z is evaluated in the working gap. The current is taken as 2A for the present case. The electromagnetic circular coil is made over the rotational mild steel tool core (Fig.6.4). Therefore, the magnitude of the total magnetic field (MF) intensity (H'_z) produced by the electromagnet through the tool core is calculated at the different measured distances of the working gap using the Eq. (6.20) and reported in Table 6.2. Further, the magnetic flux density (B_z) is induced through the tool core tip surface at any point P of the

working space (Fig.6.4) due to the total MF intensity (H'_z) produced by the electromagnet can be evaluated using Eq. (6.21).

$$B_z = \mu_0 H'_z \quad (6.21)$$

Where, H'_z is the total MF intensity at point P in a working space own to the MF induced by the electromagnet in free space. The magnetic permeability of free space is denoted as μ_0 and its value is $4\pi \times 10^{-7}$ (N/A²).

Table 6.2 Magnetic field intensity produced by the electromagnet through tool core and corresponding magnetisation of the iron particles as well as ferromagnetic cylindrical workpiece in working gap

Working gap with measured distance from the tool core tip surface, G (mm)	Magnetic field intensity produced by the electromagnet through tool core, H'_z (A/m) Eq. (6.20)	Magnetic flux density induced by the electromagnet through tool core, B_z (T) Eq. (6.21)	Magnetization of iron particles, M_{ip} (A-m ² /kg) Fig. 6.5(a)	Magnetization of H13 ferromagnetic workpiece, M_w (A-m ² /kg) Fig. 6.5(b)
0	1192.29	0.8985	200	150
0.047	1191.09	0.8976	198	149
0.094	1189.90	0.8967	196	149
0.141	1188.71	0.8958	192	146
0.188	1187.52	0.8949	188	146
0.235	1186.34	0.8940	186	146
0.282	1185.15	0.8931	184	146
0.329	1183.97	0.8922	182	146
0.376	1182.79	0.8913	178	146
0.423	1181.61	0.8904	176	146
0.470	1180.43	0.8895	174	146
0.517	1179.25	0.8886	172	146
0.564	1178.07	0.8877	168	146
0.611	1176.90	0.8869	165	146

The electromagnetic circular coil is made over the rotational mild steel core. The induced magnetic field by the electromagnetic circular coil magnetizes the tool core, MR polishing fluid in the working space and the ferromagnetic cylindrical work-part. The MR polishing fluid permeability (μ_{MRP}) is calculated by multiplying free space magnetic permeability (μ_0) and the MR polishing fluid relative permeability (μ_{rMRP}).

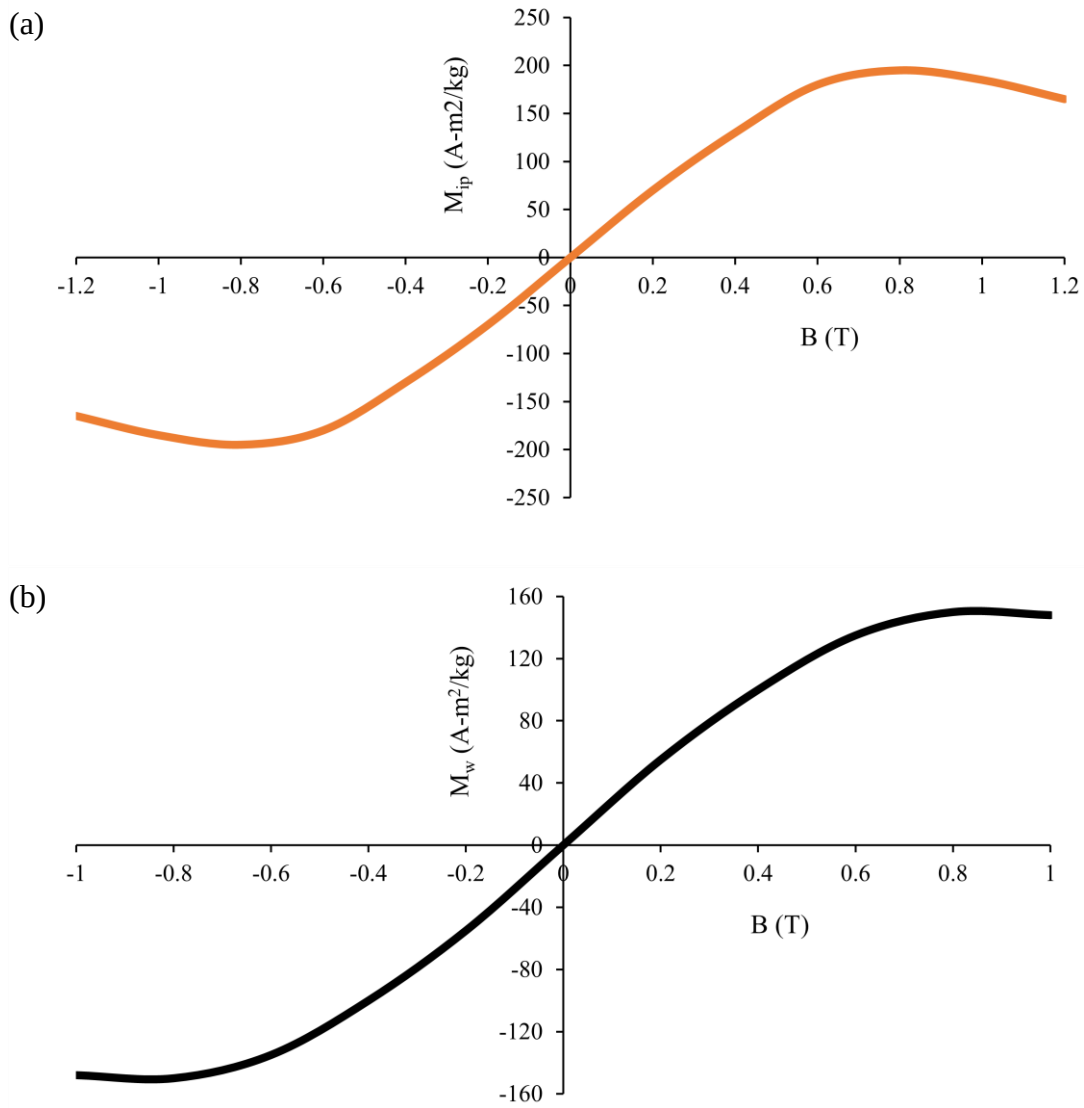


Fig. 6.5 Magnetic flux density (B) and magnetization (M) curve for (a) iron particles (Paswan *et al.*, 2017) and (b) H13 steel material workpiece.

The magnetic permeability of the tool core is denoted as μ_t and it can be calculated using the Eq. (6.22).

$$\mu_{MRP} = \mu_0 \times \mu_{rMRP} \quad (6.22)$$

Where μ_0 is the absolute magnetic permeability of free space with the value of $4\pi \times 10^{-7} \text{ N/A}^2$ and μ_{rt} is the relative permeability of the tool core (medium). The value of μ_{rt} for the mild steel tool core is taken as 600. The magnetic field (MF) or magnetic flux density induced by the electromagnet through tool core (B_z) in the different measured distances of the working gap is calculated using Eq. (21) and reported in Table 6.2.

