

EXPERIMENTAL INVESTIGATIONS OF MAGNETORHEOLOGICAL HONING PROCESS FOR IMPROVED FINISHING OF FERRO-MAGNETIC MATERIALS

A Thesis submitted in fulfillment of the requirement for the award of the degree of

**DOCTOR OF PHILOSOPHY
IN
MECHANICAL ENGINEERING**

Submitted by

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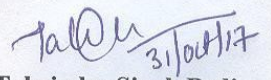
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CERTIFICATE

I, **Talwinder Singh Bedi**, Roll No. 901408002, hereby declared that the thesis entitled **“Experimental Investigations of Magnetorheological Honing Process for Improved Finishing of Ferro-Magnetic Materials”** submitted to the Department of Mechanical Engineering at Thapar University, Patiala, Punjab (India) is an authenticated record of my own work for the award of the degree “Doctor of Philosophy” under the supervision of **Dr. Anant Kumar Singh**. This report has not been submitted to any other institute for the award of any other degree.


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ABSTRACT

The various ferromagnetic cylindrical components such as injection barrel, cylindrical mold and die, hydraulic cylinders etc. are now-a-days of being a greater demand in the manufacturing industry. Today, these components are mainly finished by the traditional finishing processes namely; grinding and honing. During the finishing processes, the uncontrollable finishing forces provided by the rigid abrasive stones on the internal surface of the cylindrical workpiece which may result in various surface defects such as deeper grooves, cavities, grooves with sharper edges and ploughed materials. Such defects decrease the efficiency as well as the reliability of the cylindrical components during its actual functional applications in industries. The requirement of the highly finished surface (i.e. defect-free surface) is still important challenged in today's industry for producing a precise finish surface. The better surface characteristics requirement on these components can lead to the closer tolerance design, better surface geometry, and longer service life etc. Also, the functional capability of a surface mainly depends on the load - bearing capacity, wear and friction resistance, and fatigue strength etc. which mainly controlled by reducing the surface roughness values.

The existing developed magnetorheological (MR) fluid based finishing processes such as magnetorheological abrasive flow finishing (MRAFF) and rotational-magnetorheological abrasive flow finishing (R-MRAFF) are found more suitable for precise finishing of the internal surface of the non-ferromagnetic cylindrical workpieces made with materials such as stainless steel, brass etc. But, due to its design structure, it is likely less effective in finishing of the internal surface of ferromagnetic cylindrical workpieces. The reason is that the electromagnet is located outside the cylindrical workpiece and MR polishing fluid inside the cylindrical workpiece. Therefore, the higher magnetic flux density gradient is obtained on the internal ferromagnetic cylindrical surface than the MR polishing fluid. This result in MR polishing fluid gets stuck on the internal surface of the ferromagnetic cylindrical workpiece. Thus, there is no relative motion can be possible between the MR polishing fluid and the internal surface of the ferromagnetic cylindrical workpiece during the finishing operation. These processes are found most suitable for significant finishing of the internal surface of the non-ferromagnetic cylindrical workpiece than the ferromagnetic cylindrical workpiece.

In present research work, to overcome these challenges, a new MR honing process is developed for precise finishing of the internal surface of the ferromagnetic cylindrical workpiece. The

finishing tool has been designed along with electromagnet and made to move together inside the cylindrical ferromagnetic workpiece surface and finished the internal surface by its rotational as well as reciprocation movement like the honing tool movement with controlled magnetic field. The newly designed finishing tool provided a uniform level of finishing as its entire outer surface obtained a uniform magnetic flux density which is more useful to provide better in closer tolerance design, higher bearing load capacity and longer service life in various cylindrical machine components. This new tool design has ensured the higher magnetic flux density gradient at outer finishing tool core surface than the internal surface of ferromagnetic cylindrical workpiece. As a result, the MR polishing fluid always retained on the outer finishing tool core surface and the required relative motion can be possible between the internal surface of the ferromagnetic cylindrical workpiece and the MR polishing fluid during the actual finishing operation. This is an important need to get finishing on the internal surface of the ferromagnetic cylindrical workpiece. The developed process can be found effective in enhancement of surface characteristics (i.e. by removing the various surface defects) of traditionally finished internal surfaces of ferromagnetic cylindrical workpieces.

In present work, the MR honing tools (i.e. I-shaped core type and rectangular shaped core type) have been designed to ensure the maximum magnetic flux density always to be obtained on the outer finishing tool core surface as compared to the ferromagnetic cylindrical workpiece surface. To validate this present proposed design, the magnetostatic finite element analysis (FEA) has been carried out by using Maxwell Ansoft V13 (student version) software on the newly designed finishing tools. The finishing tool with rectangular shaped core has been found more suitable for providing a uniform level of finishing than the tool with I-shaped core as its entire outer finishing surface obtained a uniform magnetic flux density.

The different MR polishing fluids are synthesized indigenously and these have been used for different experimentation in the present research work. The rheological behavior in terms of flow stability of synthesized MR polishing fluid has been carried out with the help of magnetorheometer with shear mode.

To further check the feasibility of the present developed process, the preliminary experiments have been conducted to evaluate the finishing performance of developed MR honing setup with the designed MR honing tools for finishing of the internal surface of mild steel cylindrical workpiece. The percentage reduction in surface roughness (R_a) values with I-shaped tool core is

found as 65-78% after 150 minutes of finishing. But, in case of MR honing tool with rectangular shaped tool core, it is found as 78-81% after 90 minutes of finishing. The results clearly revealed that the present finishing tool with the rectangular shaped core is found more suitable for significant finishing of the internal surface of the mild steel cylindrical workpiece than the I-shaped core tool. This is because the finishing tool with rectangular shaped core provided a uniform and efficient finishing, as its entire outer surface obtained a uniform magnetic flux density. This is more useful to provide close tolerance design, higher bearing load capacity and longer service life in various cylindrical machine components.

