

Modeling and Experimental Investigations of Novel Magnetorheological Finishing Process for Blind Hole Surfaces

*A dissertation submitted in partial fulfilment of requirement for the award of
degree of*

**Master of Engineering
in
Production Engineering**

Submitted by
SOHAIB AHMAD SIRWAL
Roll No.: 801585024

Under the guidance of
Dr. ANANT KUMAR SINGH
Assistant Professor



DEPARTMENT OF MECHANICAL ENGINEERING

THAPAR UNIVERSITY

PATIALA (PB), INDIA, 147004

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CERTIFICATE

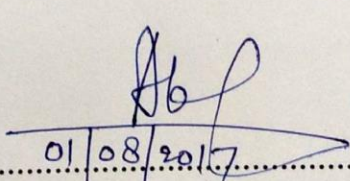
I hereby declare that the work done in this thesis entitled "**Modeling and Experimental Investigations of Novel Magnetorheological Finishing Process for Blind Hole Surfaces**" submitted towards partial fulfilment of requirement for award of degree of **Master of Engineering in Production Engineering, Thapar University, Patiala**, is an authentic record of the work carried out by me under the supervision and guidance of **Dr. Anant Kumar Singh, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala**.

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Dated: 01-AUGUST-2017

Sohaib
Sohaib Ahmad Sirwal
Roll No.: 801585024

This is to certify that above declaration made by the student concerned is correct to the best of our knowledge and belief.


.....
01/08/2017
Dr. Anant Kumar Singh

Assistant Professor
Mechanical Engineering Department
Thapar University, Patiala

Dedicated

to

my family

For their endless love, support and encouragement

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Roll No. : 801585024

Abstract

In modern high performance machinery, parts which are highly finished and dimensionally accurate play a vital role. Surface finish enhances characteristics like wear, corrosion, pitting and oxidation resistance of the surfaces. A novel magnetorheological polishing process using permanent magnets is developed to finish the internal and bottom surfaces of blind hole cylindrical workpiece. The process is capable of finishing the internal cylindrical and flat bottom surfaces of tubular and non-tubular shaped blind hole workpiece. Finishing of blind hole surfaces find extensive application in dies and automotive components such as automobile actuators, cylinder body, valve seats etc. In this study two different tools for finishing the internal and flat bottom surfaces of blind hole cylindrical workpiece have been developed. The causal factor for material removal in the form of micro-chips is abrasive wear. The present study focuses on the calculation of forces acting on abrasive particles and mathematical modeling and simulation of surface roughness. The performance of both newly developed tools for finishing the cylindrical blind hole mild steel workpiece is evaluated. After 275 finishing cycles, the R_a values improved by 55.2% in internal cylindrical ferromagnetic workpiece and by 53.33% after 75000 cycles in flat surface of ferromagnetic blind hole workpiece. The theoretical and experimental values of surface roughness are found to be consistent. The experimental surface roughness values of blind hole internal cylindrical surfaces are within 6.26 % of theoretical values whereas in finishing blind hole bottom surface it is found within 7.9% of theoretical values. The factors influencing finishing performance of both tools is also investigated for finishing P20 tool steel having 41 Rockwell C scale hardness. Response surface methodology using central composite design has been utilized for design of experiments and regression analysis. The effect process parameters like rotational speed, reciprocation speed, abrasive volume percentage and abrasive mesh size on percentage change in surface roughness has been studied and optimized. Rotational speed has significant effect on percentage change followed by abrasive volume, reciprocation speed and abrasive mesh number in surface roughness during finishing of internal cylindrical blind hole workpiece. During the finishing of bottom flat surfaces of blind hole workpiece rotational speed is the most significant parameter followed by abrasive volume and abrasive mesh number. Experimentation at optimized parameters (RPM = 700, reciprocation speed = 35 cm/min, abrasive volume % = 30 and abrasive mesh number 1000) results in final surface finish of 83 nm on internal cylindrical surface whereas at optimized parameters (RPM = 600,

abrasive volume % = 30 and abrasive mesh number 1000), 93 nm of surface finish is obtained on bottom flat surface of blind hole workpiece.

Keywords: Magnetorheological fluids; Blind holes; Surface roughness; Magnetic field; Normal force; Wear mechanism; P20 tool steel.

Table of Contents

	Page No.
<i>Certificate</i>	<i>i</i>
<i>Acknowledgement</i>	<i>iii</i>
<i>Abstract</i>	<i>iv</i>
<i>List of Figures</i>	<i>ix</i>
<i>List of Tables</i>	<i>xiii</i>
<i>Nomenclature</i>	<i>xv</i>

Chapter 1

INTRODUCTION	01-14
1.1 Introduction.....	01
1.2 Need of Nano-Finishing.....	03
1.3 Magnetorheological Fluids.....	03
1.4 Essential Features of MR Polishing Fluid.....	05
1.5 Components of MR Polishing Fluids.....	05
1.5.1 Magnetic Particles.....	05
1.5.2 Abrasive Particles.....	06
1.5.3 Carrier Liquid.....	06
1.5.4 Stabilizers, Additives.....	06
1.6 Magnetorheological Fluid Based Finishing Processes.....	07
1.6.1 Magnetorheological Finishing (MRF) Process.....	08
1.6.2 Magnetorheological Abrasive Flow Finishing (MRAFF) Process.....	09
1.6.3 Magnetorheological Jet Finishing (MRJF) process.....	10
1.6.4 Magnetorheological Abrasive Honing (MRAH) Process.....	11
1.6.5 Ball End Magnetorheological Finishing (BEMRF) Process.....	12
1.6.6 Magnetorheological External Cylindrical Surface Finishing Process.....	13
1.7 Advantages of Magnetorheological Fluid Based Finishing Processes.....	13

Chapter 2

LITERATURE REVIEW	14-24
2.1 Review of Literature.....	15

2.2 Gaps in Literature.....	22
2.3 Objectives.....	23
2.4 Methodology of Present Research.....	24

Chapter 3

DESIGN OF TOOLS FOR FINISHING BLIND HOLE SURFACES BASED ON FINITE ELEMENT ANALYSIS.....25-34

3.1 Need of Magnetorheological (MR) Fluid Based Finishing Process for Blind Hole Surfaces.....	25
3.2 Magnetostatic Modeling of MR Finishing Tools.....	26
3.3 Fabrication of Magnetorheological Finishing Tools.....	29
3.4 Experimental Setup.....	32
3.5 Fabrication of Workpiece.....	33
3.6 Conclusions.....	33

Chapter 4

MATHEMATICAL MODELING AND SIMULATION OF SURFACE ROUGHNESS.....35-63

4.1 Composition of MR Polishing Fluid.....	35
4.2 Mechanism of Surface Finishing in Blind Hole Workpiece.....	36
4.3 Analysis of Roughness on the Blind Hole Surfaces.....	40
4.4 Calculations of MR Polishing Fluid Particles and Chain Structures.....	40
4.4.1 Calculations of MR Polishing Fluid Particles For Finishing Blind Hole Internal Cylindrical Surface.....	41
4.4.2 Calculations of MR Polishing Fluid Particles For Finishing Blind Hole Bottom Surface.....	43
4.4.3. Calculation of Particles in Chain Structures.....	43
4.5 Calculation of Magnetic Field At Tool End Surfaces.....	44
4.6 Calculation of Magnetic Normal Forces on the Workpiece Surface.....	50
4.7 Modeling and Simulation of Surface Roughness.....	53
4.8 Results and Discussion.....	57
4.8.1 Experiments for Validation of Surface Roughness Model.....	57

4.8.2 Experimental Validation of Surface Roughness Model for Finishing Internal Cylindrical Surface of Blind Hole Workpiece.....	58
4.8.3 Experimental Validation of Surface Roughness Model of Flat Bottom Surface Finishing Blind Hole Workpiece.....	60
4.9 Conclusions.....	63

Chapter 5

PARAMETRIC STUDY FOR FINISHING OF CYLINDRICAL BLIND HOLE SURFACES 64-90

5.1 Introduction.....	64
5.2 Selection of Material.....	64
5.3 Selection of Process Parameters.....	65
5.4 Experimentation for Determining Percentage Change in Surface Roughness.....	67
5.5 Regression Analysis of Percentage Change in Surface Roughness ($\% \Delta R_a$).....	70
5.6 Results and Discussion.....	73
5.6.1 Experimental Analysis of Tool for Finishing Internal Cylindrical Blind Hole Surface.....	73
5.6.2 Experimental Analysis of Tool for Finishing Bottom Flat Blind Hole Surface.....	88
5.7 Confirmatory Experiments for Model Validation.....	88
5.8 Conclusions.....	89

Chapter 6

CONCLUSIONS AND SCOPE OF FUTURE WORK.....91-92

6.1 Conclusions.....	91
6.2 Scope of Future Work.....	92

References.....93-97

List of Figures

Item No.	Name	Page No.
Fig. 1.1	Achievable machining accuracy	01
Fig. 1.2	Effect on magnetorheological fluid under (a) no magnetic field and (b) externally applied magnetic field	04
Fig. 1.3	Bingham model of MR fluid	04
Fig. 1.4	Components of MR polishing fluid	07
Fig. 1.5	Magnetorheological finishing process experimental setup	08
Fig. 1.6	Magnetorheological abrasive flow finishing process setup	09
Fig. 1.7	(a) Experimental setup of magnetorheological jet finishing (b) Jet snapshot image (velocity- 30 m/s, nozzle diameter- 2 mm	10
Fig. 1.8	Schematic diagram of MRAH experimental.	11
Fig. 1.9	(a) Ball end magnetorheological finishing process experimental setup, (b) stiffened MR polishing fluid at the ball end tool tip, (c) MR polishing fluid stiffened during finishing under applied magnetic field	12
Fig. 1.10	(a) Schematic of magnetorheological external cylindrical surface finishing process, (b) flat tool tip surface and (c) stiffened MR polishing fluid during actual experimentation finishing cycle	13
Fig. 2.1	Methodology to carry out present research work	24
Fig. 3.1	Magnetostatic simulation of tool for finishing blind hole internal cylindrical surfaces (a) 3D view and (b) top view with variation of magnetic flux density in working gap	27
Fig. 3.2	Figure 3.3: Magnetostatic simulation of tool for finishing blind hole bottom flat surfaces (a) 3D view and (b) front view with variation of magnetic flux density in working gap	28
Fig. 3.3	Components and movement of tool for finishing internal cylindrical surfaces of blind holes and (b) components and movement of tool for flat surfaces	29

Fig. 3.4	Shape and dimensions of tool (mm) for finishing (a) internal cylindrical surfaces of blind holes and (b) bottom flat surfaces of blind holes	30
Fig. 3.5	(a) Tool for finishing of bottom flat surface of blind hole workpiece and (b) tool for finishing of internal cylindrical surface of blind hole workpiece	31
Fig. 3.6	Experimental setup for magnetorheological finishing of blind hole surfaces	32
Fig. 3.7	Shape of workpiece and slots to carry the removable workpiece.	33
Fig. 4.1	Mechanism of material removal and forces acting during finishing of internal cylindrical surfaces of blind holes	37
Fig. 4.2	Mechanism of material removal and forces acting during finishing flat bottom surface of blind holes	38
Fig. 4.3	(a) Forces acting on the internal cylindrical workpiece surfaces, (b) forces acting on the blind hole bottom flat workpiece surfaces and (c) different forces acting on active abrasive during finishing of the internal cylindrical and flat surfaces of ferromagnetic workpiece with the newly developed MR polishing fluid based tools	39
Fig. 4.4	(a) Sector formed by the MR polishing fluid layer within the working gap and (b) right angled triangle formed with half of the sector	41
Fig. 4.5	(a) Structure formed by the MR polishing fluid layer within the working gap and (b) right angled triangle formed with the edges of the cube in BCC unit cell	44
Fig. 4.6	Shape, size and axial orientation of permanent magnets in tool (a) for finishing internal cylindrical surface of blind hole and (b) tool for finishing blind hole bottom surface	45
Fig. 4.7	Figure 4.7: (a) Schematic of tool and measurement of distances for finishing internal cylindrical surfaces of blind holes, (b) variation of magnetic flux density from magnetic finite element analysis and (c) variation of magnetic flux density theoretically from Eq. 4.34 and Eq. 4.35	48

Fig. 4.8	(a) Schematic of tool and measurement of distances for finishing flat surfaces of blind holes, (b) variation of magnetic flux density from magnetic finite element analysis and (c) variation of magnetic flux density theoretically from Eq. 4.34 and Eq. 4.35	50
Fig. 4.9	The M-B curve of CIPs of CS grade	51
Fig. 4.10	(a) Action of forces on abrasive particle during finishing process and (b) OAB triangle formed due to indentation of active abrasive into the workpiece surface	54
Fig. 4.11	(a) Active abrasive particle approaches roughness peaks and (b) finished profile after one indentation depth	55
Fig. 4.12	Flow chart of the steps performed study the process and to predict final change in surface roughness profile	56
Fig. 4.13	Surface roughness profiles for internal cylindrical surfaces of blind hole workpiece (a) initial, (b) after 125 cycles, (c) after 200 cycles and (d) after 275 finishing cycle	59
Fig. 4.14	Surface roughness profiles bottom flat surfaces of blind hole workpiece (a) initial, (b) after 30000 cycles, (c) after 52500 cycles and (d) after 75000 finishing cycle	61
Fig. 4.15	Surface morphology with scanning electron microscopy at 500x (a) initial workpiece surface and (b) final finished surface after 275 numbers of finishing cycles on internal cylindrical surface of blind hole ferromagnetic workpiece	62
Fig. 4.16	Surface morphology with scanning electron microscopy at 500x (a) initial workpiece surface and (b) final finished surface after 75000 numbers of finishing cycles on flat surface of blind hole ferromagnetic workpiece	62
Fig. 5.1	Contribution of various parameters on the percentage change in surface roughness during finishing of internal cylindrical surface of blind hole	74
Fig. 5.2	Variation of percentage change in surface roughness with respect to (a) rotational speed of tool, (b) reciprocation speed of tool, (c) abrasive volume percentage and (d) abrasive mesh size	75

Fig. 5.3	Variation of percentage change in surface roughness with respect to (a) RPM and reciprocation speed and (b) RPM and abrasive volume percentage (c) abrasive volume percentage and abrasive mesh size	77
Fig. 5.4	Change in surface roughness with time at optimum parameters during finishing of internal cylindrical surface of blind hole workpiece	80
Fig. 5.5	Surface roughness profiles of (a) initial surface and (b) final surface after 120 minutes at optimum parameters during finishing of internal cylindrical surface of blind hole workpiece	80
Fig. 5.6	Surface morphology with scanning electron microscopy at 1000x (a) initial workpiece surface and (b) final finished surface obtained at optimum parameters during finishing of internal cylindrical surface of blind hole ferromagnetic workpiece	81
Fig. 5.7	Contribution of various parameters on the percentage change in surface roughness during finishing of bottom flat surface of blind hole	82
Fig. 5.8	Variation of percentage change in surface roughness with respect to (a) rotational speed of tool, (b) abrasive volume percentage and (c) abrasive mesh size	83
Fig. 5.9	Effect of (a) rotational speed of tool and abrasive mesh size and (b) abrasive volume percentage and abrasive mesh size on percentage change in surface roughness during finishing of internal cylindrical surface of blind hole	85
Fig. 5.10	Change in surface roughness with time at optimum parameters during finishing of bottom flat surface of blind hole workpiece	86
Fig. 5.11	Surface roughness profiles of (a) initial surface and (b) final surface after 120 minutes of finishing at optimum parameters for flat bottom surface finishing tool	87
Fig. 5.12	Surface morphology with scanning electron microscopy at 1000x (a) initial workpiece surface and (b) final finished surface obtained at optimum parameters during finishing of flat surface of blind hole ferromagnetic workpiece	88

List of Tables

Item No.	Name	Page No.
Table 3.1	Table 3.1 Input parameters for components for magnetostatic simulation of tool for blind hole	26
Table 4.1	Composition of MRP fluid	35
Table 4.2	Variation of magnetic flux density in working gap of tool for finishing internal cylindrical surfaces using finite element analysis and analytical expressions	47
Table 4.3	Variation of magnetic flux density in working gap of tool for finishing blind hole bottom flat surfaces using finite element analysis and analytical expressions	49
Table 4.4	Calculation of magnetic normal forces in working gap of tool for finishing internal cylindrical surfaces using analytical expressions	52
Table 4.5	Calculation of magnetic normal forces in working gap of tool for finishing blind hole bottom flat surfaces analytical expressions	53
Table 4.6	Experimental parameters and conditions	58
Table 4.7	Theoretical and experimental results of surface roughness values with the number of finishing cycles for internal cylindrical surfaces of blind holes	59
Table 4.8	Theoretical and experimental results of surface roughness values with the number of finishing cycles for bottom flat surfaces of blind holes	60
Table 5.1	Levels of parameters chosen for finishing the internal cylindrical surface of blind hole workpiece	65
Table 5.2	Experimental parameters and condition while finishing internal cylindrical blind hole workpiece	65
Table 5.3	Levels of parameters chosen for finishing the bottom flat surface of blind hole workpiece	66
Table 5.4	Experimental parameters and condition while finishing flat bottom surface of blind hole workpiece	67

Table 5.5	Experimental results when finishing the internal cylindrical surfaces of blind holes	68
Table 5.6	Experimental results when finishing the bottom flat surfaces of blind holes	69
Table 5.7	ANOVA table for percentage change in R_a obtained during finishing of internal cylindrical blind hole surface	71
Table 5.8:	ANOVA table for percentage change in R_a obtained during finishing of flat bottom blind hole surface	72
Table 5.9	Variation surface roughness with time at optimum parameters during finishing of internal cylindrical blind hole surface	79
Table 5.10	Variation surface roughness with time at optimum parameters during finishing of flat bottom blind hole surface	86
Table 5.11	Confirmatory tests and their comparison with the results during finishing of internal cylindrical blind hole surface	89
Table 5.12	Confirmatory tests and their comparison with the results during finishing of flat bottom blind hole surface	89

Chapter 1

Introduction

1.1 Introduction

Surface finish plays a key role in improvement of the product quality for precision fits and high strength applications in industries. Surface quality of the industrial component is very important factor which required for precision and close fitting as well as improving the operational life of the components [Bedi *et al.*, 2015]. The performance of various engineering components is influenced by its surface quality. The vital step in manufacturing of engineering components is to provide desired surface finish. Surface finish is the final operation which is to be performed on the different engineering component. Surface finish is an important parameter that affects the functional properties and mechanical properties. However, in high precision optics, lasers or X-ray surface finish plays a significant role in reflecting and/or reflecting white light. These applications require finishing up to nanometer level. To achieve ultimate precision via finishing, the chip size must reach nanometer size ($\sim 10\text{nm}$) [Taniguchi, 1983].

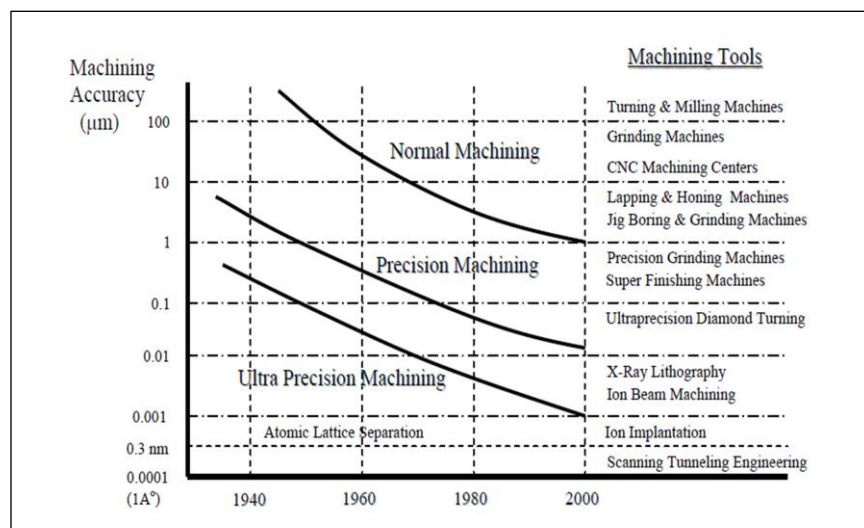


Figure 1.1: Achievable machining accuracy [Taniguchi, 1983]

Surface finish enhances characteristics like wear, corrosion, pitting and oxidation resistance of the surfaces. The techniques can be used for surface characteristics improvements are classified into the following categories:

- Surface finish improvement techniques (reducing surface roughness value).

- Deburring techniques.
- Bulk properties enhancing techniques (shot peening, heat treatment, etc.).
- Aesthetic enhancement techniques and corrosion resistance (electroplating, painting, etc.).

Non-traditional machining processes such as electrochemical machining (ECM), electric discharge machining (EDM), electron beam machining (EBM) or laser beam machining (LBM) can produce surfaces up to roughness value of few hundred microns [Ghosh and Mallik, 2010]. The various techniques that can be used for surfaces finish improvement are classified into two categories:

- ***Traditional finishing processes*** such as lapping processes, grinding processes and honing processes. Traditional abrasive based finishing processes use abrasives in bonded form. For removal of material the abrasives require high specific cutting energy. This results in generation of heat on workpiece surfaces and development of micro cracks. These processes are non-deterministic and are incapable of producing surfaces of ultrafine finish. The limitation of traditional finishing processes is that only simple shape and specific size parts can be finished. For example, lapping is befitting for mainly flat surfaces while honing is suitable for internal and external cylindrical surfaces. In these processes control of forces during the process is not possible. Another major limitation of traditional finishing processes is inability to finish 3-D and complex shaped objects. Hence the need arises to develop finishing processes which offer control on forces acting on the workpiece during finishing, ability to finish complex and freeform surface and make possible to provide surface quality better than traditional finishing processes [Jain, 2002].
- ***Advanced finishing processes*** such as magnetic float polishing (MFP) abrasive flow machining (AFM), chemo mechanical polishing (CMP), elastic emission machining (EEM), abrasive flow machining (AFM), magnetorheological finishing (MRF) and ball end magnetorheological finishing process (BEMRF). Most of these recently developed advanced finishing processes control the finishing forces by varying the electric or magnetic field.

In some of these advanced finishing processes, a medium carries the abrasive. The rheological properties of the medium can be externally controlled by varying the magnetic field. In these advanced processes like magnetic abrasive finishing (MAF), magnetic float polishing (MFP) and magnetorheological finishing (MRF), polishing pressure can be

controlled precisely as finishing forces can be varied by varying the magnetic field intensity. The advanced finishing processes have many advantages over traditional finishing processes such as ability to finish complex and freeform shaped objects, precise and in process control of forces acting on abrasive particles during finishing, protection of surface integrity as no cracks are developed and no residual thermal stresses due to negligible generation of heat [Jain, 2008].

1.2 Need of Nano-Finishing

Low surface roughness of the engineering components is necessary to improve:

- Wear resistance
- Optical properties
- Mechanical properties (fatigue life, toughness, etc.)
- Corrosion and oxidation resistance
- Loss of power due to friction
- Aesthetic appearance
- Electrical properties

1.3 Magnetorheological Fluid

Magnetorheological (MR) fluids are smart and controllable fluids. Magnetorheological fluid is in a free-flowing liquid state when no magnetic field is applied while each magnetic particle forms a dipole (north and south) on application of magnetic field. These dipoles attract each other to form a strong bonding in between them, as a result of this, chains are formed. The MR fluid was firstly discovered in 1948 by Rabinow. The MR fluid shows change in viscosity with the change of magnetic field [Rabinow, 1948]. MR fluids are non-colloidal suspensions of ferromagnetic particles in viscoelastic carrier as water, glycerol, silicone oil, paraffin oil along with stabilizing agents. The abrasives are added to the MR fluid (known as MR polishing fluid) to get material removal action. The performance of MR finishing processes depends on magnetorheological effect shown by the magnetic particles, non-magnetic abrasive and carrier medium. The MR effect is reversible. Response time is very small (millisecond) [Spaggiari, 2013].

Figure 1.2 shows the effect of externally applied magnetic field on MR fluid. The magnetic line of forces moves from the region of higher flux gradient to the region of lower flux gradient. In MR fluid, when no magnetic field is applied the magnetic are randomly

dispersed as shown in Fig 1.2. On the application of magnetic field the magnetic particles align themselves. The researchers form microscopic chains like structure which results in apparent change in viscosity. In MR polishing fluid, within these chains, the abrasive particles are embedded which provide ample support during material removal or finishing [Phulé, 2001].

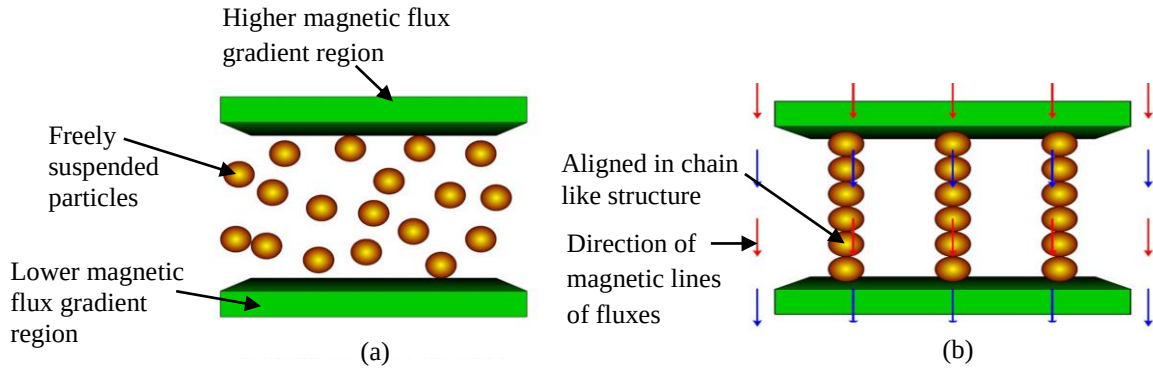


Figure 1.2: Effect on magnetorheological fluid under (a) no magnetic field and (b) externally applied magnetic field

When no magnetic field is applied, the MR fluids behave as Newtonian liquids. To explain field dependent fluid characteristics of MR fluids a Bingham plastic fluid model provides an effective description for most engineering applications. A Bingham plastic is a type of non-Newtonian fluid whose flow can begin only if certain value of yield stress must be exceeded before (Fig 1.3). Thereafter, the relationship of the rate-of-shear with respect to shear stress curve is mostly linear.

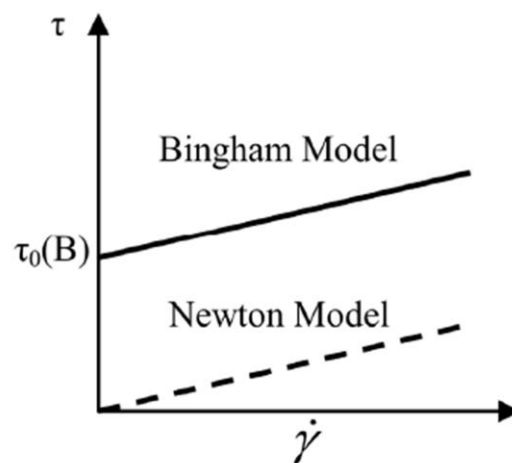


Figure 1.3: Bingham model of MR fluid [Spaggiari, 2013]

In the Bingham plastic model, the total yield stress to be applied so that the flow can begin is given by [Spaggiari, 2013]:

$$\tau = \tau_0(H) + \mu_p \dot{\gamma} \quad (1.1)$$

Where

τ_0 is the yield stress (Pa) due to the applied magnetic field intensity H (A/m)

μ_p is the constant plastic viscosity (Pa.s)

$\dot{\gamma}$ is shear-strain rate (s^{-1})

1.4 Essential Features of MR Polishing Fluid

- The magnetic particles and abrasive particles must be up to optimum concentration
- Low viscosity in the absence of applied magnetic field
- Under applied magnetic field, the MR fluid should have high yield stress
- The agglomeration of particles in MR fluid should be less
- MR fluid should have good re-dispersibility
- MR fluid should have high stability against static sedimentation (the resistance of a fluid to form a hard sediment that is difficult to redisperse)
- The polishing efficiency of MR fluid should be high (high material removal rate without any significant damage to surface)
- Resistance to corrosion

1.5 Components of MR Polishing Fluid

MR fluid componenets have significant effect on the final finished workpiece surface. The properties of MR polishing fluid such as apparent viscosity, homogeneity and temperature have detrimental effect on finishing performance. MR polishing fluid constitutes mainly of micron sized magnetic and abrasive particles, carrier medium and stablizers/additives [Jain, 2014].

1.5.1 Magnetic Particles

The micron sized magnetic particles are component of MR polishing fluid which is of utmost importance. To obtain good rheological properties, magnetic particles should have low coercivity and high saturation magnetization. Size of magnetic particles greatly influences the MR effect. Larger size results in rapid sedimentation of particles whereas smaller the sizes

lower the MR effect. The magnetic particles are usually randomly dispersed in carrier liquid in the absence of applied magnetic field. When magnetic field is applied, magnetic particles form long columnar chains are formed along the magnetic flux lines (North-pole to South-pole). Some commonly used magnetic particles are as:

- Carbonyl iron particles (CIP)
- Iron-cobalt alloy powder
- Electrolytic iron powder (EIP)

Carbonyl iron particles (CIP) are manufactured by chemical vapour deposition. Iron pentacarbonyl is decomposed during chemical vapour deposition. Electrolytic iron powder (EIP) is made by spray atomization or electrolysis. Carbonyl iron particles (CIP) are preferred because they have high magnetic saturation potential (2.1T) and chemically pure [Jain, 2014].

1.5.2 Abrasive Particles

The material removal by MR polishing fluid is due to nonmagnetic abrasive particles. Abrasive wear causing shearing of roughness peaks is the main cause of material removal. The quality of final finished surface depends upon size and hardness of abrasive particles. Abrasive particles must have high wear strength. Commonly used abrasive particles are:

- Cerium oxide (for finishing optical glasses)
- Aluminium oxide (low hardness material)
- Silicon carbide (commonly used for finishing metals)
- Diamond powder (high finishing performance but expensive)

1.5.3 Carrier Liquid

The carrier liquid provides a medium in which magnetic and abrasive particles are suspended. The carrier medium should resist corrosion; have low freezing point and high boiling temperature. For easy circulation of MR polishing fluid low off-state viscosity is desirable. Carrier medium is usually water and oil based. Oil based carrier medium have high viscosity, hence good performance in sedimentation whereas aqueous carrier medium have high yield strength.

1.4.4 Stabilizers/Additives

The stabilizers are added to the MR fluid so that magnetic particles and abrasive particles are uniformly dispersed in the suspension. Grease, glycerol or other thixotropic

additives are added MR fluid suspension to improve settling stability. The stabilizers help in easy dispersion by creating a coating on particles. Magnetic particles are coated with some materials like polystyrene (PS), gaur gum etc. Some additives are necessary to be added in water based carrier medium to prevent the oxidation of magnetic particles.

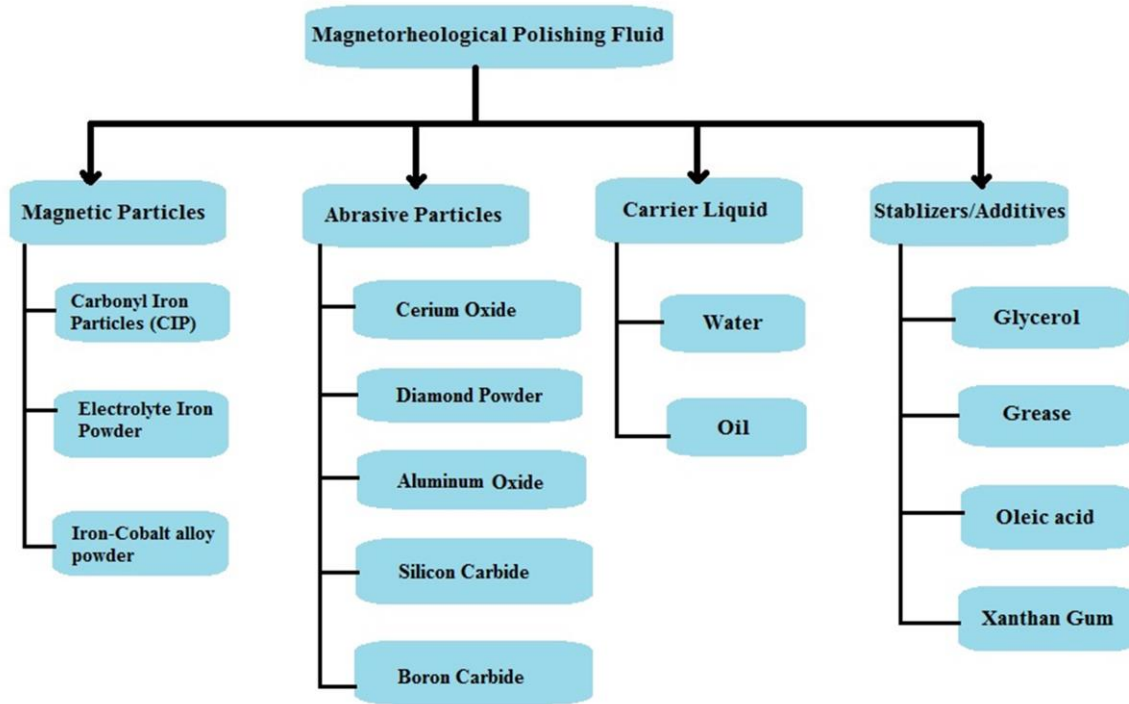


Figure 1.4: Components of MR polishing fluid

1.6 Magnetorheological Fluid Based Finishing Processes

The magnetorheological (MR) fluid based finishing processes are useful for finishing of different shapes of components and being most demanding [Jain, 2009]. The different types of MR polishing fluid based finishing process such as magnetorheological finishing (MRF), magnetorheological abrasive honing process (MRAH), magnetorheological abrasive flow finishing (MRAFF), magnetorheological jet finishing (MRJF), ball end type magnetorheological finishing (BEMRF) process and magnetorheological finishing process for external cylindrical surface have been developed for finishing of various types of surface with controlled magnetic field [Bedi and Singh, 2016].

1.6.1 Magnetorheological Finishing (MRF) Process

The finishing of optical glasses high precision lenses, ceramics and semiconductors using traditional finishing process is difficult because they mainly are made of brittle materials. Their finishing is very expensive and require intense labour. Grinding is usually used for manufacturing lenses but main disadvantage is non deterministic control of finishing forces. MRF was developed by center of Optics in Rochester, N.Y. to overcome these difficulties and automate the finishing process [Kordonski and Jacob, 1996]. In 1999, MRF was fully commercialised by QED Technologies.