The magnetic field induced by the electromagnet through tool core also magnetizes the MR polishing fluid in the working space and the ferromagnetic cylindrical work-part. The magnetic permeability of the MR polishing fluid (μ_{MRP}) is calculated using Eq. (6.23).

$$\mu_{MRP} = \mu_0 \times \mu_{rMRP} \quad (6.23)$$

Where μ_{rMRP} is the relative permeability of the MR polishing fluid and its value is taken as 5. Similarly, the magnetic permeability of the ferromagnetic cylindrical work-part (μ_w) is calculated using Eq. (6.24).

$$\mu_w = \mu_0 \times \mu_{rw} \quad (6.24)$$

Where μ_{rw} is the relative permeability of the ferromagnetic cylindrical work-part and its value for the H13 ferromagnetic cylindrical work-part is taken as 400.

The total magnitude of the magnetic flux density ($B_{t(z)}$) at any point of the working space is the sum of the magnetic flux density induced by the electromagnet through tool core (B_z) in the Z-axis direction (Eq. 6.21) and the magnetic flux density gets induced due to the magnetization of iron particles (M_{ip}) of the MR polishing fluid in the working gap as well as the magnetization of the ferromagnetic cylindrical work-part (M_w). It is calculated using Eq. (6.25).

$$B_{t(z)} = \mu_t H'_z + \mu_{MRP} M_{ip} + \mu_w M_w \quad (6.25)$$

The magnetisation of the iron particles of MR polishing fluid (M_{ip}) and the magnetisation of ferromagnetic cylindrical H13 steel workpiece (M_w) due to the effect of flux density induced by the electromagnet through tool core (Eq.6.21) in working space is calculated with the help of the M-B curves (Fig. 6.5 a and b) and reported in Table 6.2. The $B_{t(z)}$ is the total flux density induced at any point in the working space. The total flux density ($B_{t(z)}$) induced in z-axis from the rectangular tool core tip surface along with the magnetisation of the iron particles of MR polishing fluid and the ferromagnetic cylindrical workpiece is calculated at the different measured distances of the working gap (G) using the Eq. (6.25) and reported in Table 6.3. Fig. 6.6 is plotted using the calculated theoretical values of total flux density (Eq.6.25) at the different measured distances of the working gap, G (Table 6.3). From the theoretical analysis of Fig. 6.6, the general expression of the variation in total magnetic flux density ($B_{t(z)}$) in terms of working space (G) is obtained as given in Eq. (26).

$$B_t(z) = 0.9742 - 0.0218G \quad (6.26)$$

Fig. 6.6 also shows the variation in total magnetic flux density in the working space with finite element analysis (FEA), and experimentally measured values. The digital gauss meter is employed to measure the magnetic flux density in the working space. The trend of the FEA and experimental analysis helps to verify the variation of theoretical values of magnetic flux density or magnetic field (MF) in the working gap.

Table 6.3 Magnetic flux density and normal force (F_n) induced on iron particles in working gap

Working gap with measured distance from the tool core tip surface, G (mm)	Theoretically calculated total magnetic flux density, $B_{t(z)}$ (T) Eq. (6.25)	Experimentally obtained total magnetic flux density (T)	Magnetic mass susceptibility, $\chi_m \times 10^{-4}$ (m^3/kg) Eq. (6.28)	Normal magnetic force, $F_n \times 10^{-7}$ (N) Eq. (6.27)
0	0.9751	0.8651	2.584	4.1867
0.047	0.9737	0.8637	2.562	4.1690
0.094	0.9728	0.8628	2.538	4.1484
0.141	0.9703	0.8603	2.492	4.1202
0.188	0.9694	0.8594	2.443	4.0967
0.235	0.9685	0.8585	2.419	4.0825
0.282	0.9676	0.8576	2.396	4.0682
0.329	0.9667	0.8567	2.372	4.0448
0.376	0.9658	0.8558	2.322	4.0353
0.423	0.9649	0.8549	2.298	4.0272
0.470	0.9640	0.8540	2.274	4.0177
0.517	0.9631	0.8531	2.250	4.0036
0.564	0.9625	0.8525	2.199	3.9941
0.611	0.9613	0.8513	2.162	3.9831

The trend of these measured magnetic flux densities shows that the flux density is higher at the tool tip side and lower towards the cylindrical work-part. From Fig. 6.6 it is seen that the magnitude of theoretical values of the magnetic field (MF) in the working gap is found higher. This is because of various assumptions like magnetic leakage or losses are not considered in the calculation. Furthermore, in the finite element analysis (FEA), all the calculations are performed with the ideal conditions in Maxwell ansoft which may not be the same in real conditions to predict the magnetic field in the working space. But in the experimental analysis, the actual conditions are accessible that reduces the value of the magnetic field as compared to the theoretical and finite element analysis. Also, it gives the average value of the MF in the Z-axis direction from the rectangular tool core tip surface to the cylindrical work part surface in the working gap (G) for calculating the magnetic normal forces. Because of this trend i.e. owing to its magnetic flux gradient, the iron particles are drawn towards the rectangular tool core tip surface and push the non-magnetic abrasive particles towards the external surface of the cylindrical work-part and finish the surface. Since the actual abrasive particles are having an

irregular shape with the many cutting edges which help to shear out the peaks of the roughness and iron particles serve as a supporting companion during the MR finishing. However, due to the complex nature of forces among iron particles of the MR polishing fluid, the major contribution of the iron particles to indent the active abrasive particle (AAP) on the workpiece surface can be considered which are normally acted to that of the active abrasive particle. Therefore, the magnetic normal force (F_n) is transferred from the rectangular tool core tip surface to neighbouring iron particles normally each other and the cumulative average F_n is applied to the AAP. This cumulative average magnetic normal force allows the AAP to indent into the work part's external surface.