The detailed studies of the statistical design (plan of experiments) are also conducted for internal surface finishing of EN-24 steel cylindrical workpiece. The EN-24 steel is commonly used in injection barrel. The response surface methodology using “Design expert 10” software has been used to plan and analyze the effect of different process parameters on the percentage change in surface roughness (R_a) value. The analysis of experimental data showed that the percentage change in surface roughness (R_a) value is more contributed by magnetizing currents followed by tool linear speeds, mesh sizes of carbonyl iron particles, tool rotational speeds and mesh sizes of SiC abrasive particles. Based on the results of response surface model after regression analysis, the optimum process parameters are found as 800 mesh sizes of SiC abrasive particles, 400 mesh sizes of carbonyl iron particles (CIPs), magnetizing current of 1.2 A, tool rotational speed of 500 rpm and tool linear speed of 50 cm/min. Using these optimum process parameters, the change in surface roughness (R_a) value is found as 96 nm from 401 nm after 90 minutes of finishing.

The experimentation based on some industrial applications are also conducted for finishing the internal surface of ferromagnetic cylindrical materials such as gray cast iron used in the cylinder liner. The hardened EN-24 steel is used in the injection barrel of the molding machine. The improvement in surface characteristics of the internal ferromagnetic cylindrical surface clearly demonstrated the effectiveness of the present developed process. The present developed process is found effective for removing the various surface defects such as deeper grooves, honing grooves with sharper edges, torn and folded metals, cavities or holes and axial scratches from the traditionally cylindrical finished surface. These results may further lead to the enhancement of functional applications and longer service life of the components.

Also, in this research work, the internal lateral and internal bottom surfaces of cylindrical ferromagnetic blind-hole type workpiece have been finished by using the two different MR

finishing tools. The blind-hole type workpiece surfaces are mostly finished by the internal grinding (jig grinding) operations. After grinding, the surface defects such as the deep-seated groove, cavity, axial scratch, ploughed material etc. are generally induced on the blind-hole type workpiece surfaces. To further improve the surface characteristics, the experiments have been carried out on hardened EN-31 blind-hole type workpiece with the help of two MR finishing tools. The hardened EN-31 steel is commonly used in blind-hole type mold cavities. The results clearly revealed that the significant improvement in surface characteristics with almost negligible surface defects is found on final finished surfaces of blind-hole type ferromagnetic cylindrical workpiece as compared to its initial ground surfaces.

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LIST OF ABBREVIATIONS

SiC	Silicon carbide
AFF	Abrasive flow finishing
CMP	Chemo-mechanical polishing
EMM	Elastic emission machining
MFP	Magnetic float polishing
MAF	Magnetic abrasive finishing
FMAB	Flexible magnetic abrasive brush
MR	Magnetorheological
Al ₂ O ₃	Aluminium oxide
CeO ₂	Cerium oxide
CIPs	Carbonyl iron particles
EIPs	Electrolytic iron particles
MRF	Magnetorheological finishing
MRJF	Magnetorheological jet finishing
MRAFF	Magnetorheological abrasive flow finishing
MRAH	Magnetorheological abrasive honing
BEMRF	Ball end magnetorheological finishing
RMS	Root mean square
CBN	Cubic boron nitride
ZrO ₂	Zirconium dioxide
WA	White alumina
TiC	Titanium carbide
NaOH	Sodium hydroxide
MRR	Material removal rate
CNT	Carbon nano tube
I-CNT	Sintered carbon nano tube
MMC	Metal matrix composite
FEA	Finite element analysis
PLC	Programmable logic controller
HMI	Human machine interface
DC	Direct current
SWG	Standard wire gauge
FEM	Finite element methods
CAD	Computer aided design
SEM	Scanning electron microscopy

CCD	Central composite design
RSM	Response surface methodology
ANOVA	Analysis of variance
CI	Confidence interval
Df	Degree of freedom
CV	Coefficient of variation
VIF	Variance inflation factor
HRC	Rockwell hardness in “C” scale measurement

LIST OF NOMENCLATURES

τ	Shear stress (Pa)
τ_0	Magnetic field induced shear stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})
η	Dynamic viscosity (Pa.s)
F_{axial}	Axial force (N)
F_{radial}	Radial force (N)
$F_{tangential}$	Tangential force (N)
$\bar{R}$	Mean or average (nm)
σ	Standard deviation
R_a	Arithmetic mean roughness value (μm or nm)
R_q	Root mean square value (μm or nm)
R_z	Ten point mean roughness value (μm or nm)
Fe	Iron
C	Carbon
Si	Silicon
Mn	Manganese
Cr	Chromium
Mo	Molybdenum
Ni	Nickel
S	Sulfur
P	Phosphorus
$F_{indentation}$	Indentation force (N)

CHAPTER 1

INTRODUCTION

1.1 Overview of surface finishing processes

In micro or nano machining, the surface characteristics of various machine components have a greater influence on its operative functionality (Rajurkar *et al.*, 2006). The surface finishing is an important process in improving the product appearance for better tolerance and high strength applications in today's industries. The surface quality of the various industrial components is a highly important factor which requires a better design tolerance and closer fitting as well as improving the service life of the components. It also signifies an essential and expensive stage of the overall production system. The performance of various engineering components is mostly influenced by its surface quality. The quality of surface finish produced by different finishing processes mainly depends upon the material removal mechanism (Setti *et al.*, 2017). The surface finishing operation may cost as high as 10% - 15% of the total production cost (Gorana *et al.*, 2004). This may be due to the use of traditional finishing processes or manual handheld tools, which are most labour demanding, time-consuming and uncontrollable in the production of precise components. Also, the manufacturing of hard materials makes the process of finishing a difficult task and reduces the productivity. This is a challenge which requires for developing the better finishing processes as per the today's industries requirements.

The schematic of grinding process during finishing of the external cylindrical surface is shown in Fig. 1.1.