MRF process utilizes the rheological properties of MR polishing fluid to precisely finish the material surface. The experimental setup of magnetorheological finishing (MRF) process is shown in Fig. 1.5. MR polishing fluid consists of magnetic particles such as carbonyl iron particles (CIPs) and electrolytic iron powder (EIPs) and abrasive particles such as silicon carbide (SiC) or cerium oxide etc. scattered in a non-magnetic carrier like silicone oil, mineral oil or water. The MRF process finds its wide application in finishing of brittle material such as glass [Singh *et al.*, 2004]. The composition of MR polishing fluid components can be varied which can be useful for finishing of ceramic, glass, high precision lenses, optical glasses, etc. (Lambropoulo *et al.*, 1996). MRF has ability to precisely finish optical shapes such as concave, convex, flat or spherical shapes etc. [Golini *et al.*, 1999].

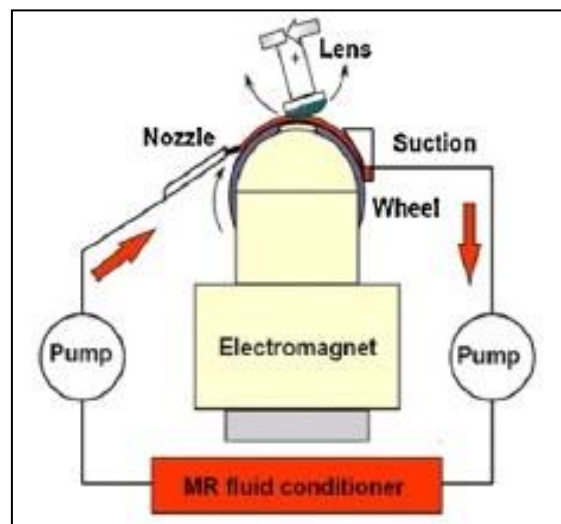


Figure 1.5: Magnetorheological finishing process experimental setup [Jain, 2009]

1.6.2 Magnetorheological Abrasive Flow Finishing (MRAFF) Process

The finishing medium in the Abrasive flow finishing process can adjust itself according to geometry which overcomes the shape constraint all the traditional processes. To overcome the eroding force that are produced on workpiece surfaces during the abrasive flow finishing process along with combining the advantages of magnetorheological finishing process for controlling the MR polishing fluid rheological properties, a finishing process known as magnetorheological abrasive flow finishing process [Jha and Jain, 2004] was introduced. The MRAFF process experimental setup is shown in Fig. 1.6. The MRAFF process is mainly used for significant finishing of internal intricate surface made of non-ferromagnetic material such as aluminium, copper and stainless steel.

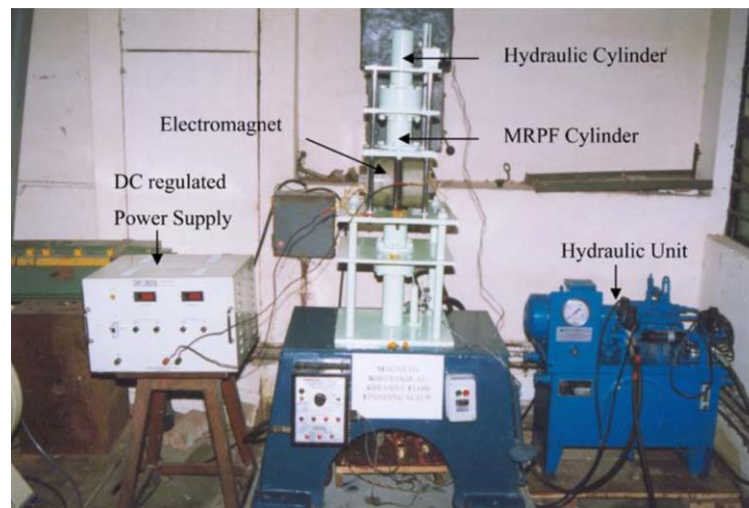


Figure 1.6: Magnetorheological abrasive flow finishing process setup [Jha *et al.*, 2007]

Further, Das *et al.* [2010] also developed R-MRAFF (rotational magnetorheological abrasive flow finishing) process. It was conceptualized from the basics of MRAFF. In this process the magnets are given the rotational motion. The MR polishing fluid inside the tubular shaped cylindrical workpiece rotates due to application of magnetic field. The finishing performance of R-MRAFF process was found significantly better than the MRAFF process.

1.6.3 Magnetorheological Jet Finishing (MRJF) process

Abrasive jets are used to polish freeform and steep optics surfaces as they are difficult to finish using the conventional techniques. However, as soon as jet leaves the nozzle it loses its

coherence and hence the instability in polishing spot. The surface is polished by impinging jet and energy is supplied by radial spread of MR polishing fluid jet. Material removal takes place when surface stresses due to shear flow of abrasive jet are developed [Kordonski *et al.*, 2006].

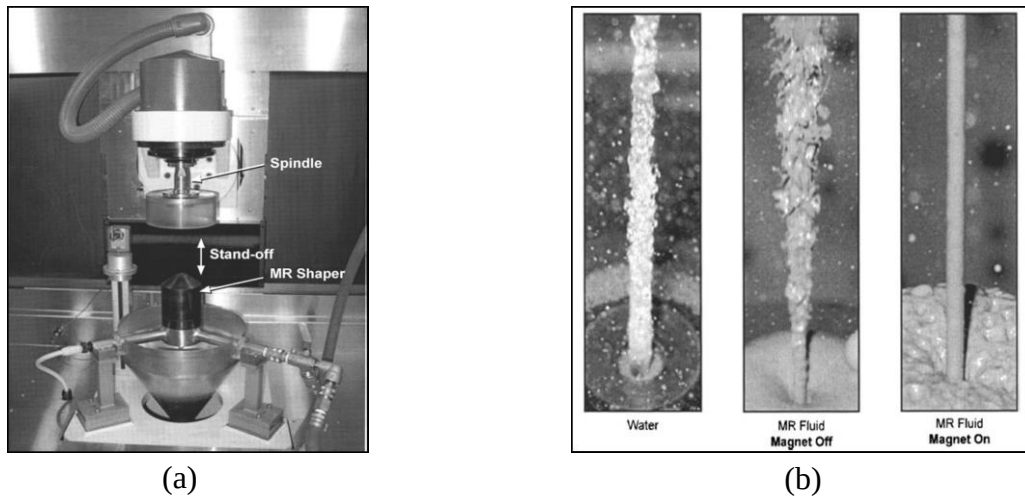


Figure 1.7: (a) Experimental setup of magnetorheological jet finishing (b) Jet snapshot image (velocity- 30 m/s, nozzle diameter- 2 mm) [Kordonski *et al.*, 2006]

The finishing of parts which have freeform surface, steep concave and convex cavities etc. can be achieved MRJF process. Figure 1.7(a) shows the experimental setup of MRJF process. Magnetorheological jet finishing (MRJF) process is a modification of MRF process. MR Jet is MR fluid mixed with magnetic abrasive. When it flows out of the nozzle, it is magnetized by an axial magnetic field and jet impinges on the internal surface of the work material [Jha and Jain, 2005]. The work material internal surface is finished more accurately by abrasive particles. The jet snapshot image of magnetic abrasive jet finishing is shown in Fig 1.7(b). The water jet loses its coherence when flows through the nozzle. When magnetic field is not applied to the jet of MR polishing fluid leaving the nozzle, it loses coherence due to its high viscosity. When the magnetic field is on, the stable jet of MR fluid flows through the nozzle with low viscosity.

1.6.4 Magnetorheological Abrasive Honing (MRAH) Process

Sadiq and Shunmugam, (2009) developed a process to finish non-ferromagnetic external curved surfaces. The MR polishing fluid with abrasives was imparted reciprocating motion while rotation was given to work surface. Therefore, the process was given the name of

magnetorheological abrasive honing (MRAH) process. Figure 1.8 shows the schematic diagram of MRAH process. From the experimental results, the greater improvement in surface finish was found significant in non-ferromagnetic work material because the position of electromagnet was kept outside the workpiece surface. During finishing of ferromagnetic work material, the MR polishing fluid gets stick towards the work material and results in no relative movement between the work material and the polishing fluid.

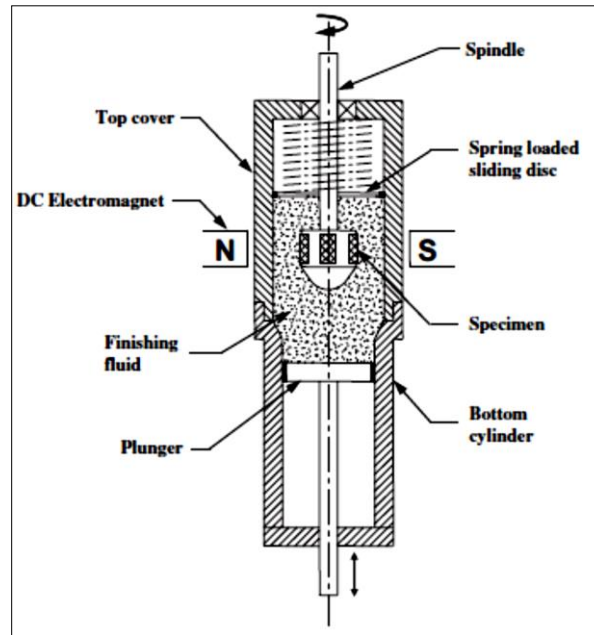


Figure 1.8: Schematic diagram of MRAH experimental setup [Sadiq and Shunmugam, 2009]

1.6.5 Ball End Magnetorheological Finishing (BEMRF) Process

As the relative motion between the finishing medium and restricted, so in the MRF and other finishing processes, only specific geometries can be finished like aspheric shapes, concave, convex and flat. BEMRF process was developed such that it was possible to finish flat as well as 3D complex surfaces [Singh *et al.*, 2011]. The BEMRF process experimental setup is shown in Fig. 1.9(a). As the magnetic field is applied across the ball end tool tip, the semi-solid ball end shape finishing spot made of MR polishing fluid is formed across it (Fig. 1.9b) and is further utilized for precise finishing of ferromagnetic as well as non-ferromagnetic materials. Figure 1.9(c) shows the actual experimentation finishing cycles during finishing of flat ferromagnetic work material.

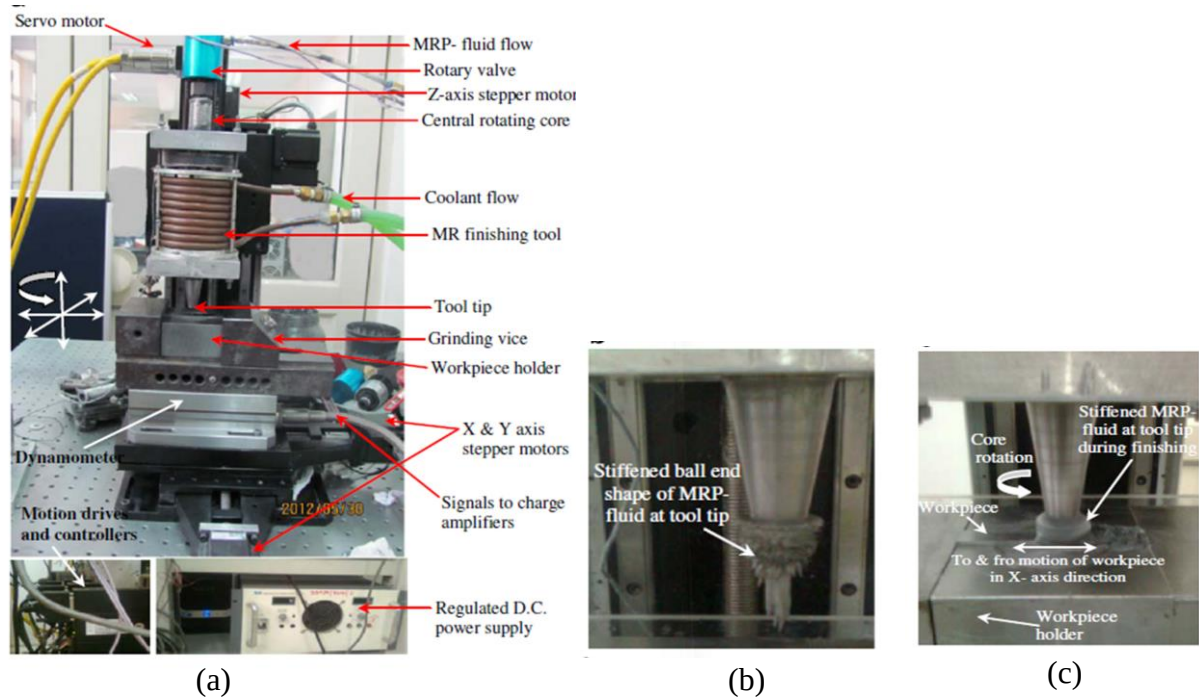


Figure 1.9: (a) Ball end magnetorheological finishing process experimental setup, (b) stiffened MR polishing fluid at the ball end tool tip, (c) MR polishing fluid stiffened during finishing under applied magnetic field [Singh *et al.*, 2013]

1.6.6 Magnetorheological External Cylindrical Surface Finishing Process

The recently developed MR polishing fluid based finishing process is able to finish the external surface of cylindrical components (made of ferromagnetic and non-ferromagnetic work material). The finishing of external cylindrical surfaces finds its broad application in aerospace, machine tool and automotive industries. Figure 1.10(a) shows the experimental setup designed to finish external surface (made of ferromagnetic material). Figure 1.10(b) shows the working gap in which MR fluid is between the flat tool tip surface and the external cylindrical surface. Figure 1.10(c) shows the retained and stiffened MR polishing fluid within the working gap formed at outer flat tool tip surface and finally performs a final surface finishing.

Singh *et al.* [2016] also compared the performance of flat tool tip surface and curved tool tip surface during precise finishing of external cylindrical surface (made of ferromagnetic material). After 90 minutes of finishing time, the final surface roughness (R_a , R_q , and R_z) values for flat tool tip the surface roughness values reduced by 54.41 %, 51.65 %, and 51.65 % respectively.

and 40 % whereas, with curved tool tip surface reduced by 80.88 %, 81.32 %, and 82.5 %, respectively.

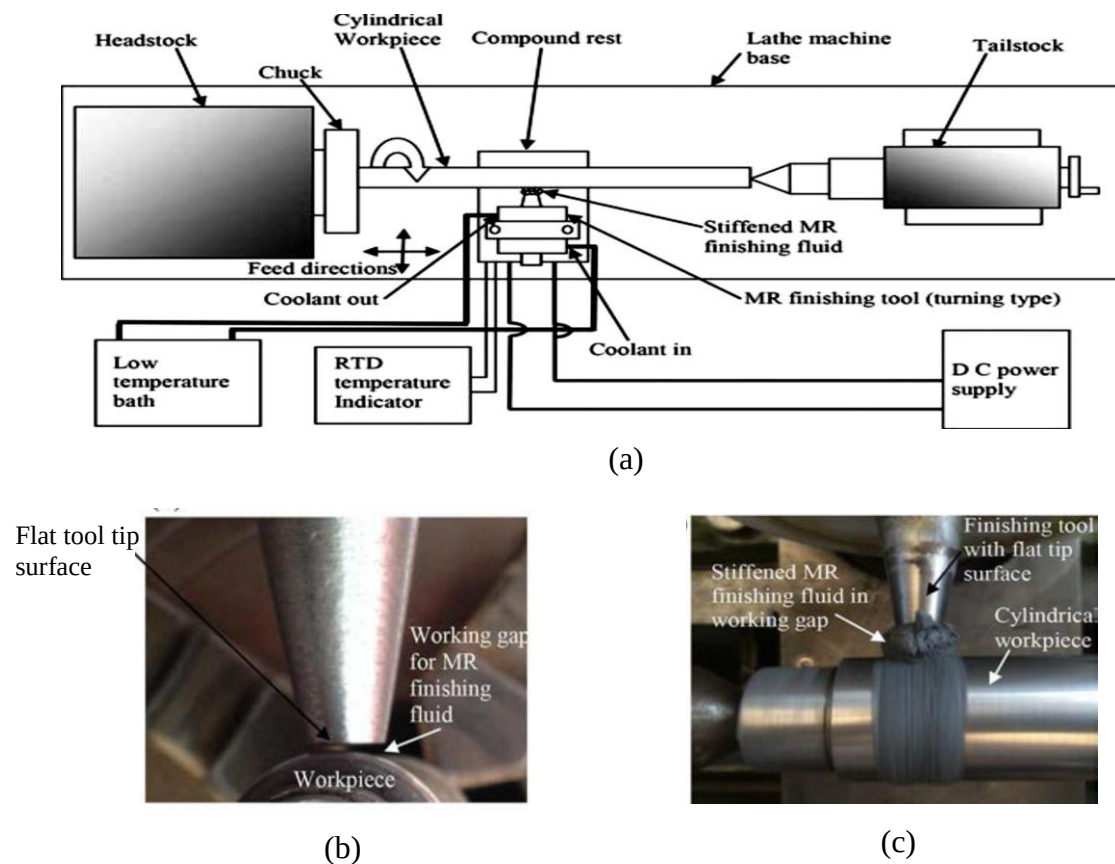


Figure 1.10: (a) Schematic of magnetorheological external cylindrical surface finishing process, (b) flat tool tip surface and (c) stiffened MR polishing fluid during actual experimentation finishing cycle [Singh *et al.* 2016]

1.7 Advantages of Magnetorheological Fluid Based Finishing Processes

- Closer tolerance in design can be achieved
- Capable to finish up to nanometer scale value
- Decreases the wear and friction losses
- Increases the life of work material
- Finishing forces exerted on the surface of workpiece can be controlled by controlling the magnetizing current as per the properties requirement of workpiece surfaces. These are not possible in conventional finishing processes

- Improves fatigue life and toughness
- Reduces the sub surface defects (such as micro cracks, cavity etc.)
- Improves corrosion resistance
- MR finishing processes are used to precisely finish the surfaces of almost any shapes

Chapter 2

Literature Review

2.1 Review of Literature

Magnetorheological finishing (MRF) process was developed by Center of Optics in Rochester, N.Y. to overcome the difficulties and automate the finishing process [Kordonski & Jacob, 1996]. In 1999, MRF was fully commercialised by QED Technologies. MRAFF process can precisely finish complex internal surfaces up to surface roughness value of nano level [Jha and Jain, 2004]. Das *et al.* [2010] developed R-MRAFF (rotational magnetorheological abrasive flow finishing) process in rotational motion was given to magnets. These processes are used to finish the internal surfaces of the workpiece. The authors found difficulty in finishing of ferromagnetic work surfaces. In majority of processes work has been done to finish non-ferromagnetic materials. The main cause is the distribution of magnetic flux density gradient is found to maximum on the ferromagnetic work surface rather than on finishing fluid, resulting in MR polishing fluid getting attached on the ferromagnetic work surface. Therefore no relative motion occurs between the MR polishing fluid and ferromagnetic workpiece surface.

There are many researches which studied and developed new magnetorheological polishing fluid based finishing techniques and find the optimum parameters to obtain the best possible surface finish. Some of previous research studies are discussed as under:

Kordonski and Golini [1999] utilizes the rheological properties of MR polishing fluid to precisely finish the material surface by using magnetorheological finishing (MRF) process. In MRF, the MR polishing fluid is transported to the workpiece surface by of a rotating wheel rim a nozzle on the rim. When the magnetic field is applied, the magnetic particles for chains of particles due to which the ribbon type structure is formed which acts as an abrasive surface. The material removal takes place due to a drag force to move the abrasives generated by the shear stress of the fluid as the MR fluid with abrasives flows over surface.

Kordonski *et al.* [2004] developed an MR Jet polishing system. It was developed by QED Technologies. It was experimentally found that MR Jet finishing can produce high precision

surfaces on the order of tens of nanometres peak-valley with roughness < 1 nm Rms. Since this technique is insensitive to the offset distance this process was very useful in finishing complex shapes. It can precisely finish convex and concave surfaces with steep slopes and variety of cavities.

Jha and Jain [2004] introduced a finishing process known as magnetorheological abrasive flow finishing (MRAFF) process to overcome the eroding force that act on workpiece surface during the abrasive flow finishing process. MRAFF involves extrusion of magnetized MR fluid and providing it to and fro motion. MRAFF was developed by combining the advantages of AFM and MRF for parts with complex geometries. In this magnetic field is developed outside the work and the MR fluid is given to and fro motion inside the work.

Bagnoud et al. [2005] performed correction of Nd:YLF rods used in high power laser by magnetorheological finishing. MRF has been utilized to correct the wave front transmitted by a laser gain material. Polishing a surface figure correction has been done for the first time. Bulk inhomogeneities can be compensated if MRF is done directly on one surface of 25.4 mm diameter laser rods. Increasing the number of passes the average power of 9W laser was found to increase by 20% to 30%.

Feng et al. [2005] developed a manufacturing system using magnetorheological finishing (MRF) process to produce aspheric mirrors. The researchers carried out experiments by finishing a parabolic SiC mirror with a 100mm diameter aperture to study the features of magnetorheological (MR) fluids. Experiments were done to demonstrate the capability of developed manufacturing system by producing an ultra-smooth SiC mirror surface with high shape accuracy and to study the effect of different MR fluid components and their concentration on material removal rate.

Kordonski et al. [2006a] discussed about abrasive jets used to polish freeform and steep optics surfaces as they are difficult to finish using the conventional techniques. However as soon as jet leaves the nozzle it loses its coherence and hence the instability in polishing spot. The surface is polished by impinging jet and energy is supplied by radial spread of liquid jet. Material removal takes place when surface stresses due to shear flow of abrasive jet are developed.

Kordonski et al. [2006b] experimentally studied the stability of polishing spot as it is most significant and deterministic characteristic needed for nano-level finishing using MR fluid jet. Flat parts of fused silica glass were polished having initial 470 nm peak-valley error. After first and second iterations the errors were reduced to 32 nm peak to valley (p-v) and 13 nm p-v respectively.

Jha and Jain [2006] employed MRAFF for the finishing hard materials. Silicon nitride (Si_3N_4) was finished using diamond abrasives, silicon carbide, and boron carbide and found the process quite capable.

Jha et al. [2007] studied the influence of extrusion pressure, number of finishing cycles and magnetic flux density on the percentage change in surface roughness. Experiments showed that magnetic flux density was the main factor influencing the improvement in surface finish. It was found that with increase in number of finishing cycles, surface roughness decreases.

Seok et al. [2007] developed a shaping process using MR finishing. A silicon wafer sliced in rectangular piece was used to make a curved surface. The researchers used MR finishing and utilized edge effect on silicon-based millistructures for developing of circular surfaces on them. The researchers performed experiments in which the shortest gap distances between the workpiece and tool, tool radius were variable. The researchers studied the changes in the radius of curvature of workpiece and found that the radius of curvature of workpiece and surface roughness can be controlled by varying above two variables.

Cheng et al. [2009] studied the effect of 2-axis wheel-shaped tool supporting dual magnetic fields on surface roughness and material removal rate. The experiments were conducted to evaluate the effects of various process parameters on material removal and performance. The researchers used a K9 glass parabolic lens workpiece. The researchers found that surface roughness of the parabolic lens was significantly reduced from an initial value.

Seok et al. [2009] proposed a material removal model to describe the tribological behaviour of the MR polishing fluid during the finishing. The authors used a wheel-type MR finishing process. In a magnetic field to describe the tribological behaviour of the MR polishing fluid, both the solid and fluid-like characteristics were studied. The researchers found that material removal rate increases with increase in the rotational velocity of the magnetic tool, shear stress

and the slip of particles. This clearly supports the assertion that abrasive wear is the mechanism of material removal.

Jung *et al.* [2009] examined the reasons which are responsible for decreasing of material removal rate using magnetorheological finishing process on a wheel-type setup for hard materials. The researchers proposed in order to improve processing conditions a rectilinear alternating motion should be given to the tool. The researchers found that keeping the tool rotational speed under the critical value, material removal rate increased and it was found directly proportion to the relative speed between the workpiece surfaces and the tool. Their second suggestion was on the use magnetisable abrasives made by sintering carbon nanotubes with iron powders. These more effective abrasive particles were found to reduce the tool aging effect and improve the material removal rate for finishing a hard material.

Sadiq and Shunmugam [2009] developed a process to finish non-ferromagnetic external curved surfaces. The MR polishing fluid with abrasives was imparted reciprocating motion while rotation was given to work surface. Therefore, the process was given the name of magnetorheological abrasive honing (MRAH) process. The researchers found greater improvement in finish that surfaces was obtained for surfaces with higher initial roughness. It was also concluded that increasing the workpiece rotation speed results in greater enhancement in surface finish, since the number of times each peak regions are acted upon by the abrasive particle increases. Improvement in surface finish obtained after 20 minute was 4.2% when finishing a non-magnetic specimen.

Sadiq and Shunmugam [2010] studied the effect of magnetic field on workpiece mounted in a holder and subjected to MRAH. It is observed that the change in the surface finish is significant when magnetic materials are finished, while the great improvement in surface finish was obtained on non-magnetic work materials. The researchers investigated the influence of magnetic flux density change in the surface finish when finishing ferromagnetic material. The researchers found that the change in roughness was not appreciable.

Das *et al.* [2010] developed R-MRAFF (rotational magnetorheological abrasive flow finishing) process. It was conceptualized from the basics of MRAFF. In this process the magnets are given the rotational motion. The MR polishing fluid inside the tubular shaped cylindrical workpiece rotates due to application of magnetic field. The finishing performance

of R-MRAFF process was found significantly better than the MRAFF process. Finishing of SS tubes of outer diameter 24mm was carried out. Surface finish of the order of 16nm was obtained.

Jang *et al.* [2010] proposed a new magnetorheological (MR) fluid based electro-chemo-mechanical polishing process. The process can be used to finish hard but electrically conductive materials. In this process the electrochemical reactions occur on the workpiece and electrolyte soaked carbonyl iron (CI) particles. Material finished was glassy carbon (GC), that has recently emerged as new mould material because of its good properties like stability at high temperature, high mechanical strength, low adhesion energy, resistance to chemicals, high softening temperature (2000 °C), and low thermal expansion coefficient. Experiments concluded that increase in the material removal rate is obtained in the developed EMMRP. The surface roughness improved by about 14 times when compared to usual MR finishing process.

Song *et al.* [2011] studied friction and wear characteristics of a magnetorheological (MR) fluid under the influence of varying magnetic fields. The author investigated the wear and friction of materials under applied magnetic field at various rotating speeds and normal loads. The results showed that compared to the condition without a magnetic field, under a magnetic field the MR polishing fluid exhibited better tribological characteristics. This indicates that the wear and friction of MR fluid can be improved by magnetic field.

Singh *et al.* [2011] designed and developed a new finishing process for flat as well as 3D complex surfaces using ball end magnetorheological (BEMRF) finishing tool. When magnetic field is not applied, from the top end of central rotating core the pressurised MR fluid enters and reaches the tool tip. When magnetic field is applied, a semi-solid ball end shape finishing spot formed. Experiments were performed on both ferromagnetic and non-ferromagnetic material. After 100 minutes of finishing the surface roughness value reduced from 414.1 nm to 70 nm ferromagnetic materials whereas surface roughness value reduced from 336.8 nm to 102 nm during finishing of non-ferromagnetic material.

Singh *et al.* [2012a] used BEMRF tool for finishing non-ferromagnetic as well as ferromagnetic materials. The surface finish obtained was of 102 nm and 70 nm on copper and EN31 workpieces respectively.

Singh et al. [2012b] used ball end magnetorheological finishing tool for finishing of 3D surfaces at variable angle of projection such as 30°, 45°, flat and curved surfaces. After 60 passes on flat, 30°, 45° and curved surfaces, the roughness was reduced to 16.6 nanometre (nm), 30.4 nm, 71 nanometre and 123.7 nanometre respectively.

Singh et al. [2012c] performed finishing of fused silica glass was conducted and studied the effect of number of passes on the R_a . Surface roughness after 90 minutes of finishing was found to be 0.146 nm from initial value of 0.74 nm.

Kang and Yamaguchi [2012] developed a finishing process for internal finishing of capillary tubes. A multiple pole-tip system using magnetic abrasive finishing has been developed in which magnetic flux concentrates at the pole-tip edges. In this method magnetic abrasive are strongly attracted to tool resulting in efficient delivery of the magnetic abrasive particles in deeper areas of tube. The entire finishing area is uniformly finished.

Jang et al. [2012] developed a unique magnetorheological fluid based deburring process. For material removal by magnetorheological fluid flow, two different types of mechanisms are involved. Material removal for sheet shaped burrs takes place by extensive yielding whereas for protrusion-shaped burrs abrasive wear is the main material removal mechanism. The size of burrs which is smaller than microns can be removed only by abrasive wear mechanism.

Pattanaik et al. [2014] developed a magnetorheological finishing (MRF) Process for freeform surfaces. A setup was developed for MRF application using a pillar drilling machine. Experiments were conducted to finish free form jobs of copper material using the developed setup. It was found that the percentage improvement in the surface finish of flat portion (77 %) is better than cylindrical surface (67 %).

Gheisari et al. [2014] developed a process for ultra-precision finishing of external cylindrical surfaces. Finishing of non-magnetic (Al) material was carried out. Workpiece is given rotating motion. A gap of 5mm was kept between surface and surface with magnetic flux. Experiments were carried out by varying the rpm of rotating workpiece. At 1000 rpm surface finish of the order of 40 nm was obtained.

Sarkar and Hirani [2015] studied the influence of sizes of particle on shear stress of magnetorheological fluids. The researchers prepared magnetorheological fluid using three sizes of particles namely small sized particles, mixed sized and large sized particles. The “mixed sized particles” were showed better finishing performance at higher shear rate when compared to the magnetorheological fluids containing “small sized particles” and “large sized particles”.

Liu et al. [2015] used nanometer Fe_3O_4 particles in preparation of silicone oil-based MRFs. The properties of various samples with different nanometer Fe_3O_4 mass fraction were prepared and examined. It was concluded that keeping concentration of Fe_3O_4 particles between 4 % and 6 wt. % reduces the zero field viscosity and sedimentation ratio of magnetorheological fluids. Improvement in shear yield stress of magnetorheological fluids by addition of nanometer Fe_3O_4 particles was also obtained.

Singh et al. [2016] carried out the design and development of new MR finishing process is to finish the external surface of cylindrical components. The finishing of external cylindrical surfaces finds its application in aerospace, machine tool and automotive industries. Experiments were conducted on ferromagnetic cylindrical workpieces for finishing cycle time of 90 minutes. The final surface roughness values with curved tool tip R_a , R_q , and R_z are reduced by 80.88%, 81.32%, and 82.5%. For flat tool tip the surface roughness values reduced by 54.41%, 51.65%, and 40%, respectively.

Verma et al. [2016] developed a process to finish internal surfaces using magnetic abrasive finishing. The process can be utilizes to finish both through and blind holes. Finishing of non-magnetic Stainless Steel pipes of diameter 25mm was carried out. Experiments were carried out by varying rotational speed of tool and abrasive concentration. Maximum R_a value up to order of 93.1 nm was obtained.

Kheradmand et al. [2016] developed a new approach using MRAFF assisted with swirling inlet flow of MR polishing fluid. It also results in increase forces on the surface, thus increasing material removal. The expense and energy consumption is lower as compared when workpiece is given rotation. The results concluded that at the entrance length of swirling-assisted inlet flow the finishing is very economical for smaller length workpieces, compared when workpiece is given rotating motion, with very comparable R_a values.

Maan *et al.* [2016] performed experiment on finishing of permanent mould die punch used in manufacture of bottle caps. Compared to BEMRF a solid rotating core was used without any central hole for fluid passage. Two different magnetorheological fluid based finishing processes such as modified ball end magnetorheological finishing with solid rotating tool core and turning type magnetorheological finishing tool were used for nano-surface-finishing the permanent mould die punch workpiece. The surface roughness value of flat surface and external circular die punch surface were reduced from 1080 nm to 30 nm and from 630 nm to 80 nm in 120 min of finishing respectively.

2.2 Gaps in Literature

Most of the research in the development of magnetorheological finishing processes has been dedicated towards processes for finishing internal cylindrical surfaces and external cylindrical surfaces of tubular shaped work material. However, negligible work has been reported in finishing internal cylindrical surfaces of blind holes. Jha and Jain [2004] introduced MRAFF and Das *et al.* [2010] developed R-MRAFF to finish non-ferromagnetic through hole surfaces but, during the finishing of ferromagnetic materials the MR polishing fluid sticks to the workpiece surfaces. Sadiq and Shunmugam [2009] developed a process to finish external curved surfaces. Gheisari *et al.* [2014] and Singh *et al.* [2016] developed a process for ultra-precision finishing of external cylindrical surfaces. From the above study the gaps found were:

- In R-MRAFF finishing is done on inner cylindrical surface of tubular shaped specimens. To finish the bottom surface of a blind hole negligible research has been done.
- The research for finishing internal surfaces is limited to through holes of tubular shaped work material. To finish internal cylindrical surface inside body of any type of workpiece is an area of research.

Kordonski & Jacob [1996], Kordonski *et al.* [2004], Jha and Jain [2004], Seok *et al.* [2007], Sadiq and Shunmugam [2009], Das *et al.* [2010], Gheisari *et al.* [2014], Verma *et al.* [2016] and Singh *et al.* [2016] all have developed the process for finishing of non-ferromagnetic materials. When finishing ferromagnetic workpiece the MR fluid would stick to the work piece rather than the tool. From the above research it was concluded that:

- MR Finishing processes for finishing internal cylindrical surfaces is R-MRAFF. Most of the work has been dedicated to finish the non-ferromagnetic materials. Thus there is scope of develop technique which can finish both ferromagnetic and non-ferromagnetic materials.

In most of the MRF processes electromagnets are used resulting in generation of heat which affects the viscosity of the MR polishing fluid. The change in viscosity influences the performance of process which is not the case in processes using permanent magnets. After studying the literature it was found that almost no work has been reported on MR finishing the bottom flat surface of blind holes or cavities. The gap in literature observed is:

- There is scope to develop the processes to finish internal cylindrical and flat surface of a part or blind holes using a permanent magnet tools.

2.3 Objectives

- Design and development of tools using permanent magnets for finishing internal and bottom surfaces of cylindrical blind holes workpiece.
- To perform finishing of ferromagnetic of cylindrical blind holes workpiece.
- Development of mathematical model to predict final surface roughness value.
- Optimisation of process parameters to obtain minimum surface roughness.