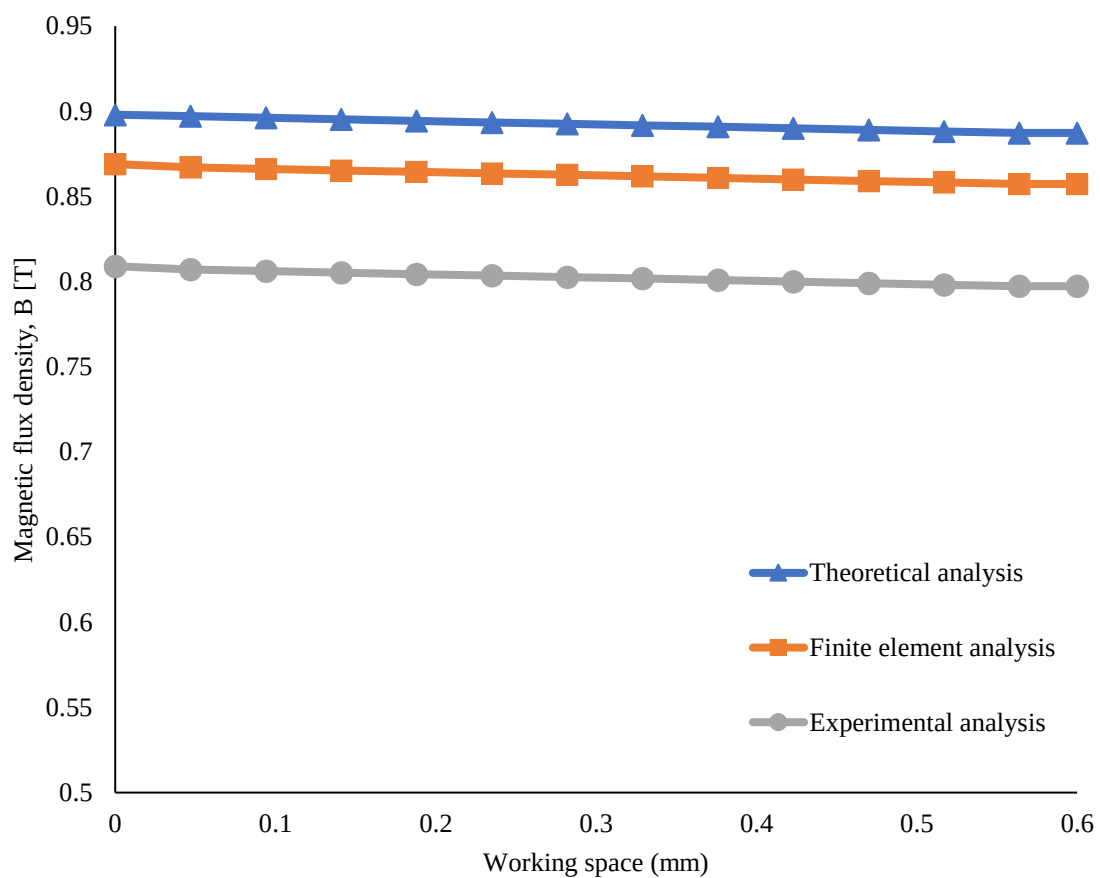


Fig. 6.6 Flux density variation with working gap in theoretically analysis, finite element analysis and with experimentally analysis.

6.4.2 Calculation of magnetic normal force acting on an active abrasive through magnetic iron particles

The indentation of the active abrasive particle (AAP) on the work-part surface is caused by the induced magnetic normal force exerted on the iron particles. The normal force (F_n) is exerted on the AAP by iron particle under the influence of the magnetic field. The finishing

performance depends on the force acting normally on the AAP which is accountable for indentation. The magnetic force imposed on an iron particle calculated by using Eq. (6.27) (Alam and Jha, 2017).

$$F_n = \frac{m_{ip} \chi_m B_{t(z)} \frac{dB_{t(z)}}{dz}}{\mu_0} \quad (6.27)$$

Where, the magnetic normal force applied by the iron particle is denoted as F_n . The iron particle's mass is denoted as m_{ip} in Kg. The iron particle magnetic mass susceptibility denoted as χ_m in m^3/kg . The flux density variation in the working space is denoted as $B_{t(z)}$. The mass of the iron particle (m_{ip}) is 2.3989×10^{-11} kg. The free space of magnetic permeability (μ_0) = $4\pi \times 10^{-7}$ (N/A²). The vibrating sample magnetometer (VSM) test is performed to derived the M-B plot. The normal force (F_n) imposed on abrasive is evaluated by calculating the magnetic force imposed on the iron particle in the working space.

Using the theoretical expression of magnetic flux density ($B_{t(z)}$) Eq. (6.26), the values of normal magnetic force (F_n) and magnetic susceptibility mass (χ_m) at any point in the working space are calculated. The iron particle's magnetic mass susceptibility (χ_m) is evaluated using Eq. (6.28).

$$\chi_m = \frac{M_{ip}}{H_z} = \frac{\mu_0 M_{ip}}{B_{t(z)}} \quad (6.28)$$

The calculated values of normal magnetic force (F_n) and magnetic susceptibility mass (χ_m) are reported in Table 6.3. M_{ip} is magnetization of an iron particle at any P point in the working space (Fig. 6.5(b)). The F_n is applied on each iron particle in the working space because of the induced MF. Further, the indentation force (F_{in}) is calculated which is the average value of the F_n at each iron particle in working space as reported in Table 6.3. The indentation force (F_{in}) is found which is equals to 4.0698×10^{-7} N.

6.4.3 Calculation of number of active abrasives

The working space amid the rectangular tool tip and the cylindrical work-part surface is filled with MR polishing fluid as depicted in Fig. 6.7(a). The MR polishing fluid stiffed over the rectangular surface of the tip due to the maximum flux density at the surface of the tip as depicted in Fig. 6.3.

In present work, the working space is varied from the central axis to the upper end surface of the rotary rectangular tool core tip surface due to the effect of the external surface of the cylindrical work-part. Further, the maximum working space amid the tool tip and the cylindrical work-part is calculated as $FP = 1.02$ mm as depicted in Fig. 6.7(a).

depicted in Fig. 6.7(b). The volume of the MR polishing fluid is calculated using Eqs. (6.29) to (6.32).

$$\text{Vol. of MR polishing fluid in the working space (V)} = (\text{area of rectangular surface FPSW} - \text{area of cylindrical segment PEWTP}) \times WM \quad (6.29)$$

$$V = FP \times FS \times WM - \left[R_w^2 \cos^{-1} \left(\frac{R_w - ET}{R_w} \right) - (R_w - ET) \sqrt{2R_w ET - ET^2} \right] \times WM \quad (6.30)$$

Where R_w is the radius of the cylindrical work-part in mm, ET is the depth of the cylindrical segment as depicted in Fig. 6.7(b).

$$= 1.02 \times 10 \times 7.85 - \left[30^2 \cos^{-1} \left(\frac{30 - 0.42}{30} \right) - (30 - 0.42) \sqrt{2 \times 30 \times 0.42 - 0.42^2} \right] \times 7.85 \quad (6.31)$$

$$V = 80.07 - 22.02 = 58.05 \text{ mm}^3 \quad (6.32)$$

The volume of the MR polishing fluid is found as 58.05 mm^3 .

Further, the number of active abrasive particles (AAPs) denoted as N_s on the curved external surface area of the cylindrical work-part is calculated. These abrasives cover acts on the curved external surface of the cylindrical work-part in front of the rectangular surface of the tool core tip in the working space. Furthermore, the projected area on the curved external surface of the cylindrical work-part from the rectangular surface of the tool core tip on which the active abrasives acts are calculated by multiplying the arc length of the MR polishing fluid (PEW) and width of the MR polishing fluid (WM). In the present study, the arc length of the MR polishing fluid (PEW) from Fig. 6.7(b) is found to be 10.04 mm and the width of the MR polishing fluid (WM) is 7.85 mm. Thus, the projected area on the curved external surface of the cylindrical work-part from the rectangular surface of the tool core tip on which the active abrasives acts (Figs.6.2 and 6.7) is found as 78.81 mm^2 . Further, the number of active abrasives (N_s) is calculated using Eq. (6.33).

$$N_s = \frac{\text{Area of active abrasives region on the cylindrical workpiece surface}}{A_{ab}} \quad (6.33)$$

Where, A_{ab} is projected area of the single active abrasive and as it assumed spherical in shape and it is calculated using Eq. (6.34).

$$A_{ab} = \pi r_{ab}^2 \quad (6.34)$$

Where, the r_{ab} is the radius of the active abrasive particle. The r_{ab} is equal to $9.5 \times 10^{-6} \text{ m}$. Further, putting the value of r_{ab} in Eq. (6.34), the projected area of the single active abrasive (A_{ab}) is calculated as $2.8352 \times 10^{-10} \text{ m}^2$. After putting the value of the curved area of active abrasive particles region on cylindrical work-part and projected area of the single active abrasive (A_{ab}) in Eq. (6.33), the number of active abrasives (N_s) is found as 277961.