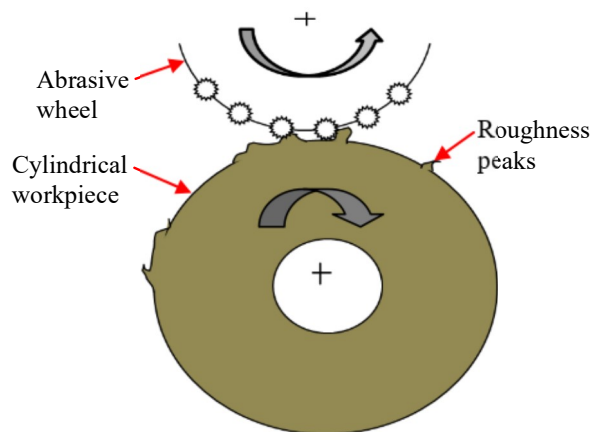


Fig. 1.1 Schematic of grinding process during finishing of external cylindrical surface (Jha and Jain, 2005).

The grinding wheel is similar to the milling machine cutter which is used for finishing the various internal or external components in a microscopic scale (Salmon, 1992). The abrasive wheel consists of embedded abrasive particles on the periphery of grinding wheel. The abrasive particles such as silicon abrasive (SiC), are closely bonded to form the dense grinding wheel. The material removal from the workpiece surface during grinding operation is because of the movement of the abrasive wheel on the workpiece surface (Shaw, 1996).

The schematic of lapping process during finishing of a flat workpiece surface is shown in Fig. 1.2. Flat lapping (also known as flat surface lapping) is most widely used lapping process (Lynah and Hoffman, 1989; Owat, 2002). It is regarded as one of the oldest process for finishing of flat surfaces. It is basically an abrasive process in which the loose abrasives slurry such as aluminium oxide, silicon carbide etc. forms a cutting action when the workpiece is in contact with it. In this process, the three body wear mechanism is used for material removal mechanism i.e. loose abrasive particles held between the workpiece surface and the back wheel (commonly known as lap) (Jha and Jain, 2005).

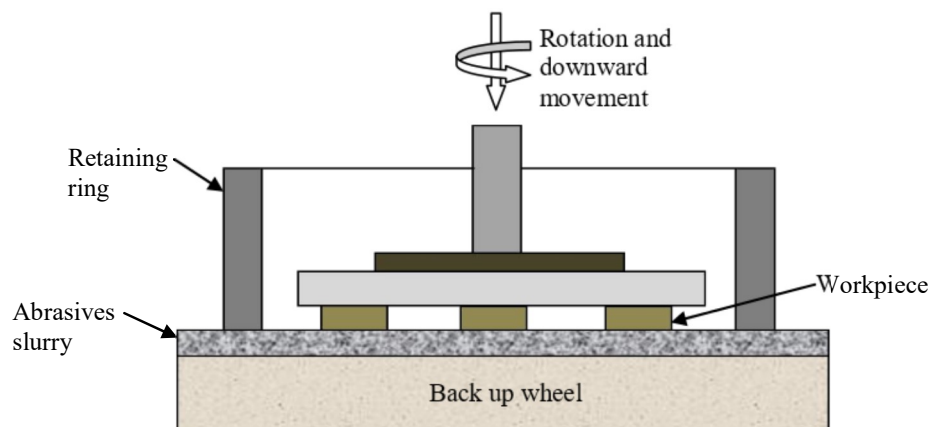


Fig. 1.2 Schematic of lapping process during flat surface finishing (Khanna and Lal, 2010).

Honing is the most important method for finishing of the internal surface of cylindrical workpieces (Khanna and Lal, 2010). The schematic of honing process during internal surface finishing of cylindrical workpiece is shown in Fig. 1.3. The honing process is used where there is a high requirement of geometric and form accuracy in order to produce a better surface finish (Todd *et al.*, 1994; Schnitzler, 2001; Schmitt *et al.*, 2011). With the help of honing tool, better dimensional tolerances and low surface roughness values can be attained. It can normally be

employed after the drilling or boring for the finishing of the internal surface of cylindrical components (Tolinski, 2008).

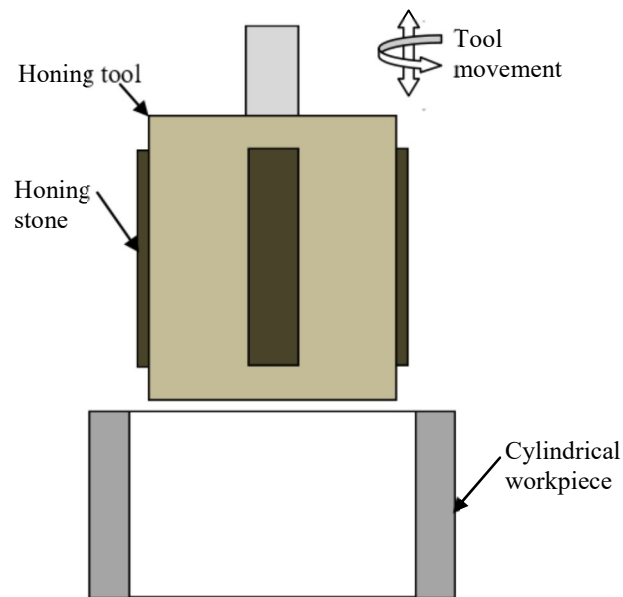


Fig. 1.3 Schematic of honing process during internal surface finishing (Schmitt and Bahre, 2014).

The above traditional finishing processes are typically used now-a-days for finishing of various industrial components such as cylinder liner, connecting rod, injection barrel etc. The traditional finishing processes are less attuned regarding the type of the material for finishing due to lesser control over the finishing forces (Shaw, 1996) and which finally produces a damage site on the workpiece material (Hoshino *et al.*, 2001). These finishing processes use a rigid type of tool i.e. loose abrasives are bonded together to form a rigid structure. Also, the uncontrollable finishing forces applied by the rigid tool on the workpiece surface produces a various types of surface defects such as deeper groove, sharper grove edges, cavity, ploughed material etc. (Gupte *et al.*, 2008).