2.4 Methodology of the Present Research

Based on the extensive literature survey and followed by analysis of gaps, the present study aims to study the effect of various process parameters on performance of newly designed magnetorheological finishing process for blind hole surfaces. The step by step procedures have been followed for accomplishing the foresaid objectives. The proposed methodology in the form of a flow chart is shown in Figure 2.1.

1. The extensive literature survey is necessary for determining the need of nanofinishing, study of presently developed process, need of developing new process, industrial application of the process and feasibility study of the new process
2. Process selection is necessary as it forms the base of tool design. From research gaps it can be identified that what type of process is necessary to be developed
3. Design of tools according to the process selected and research gaps
4. Magnetostatic simulation of tools to determine the distribution of magnetic field on tool end surface

5. Fabrication of tools according to designed dimensions
6. Analysis of forces is necessary for development of model to predict final surface roughness
7. Development of mathematical model to predict final surface roughness
8. Experimentally validate the surface roughness model by comparison with experimental results
9. Design of experiment
10. Selection of process parameters
11. Experimentation for determination of percentage change in surface roughness
12. Analyse the results to determine the effect of various process parameters
13. Optimize the process parameters

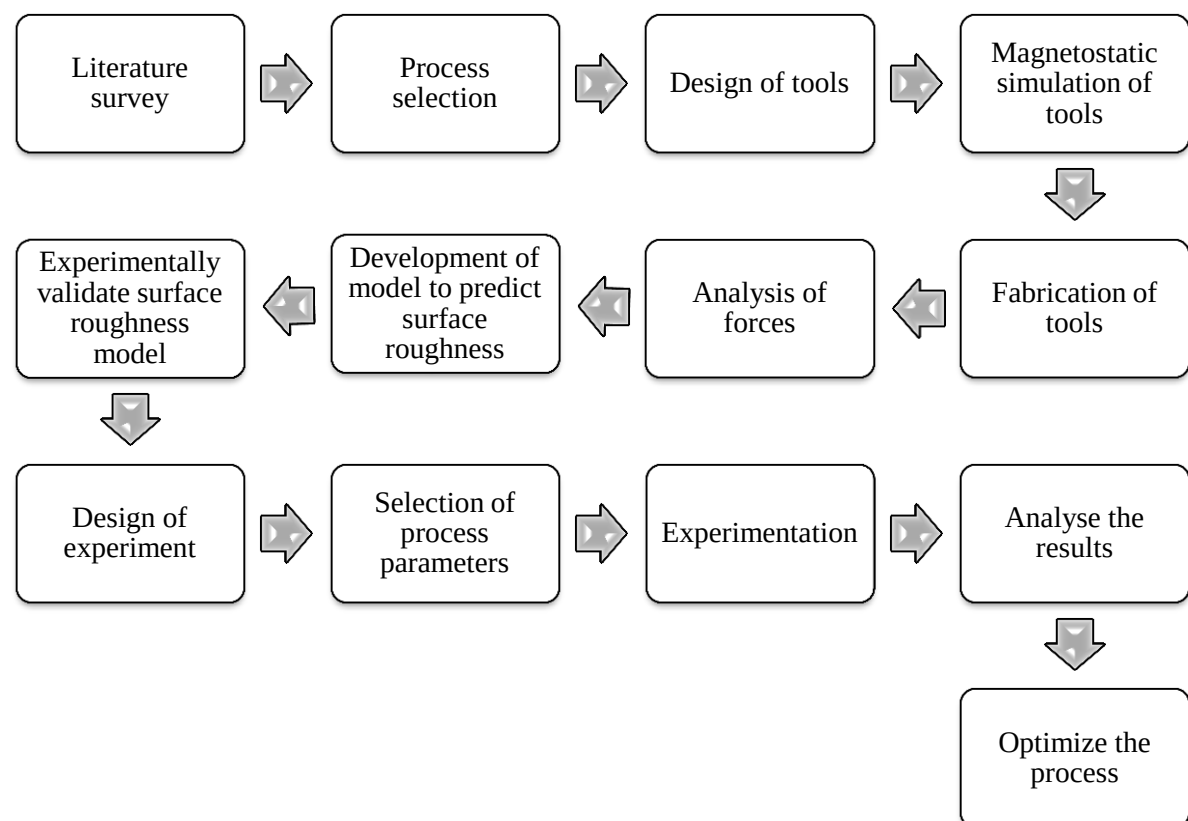


Figure 2.1: Methodology to carry out present research work

Chapter 3

Design of Tools for Finishing Blind Hole Surfaces Based on Finite Element Analysis

3.1 Need of Magnetorheological (MR) Fluid Based Finishing Process for Blind Hole Surfaces

In modern competitive manufacturing scenario, the products show rapid change and development. Efforts are made to develop processes to ensure fast paced production with minimal scrap. In performance machinery where metal surface to surface contact occurs highly finished surfaces are required. The finished blind holes find extensive application in automotive industry and die manufacturing. Various automotive components such as valve seats, manifolds, housing steering racks, actuators and cylinder body etc. require finished blind holes. The traditional process to finish bottom surface blind holes is made by using reamers or impact burnishing. However in precision equipments and performance machinery involved in racing and aviation industry various components of nanometer level finish are required which traditional processes are incapable to produce.

A new computerised process using magnetorheological polishing fluid to finish internal and bottom surfaces of blind holes to nanometer range has been made. Two different tools have been designed and developed for finishing internal cylindrical and bottom surface of blind holes. The process has been developed for finishing ferromagnetic and non-ferromagnetic work materials. In this study two separate tools are designed because the motion given to the each tool during finishing operation is different. If single tool is made the number of cycles for finishing internal cylindrical surface will not be enough to finish the bottom flat surface of blind holes.

The tools are designed with a view that in future a single tool is designed to finish both surfaces of blind hole workpiece. The tools are designed in such a way that if these two tools are merged they can finish both the blind hole surfaces. The dimensions of magnets selected and their placement in both tools is done in such a way if we overlap the tools a single tool will be formed.

3.2 Magnetostatic Modeling of MR Finishing Tools

The feasibility of presently developed tools has been validated by performing magnetostatic simulation on Ansoft Maxwell V13 (student version). The magnetostatic simulation has been performed for the developed model to analyse the shape of magnetic field produced at tool end surface. Table 3.1 shows the various input parameters for the permanent magnet models used for development and analysis of tool. The working gap between the tool end surface and the ferromagnetic surface is 2 mm.

In Ansoft Maxwell 13 the field equations solved is derived from the Maxwell's differential equations. For the equations to be valid, the field vectors are assumed to be single-valued, bounded and along with their derivatives have continuous distribution. Along the boundaries, the derivatives are meaningless and the fields are discontinuous. Table 1 provides the information about the properties selected and assigned to the permanent magnet, ferromagnetic steel and MR fluid. Initially a CAD model of the tool is imported to the Ansoft Maxwell 13. After that each component is assigned the magnetic properties. Some material properties are available in software libraries while some can be entered by the user. To analyse the simulation setup minimum 10 pass runs are required to accurately calculate the fields.

Table 3.1 Input parameters for components for magnetostatic simulation of tool for blind hole surfaces.

Component name	Material	Relative permeability
Tool body	Aluminium	1
Permanent magnets 40×20×10mm	NdFeB35	1.0099
Rotating shaft	Stainless steel	1.003
Polishing medium	MR polishing fluid	5
Ferromagnetic blind hole workpiece	Mild steel	600

Figure 3.1(a) shows the magnetic field variation within the working gap between the tool end surface and blind hole ferromagnetic cylindrical. As shown in Fig. 3.1(b), on the tool surface there is higher magnetic flux density gradient and it shows negative slope in the working gap as it goes towards the workpiece surface. This decrease in magnetic flux density helps in

keeping the MR polishing fluid to stick with the tool end surface. When the tool is given desired motion the MR polishing fluid moves along with the tool over the workpiece surface, it causes abrasive wear resulting in the removal of material.

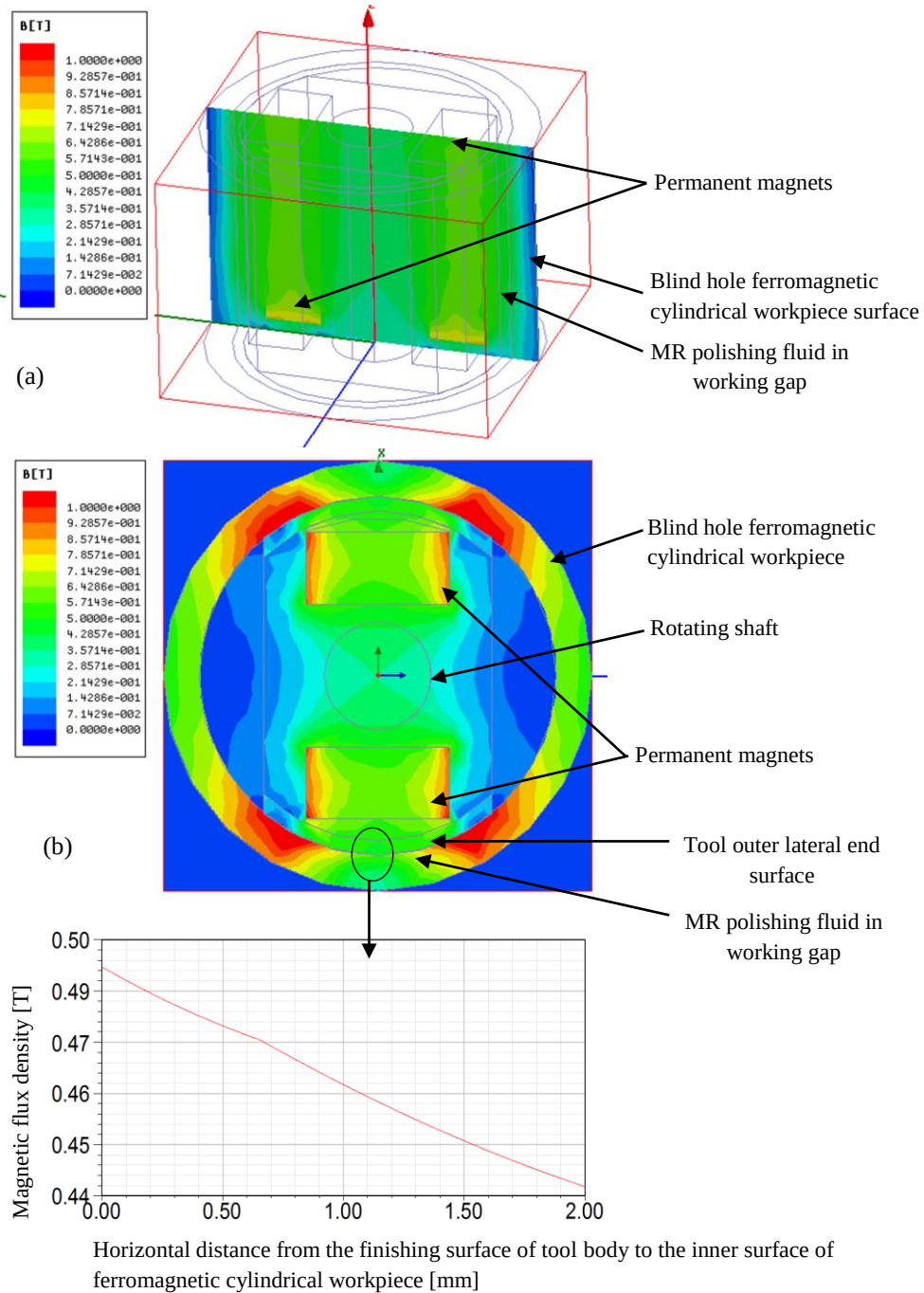


Figure 3.1: Magnetostatic simulation of tool for finishing blind hole internal cylindrical surfaces (a) 3D view and (b) top view with variation of magnetic flux density in working gap

Figure 3.(a) shows the magnetic field variation within the working gap between the tool flat bottom surface and flat workpiece surface respectively. As shown in Fig. 3.2(b), on the tool surface there is higher magnetic flux density gradient and it shows negative slope in the working gap as it goes towards the workpiece surface.

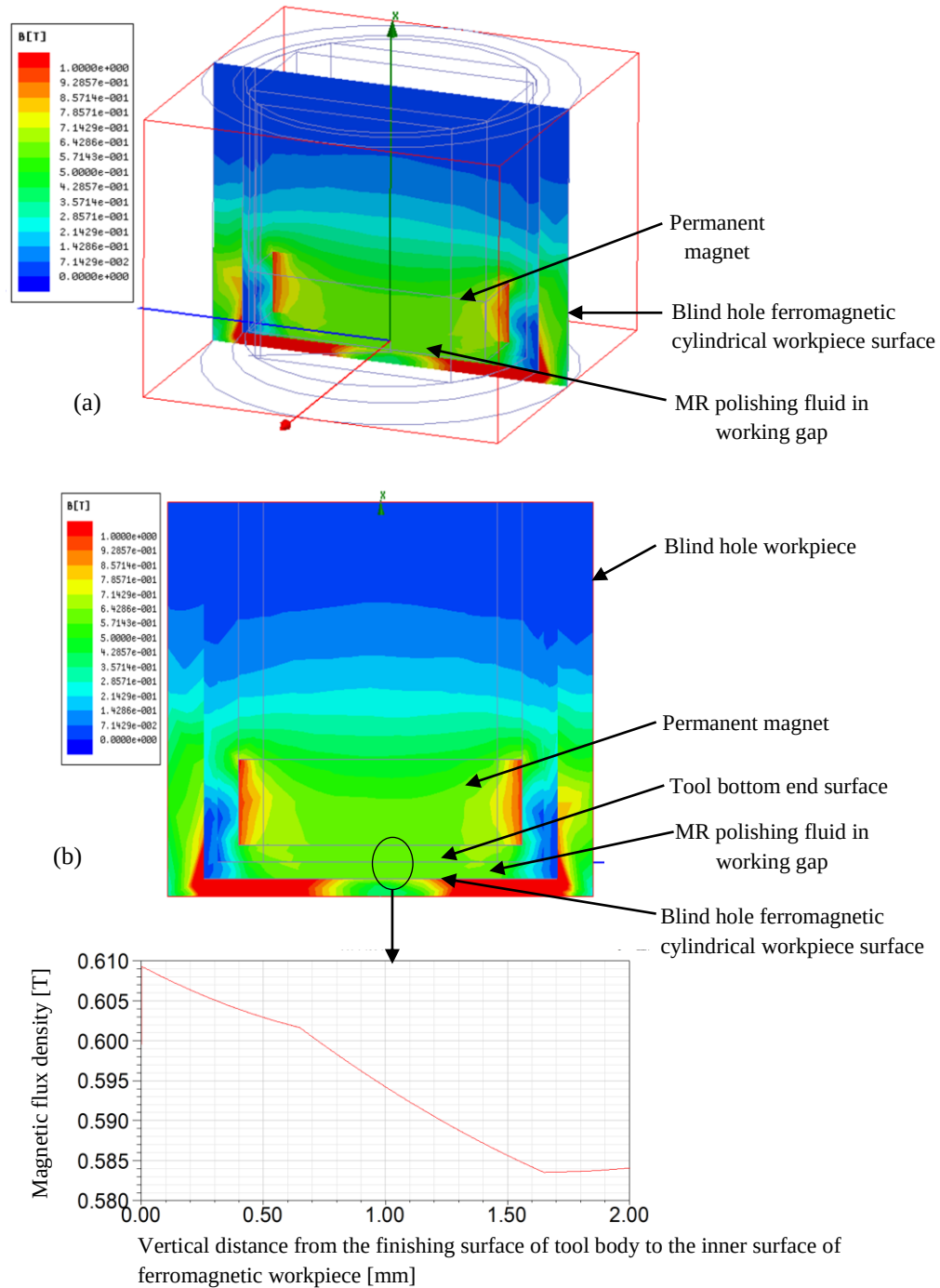


Figure 3.2: Magnetostatic simulation of tool for finishing blind hole bottom flat surfaces (a) 3D view and (b) front view with variation of magnetic flux density in working gap

The figures 3.1 and figures 3.2 show the finite element analysis values of magnetic field for the tools. The magnetic field values on workpiece surface are not used in calculation of magnetic force. As the magnetic force acting on the carbonyl iron particle (CIP) is calculated from the magnetic field intensity in working gap and not on workpiece surface. Most of the magnetorheological fluid will concentrate in high intensity regions but the forces acting on the magnetic particle along the tool end surface will remain same. When the rotation is provided to the tools the area with concentrated magnetorheological fluid will move along with the tools resulting in finishing action. Even if some MR polishing fluid sticks to the workpiece surface, when the magnetized tool end surface comes in front of the MR polishing fluid, it will stick to the tool end surface. With every rotation it will move along with the tool end surface because the magnetic field strength at tool end surface is more than the workpiece surface.

3.3 Fabrication of Magnetorheological Finishing Tools

Figure 3.3(a) shows the shape of tool and direction of motion for finishing internal cylindrical surfaces of blind holes. Two slots (40 mm×20 mm×10 mm) in the tool to carry the magnets were cut using electro-discharge machining. Two NdFeB35 permanent magnets are bolted in the aluminium body. The rectangular shaped magnets are selected for design of tool with futuristic view of development of single tool for both surfaces.

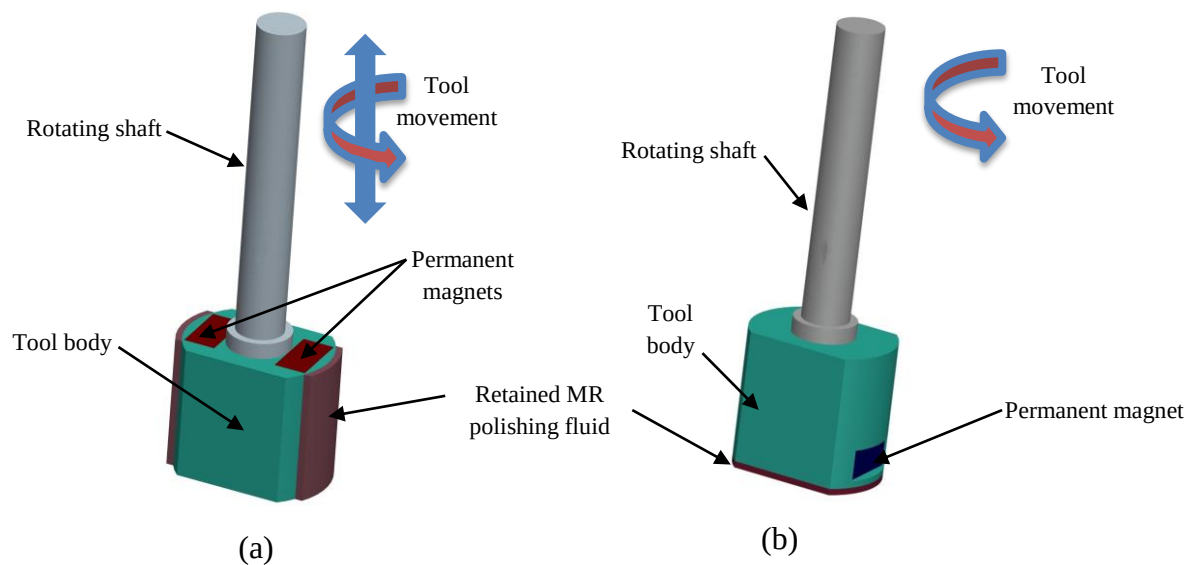


Figure 3.3: (a) Components and movement of tool for finishing internal cylindrical surfaces of blind holes and (b) components and movement of tool for flat surfaces.

Figure 3.3(b) shows the shape and direction of motion of the tool for finishing flat surfaces of blind holes. The slot in the tool body is cut using EDM leaving 2 mm thick metal gap at the bottom to support the magnet. The MR polishing fluid is applied to the bottom of the tool. The chains of magnetic particles are formed at the bottom of tool end surface resulting in stiffening of MR fluid.

Figure 3.4(a) shows the detailed dimensions of the tool (in mm) for finishing internal cylindrical surfaces. The tool is mounted on C-shaped bracket made of aluminium. Rotating shaft holding the tool body with magnets is made of stainless steel while the workpiece is ferromagnetic material. Figure 3.4(b) shows the dimensions of the tool for finishing flat surfaces of blind holes.

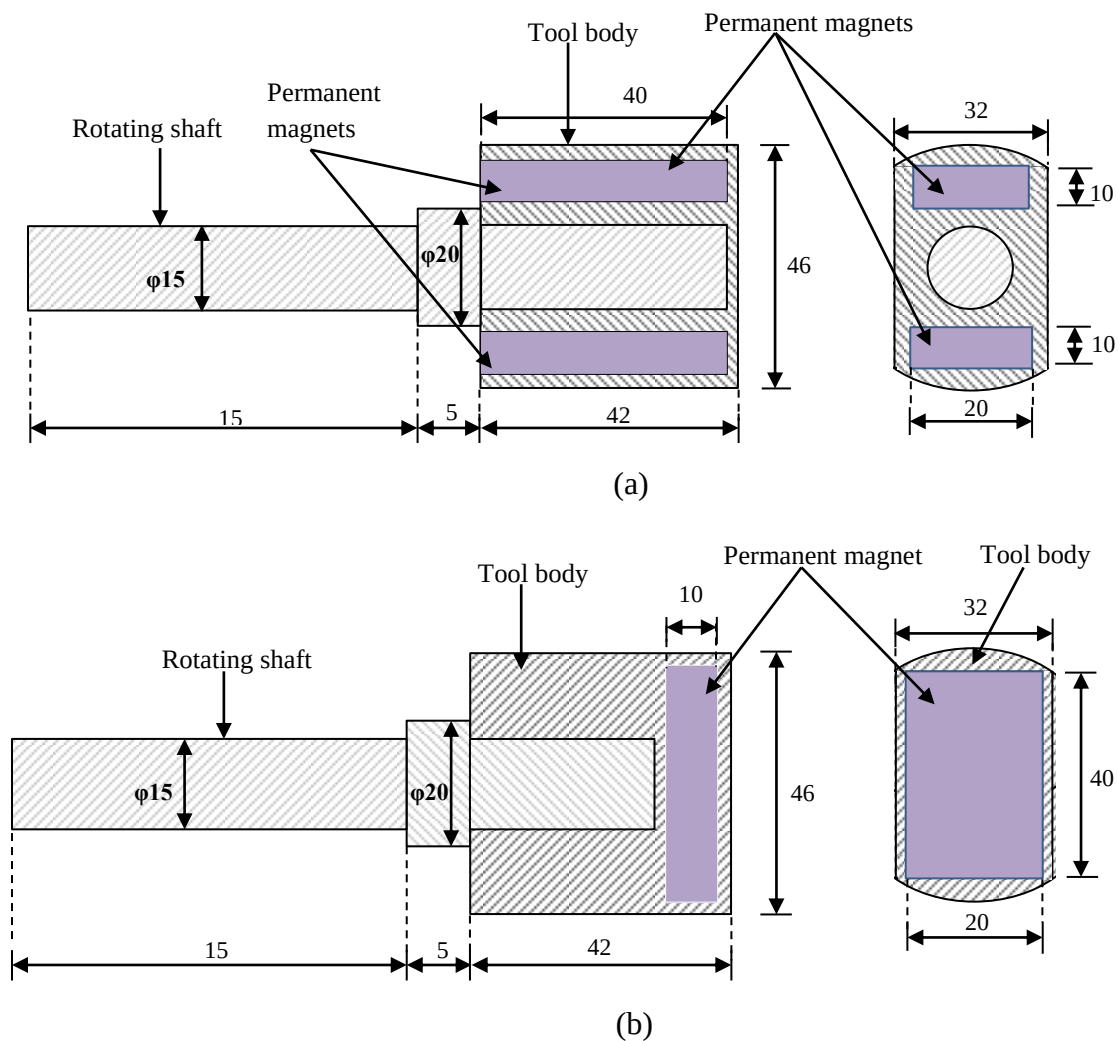


Figure 3.4: Shape and dimensions of tool (mm) for finishing (a) internal cylindrical surfaces of blind holes and (b) bottom flat surfaces of blind holes

Figure 3.5(a) shows the setup along with the designed tool to finish internal cylindrical surfaces of blind holes. Figure 3.5(b) shows the setup using designed tool to finish bottom flat surfaces of blind holes. The stiffened MR polishing fluid is with embedded abrasives (SiC) which result in material removal. As it can be seen that chains of magnetorheological fluid are formed when it comes in contact with the tool body end surface resulting in stiffening of MR polishing fluid. When the stiffened MR polishing fluid slides over rough surface metal removal of roughness peaks takes place due to abrasive wear in the form of micro-chips.

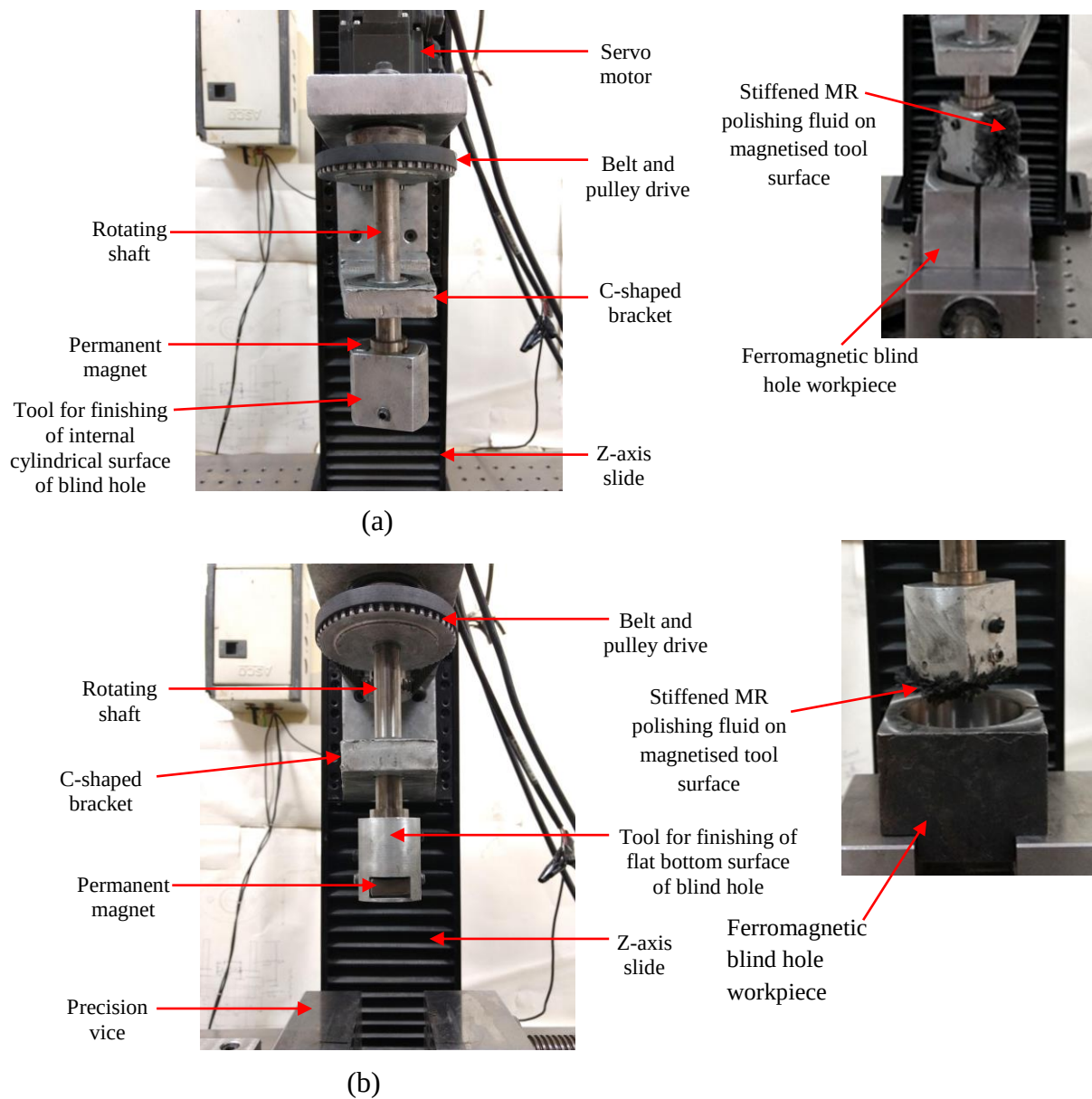


Figure 3.5: (a) Tool for finishing of bottom flat surface of blind hole workpiece and (b) tool for finishing of internal cylindrical surface of blind hole workpiece

3.4 Experimental Setup

Figure 3.6 shows the setup for MR polishing fluid based finishing process of blind holes. The body for both the tools has been manufactured using non-ferromagnetic (Aluminium) material. For the generation of magnetic field rectangular shaped neodymium magnets (NdFeB35) of size 40 mm $\times$ 20 mm $\times$ 10 mm have been used. Tools are mounted on stainless steel shafts to provide rotational motion. Both the uniquely designed tool for blind hole surfaces are attached to Z-axis slide in vertical direction using an aluminium bracket. The belt and pulley arrangement has been utilized to transfer rotational motion from servo motor to the shaft carrying the tools. The workpiece is fixed on the grinding vice which itself is mounted on linear X-Y axis slides. X-Y axis slides which help in centring of tool with respect to workpiece. The process is programmable logic controller (PLC) controlled. To control the linear motion of slides and rotational speed of tool, integrated motion controllers are used. The instructions to the controller are given via human machine interface (HMI).

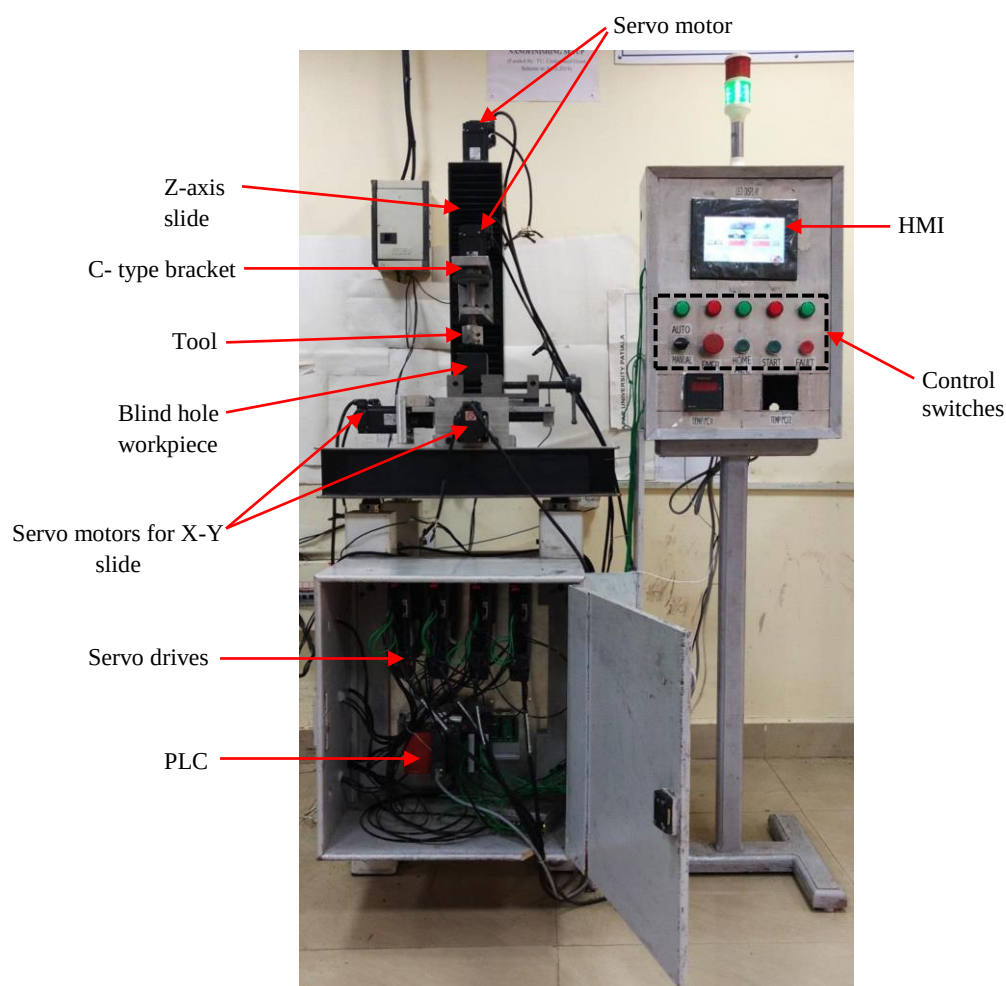


Figure 3.6: Experimental setup for magnetorheological finishing of blind hole surfaces

3.5 Fabrication of Blind Hole Workpiece

Figure 3.7(a) shows the CAD model of workpiece. The workpiece is made from cuboidal shape metal block, in which 50 mm diameter hole is drilled to depth of 40 mm. The workpiece is fixed on a precision vice. The vice is mounted on X-Y slides which help in centring the tool with respect to workpiece. In the workpiece trapezoidal slots are cut which facilitate easy removal and holding of workpiece under the influence of magnetic field.