6.4.4 Calculation of material removal by the single abrasive particle

The indentation force (F_{in}) is accountable for indenting the abrasives in the work-part, owing to which there is a fine depression takes place in the work-part surface as shown in Fig. 6.8. The indentation diameter (d_i) as indented by the active abrasive due to the indentation force (F_{in}) is calculated using the Brinell hardness model.

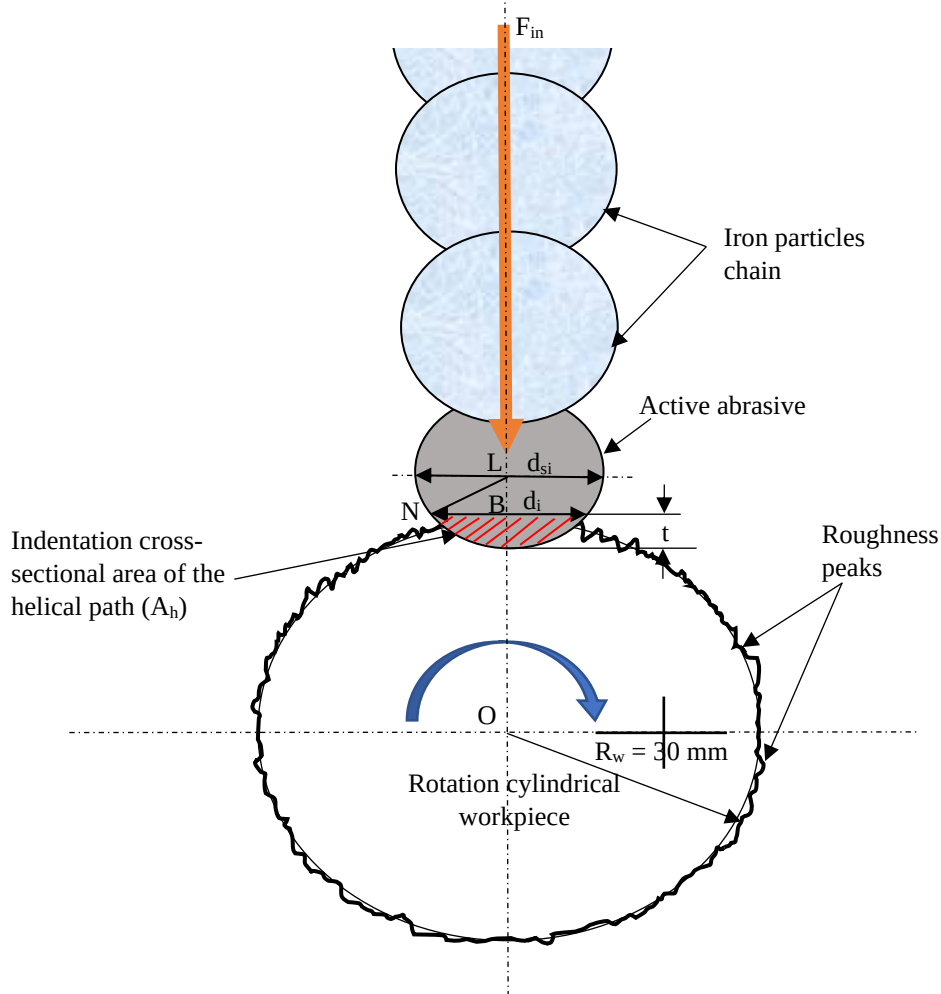


Fig. 6.8 Schematic of single active abrasive indenting into the external surface roughness peaks during the MR finishing due to the indentation force (F_{in}).

The Brinell hardness number (H_{BHN}) is given by Eq. (6.35) (Paswan and Singh, 2019).

$$d_i = \sqrt{d_{sic}^2 - \left(d_{sic} - \frac{2 \times 10^{-6} \times F_{in}}{9.8 \pi H_{BHN} d_{sic}}\right)^2} \quad (6.35)$$

Where the active abrasive's diameter is denoted as d_{sic} in m. The indentation diameter as indented by the active abrasive particle is denoted as d_i in m. For $F_{in} = 4.0698 \times 10^{-7}$ N, $H_{BHN} = 400$ kgf/mm² (H13 steel) and $d_{sic} = 19 \times 10^{-6}$ m, the value of d_i from Eq. (6.35) is calculated as $d_i = 1.5786 \times 10^{-8}$ m.

From ΔLNB in Fig. 6.8, depth of indentation (t) of the active abrasive particle can be calculated by using Eq. (6.36) (Alam and Jha, 2017)

$$t = \frac{d_{sic}}{2} - \frac{1}{2} \sqrt{d_{sic}^2 - d_i^2} \quad (6.36)$$

For $d_{sic} = 19 \times 10^{-6}$ m and $d_i = 1.5786 \times 10^{-8}$ m, the depth of indentation (t) of an active abrasive particle is evaluated by Eq. (6.36) as $t = 1.5098 \times 10^{-12}$ m.

Further, from Fig. 6.1(a), the indented cross-sectional area of the helical path (A_h) produced by active abrasive on work-part surface calculated by using Eq. (6.37) (Stradling, 1993).

$$A_h = \frac{d_{sic}^2}{4} \sin^{-1} \left\{ \frac{2\sqrt{t(d_{sic}-t)}}{d_{sic}} - \sqrt{t(d_{sic}-t)} \left(\frac{d_{sic}}{2} - t \right) \right\} \quad (6.37)$$

For $d_{sic} = 19 \times 10^{-6}$ m and $t = 1.5098 \times 10^{-12}$ m, the indented cross-sectional of the helical path (A_h) is found as 5.1457×10^{-14} m².

The removal of volume material from the cylindrical work part surface by the single active abrasive particle in a single finishing cycle (V_{as}) is calculated by Eq. (6.38).

$$V_a = A_h \times L_h \quad (6.38)$$

Where, the indented cross-sectional area of helical path is denoted as A_h and the helical path length on the cylindrical work-part surface by the active abrasive particle in a single finishing cycle is denoted as L_h .

Volume removed by the total active abrasives in i^{th} finishing cycles (V^i) is calculated by using Eq. (6.39).

$$V^i = i \times A_h \times L_h \times N_s \quad (6.39)$$

Where, i is the number of finishing cycles and N_s is the total number of active abrasive particles (AAPs).

Also, assuming finishing surface of the work-part is completely covered with the AAPs and the material removal in i number of finishing cycles (V^i) is the product of the longitudinal length of the cylindrical work-part surface to be finished (L_w), the circumferential length of the cylindrical work-part external surface ($2\pi R_w$) and depth of the indentation of the AAP (t) on the work part surface. Therefore, the volume of material removal in the i^{th} number of finishing cycles (V^i) is calculated by using Eq. (6.40).

$$V^i = i \times L_w \times 2\pi R_w \times t \quad (6.40)$$

The material removal rate (MRR) in i^{th} number of finishing cycles can be calculated from the Eq. (6.41).

$$MRR_i = \frac{i \times L_w \times 2\pi R_w \times t}{T_{ai}} \quad (6.41)$$

Where, MRR_i is material removal rate in i^{th} number of finishing cycles in m^3/min , T_{ai} is the time taken for the i^{th} number of finishing cycles in minutes.