To overcome the disadvantages of traditional finishing processes, many advanced finishing processes have been developed to finish various types of surfaces with better surface quality. These types of finishing methods have been developed to meet the high standard of surface accuracy by overcoming many fundamental limitations of the traditional finishing processes. Abrasive flow finishing (AFF) method uses the abrasive particles together with the carrier fluid

for a finishing of the wear resistant material (Rhoades, 1988). It uses a polymeric carrier in order to get a precise finishing on the internal cylindrical components (Uhlmann *et al.*, 2013). This method is mainly used for finishing of the internal surface of intake ports used in the automotive engine (Lam, 2000). Chemo-mechanical polishing (CMP) involves a chemical reaction between the workpiece and silica slurry. The rejoinder reaction product so obtained is removed by mechanical action (Nanz and Camilletti, 1995) and finally results in a defect free surface (Komanduri *et al.*, 1997). This process is mainly used in electronics industries for polishing of optical silicon, glass disk etc. Elastic emission machining (EMM) involves a chemical reaction between the ultra fine abrasive particles and the workpiece surface (Mori *et al.*, 1987; Mori *et al.*, 1990). It produces the ultra smooth and defect free surface (Mori *et al.*, 2002). This process is mainly used in the finishing of hard x-ray mirror optical surfaces (Yamauchi *et al.*, 2002b). The finishing forces produced during the above advanced finishing methods cannot be easily controlled, which sometime also results into micro-crack and produces a poorer surface finish. In order to control the finishing forces produced during the finishing processes, the magnetic assisted finishing processes such as magnetic float polishing (Komanduri, 1996) and magnetic abrasive finishing (Shinmura *et al.*, 1990) have been developed where the finishing forces can be easily controlled with the change in external magnetic field. Magnetic float polishing (MFP) process is used for precise finishing of bearing rollers and ceramic balls by using fine abrasive particles in magnetic fluid, where the finishing forces can be easily controlled by changing the magnetic field (Umehara *et al.*, 2005). The magnetic fluid contains fine abrasive particles and fine ferromagnetic particles in a carrier fluid such as water or kerosene oil. Magnetic abrasive finishing (MAF) process was first introduced in the Soviet Union (Ruben, 1987), with further essential research in the country like, Japan (Yamaguchi and Shinmura, 1999). Due to the magnetic field, the magnetic abrasive particles gets aligned themselves to appear like flexible magnetic abrasive brush (FMAB) for precise finishing of the workpiece material (Shinmura *et al.*, 1985). This process consisted of a two pair of permanent magnetic poles for finishing of external and internal surfaces of the different component (Komanduri, 1996; Kim *et al.*, 1997; Jain *et al.*, 2001) such as vacuum tubes and sanitary tubes etc. The surface and edge finishing with MAF was carried out by a vibratory motion in the magnetic field (Yamaguchi and Shinmura, 1999; Yamaguchi and Shinmura, 2004).

These magnetic assisted finishing processes with controlled finishing forces are mainly used for finishing of very hard or extraordinary engineering materials such as steels, non-ferrous metals and ceramics. The finishing medium used in these processes is the mixture of iron and abrasive particles as a dry powder. Therefore, the flowability of the magnetic brush formed with iron and abrasive particles under the magnetic field is found less on the surface during finishing i.e. absence of rheological properties. Hence, these magnetic assisted finishing processes may not be found suitable for significant finishing of the soft kind of materials, because, during the finishing operation, the abrasive particles may embed on the surface and these results in a micro marks or surface and subsurface damage.

1.2 Magnetorheological (MR) polishing fluid

Smart fluids are those fluids whose properties can be changed by applying the electric or magnetic field. The MR fluid comes under a class of smart controllable fluids (Rabinow, 1948) whose rheological behavior can be controlled by the controlling of magnetic fields. The properties such as apparent viscosity and yield strength of MR fluid are changed significantly within milliseconds when the magnetic field is applied. The MR fluids appear similar to liquid paints and exhibit comparable low levels of apparent viscosity (low-off state viscosity) when the magnetic field in the “OFF” state i.e. after the removal of the magnetic field. This effect is totally reversible within milliseconds. This makes MR fluid very promising for many technological applications.

MR fluids basically consist of suspensions of magnetic particles (micron in size) in a visco-elastic base medium such as mineral oil, water, glycerol, paraffin oil with some additives (Jain, 2009; Sidpara *et al.*, 2009). An additive includes stabilizers and surfactant for controlling the corrosion and wear rate (Genc and Phule, 2002). With the magnetic field effect, these fluids become stiffer and hence, larger shear force is necessary for the fluid to flow.

When the effect of magnetic field is OFF, the iron particles are freely suspended inside the visco-elastic base medium as shown in Fig. 1.4 (a). Under the effect of magnetic field, the iron particles built themselves to form chains structure along the magnetic lines of fluxes as shown in Fig. 1.4 (b). When the abrasive particles dispersed in MR fluid, the suspension fluid is called as MR polishing fluid which is used for fine surface finishing of different types of materials. The MR polishing fluid has been developed for finishing of different kinds of material ranging from

optical glasses to the hardest materials (Kordonski and Jacobs, 1996). MR polishing fluid is an important part of magnetorheological (MR) finishing process (Kordonski *et al.*, 1998) that shows a change in rheology due to change in magnetic field (Park *et al.*, 2009; Susan-Resiga *et al.*, 2010; Patel, 2011).