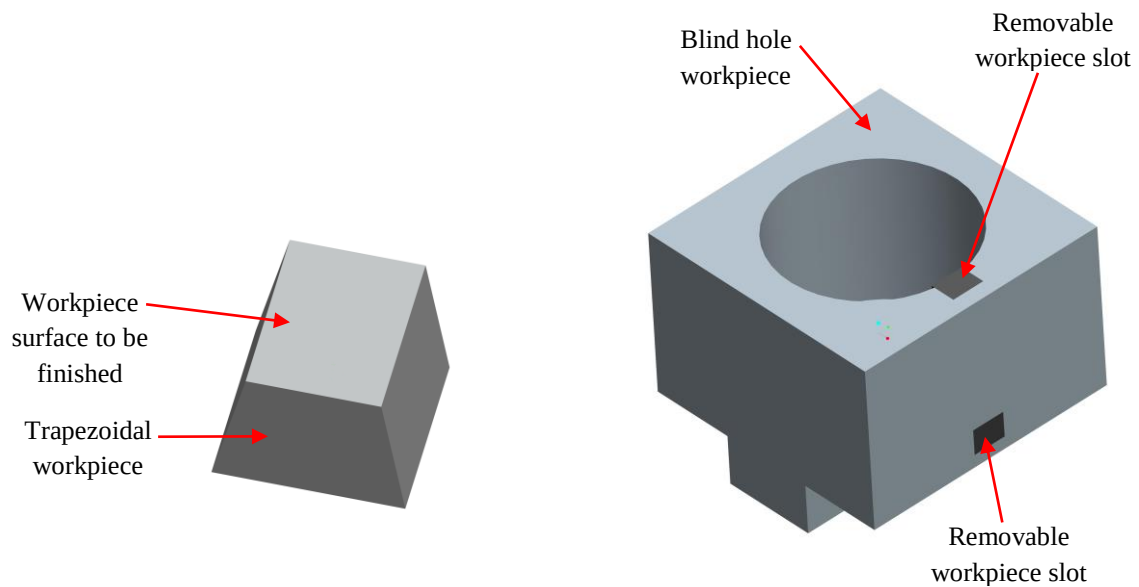


Figure 3.7: Shape of workpiece and slots to carry the removable workpiece

3.6 Conclusions

Based on the research gaps the design of tools was carried out. Magnetostatic simulations of tools have been performed to study the distribution of magnetic field around the magnets. The following results can be concluded:

- Higher magnetic flux gradient at the tool end surfaces and it decreased in the gap towards the internal lateral and bottom flat surfaces of blind hole ferromagnetic cylindrical workpiece.
- The variation in magnetic flux density helps to keep the MR polishing fluid sticking with the tool surface which helpful for surface finishing the blind hole ferromagnetic cylindrical workpiece.
- From the magnetic finite element analysis of internal cylindrical surface finishing tool, the variation of magnetic flux density in working gap was found to be 0.5053 T at the

finishing tool end surface and at the internal surface of ferromagnetic cylindrical workpiece was calculated as 0.4282 T.

- The magnetic flux density in working gap was calculated for blind hole bottom flat surface finishing tool and found to vary from 0.5993 T at the tool end surface to 0.5382 T at bottom flat workpiece surface.

Chapter 4

Mathematical Modeling and Simulation of Surface Roughness

MR finishing is a precision finishing process and hence more time consuming than traditional finishing processes. It is necessary to develop a model to predict the surface roughness because cycle time of whole process is dependent on slowest operation. The prediction of surface roughness after required number of cycles helps in optimizing the whole manufacturing process. Models for simulation and prediction of surface roughness in MRAFF, BEMRF and a new magnetorheological honing process have been developed to fully understand the impact of various parameters on finishing performance [Jha and Jain, 2006], [Singh *et al.*, 2013], [Paswan *et al.*, 2016].

4.1 Composition of MR Polishing Fluid

The tool surface in touch with MR polishing fluid is curved for tool for finishing internal cylindrical surface and flat for finishing bottom surface of blind holes. The MR polishing fluid is applied to the tool externally. When the fluid is brought in the region of magnetic field columnar chains of magnetic carbonyl iron particles (CIP) are formed which results in apparent change in viscosity. The workpiece is made from cuboidal shape mild steel block, in which 50 mm diameter hole is drilled to depth of 40 mm. It is fixed on the grinding vice which is mounted on linear X-Y axis slides. X-Y axis slides which help in centring of tool with respect to workpiece.

Table 4.1: Composition of MRP fluid

Component	% volume concentration
Carbonyl iron particle	20
Abrasive silicon carbide particles of 800 mesh size	20
Base fluid paraffin oil and AP3 grease	60

The volume percentage of components of MR polishing fluid during the experimentation were taken as 20% SiC abrasive particles of 800 mesh size, 20% carbonyl iron particles (CIPs) and 60% carrier fluid (80% heavy paraffin and 20% AP3 grease as thixotropic agent by weight). In the developed process, the tool for finishing internal cylindrical surfaces of blind hole is given continuous rotational and reciprocation motion. The tool for finishing bottom flat surfaces of blind hole is given continuous rotational motion.

4.2 Mechanism of Surface Finishing in Blind Hole Workpiece

To understand the forces acting on the work piece it is necessary to study the mechanism of material removal. The mechanism of material removal is abrasive wear due to micro-cutting of material at peaks. The hardness of workpiece material and abrasive particles greatly influence the material removal efficiency. Figure 4.1 shows the mechanism of material removal while finishing internal cylindrical surfaces of blind hole.

Figure 4.2 shows the mechanism of material removal while finishing the bottom flat surfaces of blind hole. When the MR polishing fluid is brought in the region between high magnetic flux gradient and low magnetic flux gradient long microscopic columnar chains of magnetic particles (CIP) are formed locking the abrasive particles between them. The active abrasive particles approaching towards the peaks shear off the material. The finishing performance depends upon how strongly the abrasive particles are locked in the CIP chains. The forces acting on the abrasive particles as shown in Fig. 4.1 and Fig. 4.2 depend upon the type of motion given to the tool.

As continuous rotational and reciprocating motion is given to the tool for finishing internal cylindrical surface of blind hole, the approaching active abrasive particles towards the peaks shear off the material. The normal component of the magnetic force (F_N) governs the indentation caused by the active abrasive particles during finishing in both the tools. Figure 4.3(a) shows the abrasive wear causing forces i.e. longitudinal shear force (F_{ST}) and tangential shear force (F_{SL}) components acting on active abrasive particles due to continuous rotational and reciprocating motion of tool during finishing of internal cylindrical surfaces of blind holes. The tool for finishing internal cylindrical is provided simultaneous rotational and reciprocating to continuously change the position of active abrasive particles and hence obtain uniform finish.

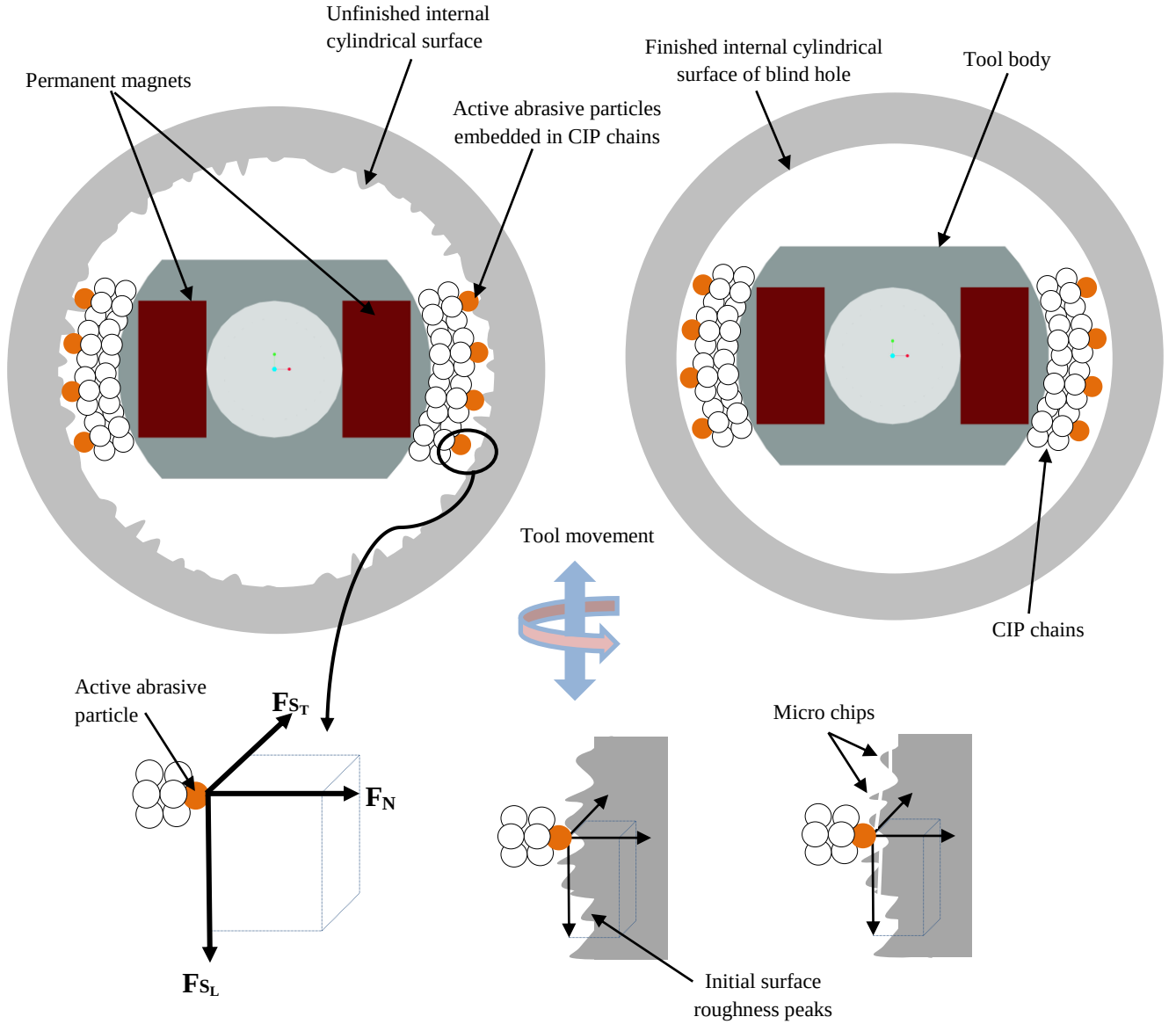


Figure 4.1: Mechanism of material removal and forces acting during finishing of internal cylindrical surfaces of blind holes

The tool to finish bottom flat surface of blind holes is given only continuous rotational motion. Abrasive wear causing micro-cutting of roughness peaks from flat ferromagnetic workpiece is a result of shear component of the magnetic force (F_S) applied by abrasive particles due to rotational motion of tool on flat surface (Fig. 4.3(b)). The material removal rate also depends on the depth of indentation caused by the active abrasive particles on the workpiece surface. The depth of indentation is dependent on the normal component of the magnetic force (F_N). Hence, in order to develop model to predict surface roughness, it is

necessary to determine the magnetic normal force, number of active abrasive particles and depth of indentation on workpiece surface.

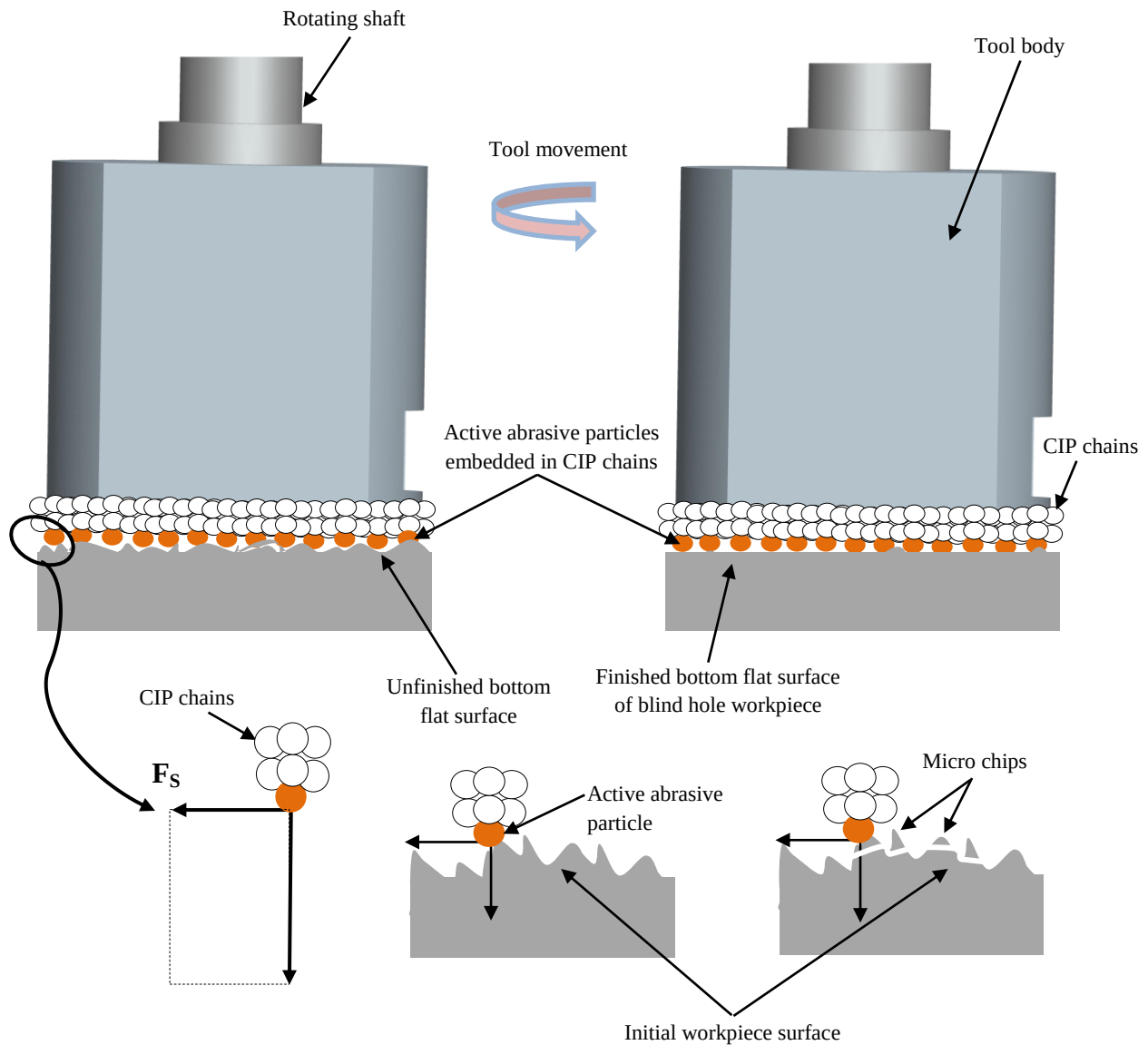


Figure 4.2: Mechanism of material removal and forces acting during finishing flat bottom surface of blind holes

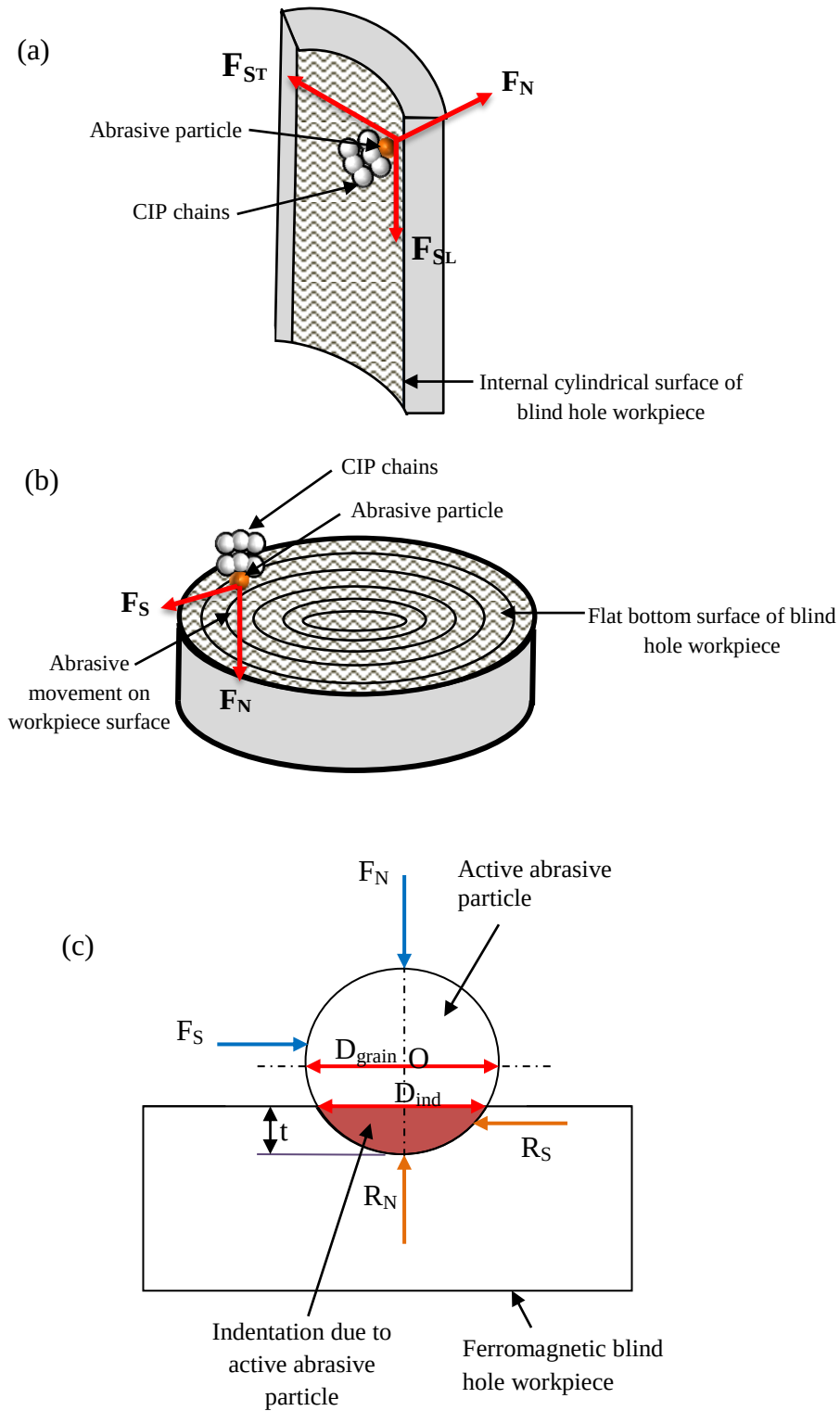


Figure 4.3: (a) Forces acting on the internal cylindrical workpiece surfaces, (b) forces acting on the blind hole bottom flat workpiece surfaces and (c) different forces acting on active abrasive during finishing of the internal cylindrical and flat surfaces of ferromagnetic workpiece with the newly developed MR polishing fluid based tools

4.3 Analysis of Roughness on the Blind Hole Surfaces

To fully understand the finishing mechanism in the developed processes, it is necessary to analyse the effect of various forces on material removal. The indentation caused by the active abrasive particles is dependent on the normal force component (F_N). Calculation of normal force using a mathematical model is necessary to analyse the effect of various parameters on the normal force (F_N).

The development of mathematical model has been done keeping in view the following assumptions.

- Uniform size and spherical shape of abrasive particles and magnetic CIPs
- The abrasive particles and magnetic particles are distributed throughout uniformly
- There is no consideration of magnetic leakages or losses in calculation of magnetic normal force
- The average diameter of magnetic particles and abrasive particles are 18 μm and 19 μm , respectively. It is assumed the both these particles are of similar size
- The normal component of magnetic force causes the indentation whereas abrasive wear is due to the shear component of magnetic force, which is responsible for material removal due to micro-cutting
- The centrifugal force, gravitational force and inertial force have no impact on finishing performance
- Induced magnetic field on workpiece surface is not used for calculation of magnetic forces

Figure 4.3(c) shows the various forces and reactions acting on the active abrasive particles. The shear force F_S is responsible for removal of peaks due to abrasive wear. R_N is the normal reaction force due to resistance to indentation on workpiece surface on the active abrasive particle. R_S is the reaction force due to resistance to deformation of active abrasive particles by shear force. Indentation and material removal only occurs when $F_N > R_N$ and $F_S > R_S$ [Jha and Jain, 2006].

4.4 Calculations of MR Polishing Fluid Particles and Chain Structures

The working gap between the finishing tool surface and the internal surface of ferromagnetic workpiece for both the tools is filled with MR polishing fluid. To study the role of different

parameters of MR polishing fluid such as volume of the MR polishing fluid, CIP and abrasive particles concentration during the finishing are necessary to be analysed.

4.4.1 Calculations of MR Polishing Fluid Particles for Finishing Blind Hole Internal Cylindrical Surface

As shown in the right-angled triangle ΔPQR (Fig. 4.4 b). The width of the permanent magnet (w) is 10 mm. The various dimensions of the tool are shown in Fig. 3.5.

$$R_2 = R_1 + x \quad (4.1)$$

where, R_2 is the radius from the centre of tool to the internal surface of cylindrical ferromagnetic workpiece = 25 mm, R_1 is the radius from the centre of tool to the finishing surface of tool body = 23 mm and working gap (x) = 2 mm. From Fig. 4.4(b),

$$\frac{\phi}{2} = \sin^{-1} \frac{w/2}{R_2}$$

$$\phi = 2 \left(\sin^{-1} \frac{w/2}{R_2} \right) \quad (4.2)$$

where, ϕ = angle subtended by an arc formed with finishing surface of the tool body surface to the central tool rotational axis (Fig. 4.4b).

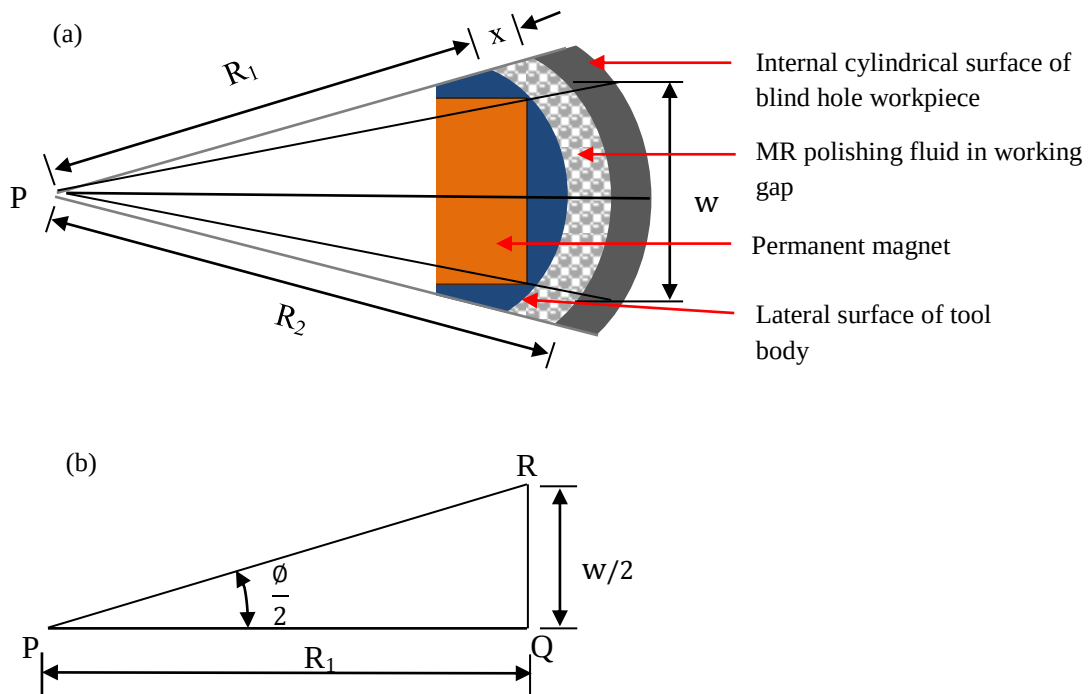


Figure 4.4: (a) Sector formed by the MR polishing fluid layer within the working gap and (b) right angled triangle formed with half of the sector

Area of MR polishing fluid layer within the working gap (Fig. 4.4a),

$$A_{\text{tool}} = \frac{\phi}{360} \pi (R_2^2 - R_1^2) \quad (4.3)$$

Using Eqs. 4.2 and 4.3, area of MR polishing layer within the working gap,

$$A_{\text{tool}} = 122.722 \text{ mm}^2 \quad (4.4)$$

Total volume of MR polishing fluid (V_{MRFluid}) in the gap at each internal finishing tool body end surface is calculated using Eq. 4.5.

$$V_{\text{MRFluid}} = A \times h \quad (4.5)$$

Using Eq. 4.4 and height of the tool body ($h = 40 \text{ mm}$) along the vertical axis of rotation of tool (Fig. 3.5a),

$$V_{\text{MRFluid}} = 6908 \text{ mm}^3 \quad (4.6)$$

Volume of CIPs in MR polishing fluid within the working gap

$$V_{\text{T_CIP}} = \text{volume fraction of CIPs in MR polishing fluid} \times V_{\text{MRFluid}} \quad (4.7)$$

Using fraction volume of CIPs as 20% in MR polishing fluid and Eq. 4.6,

$$V_{\text{T_CIP}} = 1381.78 \times 10^{-9} \text{ m}^3 \quad (4.8)$$

$$\text{The volume of single CIP, } V_{\text{One_CIP}} = \frac{4}{3} \times \pi \times \left(\frac{d_{\text{CIP}}}{2}\right)^3 \quad (4.9)$$

where, d_{CIP} is the diameter of CIP = $18 \times 10^{-6} \text{ m}$

$$\text{Therefore, } V_{\text{One_CIP}} = 3.05208 \times 10^{-15} \text{ m}^3 \quad (4.10)$$

Total number of CIPs in volume of CIPs ($V_{\text{T_CIP}}$) of MR polishing fluid =

$$\frac{\text{Total volume of CIPs present in the MR Polishing fluid}}{\text{Volume of single CIP}} = 4527333874 \quad (4.11)$$

Using Eq. 4.8 and Eq. 4.10,

Since there are two finishing tool surface on which MR polishing fluid is applied,

$$\begin{aligned} \text{The total number of CIPs in } V_{\text{T_CIPs}} \text{ of MR polishing fluid} &= 2 \times 4527333874 \\ &= 9054667748 \end{aligned} \quad (4.12)$$

The total number of active abrasive particles passing over peaks in single rotation is calculated by Eq. 4.13.

$$N_{\text{active}} = \frac{\% \text{ Vol. fraction of SiC particle} \times \text{Area of internal surface of cylindrical workpiece} \times D_g}{\text{Volume of single SiC particle}} \quad (4.13)$$

Here N_{active} is total number of active abrasive particles involved in finishing action during single stroke of tool is given by Eq. 4.14,

$$\text{Volume of single SiC particle, } V_{\text{One_SiC}} = \frac{4}{3} \pi \left(\frac{D_{\text{grain}}}{2}\right)^3 = 3.589543 \times 10^{-15} \text{ m}^3$$

where, D_{grain} = diameter of single SiC abrasive particle = $19 \mu\text{m}$.

Total internal surface area of cylindrical workpiece = $2\pi R_2 H$

$$N_{active} = 6652579 \quad (4.14)$$

4.4.2 Calculations of MR Polishing Fluid Particles for Finishing Blind Hole Bottom Surface

The volume of MR fluid within the working gap between tool body bottom surface and ferromagnetic workpiece is given by Eq. 4.15.

$$V_{MRFluid} = \text{Length of magnet} \times \text{Width of Magnet} \times \text{Working Gap} \quad (4.15)$$

$$V_{MRFluid} = 1600 \text{ mm}^3$$

Volume of CIPs in MR polishing fluid within the working gap

$$V_{T_CIP} = \text{volume fraction of CIPs in MR polishing fluid} \times V_{MRFluid} \quad (4.16)$$

Using fraction volume of CIPs as 20% in MR polishing fluid,

$$V_{T_CIP} = 320 \times 10^{-9} \text{ m}^3$$

$$\text{The volume of single CIP, } V_{One_CIP} = \frac{4}{3} \times \pi \times \left(\frac{d_{CIP}}{2}\right)^3 \quad (4.17)$$

where, d_{CIP} is the diameter of CIP = $18 \times 10^{-6} \text{ m}$

$$\text{Therefore, } V_{One_CIP} = 3.05208 \times 10^{-15} \text{ m}^3 \quad (4.18)$$

Total number of CIPs in volume of CIPs (V_{T_CIP}) of MR polishing fluid

$$= \frac{\text{Total volume of CIPs present in the MR Polishing fluid}}{\text{Volume of single CIP}} \quad (4.19)$$

Using the Eq. 4.17 and Eq. 4.18,

$$\text{The total number of CIPs in } V_{T_CIPs} \text{ of MR polishing fluid} = 104846531 \quad (4.20)$$

In tool for finishing bottom surface of blind holes the total number of active abrasive grains available for finishing are calculated where maximum number of abrasive touch the workpiece. The maximum abrasive particles act at the outermost diameter and are calculated by Eq. 4.21.

$$N_{active} = \frac{\text{Maximum Length for which MR polishing fluid in contact with workpiece}}{D_{grain}} = \frac{2\pi R_1}{D_{grain}} \quad (4.21)$$

$$N_{active} = 8268 \quad (4.22)$$

4.4.3. Calculation of Particles in Chain Structures

A structural arrangement for carbonyl iron particles (CIP) around SiC abrasive particles in MR polishing fluid has been proposed. As the diameter of both abrasive particles and CIP has been assumed to be same, considering BCC structure arrangement of MR Polishing fluid of

edge length = $a \mu\text{m}$. In every body centred cubic cell there is effectively one Carbonyl Iron particle (CIP) and one silicon carbide abrasive particle.

Let R_{CIP} and R_{SiC} be the radius of carbonyl iron particles and silicon carbide abrasive particles as shown in Fig. 4.5.

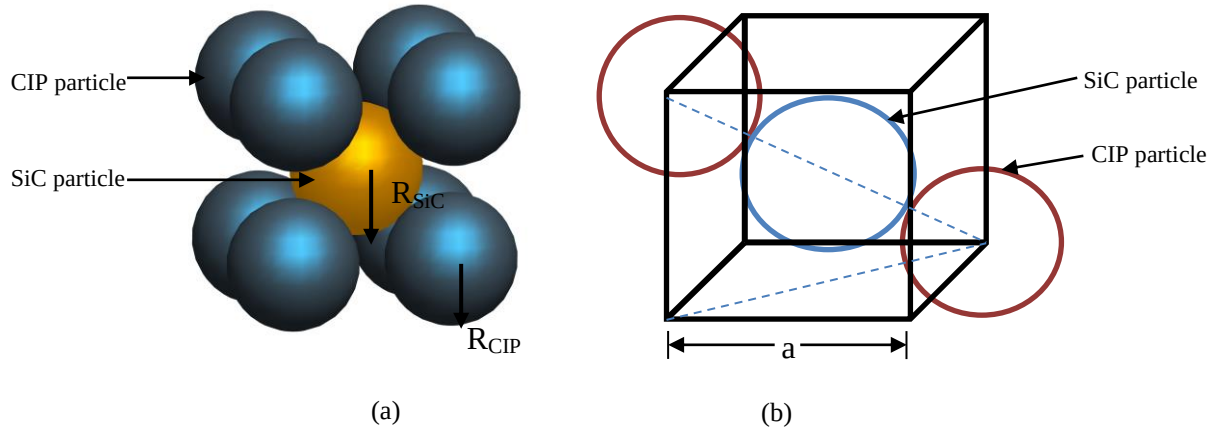


Figure 4.5: (a) Structure formed by the MR polishing fluid layer within the working gap and (b) right angled triangle formed with the edges of the cube in BCC unit cell

$$4(R_{\text{CIP}} + R_{\text{SiC}})^2 = 3a^2 \quad (4.23)$$

$$a = 21.362 \mu\text{m} \quad (4.24)$$

Total number of CIP in a single chain of MR polishing fluid in the working gap is given by Eq. 4.25.

$$N_p = \frac{\text{Working Gap}}{\text{Edge length of BCC cell}} \quad (4.25)$$

$$N_p = 98 \quad (4.26)$$

4.5 Calculation of Magnetic Field at Tool End Surfaces

To calculate the magnetic forces acting on magnetic particles and their effect on the finishing efficiency, it is necessary to determine the magnetic field intensity in the MR fluid gap between workpiece and tool. The magnetic field around the permanent magnet is derived from the given equations [Camacho and Sosa, 2013]. Figure 4.6 shows the orientation of permanent magnets in respective tools. Since magnets with same pole positions are used in design of both tools, the position of polar axis (Z axis) remains same irrespective of the magnet position.

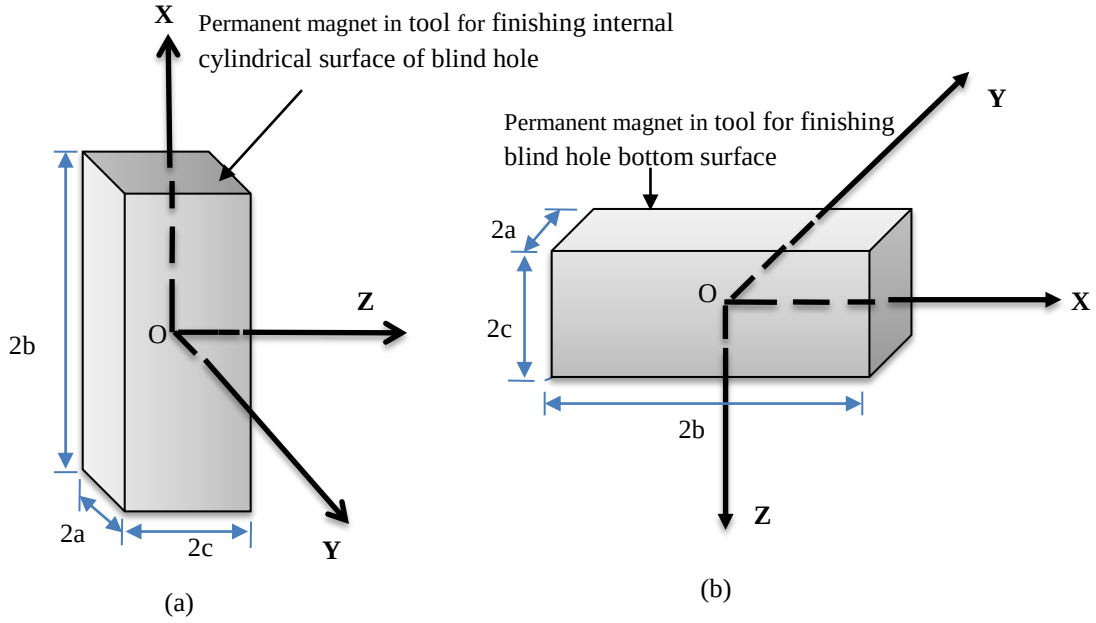


Figure 4.6: Shape, size and axial orientation of permanent magnets in tool (a) for finishing internal cylindrical surface of blind hole and (b) tool for finishing blind hole bottom surface

To calculate the magnetic normal forces, it is needed to determine the magnetic field intensity at various points. Magnetic flux density around the magnet is given by Eqs. 4.27-4.29.

$$B_x(x, y, z) = \frac{\mu_0 M}{4\pi} \ln \frac{F_2(-x, y, -z) F_2(x, y, z)}{F_2(x, y, -z) F_2(-x, y, z)} \quad (4.27)$$

$$B_y(x, y, z) = \frac{\mu_0 M}{4\pi} \ln \frac{F_2(-y, x, z) F_2(y, x, z)}{F_2(y, x, -z) F_2(-y, x, z)} \quad (4.28)$$

$$B_z(x, y, z) = \frac{\mu_0 M}{4\pi} [F_1(-x, y, z) + F_1(-x, y, -z) + F_1(-x, -y, z) + F_1(-x, -y, -z) + F_1(x, y, z) + F_1(x, y, -z) + F_1(x, -y, z) + F_1(x, -y, -z)] \quad (4.29)$$

Where,

F_1 and F_2 are the functions dependent on magnet dimensions.

$$F_1(x, y, z) = \tan^{-1} \frac{(x+a)(y+b)}{(z+c)\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}} \quad (4.30)$$

$$F_2(x, y, z) = \tan^{-1} \frac{\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}+b-y}{\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}-b-y} \quad (4.31)$$

x , y and z are distances taken from the origin of permanent magnet O in X -axis Y -axis and Z -axis directions respectively.

a, b and c are dimensions of the magnet (mm) in Y-axis, X-axis and Z-axis directions respectively as shown in Fig. 4.6.