Further, on equating the Eqs. (6.39) and (6.40), it is resulting to Eq. (6.42).

$$i \times A_h \times L_h \times N_s = i \times L_w \times 2\pi R_w \times t \quad (6.42)$$

During the calculation of volumetric material removal, the total height of the peaks cut by the active abrasive particle (t) is found as $t = 7(R_a^{i-1} - R_a^i)$. Where R_a^{i-1} is the surface roughness in $(i-1)^{th}$ number of finishing cycles, R_a^i is the surface roughness in i^{th} number of finishing cycles, Therefore, after solving the Eq. (6.42), the surface roughness model is found as

$$R_a^i = R_a^{i-1} - \frac{N_s \times L_h \times A_h}{7 \times L_w \times 2\pi R_w} \quad (6.43)$$

The Eq. (6.43) is used to calculate the reduction in surface roughness value in the i^{th} number of finishing cycles. This developed model is to be found beneficial for predicting the reduction in surface roughness value while the present process performs magnetorheological finishing on the external surface of the various cylindrical work-parts.

6.5 Experimentation

The experimentation is performed on the H13 die steel cylindrical work-part to validate the developed surface roughness model. The material H13 die steel material is used in various cylindrical-shaped industrial applications like cold rolling rolls, cylindrical punches, and automobiles components. H13 die steel material has good mechanical properties like corrosion resistance, good hardness, good toughness which helps this material to use for several applications. The ground cylindrical work-part of H13 die steel of 30 mm radius (R_w) with 100 mm of the total length has been taken and held in the present experimental setup. However, the experimentation is conducted on only 15 mm length of the cylindrical work-part (L_w) and that length is also taken for calculating the number of finishing cycles. For the validation of the surface roughness theoretical model, the five experimental trials are performed. Each trial has performed four-times and the average value of the experimental outcome is compared with the theoretical results. The experimental trials are performed at 1100 rpm rotary motion of rectangular tool core (N_t), 100 rpm rotary motion of cylindrical work-part (N_w), current (I) of 2 A, feed of tool core (v_a) as 30 cm/min and working space (G) is 0.6 mm. The experimental values and theoretical surface roughness values are compared and the percentage error is obtained. The percentage error confirms the effectiveness and repeatability of the developed

surface roughness model. Eq. (6.44) is used to check the percentage error between the experimental and theoretical results of the surface roughness value.

$$\text{percentage error} = \left(\frac{\text{Experimental } R_a \text{ value} - \text{theoretical } R_a \text{ value}}{\text{Experimental } R_a \text{ value}} \right) \times 100 \quad (6.44)$$

For the present experimentation, MR polishing fluid was prepared. The MR polishing fluid with a composition of 30% iron particles (600 mesh number), 15% silicon carbide abrasives (800 mesh number) and 55% carrier medium (80% heavy paraffin oil and 20% of grease) was used in the present experimentation. The experiment was performed for 20 min each (200 finishing cycles). The measurement of the surface roughness parameters was performed by the Mitutoyo SJ-400 surfest profilometer. The five sets of experimental trials are achieved to check the validation of the theoretical roughness model. The roughness values measurement is performed 10 different locations on the MR finished external surface of the cylindrical work-part and the average value of the surface roughness is reported in Table 6.4.

Table 6.4 Percentage error between theoretical and experimental value of surface roughness with different number of finishing cycles

Finishing time (min)	Number of finishing cycles	N_t (rpm)	N_w (rpm)	v_a (cm/min)	I (A)	G (mm)	Experimental R_a (μm)	Theoretical R_a (μm) Eq. (6.43)	Percentage error Eq. (6.44)
0	0	-	-	-	-	0.6	0.330	0.330	0
20	200	1100	100	30	2	0.6	0.240	0.248	-3.33
40	400	1100	100	30	2	0.6	0.172	0.176	-2.32
60	600	1100	100	30	2	0.6	0.098	0.095	3.06
80	800	1100	100	30	2	0.6	0.021	0.022	-4.76

6.6 Results and Discussion

The present surface roughness model is developed to know the detailed process mechanism and process performance for the precise finishing of the external surface of the cylindrical work-parts. In the present MR finishing process, the rectangular tool core tip surface is used so as to attain uniform flux density on it (Fig. 6.3). Owing to this, the iron particles produce uniformly stiffened chains which lead to uniform fine finishing by uniformly gripping the active abrasive particles on the work part surface. Initially, to find out the variation in flux density in the working space, the finite element analysis (FEA) was performed. It was found that the magnetic flux density gradient increases towards the rectangular tool core tip surface and decreases towards the cylindrical work-part surface as shown in Figs. 6.3 and 6.6, respectively. This helps to attract the iron particles towards the rectangular tool core tip surface

and abrasive particles are pushed towards the surface asperities of the work-part with uniform magnetic strength which provides uniform precise finishing. In order to obtain the expression for a theoretical model to calculate the flux density in the working space (G), initially magnetic field (MF) intensity produced by the electromagnet through tool core (H'_z) in z direction (Fig. 6.4) was obtained in the measured distances of the working gap using Eq. (20) and reported in Table 6.2 which leads to the base for the development of the theoretical model. Therefore, the magnetic field (MF) intensity produced by the electromagnet through tool core (H'_z) was considered as the main source to induce the magnetic flux density in the working space. Hence, the corresponding magnetic flux density induced by the electromagnetic tool core (B_z) was obtained using Eq. (6.21) as given in Table 6.2. Further, due to the induced MF through the electromagnetic tool core (B_z) in the working space, the magnetization of the iron particles of MR polishing fluid as well as ferromagnetic cylindrical work part (H13) was obtained using Fig.6.5 as given in Table 6.2. Later, the total induced magnetic flux density ($B_{t(z)}$) was obtained in the working space (G) with the different measured distances from the tool core tip surface using the Eq. (6.25) as given in Table 6.3. The flux density variation in working space is determined by a theoretical model which is found a similar trend to that as obtained by finite element analysis (FEA) and experimental evaluation (Fig.6.6). The difference in the gradient of the magnetic field in the working space signifies that the MR finishing fluid medium retains on the rectangular tool tip surface owing to which iron particle chains of the MR finishing fluid push the abrasive particles to the work-part surface and indent into the roughness peaks. After calculating the net magnetic flux density ($B_{t(z)}$) at the different measured distances of the working gap, the magnetic normal force (F_n) was obtained using the Eq. (6.27). Further magnetic susceptibility (χ_m) is determined using Eq. (6.28), which gives the magnetic normal force (F_n) at different points in the working space (Table 6.3). Further, the average of all the values of normal force (F_n) at different points of the working gap was used to determine the indentation force (F_{in}) which was found as 4.0698×10^{-7} N. The indentation force (F_{in}) help to indent the active abrasive into the surface asperities. The obtained indentation force signifies the total depth of indentation of the active abrasive on the surface of the cylindrical work-part during its precise finishing.

Further, the volume of MR polishing fluid was determined using the Eq. (6.30) and Fig. 6.7. Furthermore, the total number of active abrasives (N_s) were obtained using Eq. (6.33) at the external curved surface area of the cylindrical work-part. The total number of active abrasives (N_s) is acted on the projected area of rectangular tool core tip surface on the external surface of the cylindrical work-part. These active abrasive particles are accountable to shear off the

asperities from the cylindrical work-part surface in helical track during the present MR finishing process. The total number of active abrasives (N_s) are found to be 277961. Further, the diameter of indentation (d_i) of the active abrasive on the work-part surface was obtained using Eq. (6.35) and is found to be 1.5786×10^{-8} m. The diameter of indentation (d_i) depends upon the indentation force (F_{in}). As the F_{in} increase, the diameter of indentation (d_i) also gets increased. Further, the depth of indentation by the active abrasive particle (t) was obtained using Eq. (6.36) and is found to be 1.5098×10^{-12} m. This leads to the volume of material removed in a single finishing cycle (V_{as}) as obtained using Eq. (6.38). The total material removal rate (MRR) in a given number of finishing cycles or finishing time (T_{ai}) can be obtained using Eq. (6.41) in m^3/min . The reduction in surface roughness in a given number of finishing cycles or time by the total number of active abrasive particles is obtained using Eq. (6.43).