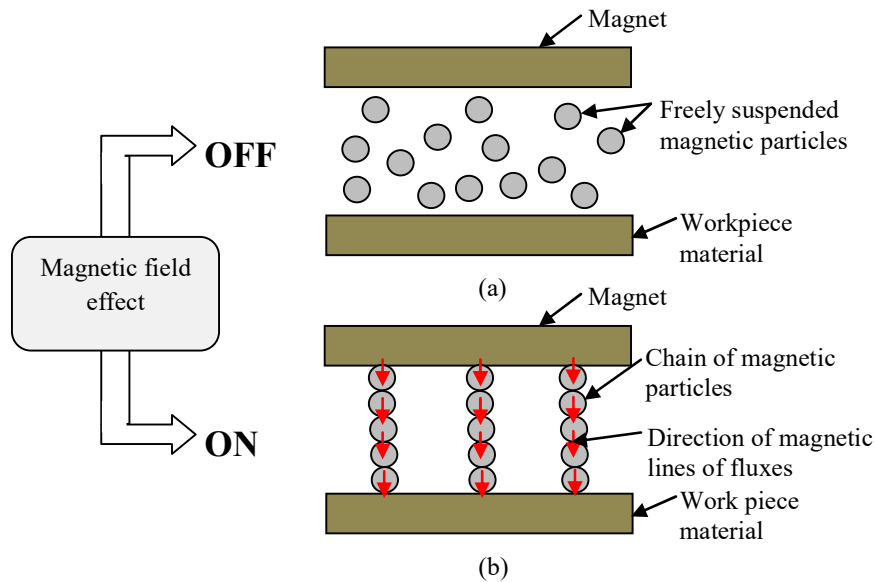


Fig. 1.4 Magnetic field effect in case of magnetorheological (MR) fluid when (a) magnet is OFF and (b) magnet is ON (Jain, 2009).

In MR polishing fluid, the chain structures of magnetic particles hold the non-magnetic abrasive particles towards the lower magnetic flux gradient region (i.e. workpiece material). The strength of active abrasives held by magnetic particles chains structure can be increased or decreased by changing the magnetizing current to the electromagnet coil. The MR polishing fluid controls the stability against sedimentation and low viscosity under the effect of the magnetic field (Bica, 2002). Due to the shear stress, the effect of the normal force acting on abrasive particles is small during MR finishing (Kordonski and Jacobs, 1996; Shorey *et al.*, 2001). With the application of magnetic field, the apparent viscosity of MR fluid also changes (Golini *et al.*, 1999; Chand *et al.* 2014). The ingredients of MR polishing fluid are discussed as follows:

1.2.1 Abrasive particles

The non-magnetic abrasive particles are an important component in MR polishing fluid. The material removal takes place by the mechanical abrasion between the abrasive particles and the workpiece materials (Singh *et al.*, 2011). The quality of surface finish produced by the abrasive

particles on the workpiece material mainly depends upon the size and strength of abrasive particles. The different types of abrasive particles such as SiC used for finishing of metals, Al_2O_3 used for low hardness materials, CeO_2 used for finishing of optical glasses, lens etc. and diamond used for higher strength materials (Jain, 2009).

1.2.2 Magnetic particles

The magnetic particles (micron-sized) are helpful for gripping the abrasive particles in MR polishing fluid with the effect of the magnetic field (Vicente *et al.*, 2011). To have better rheological behavior regarding the MR polishing fluid, the magnetic particles should have a high saturation of magnetization. Under the magnetic field effect, these magnetic particles form a chain type structure (Fig. 1.4b) along the magnetic lines of fluxes and which helps to push the non-magnetic abrasive particles towards the lower magnetic flux density gradient region. The commonly used magnetic particles are carbonyl iron particles (CIPs) and electrolyte iron particles (EIPs). The CIPs are highly purified iron manufactured by chemical vapour deposition methods, whereas the EIPs are manufactured by electro deposition in the form of an amorphous, greyish and lusterless. The CIPs are mostly preferred because these have a high range of magnetic saturation potential (Jain, 2009).

1.2.3 Carrier liquid

This is commonly a medium in which magnetic particles and abrasive particles are freely suspended (Haeri and Hashemabadi, 2008). The different types of a carrier liquid such as mineral oil, synthetic hydrocarbon, esters, water etc. are used in MR polishing fluid. While selecting the carrier fluid, the thermal properties (temperature of boiling), physical properties, and chemical properties of the carrier fluid are taken into consideration. Carrier fluid is also non-reactive to the magnetic particles (Carlson and Jolly, 2000). The carrier or base fluid is generally synthesized with a viscous liquid such as mineral oil, paraffin oil, silicone oil etc. The grease or oleic acid is used as stabilizers which control the sedimentation of particles in the base fluid. The viscous based fluid with stabilizer provides uniform distribution and better absorption of magnetic iron particle and abrasive particles when it used for synthesizing the MR polishing fluid.

1.2.4 Additives

The additives are added in the MR polishing fluids to uniformly scatter the abrasive particles as well as magnetic particles in the suspension (Genc and Phule, 2002). Grease, glycerol or other

thixotropic additives are commonly used to reduce the sedimentation. An additive helps 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 for water-based carrier medium to retard oxidation of magnetic particles.

1.3 Advantages of MR polishing fluid

-  Better absorption of iron particles and SiC abrasive particles within the base fluid
-  Better yield stress produced under the magnetic field effect
-  Low-off state viscosity
-  Stability against static sedimentation
-  Finishing without producing any surface damage.

1.4 Various magnetorheological methods with the mechanism of surface finishing

The different types of advanced finishing process have been developed based on magnetorheological (MR) fluid by different researchers. These processes are magnetorheological finishing (MRF) (Kordonski and Jacobs, 1996), magnetorheological jet finishing (MRJF) (Kordonski and Shorey, 2007) magnetorheological abrasive flow finishing (MRAFF) (Jha and Jain, 2004), magnetorheological abrasive honing process (MRAH) (Sadiq and Shunmugam, 2009) and ball end magnetorheological finishing process (BEMRF) (Singh *et al.*, 2011), in which the forces generated during the finishing operation can be easily controlled by controlling the magnetic field. The precise surface accuracy lies in the range of 10-100 nm. The magnetorheological fluid based finishing process can reduce the surface roughness value even less than 10 nm root mean square (RMS) (Zantye *et al.*, 2004).