B_x , B_y and B_z is the magnetic field strength in their respective axial directions.

M is magnetization of NdFeB35 magnet (A/m)

μ_0 is magnetic permeability of free space = $4\pi \times 10^{-7}$ (N/A²),

In order to calculate magnetic flux density on the polar axis (Z axis) of the magnet the components in X and Y axis become zero. The magnetic flux density along pole axis (Z axis) is given by the Eq. 4.32.

$$B(z) = \frac{\mu_0 M}{\pi} \left[\tan^{-1} \frac{ab}{(z-c)\sqrt{a^2+b^2+(z-c)^2}} - \tan^{-1} \frac{ab}{(z+c)\sqrt{a^2+b^2+(z+c)^2}} \right] \quad (4.32)$$

For the permanent magnet used in the present study of dimensions 40x20x10 mm, the equation (a=10, b=20 c=5) reduces to

$$B(z) = \frac{\mu_0 M}{\pi} \left[\tan^{-1} \frac{200}{(z-5)\sqrt{500+(z-5)^2}} - \tan^{-1} \frac{200}{(z+5)\sqrt{500+(z+5)^2}} \right] \quad (4.33)$$

$$B(z) = \frac{B_r}{\pi} \left[\tan^{-1} \frac{200}{(z-5)\sqrt{500+(z-5)^2}} - \tan^{-1} \frac{200}{(z+5)\sqrt{500+(z+5)^2}} \right] \quad (4.34)$$

Where B_r is the remanance of permanent magnet = 1.22 Tesla for NdFeB35 magnet.

When a ferromagnetic material is placed in a region of constant magnetic field, the total field developed inside the ferromagnetic material is given by Eq. 4.35.

$$B = B_0 + \mu_0 M_{CIP} \quad (4.35)$$

Where, B_0 is the externally applied magnetic field, μ_0 is the magnetic permeability of space and magnetization M_{CIP} of CIP is a linear function of the magnitude of the applied magnetic field calculated from Fig. 4.9. Since there is negligible difference between permeability of aluminium and air so there will be no effect on the magnetic field intensity due to permanent magnet. To calculate the field developed inside ferromagnetic CIP it is assumed that each particle is under constant magnetic field. The constant magnetic field in the gap is calculated by Eq. 4.34. Then field inside the MR fluid gap is calculated by using constant magnetic field at the given distance using the Eq. 35.

However the CIP are in the region of a ferromagnetic material rather than free space. Magnetic permeability (μ) in any medium is calculated from the relative permeability (μ_r) as

$$\mu = \mu_r \mu_0 \quad (4.36)$$

Further, by using relative permeability of mild steel workpiece as 600, the magnetic permeability is given as $\mu = 600 \times 4\pi \times 10^{-7} \text{N/A}^2$ [Singh *et al.*, 2013]. In order to incorporate the effect of ferromagnetic material near CIP in working gap replacing μ_0 by $\mu_r\mu_0$ in Eq. 4.35 will give more accurate results.

Table 4.2: Variation of magnetic flux density in working gap of tool for finishing internal cylindrical surfaces using finite element analysis and analytical expressions

Distance in working gap (mm) from the magnet origin	Magnetization of CIP (A/m)	Magnetic flux density B (T)	
		From magnetic finite element analysis	Theoretical from Eq. 4.34 and Eq. 4.35
8.00	108.108	0.5053	0.3569
8.25	105.856	0.4992	0.3493
8.50	103.991	0.4797	0.3421
8.75	102.127	0.4691	0.3349
9.00	100.263	0.4592	0.3277
9.25	99.472	0.4505	0.3214
9.50	98.399	0.4425	0.3150
9.75	94.596	0.4353	0.3066
10.00	90.091	0.4282	0.2978

Table 4.2 gives the variation of magnetic flux density in working gap of tool for finishing internal cylindrical surfaces using finite element analysis and analytical expressions. The of magnetic flux density in working gap is calculated theoretically from Eq. 4.34 and Eq. 4.35.

The variation of theoretically calculated magnetic field shows linear trend given by Eq. 4.37.

$$B(z) = 0.5877 - 0.0288z \quad (4.37)$$

Figure 4.7 shows the comparison of variation in magnetic flux density in working gap between theoretically calculated values and those obtained by finite element analysis in tool for finishing internal cylindrical surfaces. From the Fig. 4.7 it can be seen that the trend of variation of magnetic field inside working gap is decreasing. The trend obtained by analytical expressions is similar to one obtained from finite element analysis

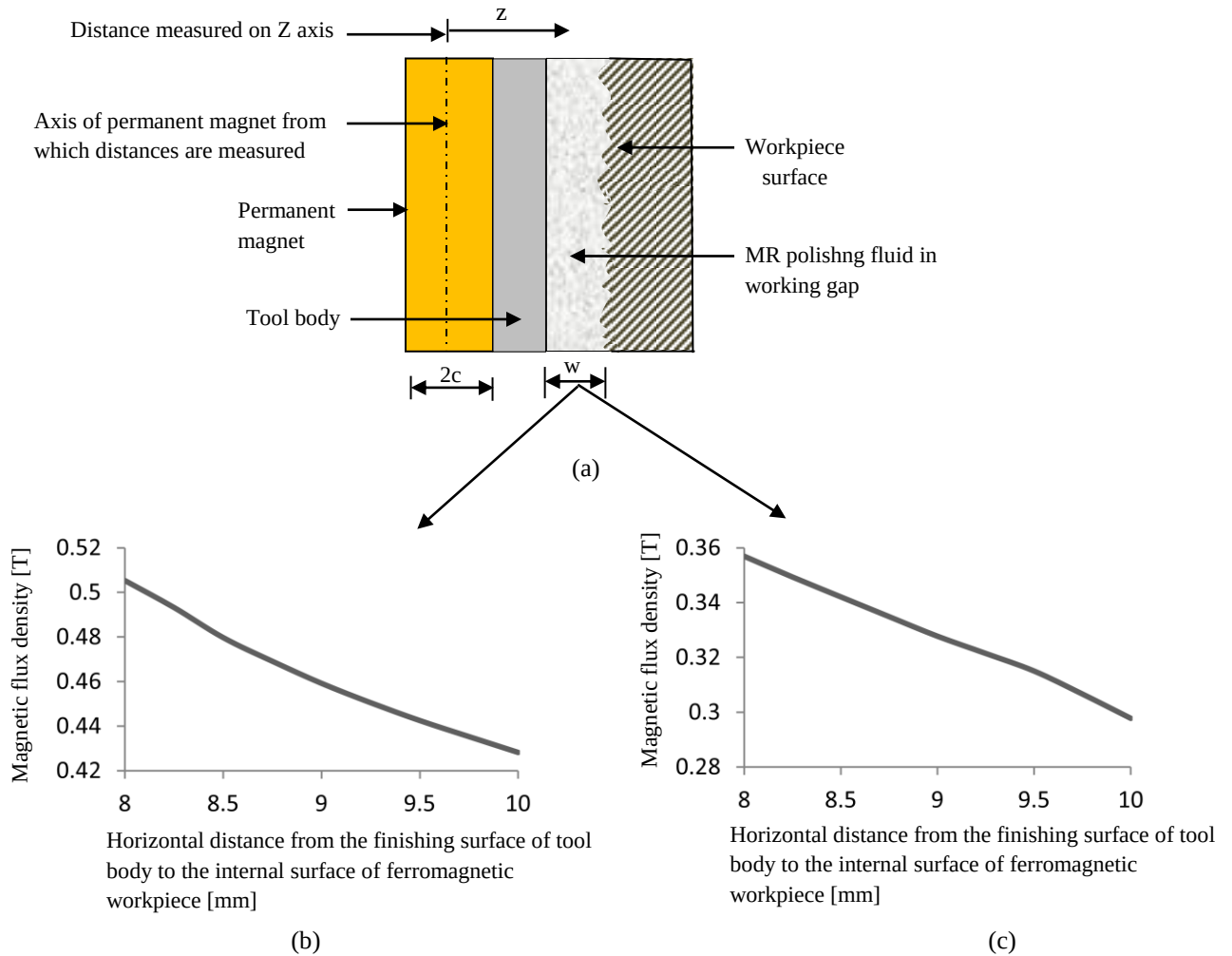


Figure 4.7: (a) Schematic of tool and measurement of distances for finishing internal cylindrical surfaces of blind holes, (b) variation of magnetic flux density from magnetic finite element analysis and (c) variation of magnetic flux density theoretically from Eq. 4.34 and Eq. 4.35

Table 4.3 provides the variation of magnetic flux density in working gap of tool for finishing blind hole bottom flat surfaces using finite element analysis and analytical expressions. The of magnetic flux density in working gap is calculated theoretically from Eq.

4.34 and Eq. 4.35. The variation of theoretically calculated magnetic field follows a linear trend and is given by Eq. 4.38.

$$B(z) = 0.5888 - 0.0290z \quad (4.38)$$

Table 4.3: Variation of magnetic flux density in working gap of tool for finishing blind hole bottom flat surfaces using finite element analysis and analytical expressions

Distance in working gap (mm) from the magnet origin	Magnetization of CIP (A/m)	Magnetic flux density B (T)	
		From magnetic finite element analysis	Theoretical from Eq. 4.34 and Eq. 4.35
7.00	114.865	0.5993	0.3857
7.25	113.040	0.5952	0.3784
7.50	111.215	0.5927	0.3711
7.75	109.389	0.5901	0.3638
8.00	107.564	0.5892	0.3565
8.25	105.739	0.5805	0.3492
8.50	103.914	0.5625	0.3420
8.75	102.088	0.5453	0.3348
9.00	100.263	0.5382	0.3277

Figure 4.8 shows the comparison of variation in magnetic flux density in working gap between theoretically calculated values and those obtained by finite element analysis in tool for finishing blind hole bottom flat surfaces. From the Fig. 4.8 it can be seen that the trend of variation of magnetic field inside working gap is decreasing. The trend obtained by analytical expressions is similar to one obtained from finite element analysis.

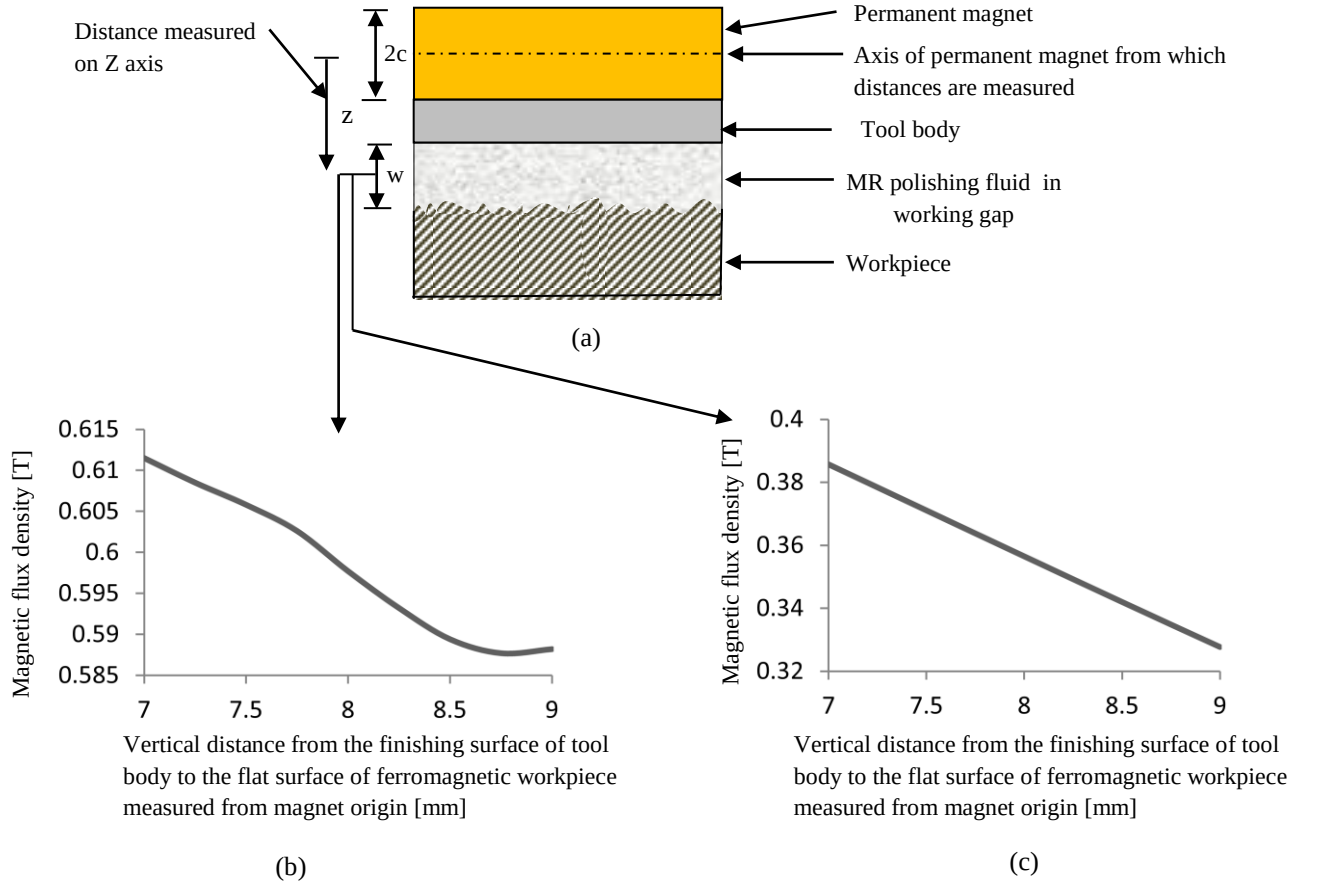


Figure 4.8: (a) Schematic of tool and measurement of distances for finishing flat surfaces of blind holes, (b) variation of magnetic flux density from magnetic finite element analysis and (c) variation of magnetic flux density theoretically from Eq. 4.34 and Eq. 4.35

4.6 Calculation of Magnetic Normal Forces on the Workpiece Surface

During finishing the force acting on the workpiece surface is by the indenting SiC abrasive particle. The carbonyl iron particles under the influence of magnetic flux density apply force on the active abrasive particles thus causing indentation. The finishing performance depends upon magnetic force applied on carbonyl iron particles (CIPs) which influences the indentations caused by the abrasive particles. The forces acting on abrasive particles due to CIPs are shown in Fig.4.3. The magnetic forces can be calculated from Eq. 4.39 [Stradling, 1993].

$$F_{\text{mag}} = m_c \mu_0 \chi_m H \nabla H \quad (4.39)$$

where,

F_{mag} is magnetic force (N) exerted by the carbonyl iron particle (CIP),

$$F_{mag} = \frac{m_c \chi_m B \nabla B}{\mu_0} \quad (4.40)$$

$$F_{mag} = \frac{m_c \chi_m B(z) \frac{dB(z)}{dz}}{\mu_0} \quad (4.41)$$

where

m_c is the mass of CIP particle = $2.3989 \times 10^{-11} kg$

Mass of magnetic susceptibility χ_m is defined as $\chi_m = \frac{M_{CIP}}{H} = \frac{\mu_0 M_{CIP}}{B}$ (m^3 / kg) and is calculated from Fig. 4.9.

μ_0 is magnetic permeability of free space and its value is $4\pi \times 10^{-7}$ (N/A²),

H is the magnetic field intensity (A/m) and ∇H is derivative of magnetic field intensity.

To evaluate the forces acting on CIPs, mass susceptibility χ_m of CS grades is calculated using the M–B curves as shown in Fig. 4.9 The M–B curve is derived experimentally by vibrating sample magnetometer (VSM) test [Jha and Jain, 2006].

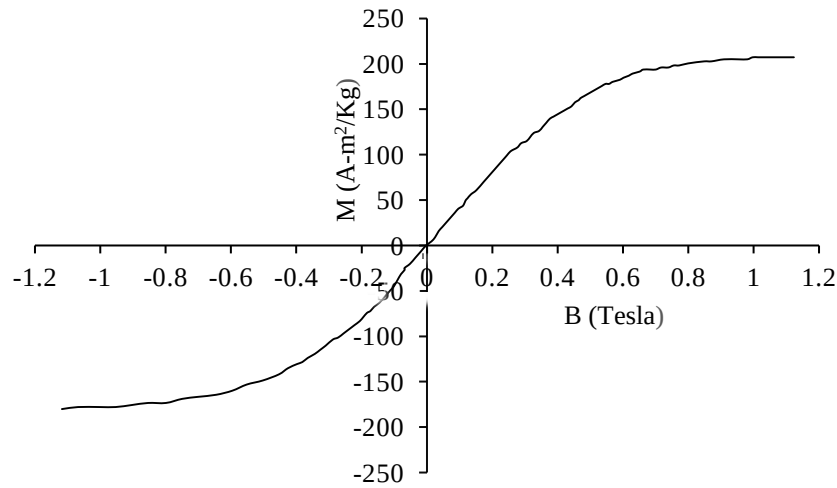


Figure 4.9: The M-B curve of CIPs of CS grade[Jha and Jain, 2006].

F_{ind} is indentation force (N) exerted by the carbonyl iron particle (CIP). Since it is assumed that size of abrasive particles and CIP particles is same, it is assumed that magnetic normal force exerted by a single CIP particle is completely transferred to the active abrasive particle. Indentation force acting by the CIP on abrasive is calculated by averaging the magnetic force in the gap. The indentation force on the abrasive particles causes indentation on the workpiece.

Table 4.4 calculation of magnetic normal forces in working gap of tool for finishing internal cylindrical surfaces using Eq. 4.41. For the tool for finishing internal cylindrical

surfaces the variation of magnetic flux density is given by Eq. 4.42. The negative value signifies that the magnetic flux density is decreasing in the working gap between tool lateral end surface and workpiece surface.

$$B(z) = 0.5877 - 0.0288z \quad (4.42)$$

$$\frac{dB(z)}{dz} = -0.0288 \quad (4.43)$$

The indentation force on internal cylindrical surface of blind hole workpiece is calculated as average of magnetic normal forces and is given by Eq. 4.44:

$$F_{ind} = 9.009 \times 10^{11} \text{ N} \quad (4.44)$$

Table 4.4: Calculation of magnetic normal forces in working gap of tool for finishing internal cylindrical surfaces using analytical expressions

Distance in working gap (mm) from the magnet origin	Magnetic flux density (T)	Mass of magnetic susceptibility (χ_m) $\times 10^{-4} \text{ m}^3/\text{Kg}$	Magnetic force (F_m) $\times 10^{-10} \text{ N}$
8	0.3569	4.93	- 0.9680
8.25	0.3493	4.94	- 0.9479
8.5	0.3421	4.96	- 0.9321
8.75	0.3349	4.98	- 0.9163
9	0.3277	5.00	- 0.9004
9.25	0.3215	5.07	- 0.8964
9.5	0.3150	5.13	- 0.8893
9.75	0.3066	5.05	- 0.8517
10	0.2978	4.93	- 0.8064

Table 4.5 provides the calculation of magnetic normal forces in working gap of tool for finishing blind hole bottom flat surfaces using Eq. 4.41. For the tool for finishing blind hole bottom surface the variation of magnetic flux density is given by Eq. 4.45. The negative

value shows that the magnetic flux density is decreasing in the working gap between tool bottom end surface and workpiece surface.

$$B(z) = 0.5888 - 0.0290z \quad (4.45)$$

$$\frac{dB(z)}{dz} = -0.0290 \quad (4.46)$$

The indentation force on bottom flat surface of blind hole workpiece is calculated as average of magnetic normal force is given by Eq. 4.47.

$$F_{ind} = 9.669 \times 10^{11} \text{ N} \quad (4.47)$$

Table 4.5: Calculation of magnetic normal forces in working gap of tool for finishing blind hole bottom flat surfaces using analytical expressions

Distance in working gap (mm) from the magnet origin	Magnetic flux density (T)	Mass of magnetic susceptibility (χ_m) $\times 10^{-4} \text{ m}^3/\text{Kg}$	Magnetic force (F_m) $\times 10^{-10} \text{ N}$
7	0.3857	4.83	- 1.0319
7.25	0.3784	4.85	- 1.0164
7.5	0.3711	4.87	- 1.0009
7.75	0.3638	4.89	- 0.9855
8	0.3565	4.91	- 0.9700
8.25	0.3492	4.93	- 0.9545
8.5	0.3420	4.95	- 0.9390
8.75	0.3348	4.98	- 0.9235
9	0.3277	5.00	- 0.9079

4.7 Modeling and Simulation of Surface Roughness

The abrasive particles under the influence of magnetic normal force F_N indent the work piece surface while shear force F_S is responsible for removal of peaks due to abrasive wear. Indentation and material removal only occurs when $F_N > R_N$ and $F_S > R_S$. Let D_{grain} be the diameter of SiC abrasive grain, D_{ind} be the diameter of indentation, t be the depth of

indentation (m). The forces acting on the abrasive grains and their respective reactions are shown in the Fig. 4.3 and Fig. 4.10(a).

Figure 4.10(b) helps in providing the basic relation between the various dimensions. Using Pythagoras theorem, the relation between t , D_{ind} , and D_{grain} is given Eq. 4.48.

$$t = \frac{D_{grain}}{2} - \frac{1}{2} \sqrt{D_{grain}^2 - D_{ind}^2} \quad (4.48)$$

where, D_{grain} is diameter of active SiC abrasive grain= $19 \times 10^{-6}m$, and D_{ind} is calculated from the relation of Brinell hardness number ($H_w = 204$). The Brinell hardness number of the machined workpiece surface was measured by Brinell hardness tester.

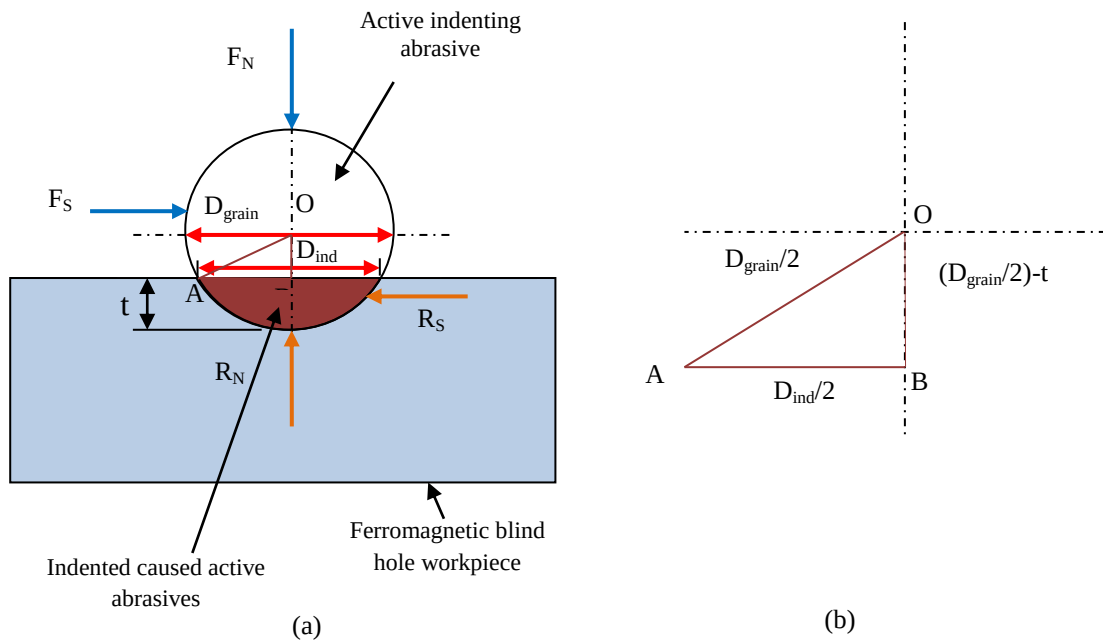


Figure 4.10: (a) Action of forces on abrasive particle during finishing process and (b) OAB triangle formed due to indentation of active abrasive into the workpiece surface

The Brinell hardness number kgf/mm^2 is given by Eq. 4.49 for calculating the diameter of indentation by active abrasive particles.

$$H_w = \frac{2F_{ind}}{\pi D_{grain} (D_{grain} - \sqrt{D_{grain}^2 - D_{ind}^2})} \quad (4.49)$$

By rearranging, the diameter of indentation profile made by the intended active abrasive particles is given by Eq. 4.50.

$$D_{ind} = \sqrt{D_{grain}^2 - \left(D_{grain} - \frac{2 \times 10^{-6} \times F_{ind}}{9.8 \pi H_w D_{grain}}\right)^2} \quad (4.50)$$

Consider the initial roughness profile of the ferromagnetic workpiece as shown in Fig. 4.11(a). Let Z_a Z_c Z_e and Z_g be the peaks and Z_b Z_d and Z_f be the valleys on the initial workpiece surface. After a finishing stroke, by an active abrasive particle the peaks are reduced by depth of indentation 't' due to micro-cutting by the shear forces. Let the final peaks be Z_a' Z_c' Z_e' and Z_g' as shown in Fig. 4.11 (b).

The generalized representation of the profile after single stroke of finishing tool is given by Eq. 4.51.

$$Z'_i = Z_i - N_{active} \times t \quad (4.51)$$

Where Z_i is the peak heights in roughness profile data and Z'_i is the updated peak heights after each stroke.

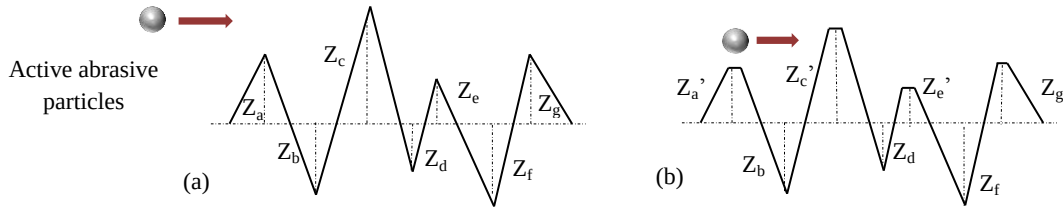


Figure 4.11: (a) Active abrasive particle approaches roughness peaks and (b) finished profile after one indentation depth

The initial value of surface roughness profile of cylindrical workpiece was measured using Mitutoyo SJ-400 surftest (make Mitutoyo). After each stroke, a new centre line average surface roughness values (R_a) is calculated. Using the surface roughness profile data of initial roughness profile the final surface roughness after all the finishing strokes is calculated using MS Excel. The surface roughness value after each stroke is calculated using the formula given by Eq. 4.52.

$$R_a = \frac{\sum_{i=1}^n Z'_i}{n} \quad (4.52)$$

where n is number of profile data points of initial surface roughness profile.

During the calculation of roughness values, the continuous material removal takes place until the height of profile touches zero or non negative height is achieved after which no further material removal takes place on that point. The flowchart showing the sequence of steps in calculation of final roughness profile is given in Fig. 4.12.

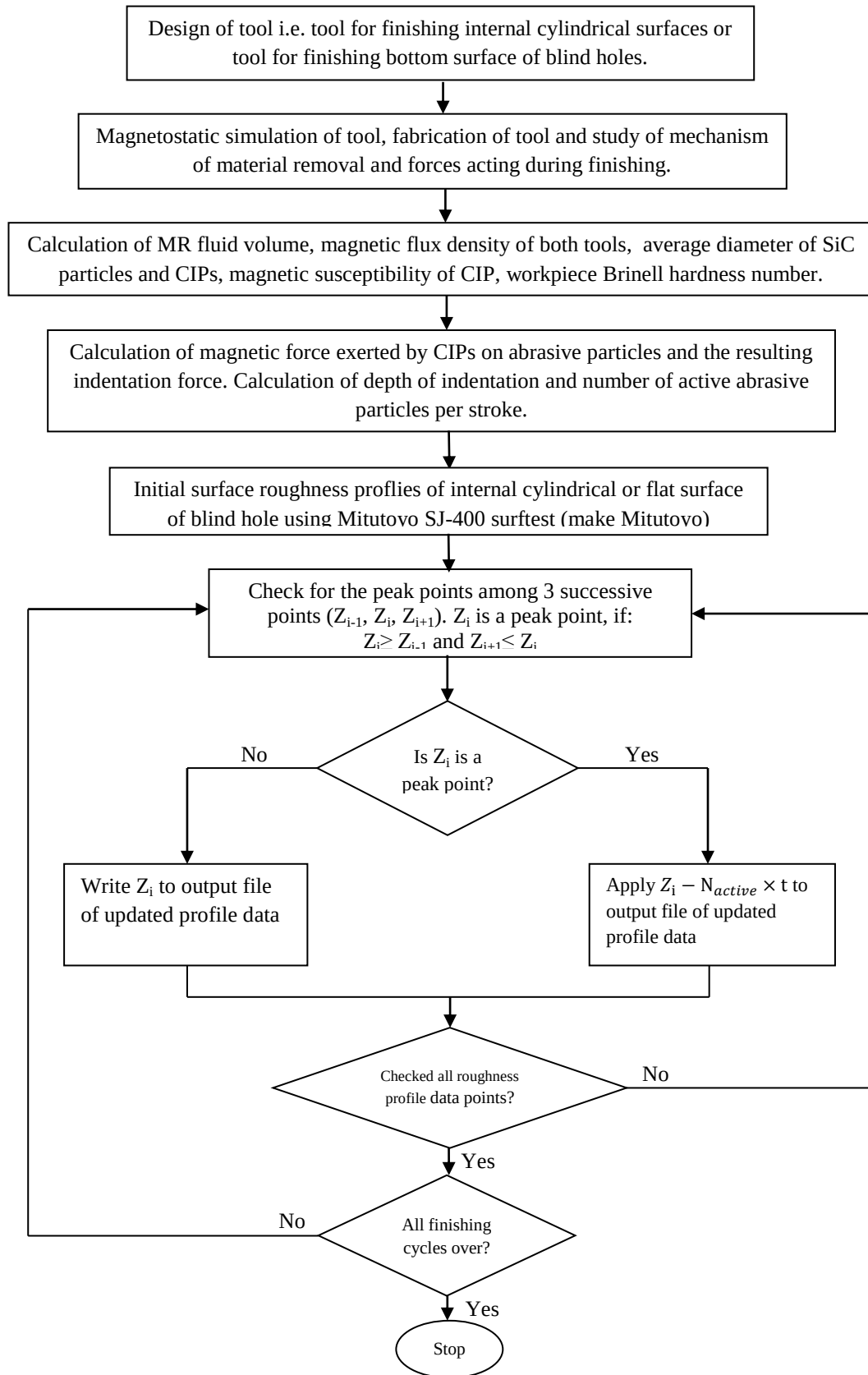


Figure 4.12: Flow chart of the steps performed study the process and to predict final change in surface roughness profile

4.8 Results and Discussion

The analysis of tool performance and validity of the model developed to predict the final surface roughness value has been done by comparing the theoretical value and actual value of surface roughness. Ansoft Maxwell V13 (student version) has been used to perform magnetostatic finite element analysis (FEM) of both tools. The induced magnetic flux density obtained from Ansoft Maxwell V13 (student version) was compared theoretical value derived from the formulas. The calculation of indentation force and its influence on surface roughness was calculated using theoretical magnetic flux density. The calculated magnetic flux density is found maximum at tool surface and shows a negative slope in 2 mm of MR polishing fluid working gap.

The magnetic flux density for internal cylindrical surface finishing tool was calculated theoretically by using Eq. 4.34 and Eq. 4.35 within the working gap of 2 mm. The theoretical magnetic flux density was calculated and found to vary from 0.3569 T at the finishing tool body surface to 0.2977 T at cylindrical workpiece surface, whereas from the magnetic finite element analysis the variation as found to be 0.5053 T at the finishing tool body surface and at the internal surface of ferromagnetic cylindrical workpiece was calculated as 0.4282T. Similarly, for the blind hole bottom surface finishing tool the variation of theoretical magnetic flux density was found 0.3857 T at the finishing tool body surface to 0.3277 T at workpiece surface. From the magnetic finite element analysis, the magnetic flux density was calculated and found to vary from 0.5993 T at the finishing tool body surface to 0.5382 T at flat workpiece surface.

4.8.1 Experiments for Validation of Surface Roughness Model

To validate the developed model, the calculation of final surface roughness profile points using the derived formulas has been done. The initial surface roughness profile data is measured using Mitutoyo SJ-400 surftest (make Mitutoyo). During the experimentation, the MR polishing fluid has the composition of 20% SiC abrasive particles, 20% CIPs as magnetic particles and 60% carrier medium (80% heavy paraffin and 20% AP3 grease as thixotropic agent). To prevent the reduction in finishing performance due to blunted abrasives, the MR polishing fluid was replaced after every 60 cycles on tool for finishing internal cylindrical surfaces and after every 15000 finishing cycle on tool for finishing blind hole bottom surface. Table 4.6 shows the experimental parameters and conditions during the finishing operation. For the same number of finishing cycles and conditions, the theoretical calculated values of

surface roughness with number of finishing cycles are validated with experimentally obtained surface roughness values. The theoretically calculated values of surface roughness for both tools are validated with experimentally obtained values of surface roughness.