Mechanism of material removal is governed to obtain the reduction in surface roughness during the present MR finishing of the cylindrical work-part surface. The reciprocating and rotary speed of the rectangular tool core generates the helical path over the external surface of the cylindrical work-part by the active abrasive particles. The reciprocation and rotary speed of the rectangular tool core enhance the relative velocity of the active abrasives over the rotating cylindrical work-part surface. This enhancement in the active abrasive's relative speed decreases the helical pitch (p_h) and helix angle (β) which leads to an increase in the helical path length (L_h). Owing to this, the turns of the helical path increase which enhances the uniform fine finishing of the work-parts in lesser time. The helical path parameters are determined using the Eq. (6.1) to Eq. (6.6). The rotary and reciprocating motion of the active abrasives over the rotating cylindrical work-part provide effective and larger interactions over the roughness peaks. This results in an increased finishing rate that further improves the process performance. So, the developed theoretical model of surface roughness reveals that the process performance gets enhanced by participating the more process path parameters. This improved process performance is useful for the various industrial applications to provide the uniform finishing in lesser finishing time.

Also, from Fig. 6.3(a) it is clear that the minor flux density variation is observed in the working space due to the cylindrical curved surface. This flux density variation in the variable working space may help for getting more removal of asperities from the rotating cylindrical work-part surface. When rectangular tool core rotates in the variable working space, the active abrasives are shuffled continuously. This helps to provide the fresh cutting edges of the active abrasives

during MR finishing of cylindrical work-part, which improves the efficiency and productivity of the present rotary rectangular tool core MR finishing process.

Before experimentation, the initial surface roughness was measured as $0.330\mu\text{m}$ (Fig.6.9(a)). After experimentation, it is decreased to $0.240\mu\text{m}$, $0.172\mu\text{m}$, $0.0980\mu\text{m}$, and $0.021\mu\text{m}$ in 200, 400, 600, and 800 finishing cycles respectively as reported in Table 6.4.

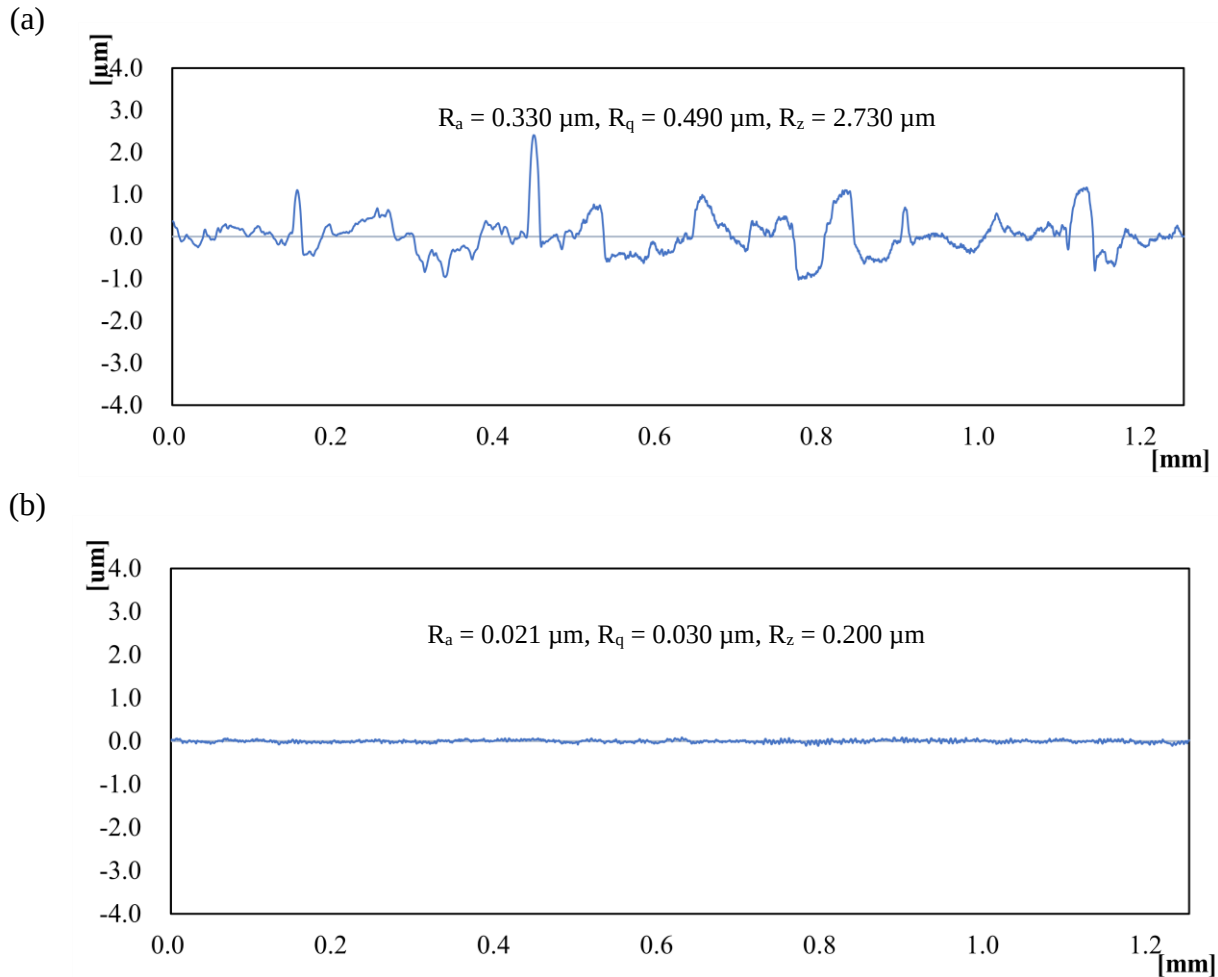
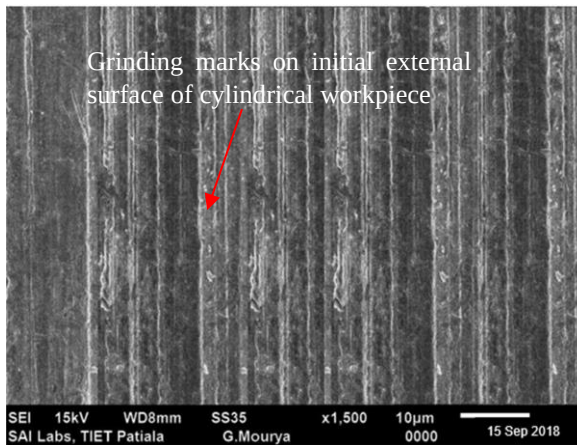


Fig. 6.9 Surface roughness profile of (a) initial ground surface and (b) after 1600 finishing cycles MR finished cylindrical surface.