1.4.1 Magnetorheological method for finishing of flat, concave, convex or spherical shapes of surfaces

Magnetorheological finishing (MRF) uses the MR polishing fluid for the precise finishing of the component. The experimental setup of magnetorheological finishing (MRF) process is shown in Fig. 1.5. In the absence of magnetic field, the MR polishing fluid exhibits a non-newtonian behavior. The effect of MR behavior was observed by the application of an external magnetic field to the MR polishing fluid. The particles are randomly distributed due to the absence of an external magnetic field as shown in Fig. 1.6 (a). Due to the effect of external magnetic field, the carbonyl iron particles (CIPs) become magnetized and form a columnar structure as shown in

Fig. 1.6 (b). The increase in the resistance to an applied strain rate due to the yield stress is shown in Fig. 1.6 (c) (Jain, 2008). The MR polishing fluid due to the external magnetic field is represented by the Bingham plastic model (Kordonski *et al.*, 2001) and can be represented in Eq. (1.1).

$$\tau = \tau_o + \gamma\eta \quad (1.1)$$

where, τ is the fluid shear stress, τ_o is the magnetic field induced shear stress, γ is the shear rate and η is the dynamic viscosity of MR polishing fluid.

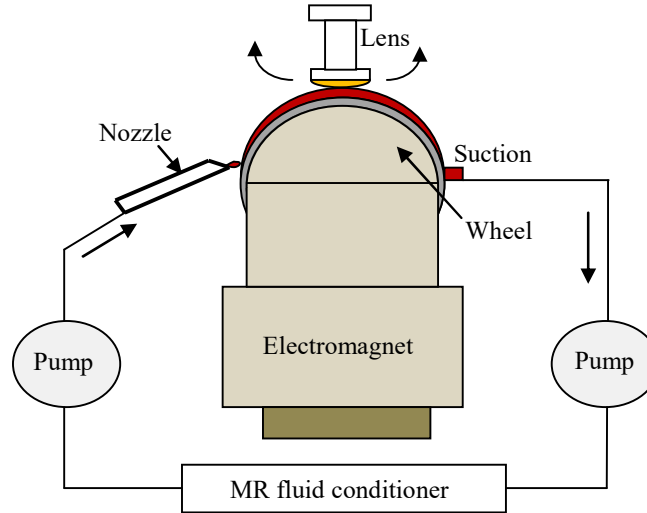


Fig. 1.5 Schematic of experimental setup of magnetorheological finishing process (Jain, 2009).

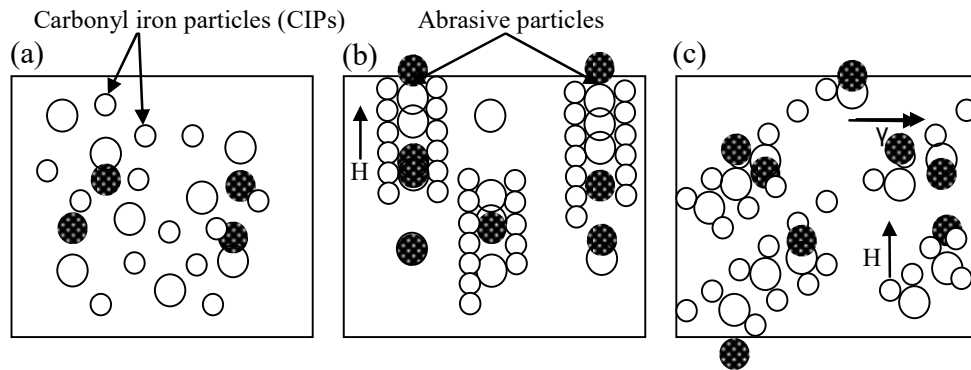


Fig. 1.6 Magnetorheological effect (a) MR polishing fluid at no magnetic field, (b) at magnetic field strength H and (c) at magnetic field strength H & applied strain rate γ (Jain, 2008).

The MR polishing fluid is useful for finishing of various types of materials such as optical glasses, ceramic etc. (Lambropoulo *et al.*, 1996) having different type of shapes such as concave, convex, flat or spherical etc. (Golini *et al.*, 1999).

1.4.2 Magnetorheological method for finishing of internal intricate surfaces

Magnetorheological abrasive flow finishing (MRAFF) process was developed for finishing of internal intricate surfaces made of non-ferromagnetic materials (Jha and Jain, 2004). In order to overcome the limitation of an abrading force produced during the abrasive flow finishing process, this process was developed by combining the abrasive flow finishing and the magnetorheological finishing for better controlling the rheological properties. The smart behavior of MR polishing fluid was utilized to precisely control the finishing forces for obtaining better surface finish. The mechanism of material removal used in magnetorheological abrasive flow finishing (MRAFF) process is shown in Fig. 1.7.

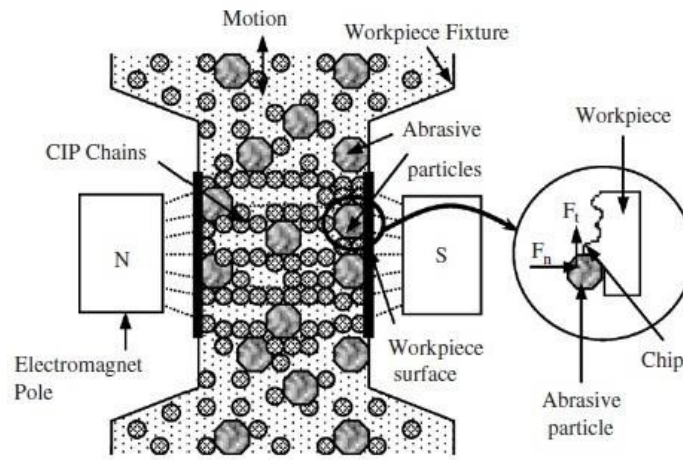


Fig. 1.7 Mechanism of material removal used for material removal in magnetorheological abrasive flow finishing (MRAFF) process (Jha and Jain, 2004).