The percentage (%) error is calculated using the Eq. 4.53.

$$\text{Percentage error} = \frac{(\text{Experimental surface roughness} - \text{Theoretical surface roughness})}{\text{Experimental surface roughness}} \times 100 \quad (4.53)$$

Table 4.6: Experimental parameters and conditions

Parameters	Tool for finishing internal cylindrical surfaces of blind holes	Tool for finishing bottom flat surfaces of blind holes
Total finishing cycles	275	750000
Tool rotational speed	500 rpm	500 rpm
Cycle time for one reciprocating stroke	25 seconds	-
Working gap	2 mm	2 mm

4.8.2 Experimental Validation of Surface Roughness Model for Finishing Internal Cylindrical Surface of Blind Hole Workpiece

In Table 4.7, the % error columns shows the deviation in surface roughness for internal cylindrical surface finishing tool between the experimental value and theoretically calculated values. The initial surface roughness of cylindrical work piece as obtained using Mitutoyo SJ-400 surf test was 0.94 μm . After 125 cycles, 200 cycles and 275 cycles, the experimentally obtained surface roughness values were 0.72 μm , 0.57 μm and 0.38 μm respectively. These values were validated by theoretically and after 125 cycles, 200 cycles and 275 cycles were calculated to be 0.67 μm , 0.54 μm and 0.395 μm respectively. The maximum error between the theoretically calculated and experimentally found values was found to be 6.26%.

The finishing cycle time of single is = 25 seconds.

$$\text{Total number of finishing cycles} = \frac{\text{Total duration of finishing operation}}{\text{Cycle time}} \quad (4.54)$$

Depth of indentation as calculated from Eq. 4.48 is

$$t = 7.54198 \times 10^{-16} \text{ m} \quad (4.55)$$

Using Eq. 4.51 and Eq. 4.52, the final value of surface roughness after defined finishing cycles is given in Table 4.7.

Table 4.7: Theoretical and experimental results of surface roughness values with the number of finishing cycles for internal cylindrical surfaces of blind holes

S. No	Number of cycles	Experimental R_a (μm)		Theoretical R_a (μm)		% Error
		Initial R_a (μm)	Final R_a (μm)	Initial R_a (μm)	Final R_a (μm)	
1	125	0.94	0.72	0.94	.67	6.26
2	200	0.72	0.57	0.72	0.54	4.6
3	275	0.57	0.38	0.57	0.395	-3.4

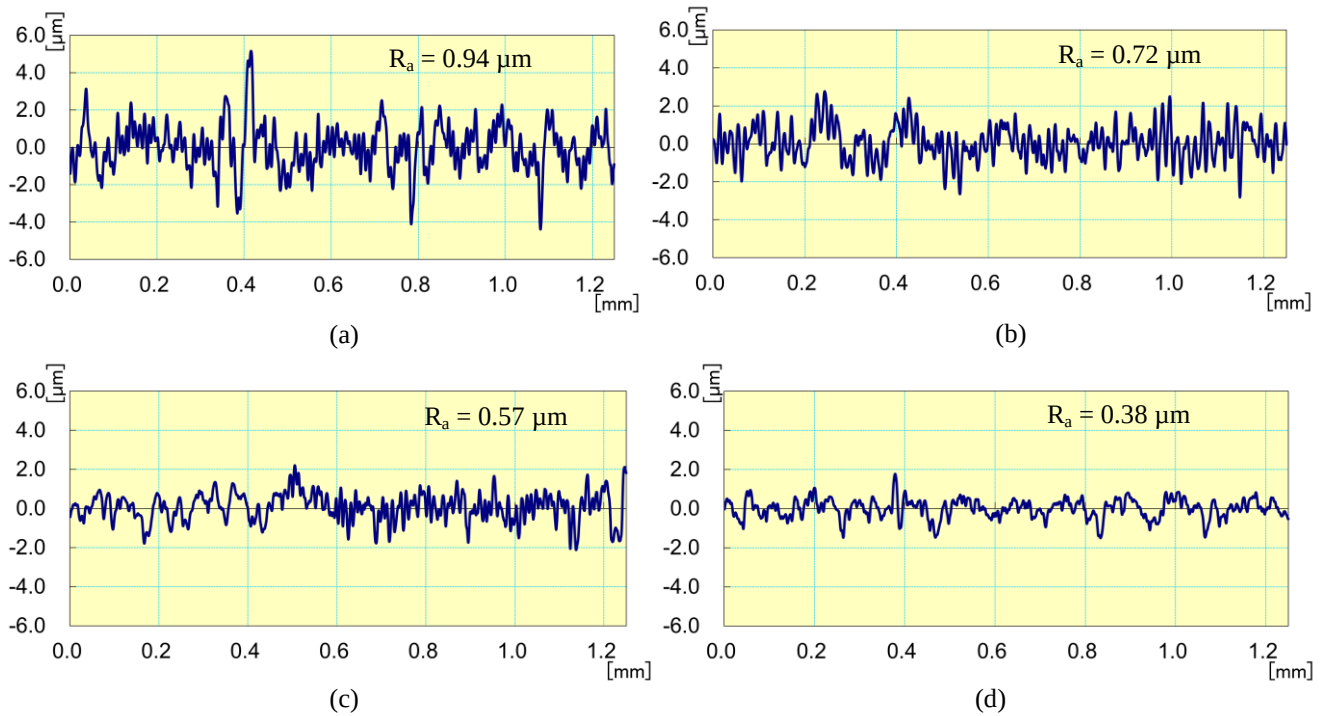


Figure 4.13: Surface roughness profiles for internal cylindrical surfaces of blind hole workpiece (a) initial, (b) after 125 cycles, (c) after 200 cycles and (d) after 275 finishing cycle

After 275 finishing cycles, the R_a values improved by 55.2% in internal cylindrical ferromagnetic blind hole workpiece. The process is capable to finish up to nanometer range

however, to gauge the performance of the tool few experiments has been performed. The change in surface roughness profiles in tool for finishing internal cylindrical surfaces during different finishing cycles are shown in Fig 4.13 (a-d).

4.8.3 Experimental Validation of Surface Roughness Model of Flat Bottom Surface Finishing Blind Hole Workpiece

In Table 4.8, the % error columns shows the deviation in between the experimental value and theoretically caculated values surface roughness for blind hole flat bottom surface finishing tool. The initial surface roughness of blind hole bottom flat workpiece as obtained using Mitutoyo SJ-400 surftest was 0.63 μm . After 30000 cycles, 52500 cycles and 75000 cycles, the experimentally obtained surface roughness values were 0.50 μm , 0.38 μm and 0.263 μm respectively. These values were validated by theoretically and after 30000 cycles, 52500 cycles and 75000 cycles were calculated to be 0.52 μm , 0.41 μm and 0.29 μm respectively.

The maximum error between the theoretically calculated and experimentally found values was found to be 7.9%.

$$\text{Total number of finishing cycles} = \text{rpm} \times \text{Total duration of finishing operation} \quad (4.56)$$

Depth of indentation as calculated from Eq. 4.48 is

$$t = 8.10873 \times 10^{-16} \text{ m} \quad (4.57)$$

Using Eq. 4.51 and Eq. 4.52, the final value of surface roughness after many finishing cycles is given in Table 4.8.

Table 4.8: Theoretical and experimental results of surface roughness values with the number of finishing cycles for bottom flat surfaces of blind holes

S. No	Number of cycles	Experimental R_a (μm)		Theoretical R_a (μm)		% Error
		Initial R_a (μm)	Final R_a (μm)	Initial R_a (μm)	Final R_a (μm)	
1	30000	0.63	0.50	0.63	0.52	-4.0
2	52500	0.50	0.38	0.5	0.41	7.9
3	75000	0.38	0.293	0.38	0.29	1.03

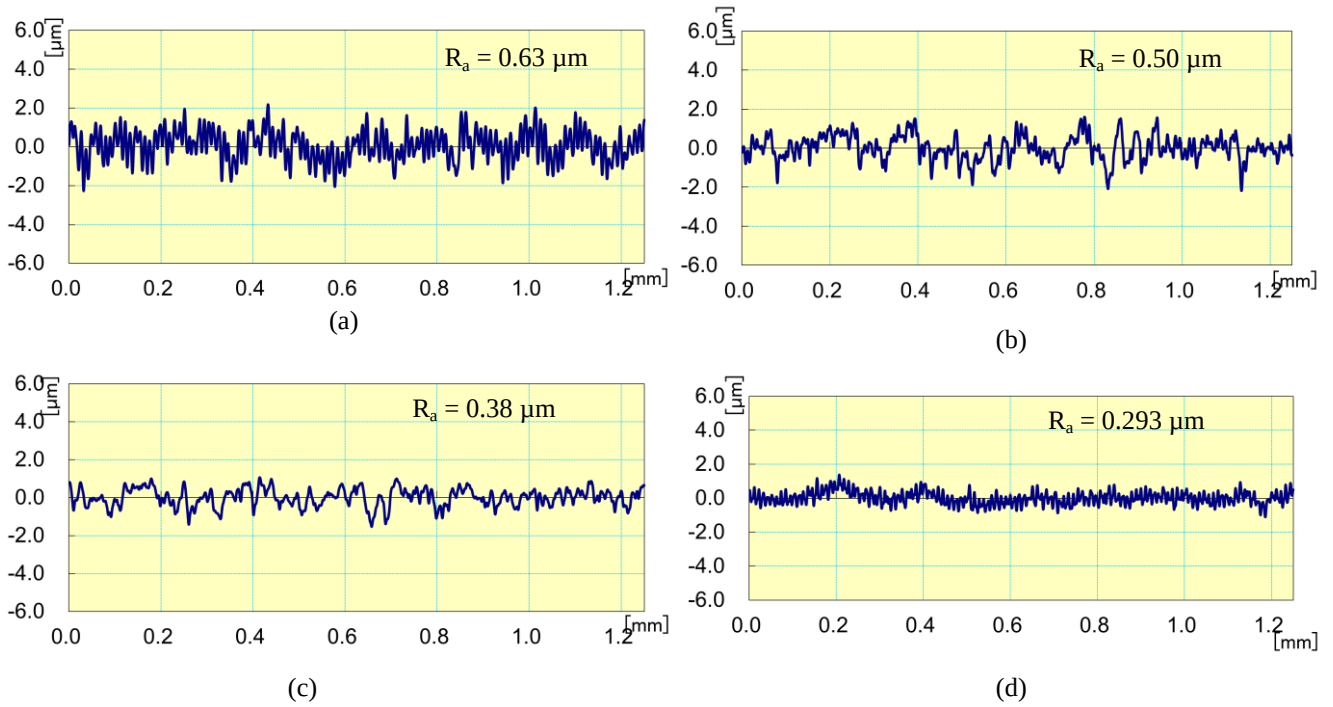


Figure 4.14: Surface roughness profiles bottom flat surfaces of blind hole workpiece (a) initial, (b) after 30000 cycles, (c) after 52500 cycles and (d) after 75000 finishing cycle

The R_a values improved by 53.33% after 75000 cycles in flat surface ferromagnetic blind hole workpiece. The % error while finishing blind hole flat bottom surface is more as there is no change in relative position of abrasives. The process is capable to finish up to nanometer range however, to gauge the performance of the tool few experiments has been performed for limited length of time. As finishing process continues the abrasive particles become blunt, resulting in loss in performance. The change in surface roughness profiles in tool for finishing blind hole bottom surface during different finishing cycles are shown in Fig. 4.14 (a-d).

The microscopy studies of the abrasive wear mechanism have been performed which is responsible for material removal during finishing. Figure 4.15 and Figure 4.16 shows the scanning electron microscopy (SEM) images of ferromagnetic blind hole surfaces carried out at 500x magnification. Figure 4.15(a) and Figure 4.16(a) shows the initial ground surfaces of internal cylindrical and bottom flat surface of blind hole workpiece. It can be observed that initial ground surfaces have surface defects and cavities. The performance of newly developed tools for finishing blind hole surfaces can be gauged by the scanning electron microscopy (SEM) images of final finished surfaces. Figure 4.15 (b) shows the improved surface quality of internal cylindrical surface obtained after 275 numbers of cycles. Figure

4.16(b) provides the surface morphology of bottom flat surface of blind hole after 75000 finishing cycles. It can be concluded that the developed process is capable of improving the surface quality due to abrasive wear. Hence the newly developed process is capable to finish the blind hole surfaces. The improved surface quality results in enhancing wear resistance, corrosion resistance, oxidation resistance and loss of power due to friction.

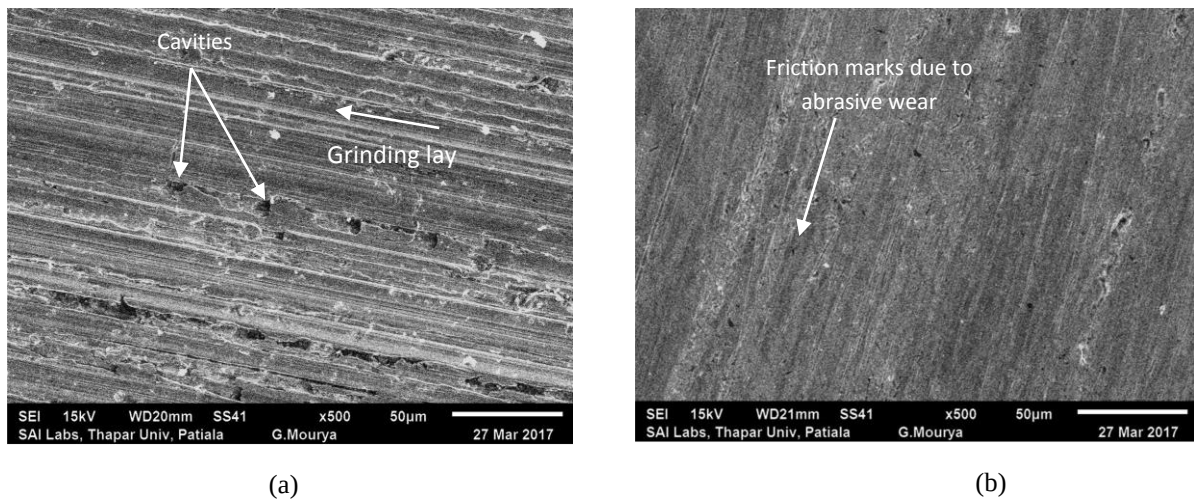


Figure 4.15: Surface morphology with scanning electron microscopy at 500x (a) initial workpiece surface and (b) final finished surface after 275 numbers of finishing cycles on internal cylindrical surface of blind hole ferromagnetic workpiece

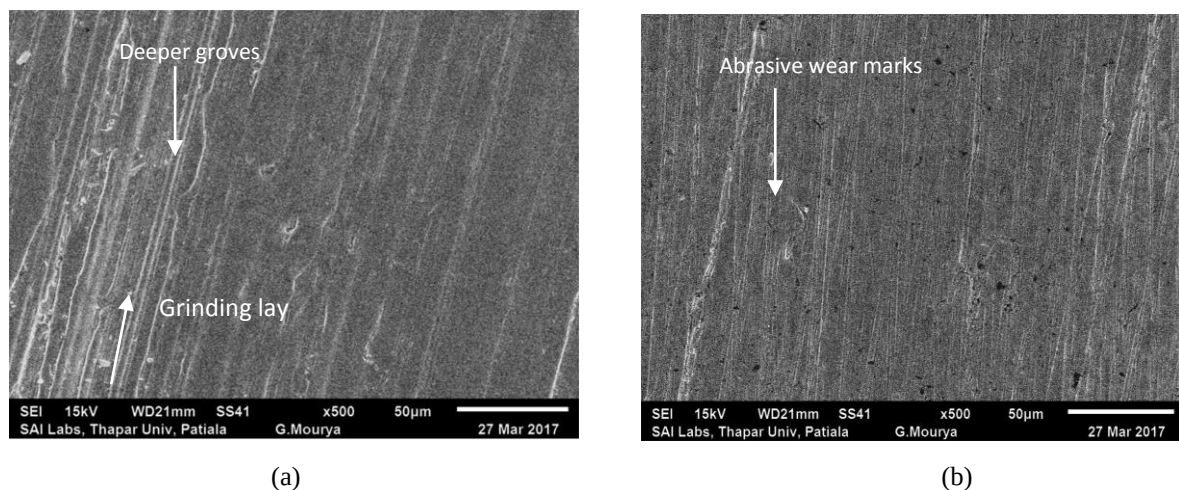


Figure 4.16: Surface morphology with scanning electron microscopy at 500x (a) initial workpiece surface and (b) final finished surface after 75000 numbers of finishing cycles on flat surface of blind hole ferromagnetic workpiece

4.9 Conclusions

The modeling and calculation of magnetic flux density, indentation force and subsequently depth of indentation have been done. To predict the final surface roughness from initial profile data, simulation using the developed model has been performed. The main conclusions derived after experimentation, modeling and simulation are as follows:

- The magnetic flux density for internal cylindrical surface finishing tool was calculated theoretically by using Eq. 4.34 and Eq. 4.35 within the working gap of 2 mm. The theoretical magnetic flux density was calculated and found to vary from 0.3569 T at the finishing tool body end surface to 0.2977 T at cylindrical surface of blind hole workpiece.
- For the blind hole bottom surface finishing tool the variation of theoretical magnetic flux density was found 0.3857 T at the finishing tool end surface to 0.3277 T at workpiece surface.
- Indentation force on abrasive particles and depth of indentation is dependent on the magnetic flux density and size of abrasive particles. Therefore the finishing performance is entirely dictated by magnetic field strength because it results in strongly locked the abrasive particles in carbonyl iron particles chains.
- Surface roughness after 275 finishing cycles improved by 55.2% in internal lateral surface and by 53.33% after 75000 cycles in bottom flat surface of ferromagnetic blind hole cylindrical workpiece.
- Theoretical calculated value of surface roughness for either tool is found in good agreement with experimental value. In tool for finishing internal cylindrical surfaces R_a value is within 6.26 % whereas in tool for finishing blind hole workpiece bottom surface it is found within 7.9%. The % error while finishing blind hole flat bottom surface is more as there is no change in relative position of abrasives as compared to reciprocation as well as rotational motion for lateral surface finishing of blind hole workpiece.

Chapter 5

Parametric Study for Finishing of Cylindrical Blind Hole Surfaces

5.1 Introduction

In present highly competitive market products undergo rapid change and development. The variation in products demands a manufacturing process which can produce rapidly with minimal scrap. The finished blind hole finds application manufacturing and automotive sector. Permanent mould dies are used for casting of various plastic products. For minimal scrap it is necessary to have die cavity surfaces highly finished and free from defect. Most of the die cavities are blind and henceforth difficult to finish. The surface quality of final product manufactured using die casting and injection moulding depends upon the surface finish of die cavity and punch. Recently the process for finishing of die materials has seen vast development. High speed milling is a cost effective manufacturing process of producing highly finished and dimensionally accurate surfaces. It has been developed to machine hardened alloy steels using advanced cutting tool materials and technologies [Fallböhmer *et al.*, 2000]. A process using ultrasonically assisted grinding for finishing of die surfaces has been developed. Electroplated diamond tools have been utilized to obtain mirror like finish [Isobe *et al.* 2007]. The traditional finishing processes are not capable of finishing 3D or freeform surfaces. As most of the die surfaces are freeform surfaces, this has led to the development of magnetic machining process for finishing of complex shapes [Jain, 2009]. The advanced finishing process for nanofinishing of external cylindrical surfaces of permanent mould die punch using modified BEMRF is carried out [Singh *et al.*, 2016].

5.2 Selection of Material

The material of the die is P20 tool steel having 41 HRC hardness. P20 tool steel finds application in die casting and moulds for injection moulding of plastics and rubber. P20 tool steel has good resistance to wear and high machinability. The workpiece is fixed on a precision vice. In the P20 tool steel workpiece, trapezoidal slots are cut which facilitate easy removal and holding of workpiece under the influence of magnetic field. After each trial a new workpiece is inserted in the slot. The final surface roughness of the workpiece is

measured using Mitutoyo SJ-400 surftest. Surface roughness is measured at three different places and is averaged to obtain final surface roughness.

5.3 Selection of Process Parameters

To analyse performance of the newly developed magnetorheological polishing fluid based tools, the process parameters like rotational speed of tool (RPM), reciprocation speed of tool, abrasive volume percentage, and abrasive particle mesh size were selected as variable process parameters to analyse the performance.

Table 5.1: Levels of parameters chosen for finishing the internal cylindrical surface of blind hole workpiece

Factors		Levels				
Representation	Description	-2	-1	0	1	2
X_1	Rotational speed (RPM)	300	600	900	1200	1500
X_2	Reciprocation speed (cm/min)	15	20	25	30	35
X_3	Abrasive volume percentage	15	20	25	30	35
X_4	Abrasive mesh number	400	600	800	1000	1200

Table 5.2: Experimental parameters and condition while finishing internal cylindrical blind hole workpiece

Parameters	Condition
Finishing cycle time	45 minutes
Electrolytic iron particle (EIP) (20% volume)	800 mesh size
Workpiece material	Ferromagnetic

Table 5.1 shows the list of parameters chosen for the blind hole internal cylindrical surface finishing tool. The process parameters like rotational speed of tool (RPM), reciprocation speed of tool, abrasive volume percentage and abrasive particle mesh size were

selected. The potency range of process parameters has been decided based on pilot experiments. The increase in rotational and reciprocation speed results in increase of finishing performance but it decreases as the speed of tool increases beyond a limit due to breakage of EIP chains off MR polishing fluid. The rotational speed was varied from 300 rpm to 1500 rpm to analyse the effect of speed variation on finishing performance. The reciprocation speed was varied from 15 cm/min to 35 cm/min. The volume percentage of EIP particles in the MR polishing fluid is 20%. The volume percentage of silicon carbide (SiC) abrasive particles in the MR polishing fluid is varied from 15% to 35%. The size of abrasives also significantly influences the performance of the process. By decreasing the size of abrasive particles, number of abrasive particles per unit area of MR polishing fluid increases resulting in more available cutting edges in the fluid. The size of abrasive particles has been selected from coarse (400 mesh size) to fine abrasive size (1200 mesh size). The magnetic particles used are electrolytic iron powder (EIP) of 400 mesh size. Heavy paraffin (80% by weight of carrier fluid) and AP3 grease (20% by weight of carrier fluid) as thixotropic agent are used as carrier medium vary accordingly. Table 5.2 shows experimental parameters and condition while finishing internal cylindrical blind hole workpiece.

Table 5.3: Levels of parameters chosen for finishing the bottom flat surface of blind hole workpiece

Factors		Levels				
Representation	Description	-2	-1	0	1	2
Y_1	Rotational speed (RPM)	100	400	700	1000	1300
Y_2	Abrasive volume percentage	15	20	25	30	35
Y_3	Abrasive mesh number	400	600	800	1000	1200

Table 5.3 show the list of parameters chosen for the flat bottom surface finishing tool. The process parameters selected were rotational speed (RPM), abrasive volume percentage and abrasive particles mesh size. Based on the pilot experimentations the abrasive volume percentage was selected such that the rheological properties of the applied MR polishing fluid can be studied to obtain effective finishing performance. The abrasive volume percentage is varied from 15% to 35%. Also the size of abrasive particles has been selected from coarse to fine abrasive size. The magnetic particle utilized in the preparation of MR polishing fluid is

electrolytic iron powder (EIP) having 400 mesh size with the volume percentage of 20%. In the MR polishing fluid, the volume percentage of silicon carbide (SiC) abrasive particles is varied. As a result the volume percentage of carrier medium also changes. Heavy paraffin (80% of carrier fluid by weight) and AP3 grease (20% of carrier fluid by weight) as thixotropic agent are used as components of carrier medium. Table 5.4 shows experimental parameters and condition while finishing flat bottom surface of blind hole workpiece.

Table 5.4: Experimental parameters and condition while finishing flat bottom surface of blind hole workpiece

Parameters	Condition
Finishing cycle time	45 minutes
Electrolytic iron particle (EIP) (20% volume)	800 mesh size
Reciprocation speed of tool	Nil
Workpiece material	Ferromagnetic

5.4 Experimentation for Determining Percentage Change in Surface Roughness

To evaluate the performance of developed tools, design of experiments was done based on selected process parameters. The response surface methodology (RSM) technique was used for design of experiments as it reduces the number of experimental trials. A collection of mathematical and statistical techniques response surface methodology (RSM) technique is very effective for development of relationship between the control variables and response of interest. Also it allows in analysing the effect of variables which are of second order with minimum trials. To conduct the experiments, full factorial designs of two levels having six axial runs and six central runs leading to the second order central composite rotatable design has been implemented.

Table 5.5: Experimental results when finishing the internal cylindrical surfaces of blind holes

Exp No.	Time (min)	RPM	Reciprocation speed (cm/min)	Abrasive volume percentage	Abrasive mesh number	Initial R_a (μm)	Final R_a (μm)	(% ΔR_a)
1	45	900	35	25	800	530	325	38.66
2	45	600	20	30	600	523	322	38.4
3	45	600	30	30	600	532	316	40.55
4	45	1200	30	30	1000	531	367	30.9
5	45	300	25	25	800	518	339	34.63
6	45	900	25	35	800	540	347	35.8
7	45	600	20	20	1000	523	360	31.25
8	45	900	25	15	800	530	364	31.38
9	45	1200	30	30	600	512	362	29.33
10	45	600	30	20	600	518	319	38.33
11	45	1200	30	20	1000	535	373	30.19
12	45	600	20	20	600	522	339	34.98
13	45	900	25	25	800	530	328	38.07
14	45	900	25	25	1200	518	355	31.54
15	45	900	25	25	800	508	321	36.87
16	45	900	25	25	400	517	344	33.5
17	45	600	30	30	1000	524	315	39.89
18	45	1500	25	25	800	511	374	26.8
19	45	600	20	30	1000	516	323	37.44
20	45	900	25	25	800	533	335	37.12
21	45	1200	20	30	600	537	374	30.34
22	45	1200	30	20	600	518	340	34.39
23	45	1200	20	20	1000	513	360	29.79
24	45	900	15	25	800	530	347	34.47
25	45	1200	20	20	600	518	351	32.24
26	45	900	25	25	800	515	318	38.2
27	45	1200	20	30	1000	508	346	31.9
28	45	900	25	25	800	529	330	37.54
29	45	600	30	20	1000	521	341	34.46
30	45	900	25	25	800	530	330	37.67

In order to evaluate performance of finishing tools, response variable selected was percentage change in surface roughness. Percentage change in surface roughness was selected because the initial roughness of the workpiece surfaces is not same for all the specimens. The experiments were performed on the P20 tool steel workpieces having 41 HRC (Rockwell hardness measured on C scale) hardness. The gap between the tools end surface and blind hole workpiece surfaces was fixed at 2 mm. The experimental results reported in Table 5.5 are roughness values obtained when finishing internal cylindrical surfaces of blind holes.

Table 5.6: Experimental results when finishing the bottom flat surfaces of blind holes

Exp No.	Time (min)	RPM	Abrasive volume percentage (%)	Abrasive mesh number	Initial R_a (μm)	Final R_a (μm)	(% ΔR_a)
1	45	100	25	800	541	317	41.38
2	45	700	25	800	531	281	47.06
3	45	700	25	800	540	290	46.29
4	45	400	30	1000	523	261	50.12
5	45	700	25	400	474	283	40.29
6	45	700	35	800	429	242	43.54
7	45	700	25	800	535	295	44.87
8	45	400	30	600	450	259	42.48
9	45	1000	20	1000	492	301	38.77
10	45	400	20	1000	468	270	42.26
11	45	700	25	800	539	283	47.5
12	45	400	20	600	490	289	40.97
13	45	1000	30	1000	523	293	43.99
14	45	1300	25	800	544	352	35.25
15	45	700	15	800	524	312	40.44
16	45	1000	30	600	475	279	41.21
17	45	700	25	800	532	282	46.97
18	45	700	25	800	545	288	47.16
19	45	700	25	1200	465	259	44.28
20	45	1000	20	600	510	301	41.01

Table 5.6 shows experimental results obtained when finishing flat bottom surface of blind hole.

The percentage (%) change in surface roughness is calculated using the Eq. (5.1).

$$\% \Delta R_a = \frac{(\text{Initial surface roughness} - \text{Final surface roughness})}{\text{Initial surface roughness}} \times 100 \quad (5.1)$$

5.5 Regression Analysis of Percentage Change in Surface Roughness ($\% \Delta R_a$)

Analysis of variance (ANOVA) was utilized for analysis experimental data as reported in Table 5.7 and Table 5.8. In order to obtain multi-variable regression model, regression analysis was performed. The verification of adequacy of the respective developed models for finishing internal cylindrical and bottom flat surface of blind hole (at 95% confidence) was done by comparison of standard F value to the obtained F values of respective models. A p -value in the model less than 0.05 implies the model terms are significant. The insignificant terms were removed from the model and regression analysis was performed again.

Initially during the development of model for internal cylindrical surface finishing of blind hole all terms such as X_1 , X_2 , X_3 , X_4 , X_1X_2 , X_1X_3 , X_1X_4 , X_2X_3 , X_2X_4 , X_3X_4 , X_1^2 , X_2^2 , X_3^2 and X_4^2 were included in regression model. Table 5.7 shows the analysis of variance (ANOVA) model developed from experimental values when finishing using internal cylindrical surface finishing tool. A p -value of model terms which are more than 0.05 signifies that these terms do not significant effect on percentage change in surface roughness. X_1 , X_2 , X_3 , X_4 , X_1X_2 , X_1X_3 , X_3X_4 , X_1^2 , X_3^2 and X_4^2 were found to be significant. The model is again developed after removing insignificant terms. From Table 5.7 it can be seen that model developed is significant and lack of fit is insignificant. The statistical model developed after removing the insignificant terms to predict the surface roughness when finishing internal cylindrical surfaces of blind holes is given by Eq. 5.2.

Percentage (%) change in surface roughness ($\% \Delta R_a$)

$$\begin{aligned} &= -25.11083 + 0.05642X_1 + 0.56558X_2 + 1.92607X_3 + 0.017176X_4 \\ &- 0.0004425 X_1X_2 - 0.000891667X_1X_3 + 0.000985X_3X_4 - 0.0000175893X_1^2 \\ &- 0.034571X_3^2 - 0.0000282946X_4^2 \end{aligned} \quad (5.2)$$

where X_1 is rotational speed (RPM) of tool, X_2 is reciprocation speed of tool, X_3 is the abrasive volume percentage and X_4 is abrasive mesh size.

Other ANOVA parameters are given in Table 8 such as R², predicted R², adjusted R² and adequate precision. The ‘predicted R²’, measures how accurate the developed model is in predicting a response value. For the model to be accurate, adjusted R² has to be within approximately 0.20 of predicted R² and vice versa. The predicted R² value of 0.854 and adjusted R² value of 0.931 are within a reasonable distance to the each other. Adequate precision gives a measure signal to noise (S/N) ratio of model. Having greater than 4 signal to noise (S/N) ratio is always desirable. In the developed model, S/N ratio of 25.2 implies an adequate signal.

Table 5.7: ANOVA table for percentage change in R_a obtained during finishing of internal cylindrical blind hole surface

Source	Sum of squares	Degree of freedom	Mean square	F value	p-value Prob > F	
Model	363.2946	10	36.32946	40.06406	< 0.0001	significant
X ₁	159.5473	1	159.5473	175.9484	< 0.0001	
X ₂	16.80027	1	16.80027	18.5273	0.0004	
X ₃	20.0934	1	20.0934	22.15896	0.0002	
X ₄	11.56482	1	11.56482	12.75366	0.0020	
X ₁ X ₂	7.049025	1	7.049025	7.773651	0.0117	
X ₁ X ₃	28.6225	1	28.6225	31.56484	< 0.0001	
X ₃ X ₄	15.5236	1	15.5236	17.1194	0.0006	
X ₁ ²	70.16806	1	70.16806	77.3812	< 0.0001	
X ₃ ²	20.91571	1	20.91571	23.06581	0.0001	
X ₄ ²	35.86629	1	35.86629	39.55327	< 0.0001	
Residual	17.2289	19	0.906784			
Lack of Fit	15.87902	14	1.134216	4.201162	0.0609	not significant
Pure Error	1.349883	5	0.269977			
Total	380.5235	29				
Std. Dev.	0.952252		R-Squared	0.955		
Mean	34.55433		Adjusted R-Squared	0.931		
C.V. %	2.755811		Predicted R-Squared	0.854		
PRESS	55.60539		Adequate Precision	25.2		

Again during development of the model for flat bottom surface finishing of blind hole all terms such as Y_1 , Y_2 , Y_3 , Y_1Y_2 , Y_2Y_3 , Y_1Y_3 , Y_1^2 , Y_2^2 and Y_3^2 were included as model terms in response surface model. Table 5.8 shows the ANOVA model of developed for bottom flat surface finishing tool. The model terms having p- values less than 0.05 imply that these terms have significant influence on final surface roughness values obtained after finishing. Y_1 , Y_2 , Y_3 , Y_1Y_3 , Y_2Y_3 , Y_1^2 , Y_2^2 and Y_3^2 were found to be the significant terms. The model is redeveloped after removing insignificant terms. From Table 5.8 it can be seen that model developed is significant and lack of fit has insignificant effect on tool performance.

Table 5.8: ANOVA table for percentage change in R_a obtained during finishing of flat bottom blind hole surface

Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob > F	
Model	230.6133	8	28.82667	26.47461	< 0.0001	significant
Y_1	33.35351	1	33.35351	30.63209	0.0002	
Y_2	27.51894	1	27.51894	25.27358	0.0004	
Y_3	18.98999	1	18.98999	17.44053	0.0015	
Y_1Y_3	8.789367	1	8.789367	8.072214	0.0160	
Y_2Y_3	16.17724	1	16.17724	14.85729	0.0027	
Y_1^2	106.2446	1	106.2446	97.5758	< 0.0001	
Y_2^2	32.46738	1	32.46738	29.81826	0.0002	
Y_3^2	28.38451	1	28.38451	26.06853	0.0003	
Residual	11.97726	11	1.088842			
Lack of Fit	7.430319	6	1.238387	1.361779	0.3760	not significant
Pure Error	4.546944	5	0.909389			
Total	242.5906	19				
Std. Dev.	1.043476	R-Squared		0.95		
Mean	43.29133	Adjusted R-Squared		0.91		
C.V. %	2.410358	Predicted R-Squared		0.79		
PRESS	50.93459	Adequate Precision		18.82		

The statistical model developed to predict the surface roughness when finishing bottom flat surfaces of blind holes is given by Eq. 5.3.

$$\begin{aligned}
 \text{Percentage (\%) change in surface roughness } (\% \Delta R_a) = & \\
 = 1.20531 + 0.04114Y_1 + 1.39739Y_2 + 0.024626Y_3 - 0.0000174696Y_1Y_3 & \\
 + 0.00142203Y_2Y_3 - 0.0000228404Y_1^2 - 0.045454Y_2^2 & \\
 - 0.0000265628Y_3^2 & \quad (5.3)
 \end{aligned}$$

where Y_1 is rotational speed of tool (RPM) of tool, Y_2 is reciprocation speed of tool and Y_3 is abrasive mesh size.