The initial ground surface roughness profile is depicted in Fig. 6.9(a). After MR finishing, the final surface roughness profile is depicted in Fig. 6.9(b). The reduction in surface roughness after 800 finishing cycles reveal the precisely finished surface of the cylindrical work-part. The scanning electron microscopy (SEM) photographs of the initial ground surface and after experimentation are depicted in Figs. 6.10(a) and (b). In Fig. 6.10(a), the grinding marks are easily seen in the SEM image. After 800 finishing cycles, the work-part surface gets fine finished as depicted in Fig. 6.10(b).

(a)



(b)

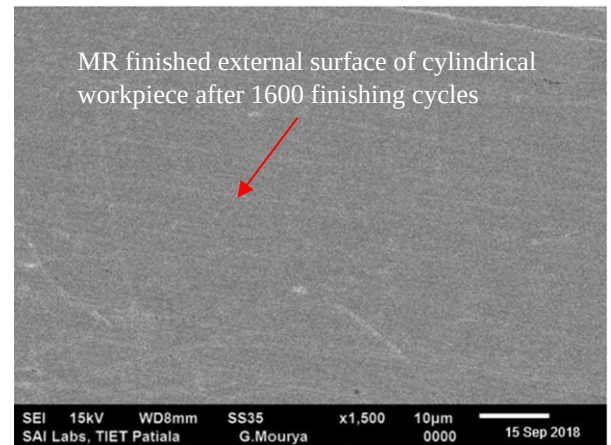


Fig. 6.10 Scanning electron microscopy images of (a) initial ground surface and (b) after 1600 finishing cycles MR finished cylindrical surface.

The reflection test of the initial ground surface and after experimentation are depicted in Figs. 6.11(a) and (b). The text ‘TIET’ was not clearly visible on the ground surface of the H13 cylindrical work-part. But after the MR finishing of 800 finishing cycles, the text ‘TIET’ was easily visible on the surface of the H13 cylindrical work-part as depicted in Fig. 6.11(b).

The theoretical model developed for surface roughness is validated experimentally during the MR finishing of a cylindrical work-part surface. The predicted value is found to be having a percentage error in experimental R_a value and theoretical R_a value in a range of -4.76% to 3.06% respectively which show a good agreement in the theoretical model and experimental results. The present developed roughness model is beneficial to predict the reduction in roughness value in different finishing cycles with the present process for fine finishing of the several cylindrical work-parts used in various industrial applications such as cold rolling rolls, cylindrical extrusion micro-punches and spline shafts, etc.

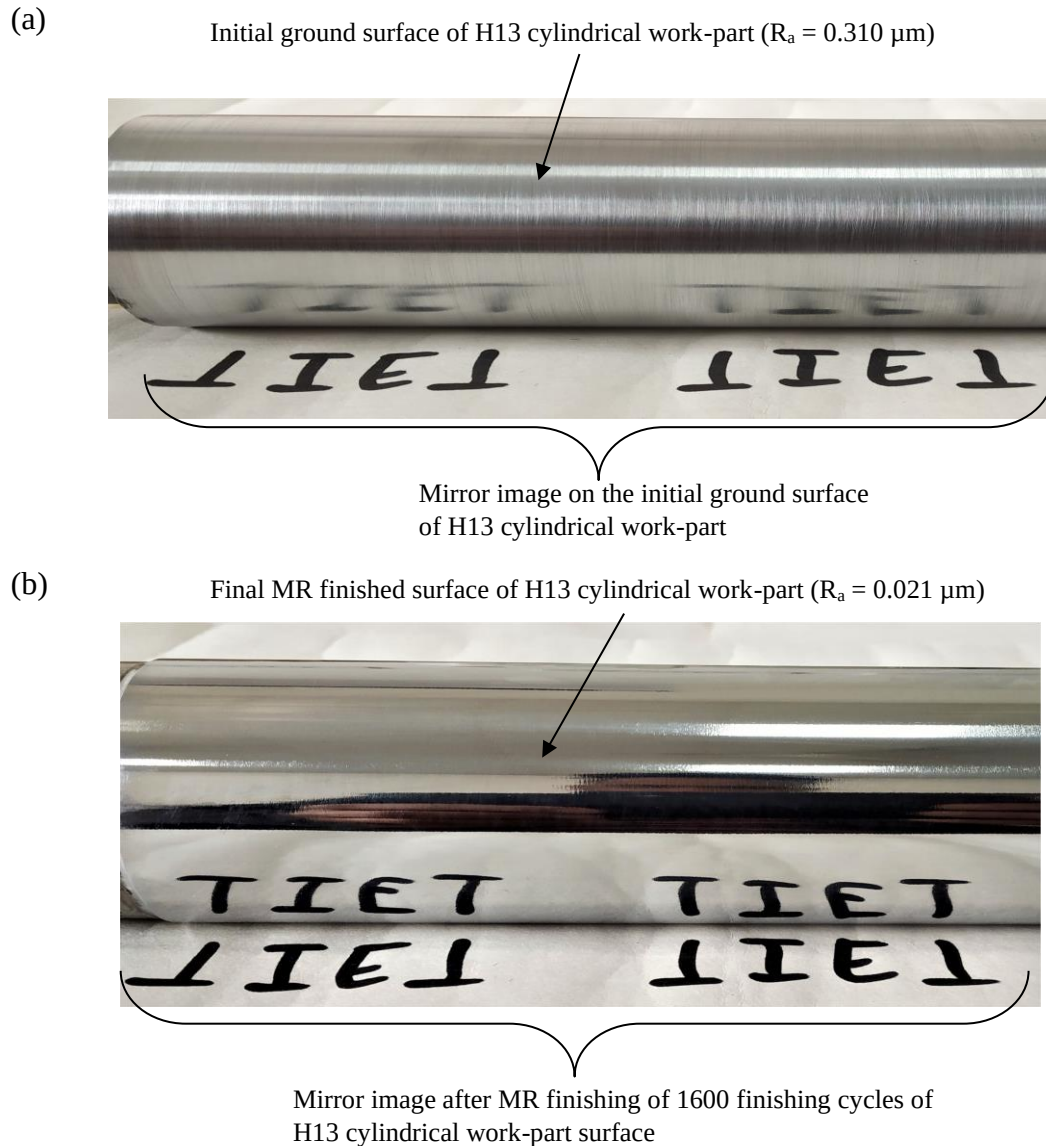


Fig. 6.11 Reflection images of (a) initial ground surface and (b) after 1600 finishing cycles MR finished cylindrical surface

6.7 Conclusions

The developed theoretical model predicts the reduction in roughness value while fine finishing performs on the external surface of the cylindrical work-parts using the rotary rectangular tool core magnetorheological (MR) finishing process in a given number of finishing cycles. The finishing mechanism with the helical path parameters, the net magnetic flux density induced in the working gap, the magnetic indentation force and depth of indentation during removal of surface asperities are also analysed in the process of developing the theoretical model for the reduction in roughness value. The following specific conclusions are drawn from the present work.

- 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 MR polishing as well as the ferromagnetic cylindrical work part.
- The flux density is found higher on the rectangular tool core tip surface and decreased towards the cylindrical work-part surface linearly in the working space which confirms that the indentation force applying on the active abrasive particles and surface asperities gets removed while indented active abrasive particles move on the cylindrical work-part surface.
- The rotary motion of the rectangular tool core tip surface with respect the rotating cylindrical work-part decreases the helix pitch and helix angle which increases the helical path length. This increased helical path length enhances the finishing rate which further improves the process performance and provides the uniformity in the MR finishing of cylindrical work-parts surface.
- Surface roughness gets reduced from $0.330\text{ }\mu\text{m}$ to $0.021\text{ }\mu\text{m}$ in 800 number of finishing cycles reveal the fine finishing on the H13 cylindrical work-part surface with the present MR finishing process.
- Percentage error between the results obtained from the theoretically calculated surface roughness values and experimental values were found in the range of -4.76% to 3.06%. This validates the effectiveness and repeatability of the developed roughness model.
- The developed theoretical model is found to be beneficial for predicting the reduction in surface roughness value while MR finishing performs on the various cylindrical work-parts surface for their precise applications with improved working performance.