The different finishing actions on a single roughness profile in the presence of external magnetic field are shown in Fig. 1.8. Due to the increase in the magnetic field, the carbonyl iron particles (CIPs) forms chains over the abrasive particles for precise surface finishing. The amount of material sheared from the roughness peaks by the abrasive particles depends on the bonding strength provided by the magnetic field induced structure of MR polishing fluid and the extrusion pressure applied by a piston. The extent to which the magnetic particles stiffened is sturdily dependent on the external magnetic field by controlling the viscosity of the fluid (Seok *et al.*, 2007; Kordonski and Golini, 1999). When the magnetic field is applied across the MR polishing fluid, the CIPs forms chains like structure with the abrasive particles surrounded in between and inside the chains. Figs. 1.9 (a) and (b) shows the actual microscopic image of

particles rheological behavior in MR polishing fluid when no magnetic field is applied and in the presence of an applied magnetic field.

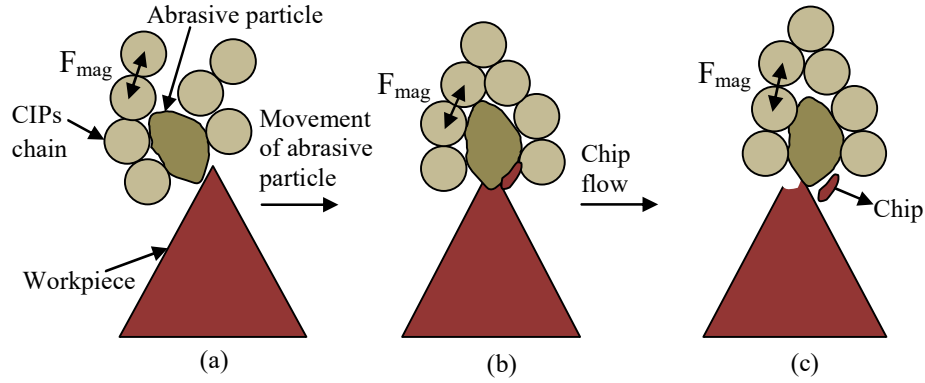


Fig. 1.8 Finishing action on a single roughness profile in the presence of external magnetic field (a) abrasive particle along with CIPs chain approaching the roughness peak, (b) abrasive particle takes a small cut on the roughness peak in presence of bonding forces and (c) abrasive particle crossing the roughness peak after removing a micro chip during cutting action (Jha and Jain, 2004).

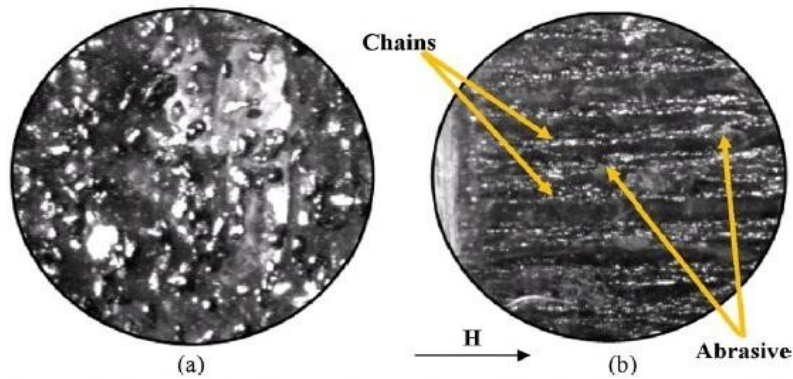


Fig. 1.9 Formation of carbonyl iron particles (CIPs) chains structure along with abrasive particles (a) in the absence of magnetic field and (b) on the application of magnetic field (Jha and Jain, 2004).

1.4.3 Magnetorheological method for finishing of steep concave, cavities and dome optics surfaces

Magnetorheological jet finishing (MRJF) process was developed for finishing of a workpiece material with a freeform dome optics, steep concave, cavities etc. (Kordonski and Shorey, 2007). The experimental setup of magnetorheological jet finishing is shown in Fig. 1.10 (a). The CAD model of the workpiece with a cavity that finished by MR jet is shown in Fig. 1.10 (b).

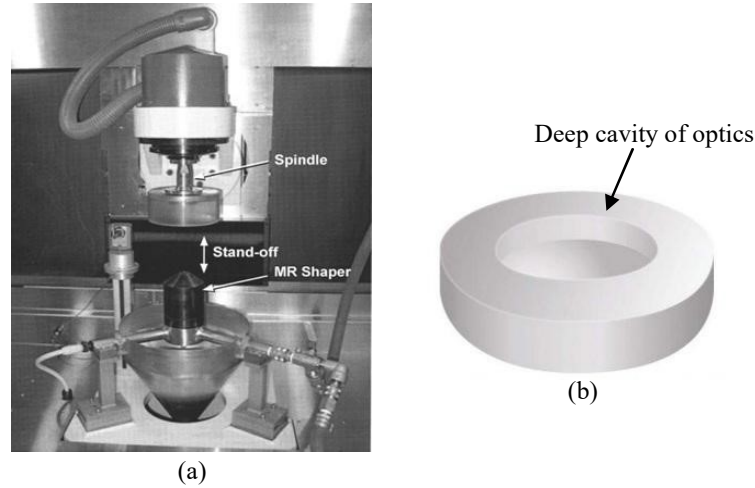


Fig. 1.10 (a) Experimental setup of magnetorheological jet finishing and (b) CAD model of cavity that finished with MR jet (Tricard *et al.*, 2006).

The jet snapshot image of magnetic abrasive jet finishing (MRJF) is shown in Fig 1.11.