Table 5.8 also shows other ANOVA parameters such as R^2 , predicted R^2 , adjusted R^2 and adequate precision. The predicted R^2 value of 0.79 and adjusted R^2 value of 0.91 are within a reasonable distance to the each other. Adequate precision gives a measure of model signal to noise (S/N) ratio. Having the signal to noise (S/N) ratio of 18.82 in model developed for flat bottom surface finishing of blind hole, is an indication of adequate signal.

5.6 Results and Discussion

Two separate tools have been designed to finish the internal cylindrical and bottom flat surfaces of blind hole workpiece. The experiments were performed and to evaluate the finishing performance regression analysis was for both the tools. The development of regression models was carried out to study the influence of various process parameters and their interaction on performance of tools.

5.6.1 Experimental Analysis of Tool for Finishing Internal Cylindrical Blind Hole Surfaces

The percentage contribution of various process parameters when finishing internal cylindrical surface of blind hole workpiece is shown in Fig. 5.1. The process parameters like rotational speed, reciprocation speed, abrasive volume percentage and abrasive mesh size are found to be significant while finishing internal cylindrical blind hole surface. Rotational speed of tool (RPM) was found to be the factor which has most significant influence on $\% \Delta R_a$. Figure 5.2 shows the effect of various process parameters on $\% \Delta R_a$.

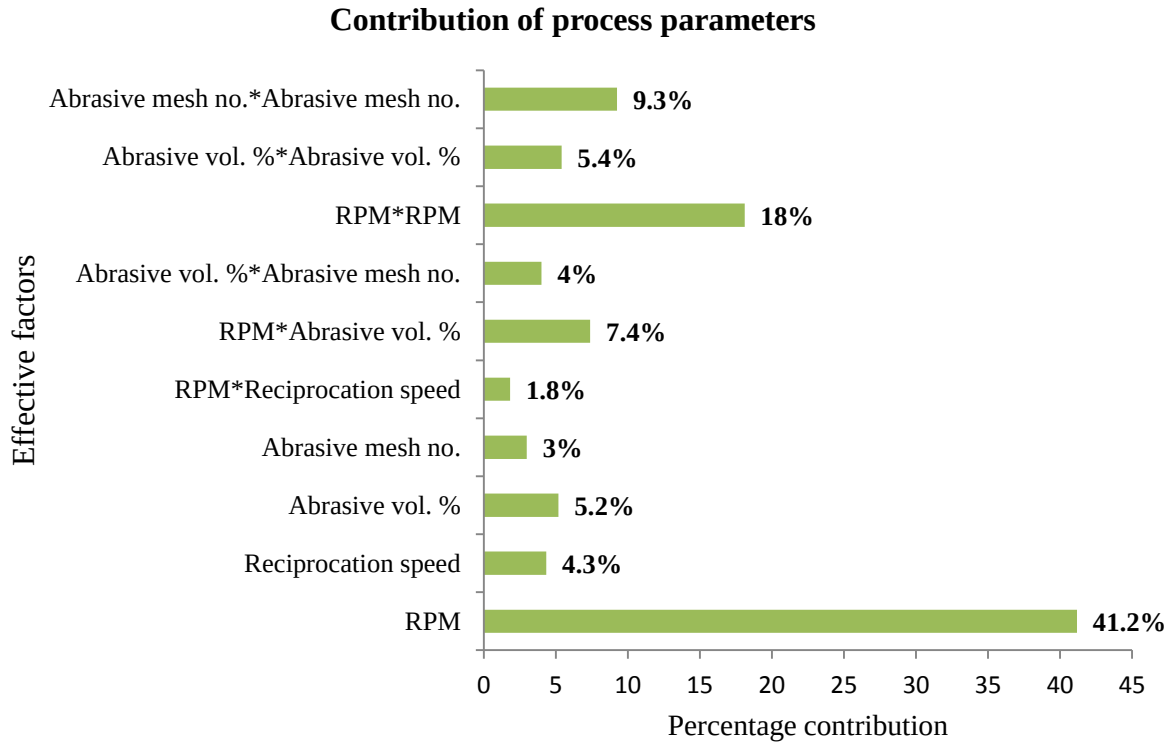


Figure 5.1: Contribution of various parameters on the percentage change in surface roughness during finishing of internal cylindrical surface of blind hole

Effect of Rotational Speed of Tool (RPM)

Figure 5.2(a) shows the relationship of percentage change in surface roughness ($\%\Delta R_a$) with variation in rotational speed of tool (RPM) when finishing internal cylindrical surface of blind hole workpiece. The $\%\Delta R_a$ firstly increases then decreases. This occurs because by increasing the rotational speed (RPM) of the tool, number of active abrasives particles performing finishing action at given area per unit time on the workpiece surface increases. This result in increase in material removal at the surface of workpiece and hence the improvement in finishing rate is obtained.

However, if rotational speed of tool (RPM) is increased above a critical limit, it results in decrease of tool performance. It occurs because the centripetal forces acting on the micron sized magnetic particles due to magnetic field at higher rotational speed is not sufficient to hold the abrasive particle in the electrolytic iron particle (EIP) chains. This results in breaking of the EIP chains of MR polishing fluid. The breaking of chains results in decrease of finishing force and hence in a drop in $\%\Delta R_a$ values.

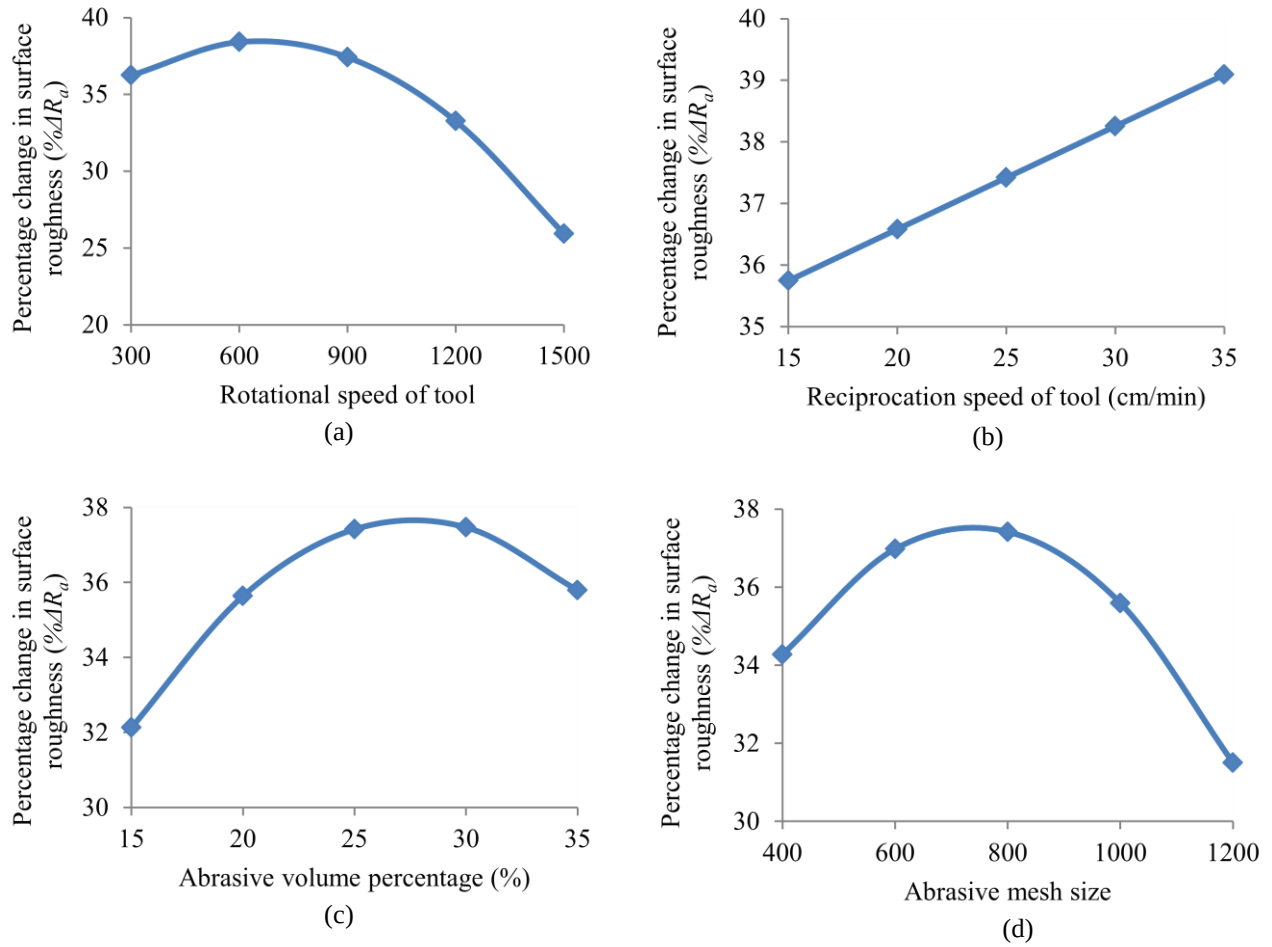


Figure 5.2: Variation of percentage change in surface roughness with respect to (a) rotational speed of tool, (b) reciprocation speed of tool, (c) abrasive volume percentage and (d) abrasive mesh size

Effect of Reciprocation Speed of Tool

Figure 5.2(b) shows variation of $\% \Delta R_a$ with respect to reciprocation speed. The percentage change in surface roughness value ($\% \Delta R_a$) increases by increasing the reciprocation speed. This occurs due to reason that with increase in reciprocation speed the relative positions of abrasives at a place with respect to the workpiece surface changes continuously. It results in increase of material removal performance because during each stroke new abrasive particles are in action on the internal cylindrical blind hole workpiece surface. Thus improved performance is obtained.

Effect of Abrasive Volume Percentage

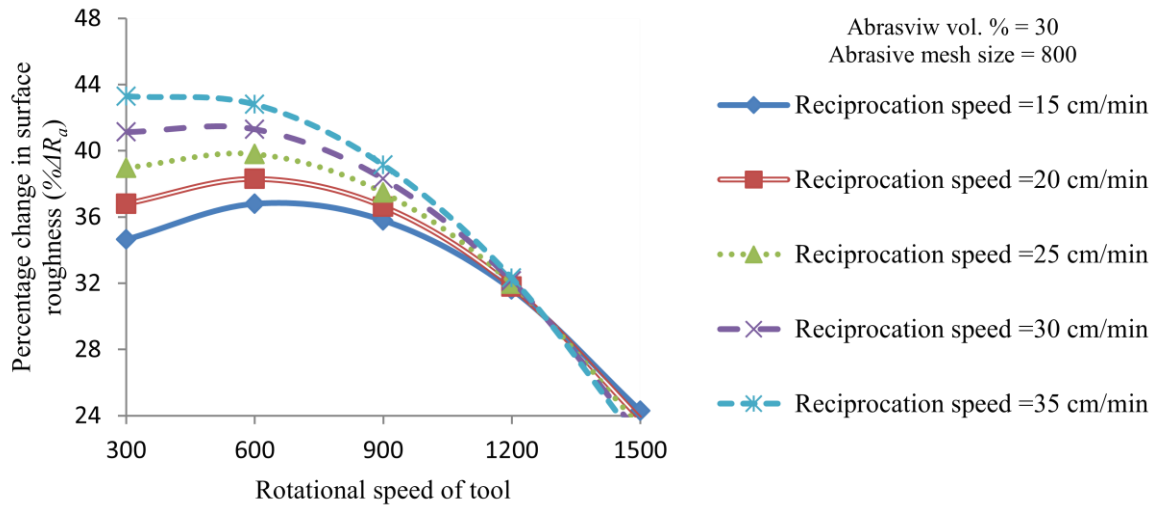
Figure 5.2(c) shows the variation of percentage change in surface roughness ($\%\Delta R_a$) with respect to abrasive volume percentage when finishing internal cylindrical surfaces of blind hole workpiece. The percentage change in surface roughness ($\%\Delta R_a$) firstly increases then decreases. As the volume percentage of abrasive particles in magnetorheological polishing fluid increases, the number of cutting edges available to perform finishing action also increases.

When the volume percentage of abrasive is increased, the amount of nonmagnetic abrasive particles in magnetorheological polishing fluid also increases. Since the magnetic particles are able to hold the nonmagnetic abrasive particles only up to some optimum concentration. However increasing the nonmagnetic abrasive particles concentration weakens the strength of MR polishing fluid chains, resulting in loss in finishing performance.

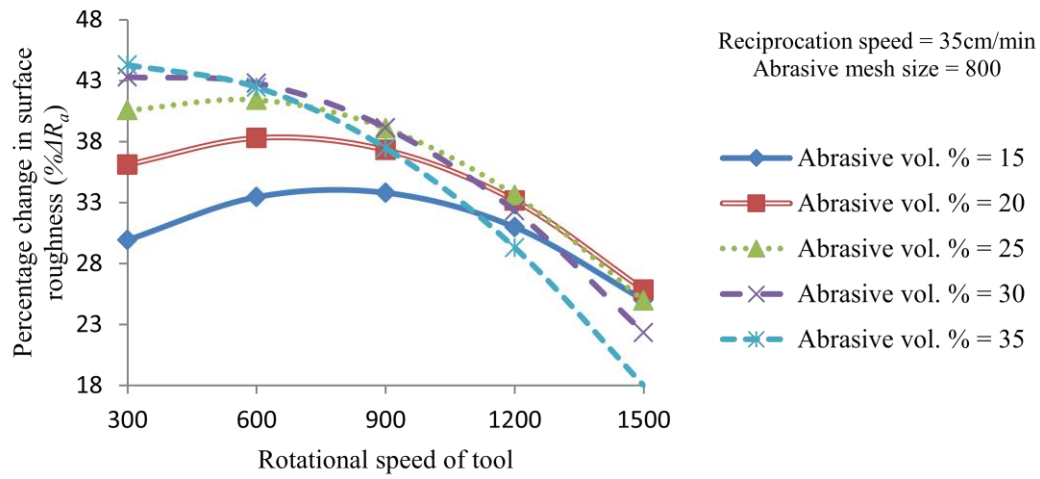
Effect of Abrasive mesh size

Figure 5.2(d) presents the variation of percentage change in surface roughness ($\%\Delta R_a$) by varying the abrasive volume percentage when finishing internal cylindrical surface of blind hole workpiece surface. The $\%\Delta R_a$ firstly increases then decreases. As the abrasive particle volume percentage in the magnetorheological polishing fluid increases, the number of available abrasive cutting edges to perform material removal also increases. When the volume percentage of abrasive is increased, the amount of nonmagnetic abrasive particles in magnetorheological polishing fluid is also increased. The magnetic particles are able to hold the nonmagnetic abrasive particles only up to some optimum concentration. However increasing the nonmagnetic abrasive particles concentration weakens the strength of MR polishing fluid chains, resulting in loss in finishing performance.

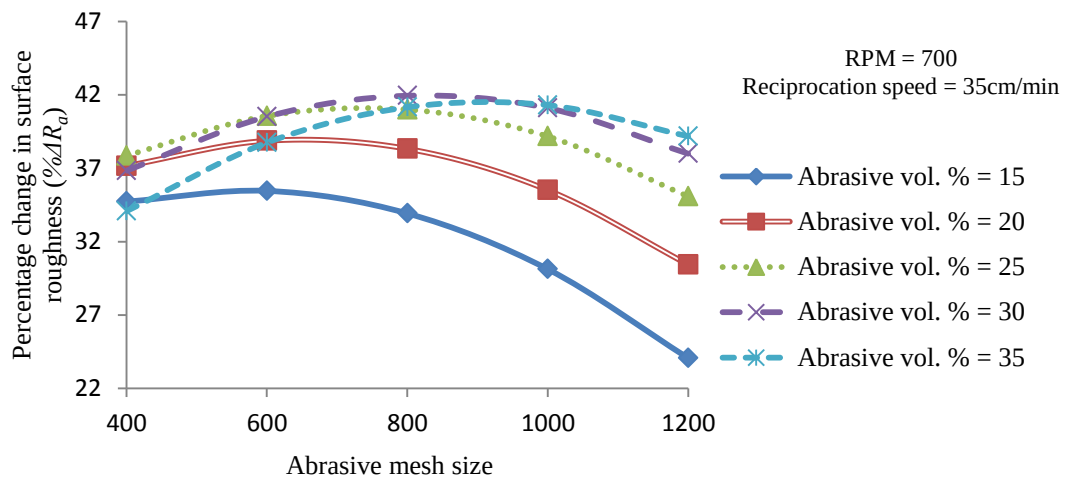
From Fig. 5.2 optimum parameters at which maximum $\%\Delta R_a$ is obtained are rotational speed of tool (RPM) of 700, reciprocation speed of 35 cm/min, abrasive volume percentage of 30% and abrasive mesh number of 800. Besides the process parameters, ANOVA table also revealed that the parameter interactions also have influence on $\%\Delta R_a$. The regression analysis revealed significant interaction between: (a) rotational speed (RPM) of tool and reciprocation speed (b) rotational speed (RPM) of tool and abrasive volume percentage (%) and (c) volume percentage of abrasive (%) and mesh number of abrasive.



(a)



(b)



(c)

Figure 5.3: Variation of percentage change in surface roughness with respect to (a) RPM and reciprocation speed and (b) RPM and abrasive volume percentage (c) abrasive volume percentage and abrasive mesh size

Effect of Interaction between Rotational Speed of Tool (RPM) and Reciprocation Speed

Figure 5.3(a) shows the variation of $\% \Delta R_a$ with respect to rotational speed of tool (RPM) and reciprocation speed at 30% of abrasive volume percentage and abrasive mesh number of 800. Initially at lower reciprocation speeds, the surface roughness ($\% \Delta R_a$) firstly increases then decreases. The reason is the number of abrasive particles performing finishing on workpiece surface per unit time increases with the increase in rotational speed of tool (RPM). With increase in rotational speed, the decrease in percentage change in surface roughness ($\% \Delta R_a$) occurs because the centripetal forces acting on the magnetic particles due to magnetic field at higher rotational speed is not sufficient to hold the abrasive particle in the chain. This results in breaking of the chains and drop in $\% \Delta R_a$. At lower rotational speed increase in reciprocation speeds the percentage change in surface roughness increases as there is continuous change in position of abrasive particles. When the reciprocation speed becomes very large it results in decrease in time the tool is performing finishing at particular position. At lower rotational speed increase in reciprocation speed has less effect on tool performance because MR polishing fluid is stiff enough to effectively perform finishing operation. Combining the more dominant effect of decrease in performance with increase in rotational speed with effect of higher reciprocation speed, the decrease in performance of tool is obtained.

Effect of Interaction between Rotational Speed of Tool and Abrasive Volume Percentage

Figure 5.3(b) shows the variation of $\% \Delta R_a$ with respect to rotational speed of tool and abrasive volume percentage at reciprocation speed of 35 cm/min and abrasive mesh number of 800. Initially at lower rotational speed of tool, with increase in volume percentage of abrasives the percentage change in surface roughness also increases. However with increase in the abrasive volume percentage, the number of non-magnetic particles in MR polishing fluid increases. This reduces the strength of stiffened MR polishing fluid. Combining the disadvantages of higher rotational speeds of tool and high abrasive volume percentage, it results in steep decrease of performance ($\% \Delta R_a$).

Effect of Interaction between Abrasive Volume Percentage and Abrasive Mesh Size

Figure 5.3(c) shows the relationship of $\% \Delta R_a$ with respect to abrasive volume percentage and abrasive mesh size at rotational speed of tool (RPM) = 700 and reciprocation speed = 35 cm/min. When low volume percentage of abrasives is used in MR polishing fluid, with decreasing the size of abrasive particles i.e. increasing mesh number, results in decrease in

$\% \Delta R_a$. This occurs because when the size of abrasive particles decreases the abrasive particles number in a given volume increases, however the combination of lesser number of abrasive particles available for material removal or finishing and inability of smaller particle to provide enough force for material removal results in significant decrease in performance. When the volume percentage of abrasive particles in MR polishing fluid is high, concentration of abrasive particles is higher and decreasing of size means more number of particles in MR polishing fluid which results in increase in $\% \Delta R_a$. Although at high abrasive concentration, the MR polishing fluid is weakened but excess number of available abrasive particles helps in increasing of performance.

Based on the results obtained during finishing and studying the variation process parameters the optimum parameters for finishing of internal surface of cylindrical blind hole workpiece have been decided. The optimum parameters selected are rotational speed of tool (RPM) = 700, reciprocation speed = 35 cm/min, abrasive volume percentage = 30 and abrasive mesh number of 800. The finishing was performed on these optimum parameters. Table 5.9 shows the variation of surface roughness with respect to time.

Table 5.9: Variation surface roughness with time at optimum parameters during finishing of internal cylindrical blind hole surface.

Time	Surface roughness (nm)	$\% \Delta R_a$
Initial	500	-
30 minutes	335	33
60 minutes	254	35.7
90 minutes	157	40.5
120 minutes	83	47.1

Figure 5.4 shows the decrease in surface roughness with finishing cycle time when finishing internal cylindrical surface of blind hole workpiece. The value of surface roughness was measured after every 30 minutes cycle. After two hours of finishing the surface roughness values decreased from initial value of 500 nm to 83 nm. Figure 5.5(a) shows the

initial surface roughness and Fig. 5.5(b) shows final roughness profile after 120 minutes of finishing on the internal cylindrical surface of blind hole workpiece.

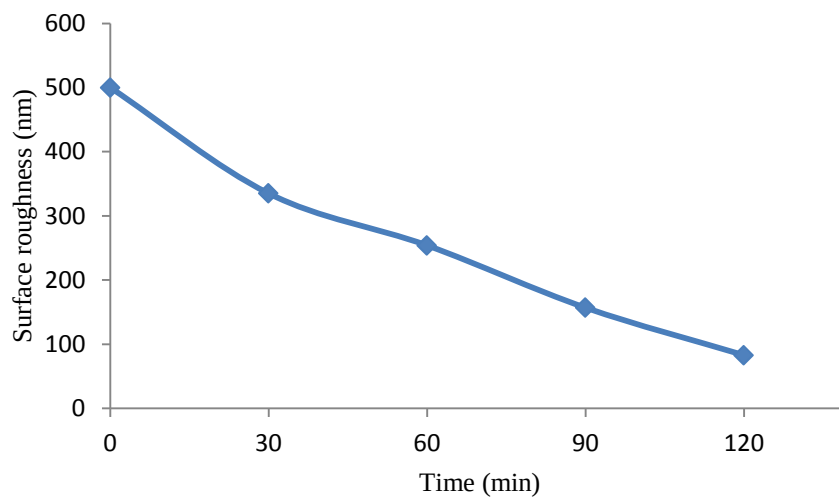


Figure 5.4: Change in surface roughness with time at optimum parameters during finishing of internal cylindrical surface of blind hole workpiece

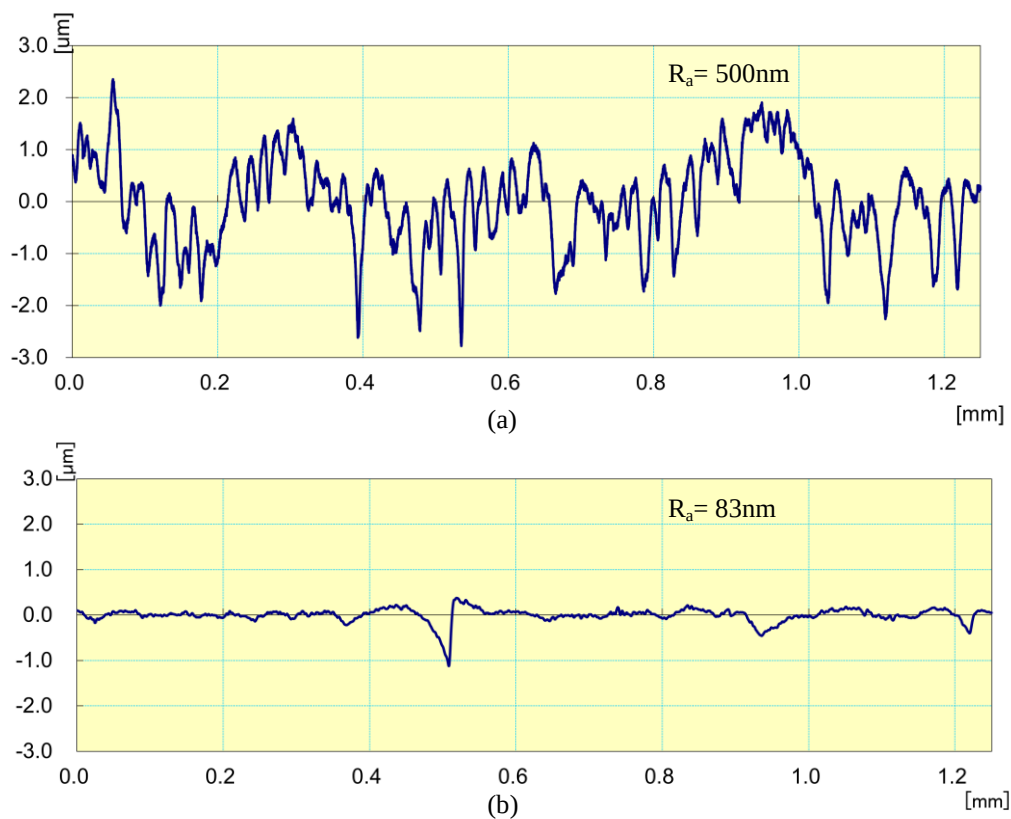


Figure 5.5: Surface roughness profiles of (a) initial surface and (b) final surface after 120 minutes at optimum parameters during finishing of internal cylindrical surface of blind hole workpiece.

The surface morphology for initial and final workpiece surface was observed optimum finishing conditions by using scanning electron microscopy (SEM) at 1000× as shown in Fig. 5.6(a) and Fig. 5.6(b), respectively. It can be seen from scanning electron microscopy images that the characteristics of the finished final surface are vastly improved compared with the initial workpiece surface.

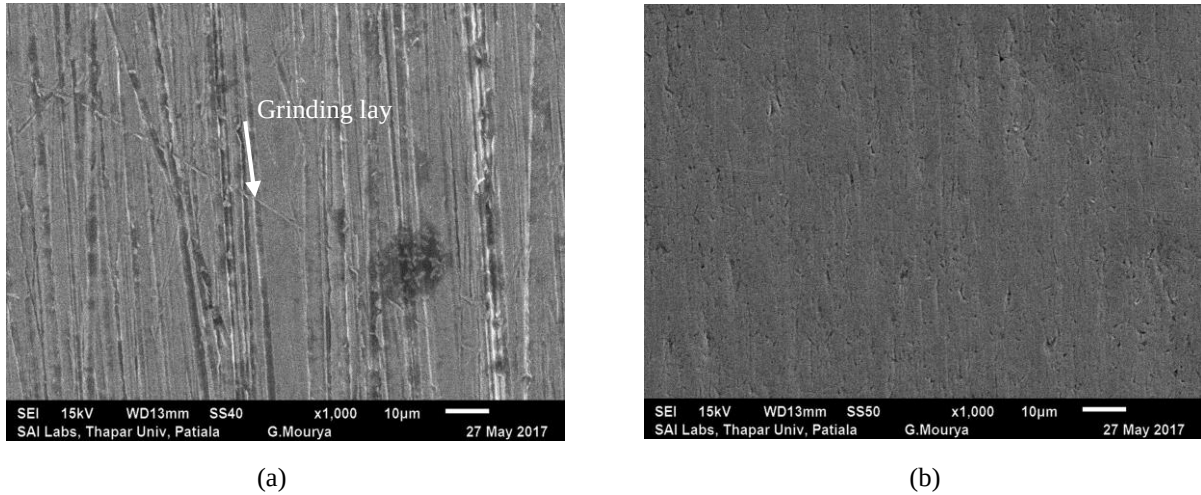


Figure 5.6: Surface morphology with scanning electron microscopy at 1000x (a) initial workpiece surface and (b) final finished surface obtained at optimum parameters during finishing of internal cylindrical surface of blind hole ferromagnetic workpiece

5.6.2 Experimental Analysis of Tool for Finishing Bottom Flat Blind Hole Surfaces

The percentage effect of various process parameters when finishing bottom flat surface of blind hole is shown in Fig. 12. Rotational speed, abrasive mesh size, and abrasive volume percentage are found to be process parameters which have significant influence on the percentage change in surface roughness. Rotational speed is the most significant parameter effecting the percentage change in surface roughness during finishing bottom surface of blind hole workpiece. The plot showing effect of process variables and their interactions on $\% \Delta R_a$ is shown in Fig. 5.8 and Fig. 5.9.

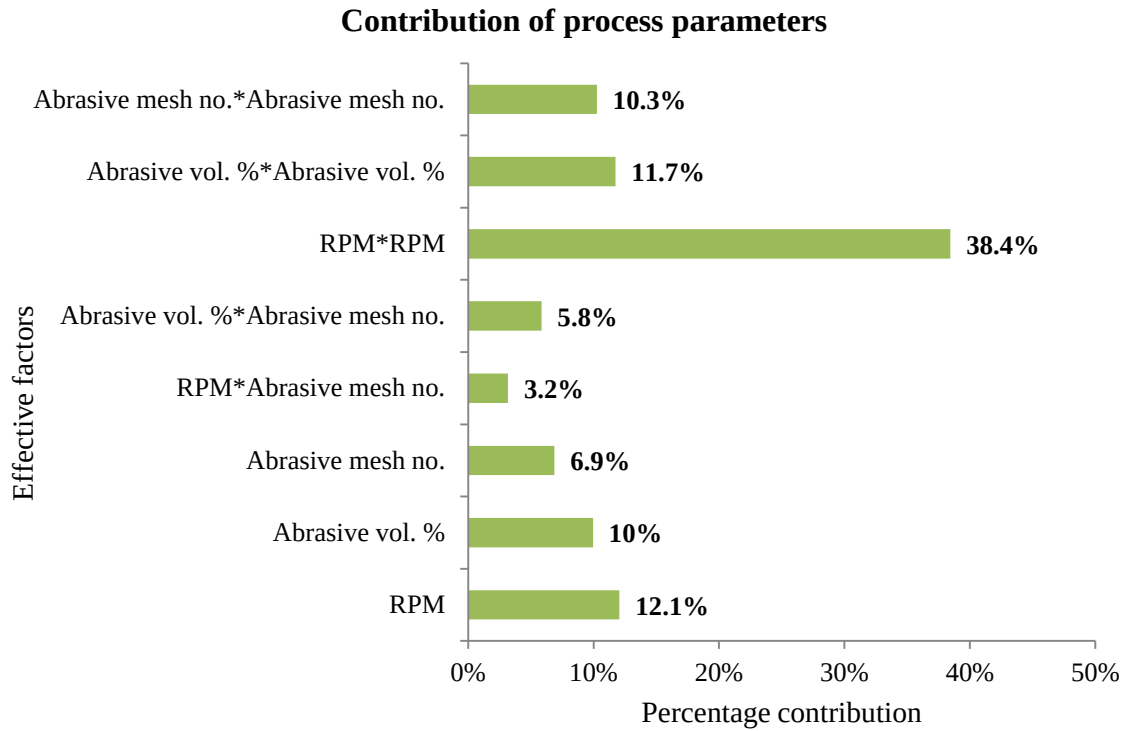


Figure 5.7: Contribution of various parameters on the percentage change in surface roughness during finishing of bottom flat surface of blind hole

Effect of Rotational Speed of Tool (RPM)

Figure 5.8(a) shows the relationship between percentage change in surface roughness ($\%\Delta R_a$) and rotational speed (RPM) of tool. The $\%\Delta R_a$ initially increases then decreases. This occurs because with increase in rotational speed (RPM) of tool, number of abrasives involved in micro cutting of roughness peaks per unit time on workpiece surface increase. The decrease in finishing performance occurs because the centrifugal force acting on the electrolytic iron particle (EIP) and active abrasives at higher rotational speed overcomes the forces due to magnetic field and becomes insufficient to hold the abrasive particle in the chain. This results in breakage of the EIP chains and loss on finishing performance.

Effect of Abrasive Volume Percentage

Figure 5.8(b) shows the variation of $\%\Delta R_a$ with abrasive volume percentage. With increase in the volume percentage of abrasive particles, it results in increase of numbers of active abrasive particles per unit area available for finishing. As a result the available numbers of cutting edges also increase which increases the number of point where material removal takes place thus increasing the $\%\Delta R_a$. As the abrasive volume percentage further increases, only

optimum number of non-magnetic abrasive particles can be retained by magnetic particle chains so decrease in performance occurs.