CHAPTER 7

CONCLUSIONS AND SCOPE OF FUTURE WORK

7.1 Conclusions

A rotating core based magnetorheological (MR) finishing process is developed and found effective for improved process performance with increase in relative motion of the active abrasive particles. The magnetostatic finite element (FE) analysis is utilized to design the effective tool core tip surface for proving uniform and higher magnitude of magnetic flux density in fine finishing the external surface of the different cylindrical workpieces. For fine finishing the external surface of the tapered cylindrical workpieces, a swivel vise is fabricated. The dimensions of the swivel vise are taken based on the industrial applications and ensured that this vise can be utilized in fine finishing the any tapered angle external surface of the cylindrical workpieces for industrial applications. Further, the best rotating tool core tip surface has been designed as a rectangular shape based on the edge effect phenomena for proving uniformly higher magnitude of the magnetic flux density for its tip surface. The capability of the designed rectangular shaped tool core tip surface has been successfully demonstrated for the fine finishing of the various real time industrial applications of ferromagnetic and non-ferromagnetic (diamagnetic) cylindrical workpieces. Results obtained in the present work is evident that the developed rotating core-based magnetorheological (MR) finishing process is more competent to fine finish the external surface of the cylindrical workpieces for different industrial applications. The mathematical modeling for change in surface roughness in present developed rotating core-based MR finishing process detailed the in-sight mechanism of material removal during fine finishing the external surface of the cylindrical workpieces. Following specific conclusions have been drawn on the basis of results obtained from the present research work.

- After experimentation, the reduction in R_a value on the external surface of the mild steel cylindrical workpiece from 740 nm to 210 nm with the stationary curved core tool tip surface and 40 nm with the rotating flat core tool tip surface in the same 90 minutes show the effectiveness of the present developed rotating core based MR finishing process. Because the rotational speed of the tool core enhances the relative motion of the active abrasive particles over the external surface of the cylindrical workpiece which helps in improving the efficiency of the MR finishing process.

- Also, the tapered external surface of the AISI D2 tool steel cylindrical workpiece gets fine finishing using the rotating core based MR finishing process. The average R_a value gets decreased significantly to 19 nm from 700 nm on the external surface of the tapered cylindrical workpiece (60 mm length and 49.5 mm average diameter) after 120 minutes of MR finishing with the optimum parametric combination. The surface characteristics also gets improved significantly. Therefore, the presently developed rotating core based MR finishing process is found to be more useful in improving the functional application after fine finishing of the tapered cylindrical parts such as tapered punches, tapered roller for bearings and tapered cylindrical components used in various machines.
- The flux density over the designed rectangular shaped tool core tip surface was found uniformly in higher magnitude as compared to the circular or other shapes of the tool core tip surfaces. The average surface roughness value was decreased to 18 nm and 45 nm from the initial ground surface roughness value of 310 nm after 60 minutes MR finishing with the rectangular and circular shaped tool core tip surfaces which demonstrate the effectiveness of the rectangular shaped tip surface of the present improved rotating tool core MR finishing process.
- Regression analysis with response surface methodology reveals the optimized parameters for effective improvement in the surface finish of the H13 die steel rolls surface. The surface roughness of the industrial rolls (60 mm diameter and 240 mm length (14,400 mm² surface area)) gets significantly reduced to 18 nm from 200 nm with the rotating rectangular tool core tip surface in 12 hrs MR finishing. The surface characteristics of MR finished rolls show a great improvement in comparison to the ground rolls surface. The MR finished rolls surface with the present MR finishing process predicts the cost of power saves approximately INR 38,800 per year for their operation in the cold rolling process.
- Fine finishing of the micro-punches with the present improved MR finishing process reduced the surface roughness R_a value from 210, 230, 250, and 200 nm to 20, 20, 30, and 10 nm respectively in 60 minutes. This enhance the surface characteristics which reduces the frictional force between the outer surface of micro-punch and billet material during micro-extrusion process. This reduction in extrusion force enhances the final product quality in terms of roundness, and surface roughness.
- Taguchi technique reveals the optimized parametric combination for effective improvement in the grooved surface finish of the winding drum. The average surface

roughness of the grooved surface of the winding drum gets reduced from the initial ground surface of 200 nm to 10 nm in 60 minutes with the optimized parametric combination. The improvement in surface characteristics of the grooved surface of the winding drum with the present MR finishing process confirms the reduction in breakage of the yarn. Because the average breakage of yarn before and after MR finishing of the grooved surface of the winding drum is found as 11 and 6 respectively.

- After the MR finishing of spline shaft, the R_a value is obtained 20 nm from 270 nm on shaft 's external teeth (top land) surface and the profile (face and bottom land) surfaces reduction in R_a value is obtained from 300 nm to 30 nm at optimum process parameters. This signifies that the uniform finishing reduces the generation of micro-cracks which improve the life span of the spline shaft. Also, there is increased in micro-hardness which improves the life span and provider better resistance to wear.
- The surface roughness of copper cylindrical roller (120 mm length and 25 mm diameter) is reduced from 190 nm to 25 nm using the optimum process parameters in 4 hrs of the MR finishing. This signifies that the reduced surface roughness tends to reduce the friction which is critical to reduce the wear and increasing efficiency of the printing operation.
- From theoretical analysis for reduction in surface roughness value, it is revealed that the rotary motion of the rectangular tool core tip surface with respect the rotating cylindrical work-part decreases the helix pitch and helix angle which increases the helical path length. This increased helical path length enhances the material removal rate which enhances the process performance and provides the uniformity in the MR finishing of cylindrical work-parts. This theoretical analysis is found to be beneficial in predicting the fine finishing of the external surface of the cylindrical workpieces for industrial applications.
- Overall results show that the presently developed rectangular rotating core MR finishing process is found to be effective for fine finishing of the external surface of the cylindrical components which are beneficial for various industries such as sheet metal, automobile, die making, printing, textile, micro parts fabrication etc.

7.2 Future scope

The recently developed rotating core-based magnetorheological (MR) finishing process has proved its capability to finish the external surface of the different industrial applications of the ferromagnetic and non-ferromagnetic (diamagnetic) workpieces. Some of the scopes of future

work by which efforts can be made to further enhance the finishing performance of the present rotating core-based MR finishing process are listed as follows.

- The flexible fixture may be developed in the future to easily hold the various shape and size of industrial applications workpieces. Also, the fixture can freely rotate in any direction to provide the freedom to the workpieces for finishing industrial applications.
- Also, explore the multiple grooved or complex shapes industrial application's finishing can be done through the MR finishing process.
- Explore MR finishing on the different types of material such as ceramics, polymers and composites, since there are highly demanded in various industrial applications.
- In order to find out the feasibility of the magnetorheological fluid-based finishing process and to validate the real-time performance of industrial applications for fine finishing, industrial partnerships need to be developed.

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