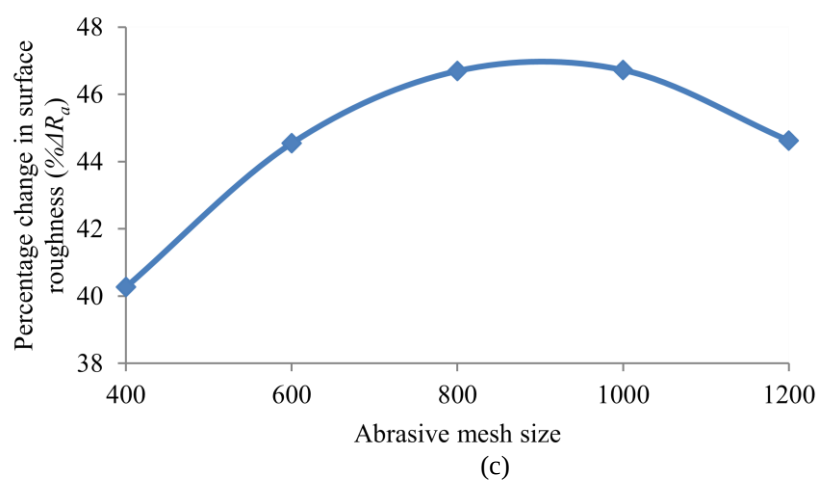
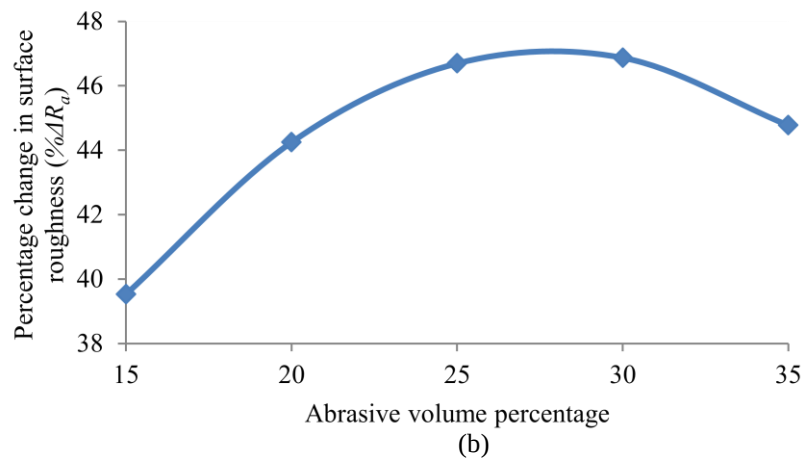
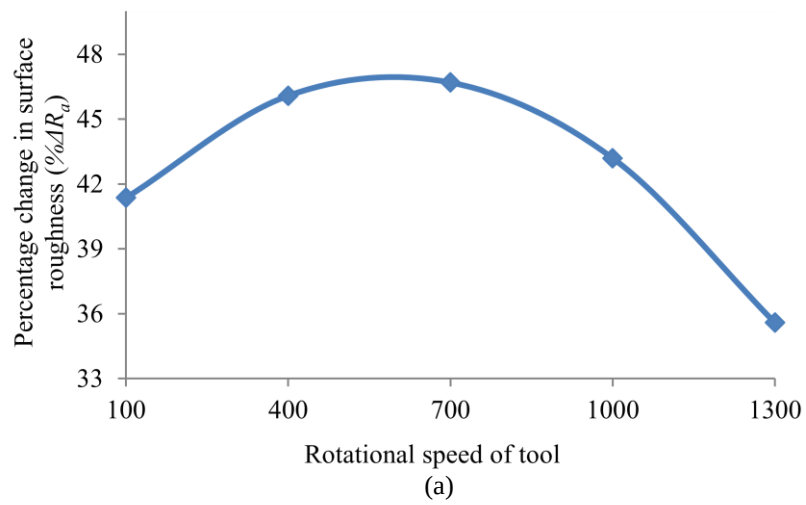


Figure 5.8: Variation of percentage change in surface roughness with respect to (a) rotational speed of tool, (b) abrasive volume percentage and (c) abrasive mesh size

Effect of Abrasive mesh size

Figure 5.8(c) shows the variation of percentage change in surface roughness ($\% \Delta R_a$) with respect to abrasive mesh number when finishing internal cylindrical surface of blind hole. It shows that decreasing the mesh size of abrasive, the number of abrasive particles in the MR polishing fluid increases which in turn increases the points where finishing occurs thus increasing the $\% \Delta R_a$. As the size gets smaller the abrasive particles lose their potency to perform finishing on the workpiece surface.

From Fig. 5.8 the optimum parameters at which maximum $\% \Delta R_a$ is obtained are rotational speed of tool (RPM) = 600, abrasive volume % = 30 and abrasive mesh number 1000. The finishing was performed on these optimum parameters. Apart from process parameters, the ANOVA table revealed that the parameter interactions also have influence on $\% \Delta R_a$. The significant interaction that ANOVA revealed are (a) rotational speed of tool (RPM) and mesh number of abrasive particles (b) abrasive volume percentage and mesh number of abrasive particles.

Effect of Interaction between Rotational Speed of Tool and Abrasive Mesh Size

Figure 5.9(a) shows the $\% \Delta R_a$ with respect to tool rotational speed (RPM) and abrasive mesh number at abrasive volume % = 30. As the RPM of the tool increases, interaction between abrasive and workpiece per unit time also increase. At high speed the centripetal forces acting on the magnetic electrolytic iron particle (EIP) due to magnetic field becomes insufficient to hold the abrasive particle in the EIP chains at higher rotational speed. These results in breakage of the chains and hence drop in finishing performance. With decrease in size of abrasive particles, the number of abrasive particle in given volume of MR polishing fluid also increases. As a result performance of tool increases but as the size becomes too small it loses potency to finish. At low rotational speed, the small size abrasives which are in large quantity overcome the impotency to finish and improve finishing performance. Combining the effect of small size of abrasive and high rotational speed, the steep decrease in performance is observed.

Effect of Interaction between Abrasive Volume Percentage and Abrasive Mesh Size

Figure 5.9(b) shows combined effect of volume percentage of abrasive particles and mesh size of abrasive on percentage change in surface roughness at rotational speed of tool (RPM) = 600. Decreasing the mesh size of abrasive particles results in increasing of $\% \Delta R_a$ at higher

concentration of abrasive particles. This is because more number of abrasive particles are available for finishing workpiece surface which overcome the impotency of smaller abrasive particles to perform finishing on the blind hole workpiece surface. The quantity small sized abrasive particles at high abrasive volume percentage are so high that improvement in finishing performance occurs.

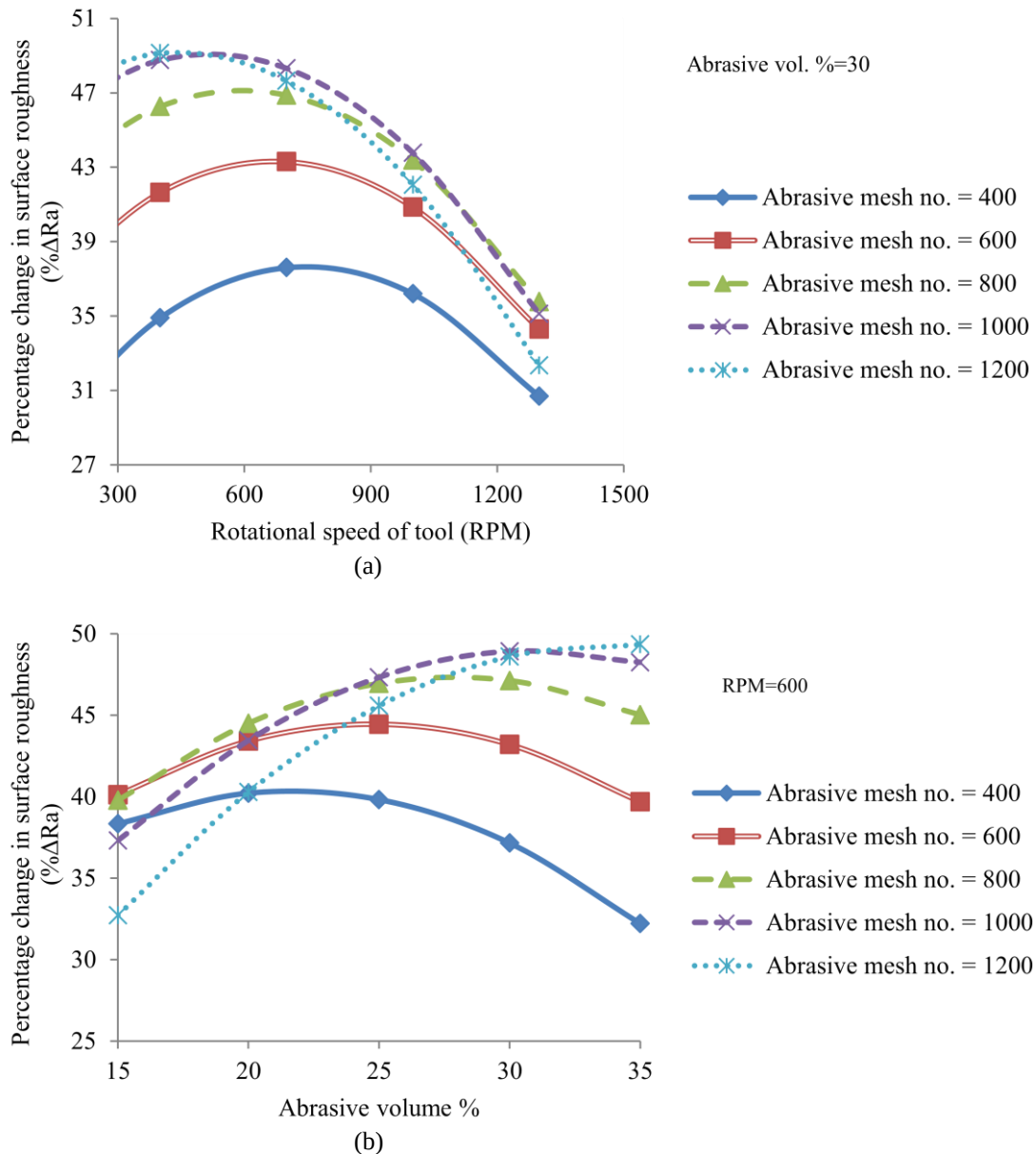


Figure 5.9: Effect of (a) rotational speed of tool and abrasive mesh size and (b) abrasive volume percentage and abrasive mesh size on percentage change in surface roughness during finishing of internal cylindrical surface of blind hole

Based on the results obtained during finishing and studying the variation process parameters the optimum parameters have been decided. The optimum parameters selected are rotational speed of tool (RPM) = 600, abrasive volume % = 30 and abrasive mesh number 1000. The finishing was performed on these optimum parameters. Table 5.10 shows the variation of surface roughness with respect to time. After two hours of finishing the surface roughness values decreased from initial value of 621 nm to 93 nm. The value of surface roughness was measured after every 30 minutes.

Table 5.10: Variation surface roughness with time at optimum parameters during finishing of flat bottom blind hole surface

Time	Surface roughness (nm)	$\% \Delta R_a$
Initial	621	-
30 minutes	401	35.42673
60 minutes	275	31.42145
90 minutes	167	39.27273
120 minutes	93	44.31138

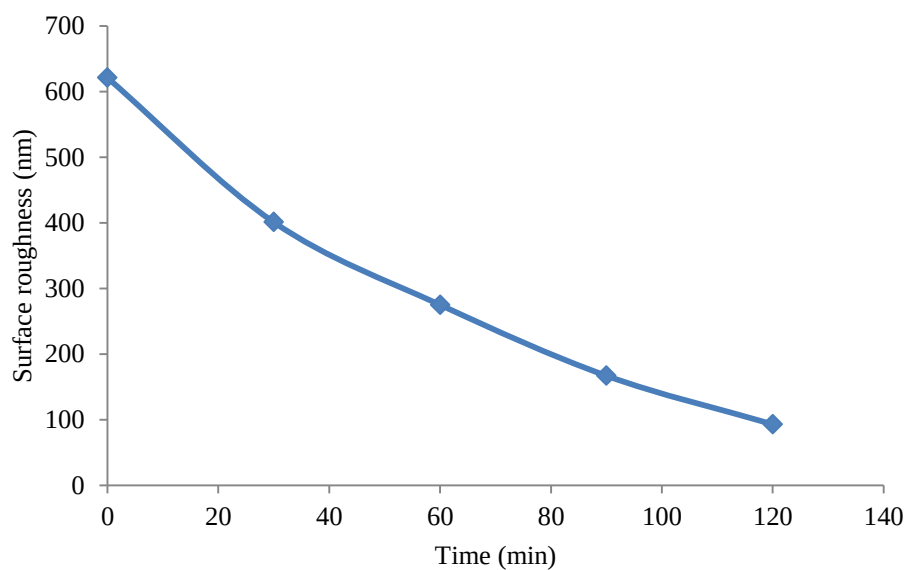
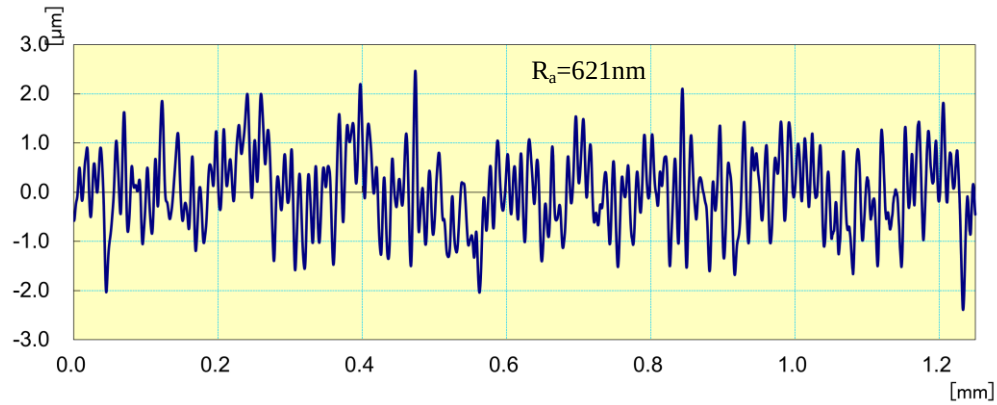
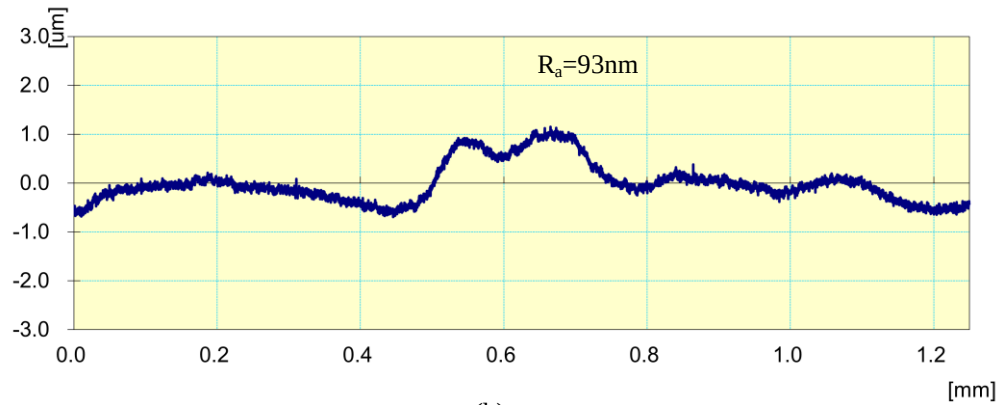


Figure 5.10: Change in surface roughness with time at optimum parameters during finishing of bottom flat surface of blind hole workpiece



(a)



(b)

Figure 5.11: Surface roughness profiles of (a) initial surface and (b) final surface after 120 minutes of finishing at optimum parameters for flat bottom surface finishing tool

Figure 5.10 shows the variation of surface roughness with time when finishing bottom flat surfaces of blind holes. Figure 5.11(a) shows the initial surface roughness and Fig. 5.11(b) shows final roughness profile after 120 minutes of finishing at optimum parameters on the bottom face of blind hole workpiece.

Figure 5.12(a) and Fig. 5.12(b) show the surface morphology using scanning electron microscopy (SEM) for initial and final workpiece surface at 1000 $\times$ resolution. The surface morphology was observed after finishing at optimum conditions. Vast improvement in the characteristics of the finished final surface compared with the initial workpiece surface can be seen from scanning electron microscopy images.

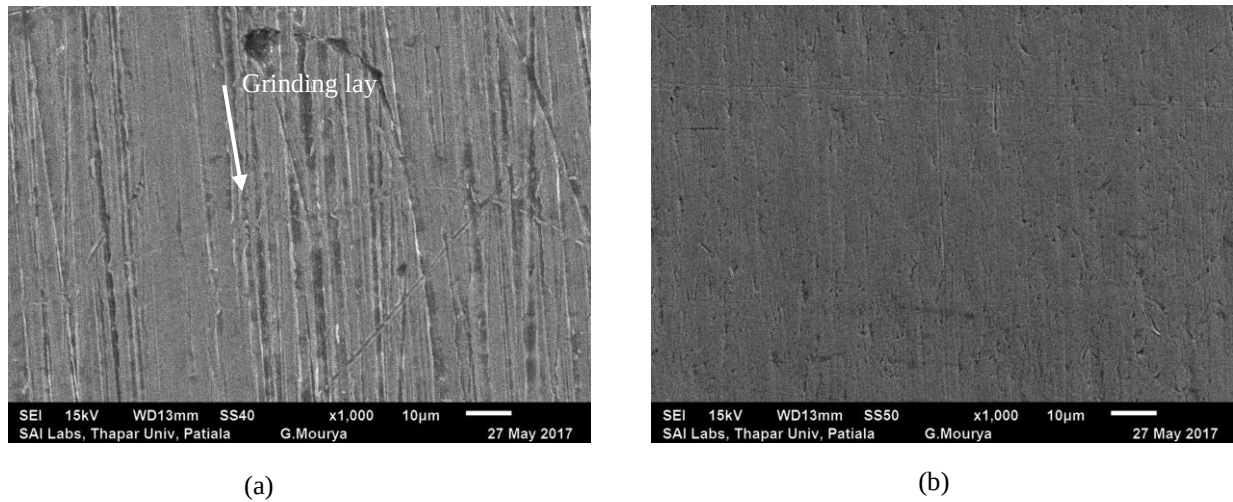


Figure 5.12: Surface morphology with scanning electron microscopy at 1000x (a) initial workpiece surface and (b) final finished surface obtained at optimum parameters during finishing of flat surface of blind hole ferromagnetic workpiece

5.7 Confirmatory Experiments for Model Validation

In order to validate the precision and accuracy of developed models for both the tools, confirmatory experiments for model validation were carried out. These values lie within the ranges for which the formula has been calculated. Three experiments for each tool were carried out. Table 5.11 and Table 5.12 provides the comparison of percentage change in surface roughness values between experimental values and those obtained from developed mathematical model. From the results it can be seen that maximum difference between experimental and derived model value is -8.4% for internal surface finishing tool and -9.6% for finishing bottom surface of blind hole workpiece. This shows good agreement between experimental and derived model values of percentage change in surface roughness.

It can be concluded from the above research that the developed magnetorheological finishing process is capable of improving the surface quality. Hence the newly developed magnetorheological finishing process is capable of finishing the blind hole surfaces. The improvement in surface quality results in enhancement of wear, corrosion resistance, oxidation resistance loss of power due to friction and improvement in fatigue life and toughness.

Table 5.11: Confirmatory tests and their comparison with the results during finishing of internal cylindrical blind hole surface

Time	Experimental conditions				Experimental $\% \Delta R_a$	Predicted $\% \Delta R_a$	Error (%)
	RPM	Reciprocation speed (cm/min)	Abrasive Volume %	Abrasive mesh number			
45	600	25	30	600	35.37	38.37	-8.4
45	900	30	25	1000	34.73	36.43	-4.9
45	1200	20	20	800	30.41	32.63	-7.3

Table 5.12: Confirmatory tests and their comparison with the results during finishing of flat bottom blind hole surface

Time (min)	Experimental conditions			Experimental $\% \Delta R_a$	Predicted $\% \Delta R_a$	Error (%)
	RPM	Abrasive volume %	Abrasive mesh number			
45	700	30	600	40.38	43.29691	-7.2
45	400	25	1000	49.8	47.15896	5.3
45	1000	20	800	37.2	40.74852	-9.6

5.8 Conclusions

The performance of newly developed tools for finishing internal and flat bottom surfaces of ferromagnetic cylindrical blind hole workpiece has been evaluated. The experimental study for finishing of ferromagnetic (P20 tool steel) blind hole workpiece was successfully carried out. Response surface methodology using central composite design (CCD) technique has been utilized for statistical design of experiment and analysis of various parameters on percentage change in surface roughness. Analysis of design of experiments leads to following conclusions:

- The tools fabricated using permanent magnets are capable of finishing ferromagnetic (P20 tool steel) blind hole surfaces of specified dimensions.

- Rotational speed has significant effect on percentage change followed by abrasive volume, reciprocation speed and abrasive mesh number in surface roughness during finishing of internal cylindrical blind hole workpiece.
- During the finishing of bottom flat surfaces of blind hole workpiece, rotational speed is the most significant parameter followed by abrasive volume and abrasive mesh number.
- Finishing internal cylindrical surface of blind hole at optimum parameters for 120 minutes (RPM = 700, reciprocation speed = 35 cm/min, abrasive volume % = 30 and abrasive mesh number 800) results in 83 nm of surface finish and 83.4 % decrease in surface roughness.
- Finishing bottom flat surface of blind hole at optimum parameters for 120 minutes (RPM = 600, abrasive volume % = 30 and abrasive mesh number 1000) results in 93 nm of surface finish and 85 % decrease in surface roughness.

Chapter 6

Conclusions and Scope of Future Work

6.1 Conclusions

The design and development of new magnetorheological finishing process for finishing blind hole surfaces has been carried out. The main conclusions derived after experimentation, modeling and simulation are as follows.

- The higher magnetic flux gradient at the tool end surface and it decreases in the gap towards the tool. This variation in magnetic flux density inside the helps to keep the MR polishing fluid sticking with the tool end surface.
- Theoretical calculated value of surface roughness for either tool is found in good agreement with experimental value. In tool for finishing internal cylindrical surfaces R_a value was within 6.26 % whereas in tool for finishing blind hole bottom surface it was found within 7.9%. The % error while finishing blind hole flat bottom surface is more as there is no change in relative position of abrasive particles.
- The process has been optimized for finishing blind hole surface of P20 tool steel workpiece. Response surface methodology technique and central composite design for design of experiments have been utilized for experimental investigation of magnetorheological finishing tools for blind hole surfaces.
- The process parameters like rotational speed, reciprocation speed and abrasive mesh size are selected while finishing internal cylindrical blind hole surface.
- Rotational speed, abrasive mesh size, and abrasive volume percentage are the process parameters selected to study their influence the change in surface roughness while finishing bottom flat surfaces of blind hole workpiece.
- Rotational speed has significant effect on percentage change followed by abrasive volume, reciprocation speed and abrasive mesh number in surface roughness during finishing of internal cylindrical blind hole workpiece.
- During the finishing of bottom flat surfaces of blind hole workpiece rotational speed is the most significant parameter followed by abrasive volume and abrasive mesh number.
- Finishing internal cylindrical surfaces at optimum parameters for 120 minutes (RPM = 700, Reciprocation speed = 35 cm/min, Abrasive volume % = 30 and Abrasive mesh

number 1000) results in 83.4 % change in surface roughness and 83 nm of surface finish.

- Finishing bottom flat surfaces at optimum parameters for 120 minutes (RPM = 600, Abrasive volume % = 30 and Abrasive mesh number 1000) results in 85 % change in surface roughness and 93 nm of surface finish.
- The newly developed process showed that significant improvement in surface finish for finishing of both internal and bottom flat surfaces of cylindrical blind hole type workpiece. The results are also ratified from the microscopic study of surfaces with scanning electron microscopy.
- Surface finish enhanced the functional properties and mechanical properties of an engineering component such as wear resistance, loss of power due to friction, corrosion resistance, oxidation resistance, fatigue life and toughness etc.
- Finishing of blind hole surfaces find extensive application in dies and automotive components such as automobile actuators, cylinder body, valve seats etc.

6.2 Scope of Future Work

This report is study of development of magnetorheological finishing process for blind hole surfaces. The present work provides significant potential for future work.

- Development of single magnetorheological finishing tool for finishing blind hole surfaces.
- Effect of using different shapes of permanent magnets for enhancement in finishing performance by redesigning of both the tools.
- Effect of magnetic particle size on finishing performance of both tools when finishing P20 tool steel workpiece.
- Development of variable diameter tool using permanent magnets for MR finishing of different size of blind hole surfaces.

References

- Bagnoud V., Guardalben M. J., Puth J., Zuegel J. D., Mooney T. and Dumas P., “High-energy, high-average power laser with Nd:YLF rods corrected by magnetorheological finishing,” *Applied Optics*, **44:2**, 282–288 (2005).
- Bedi T. S. and Singh A. K., “A new magnetorheological finishing process for ferromagnetic cylindrical honed surfaces”, *Materials and Manufacturing Processes*, (2016), DOI.10.1080/10426914.2016.1269925.
- Bedi T. S. and Singh A. K., “Magnetorheological methods for nanofinishing- a review”, *Particulate Science and Technology*, **34:4**, 412-422 (2016).
- Camacho J. M. and Sosa V., “Alternative method to calculate the magnetic field of permanent magnets with azimuthal symmetry”, *Revista Mexicana de Física E*, **59**, 8–17 (2013).
- Cheng H. B., Yam Y. and Wang Y. T., “Experimentation on MR fluid using a 2-axis wheel tool”, *Journal of Materials Processing Technology*, **209**, 5254–5261 (2009).
- Das M., Jain V. K. and Ghoshdastidar P. S., “Nano-finishing of stainless-steel tubes using rotational magnetorheological abrasive flow finishing process” *Machining Science and Technology*, **14:3**, 365-389 (2010).
- Fallböhmer P., Rodríguez C. A., Özel T., and Altan T., “High-speed machining of cast iron and alloy steels for die and mold manufacturing”, *Journal of Materials Processing Technology*, **98(1)**, 104–115 (2000).
- Feng Z., Cheng H., Wang Y. and Lei S., “Magnetorheological Finishing of SiC Aspheric Mirrors” *Materials and Manufacturing Processes*, **20:6**, 917–931 (2005).
- Gheisari R., Ghasemi A.A., Jafarkarimiand M. and Mohtaram S., “Experimental studies on the ultra-precision finishing of cylindrical surfaces using magnetorheological finishing process”, *Production & Manufacturing Research*, **2:1**, 550–557 (2014).
- Ghosh A. and Mallik A. K., “Manufacturing science”, *Affiliated East-West Press Pvt. Ltd.* (2010) ISBN-10. 8176710636.
- Golini D., Kordonski W. I., Dumas P. and Hogan S., “Magnetorheological finishing (MRF) in commercial precision optics manufacturing”, *Proceeding of SPIE Conference on Optical Manufacturing and Testing*, **3782**, 80–91 (1999).
- Isobe H., Hara K., Kyusojin A., Okada M., and Yoshihara H., “Ultrasonically assisted grinding for mirror surface finishing of dies with electroplated diamond tools”,

- International Journal of Precision Engineering and Manufacturing*, **8(2)**, 38–43 (2007).
- Jain V. K., “Abrasive-Based Nano-Finishing Techniques: An Overview” *Machining Science and Technology*, **12**, 257–294 (2008).
- Jain V. K., “Advanced Machining Processes”, *Allied Publishers Pvt. Ltd., Delh*, (2002).
- Jain V. K., “Introduction to Micromachining”, *Alpha Science International Ltd; 2nd Revised edition edition*. (2014) ISBN-13. 978-1842658918.
- Jain V. K., “Magnetic field assisted abrasive based micro-/nano-finishing”, *Journal of Materials Processing Technology*, **209**, 6022–6038 (2009).
- Jang K., Kim D., Maeng S., Lee W., Han J., Seok J., Je T., Kang S. and Min B., “Deburring microparts using a magnetorheological fluid” *International Journal of Machine Tools & Manufacture*, **53**, 170–175 (2012) DOI:10.1016/j.ijmachtools.2011.11.002.
- Jang K., Seok J., Min B. and Lee S. J., “An electrochemomechanical polishing process using Magnetorheological fluid” *International Journal of Machine Tools & Manufacture*, **50**, 869–881 (2010) DOI:10.1016/j.ijmachtools.2010.06.004.
- Jha S. and Jain V. K., “Design And Development of Magnetorheological Abrasive Flow Finishing Process” *International Journal of Machine Tools and Manufacture*, **44:10**, 1019–1029 (2004).
- Jha S. and Jain V. K., “Nanofinishing of silicon nitride workpieces using magnetorheological abrasive flow finishing”, *International Journal of Nanomanufacturing*, **1:1**, 17–25 (2006).
- Jha S. and Jain V. K., “Modeling and simulation of surface roughness in magnetorheological abrasive flow finishing (MRAFF) process”, *Wear*, **261**, 856–866 (2006).
- Jha S., Jain V. K. and Komanduri R., “Effect of extrusion pressure and number of finishing cycles on surface roughness in Magnetorheological Abrasive Flow Finishing (MRAFF) process”, *The International Journal of Advanced Manufacturing Technology*, **33:7-8**, 725–729 (2007).
- Jung B., Jang K., Min B., Lee S. J. and Seok J. “Magnetorheological finishing process for hard materials using sintered iron-CNT compound abrasives”, *International Journal of Machine Tools & Manufacture*, **49**, 407–418 (2009).
- Kang J. and Yamaguchi H., “Internal finishing of capillary tubes by magnetic abrasive finishing using a multiple pole-tip system”, *Precision Engineering*, **36**, 510–516 (2012).

- Kheradmand S., Esmailian M. and Fatahy A., “A novel approach of magnetorheological abrasive fluid finishing with swirling-assisted inlet flow”, *Results in Physics*, **6**, 568–580 (2016).
- Kordonski W. I. and Jacobs S. D., “Magnetorheological finishing” *International Journal of Modern Physics*, **10:23-24**, 2837–2848 (1996).
- Kordonski W. I. and Golini D., “Progress update in Magnetorheological finishing” *International Journal of Modern Physics B*, **13:14-16**, 2205–2212 (1999).
- Kordonski W. I., Shorey A. and Tricard M., “Magnetorheological jet finishing technology.” *Transactions of ASME*, **128**, 20-26 (2006).
- Kordonski W. I., Shorey A. B. and Sekers A., “New Magnetically Assisted: Material Removal with Magnetorheological Fluid Jet”, *Proceedings SPIE*, **5180**, 107–114 (2004).
- Kordonski W. I., Shorey A. B., and Tricard M., “Magnetorheological Jet Finishing Technology”, *Proceedings of IMECE04-2004 ASME International Mechanical Engineering Congress*, (2006a).
- Kordonski W. I., Tricard M., Shorey A. B. and Evans C., “ Magnetorheological jet finishing of conformal, freeform and steep concave optics”, *CIRP Annals-Manufacturing Technology*, **55:1**, 309–312 (2006b).
- Lambropoulo S. J., Yang F. and Jacob S. D., “Optical fabrication and testing”, *Technical digest series(Optical Society of America, Washington DC)*, **7**, 150–153(1996).
- Liu X., Wang L., Lu H., Wang D., Chen Q. and Wang Z., “A Study of the Effect of Nanometer Fe₃O₄ Addition on the Properties of Silicone Oil-based Magnetorheological Fluids” *Materials and Manufacturing Processes*, **30**, 204–209 (2015), DOI: 10.1080/10426914.2014.941875.
- Maan S., Singh G., Singh A. K., “Nano-Surface-Finishing of Permanent Mould Punch Using Magnetorheological Fluid Based Finishing Processes”, *Materials and Manufacturing Processes*, (2016), DOI: 10.1080/10426914.2016.1232823
- Paswan S. K., Bedi T. S. and Singh A. K., “Modeling and simulation of surface roughness in magnetorheological fluid based honing process”, *Wear*, (2016). DOI.10.1016/j.wear.2016.11.025.
- Pattanaik L.N. and Agarwal H., “Development of Magnetorheological Finishing (MRF) Process for Freeform Surfaces”, *International Journal of Advanced Mechanical Engineering*, **4:6**, 611–618(2014).

- Phulé P., “Magnetorheological (MR) fluids: principles and applications” *Smart Materials Bulletin*, **2**, 7–10(2001).
- Rabinow J., “The magnetic fluid clutch” *Electrical Engineering*, **67:12**, 1167-1167 (1948).
- Sadiq A. and Shunmugam M. S., “Investigation into Magnetorheological abrasive honing (MRAH)”, *International Journal of Machine Tools & Manufacture*, **49**, 554–560 (2009)DOI:10.1016/j.ijmachtools.2009.02.009.
- Sadiq A. and Shunmugam M. S., “A novel method to improve finish on non-magnetic surfaces in magnetorheological abrasive honing process”*Tribology International*, **43**, 1122–1126 (2010) DOI:10.1016/j.triboint.2009.12.038.
- Sarkar C. and Hirani H., “Effect of Particle Size on Shear Stress of Magnetorheological Fluids”, *Smart Science*, **3:2**, 65–73 (2015).
- Seok J., Kim Y., Jang K., Min B. and Lee S. J., “A study on the fabrication of curved surfaces using Magnetorheological fluid finishing”, *International Journal of Machine Tools & Manufacture*, **47**, 2077–2090 (2007).
- Seok J., Lee S. O., Jang K., Min B. and Lee S. J., “Tribological Properties of a Magnetorheological (MR) Fluid in a Finishing Process” *Tribology Transactions*, **52:4**, 460-469 (2009) DOI: 10.1080/10402000802687932.
- Singh A. K, Jha S. and Pandey P. M., “Nanofinishing of a typical 3D ferromagnetic workpiece using ball end magnetorheological finishing process”, *International Journal of Machine Tools and Manufacture* , **63:0**, 21–31 (2012b).
- Singh A. K., Jha S. and Pandey P. M., “Design and development of nanofinishing process for 3D surfaces using ball end MR finishing tool”, *International Journal of Machine Tools and Manufacture*,**51:2**, 142–151 (2011).
- Singh A. K., Jha S. and Pandey P. M., “Magnetorheological Ball End Finishing Process”, *Materials and Manufacturing Processes*, **27**, 389–394, (2012a), DOI: 10.1080/10426914.2011.551911.
- Singh A. K., Jha S. and Pandey P. M., “Mechanism of material removal in ball end magnetorheological finishing process”, *Wear*, **302**, 1180–1191 (2013).
- Singh A. K., Jha S. and Pandey P. M., “Nanofinishing of Fused Silica Glass Using Ball-End Magnetorheological Finishing Tool”, *Materials and Manufacturing Processes*, **27:10**, 1139–1144 (2012c).
- Singh D. K., Jain V. K. and Raghuram V., “Parametric study of magnetic abrasive finishing process”, *Journal of Materials Processing Technology*, **149**, 22–29 (2004).

- Singh G., Singh A. K. and Garg P., “Development of magnetorheological finishing process for external cylindrical surfaces” *Materials and Manufacturing Processes*, (2016) DOI: 10.1080/10426914.2016.1221082.
- Song W., Choi S., Choi J. and Lee C., “Wear and Friction Characteristics of Magnetorheological Fluid under Magnetic Field Activation” *Tribology Transactions*, **54:4**, 616–624(2011) DOI: 10.1080/10402004.2011.584365.
- Spaggiari A., “Properties and applications of Magnetorheological fluids”, *Frattura ed Integrità Strutturale*, **23**, 57–61(2013).
- Stradling A. W., “The physics of open-gradient dry magnetic separation”, *International Journal of Mineral Processing*, **39**, 19–29 (1993).
- Taniguchi N., “Current status in, and future trends of ultraprecision machining and ultrafine material processing” *Annals of CIRP*, **32:2**, 573–582 (1983).
- Verma G. C., Kala P., and Pandey P.M., “Experimental investigations into internal magnetic abrasive finishing of pipes”, *International Journal of Advanced Manufacturing Technology*, 1–12 (2016). DOI: 10.1007/s00170-016-8881-0.