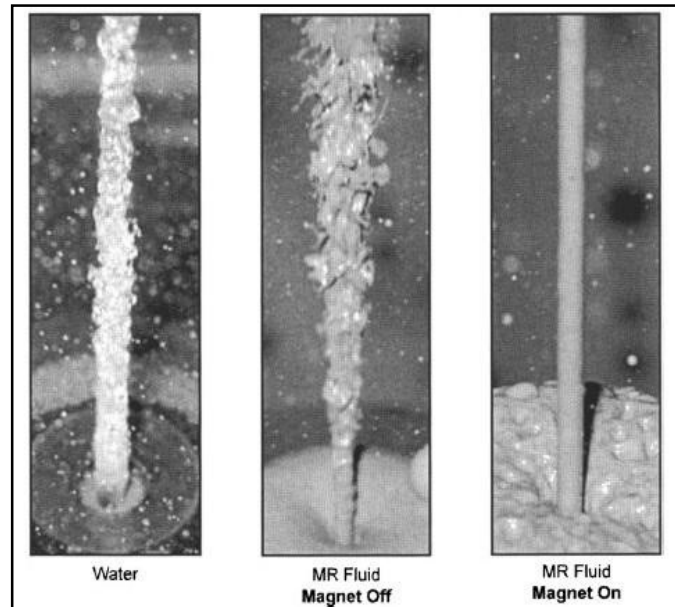


Fig. 1.11 Jet snapshot image (velocity of jet as 30 m/s and nozzle tip diameter as 2 mm) (Tricard *et al.*, 2006).

The water jet loses its coherence when it flows through the nozzle. When the magnet is OFF, the jet of MR polishing fluid flows through nozzle loses its coherence due to its high velocity. When the magnet is ON, the stable jet of MR polishing fluid flows through the nozzle with low velocity. This type of finishing process is a modification of MR finishing process in which MR

polishing fluid mixed with magnetic abrasive is jetted into the internal surface of the workpiece material and is magnetized by an axial magnetic field. The abrasive particles while striking the workpiece surface eliminate the roughness profiles that are situated at the workpiece surface which in turn produces a precise surface finish.

1.4.4 Magnetorheological method for finishing of external curved surfaces

Magnetorheological abrasive honing (MRAH) process for finishing of external curved surfaces made of non-ferromagnetic materials (Sadiq and Shunmugam, 2009) was developed. The schematic of an experimental setup of the magnetorheological abrasive honing process during external curved surface finishing is shown in Fig. 1.12. The electromagnet was placed outside the top cylindrical cover, whereas workpiece was placed inside the top cylindrical cover. Within the top cylindrical cover, the mixer of MR fluid and abrasive particles was imparted to and fro motion through plunger arrangement. Simultaneously, the rotational movement was also given to the workpiece. As a result, the finishing of the external curved surface of workpiece takes place.

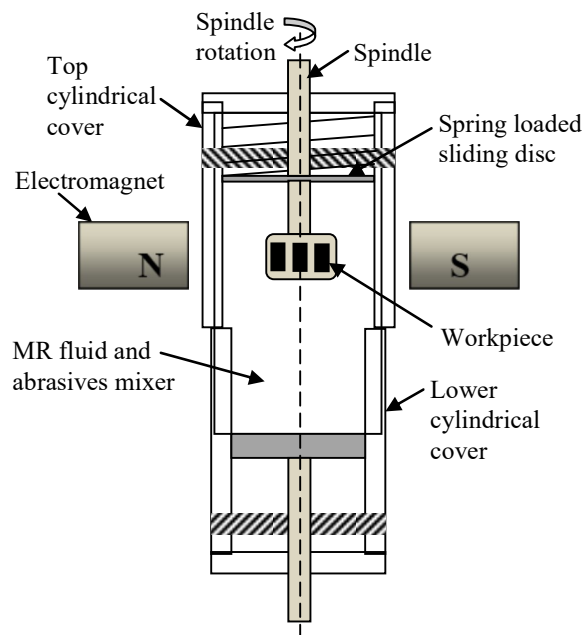


Fig. 1.12 Schematic of magnetorheological abrasive honing process (Sadiq and Shunmugam, 2009).

During the external curved surface finishing, the rearrangement of carbonyl iron particles (CIPs) along with abrasive particles under the effect of magnetic field is shown in Fig. 1.13. The CIPs in the MR polishing fluid mixture get aligned themselves in the presence of magnetic field as

shown in Fig. 1.13 (a). Beyond a certain value of magnetic field, the CIPs in the MR polishing fluid is attracted magnetically towards higher magnetic field region near magnetic pole as shown in Fig. 1.13 (b). This may even lead to the increased concentration of abrasives near the workpiece surface as shown in Fig. 1.13 (c).

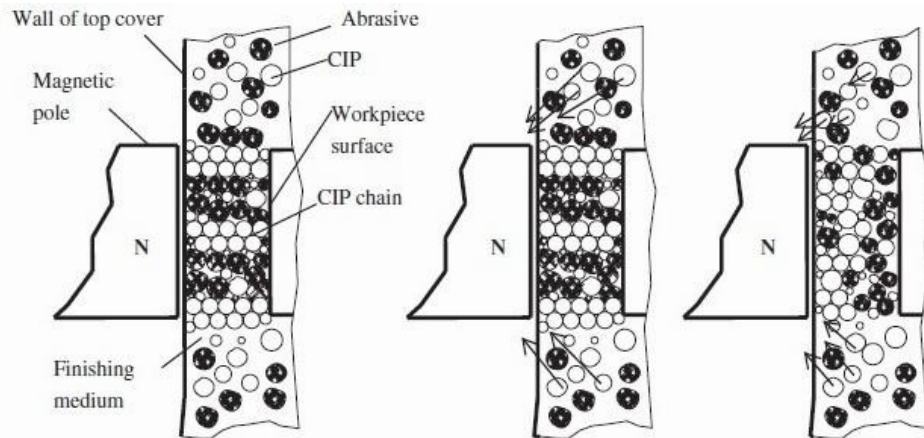


Fig. 1.13 Rearrangement of CIPs and abrasives particles (a) CIPs entrapping the active abrasives during the normal conditions, (b) and (c) CIPs concentration near pole face beyond threshold magnetic field (Sadiq and Shunmugam, 2009).

1.4.5 Magnetorheological method for finishing of flat and three dimensional complex surfaces

A newly ball end type magnetorheological finishing (BEMRF) process was developed for finishing of both flat and three dimensional complex surfaces (Singh *et al.*, 2011). The experimental setup of a ball end type magnetorheological finishing process is shown in Fig. 1.14 (a). The MR polishing fluid delivery system is shown in Fig. 1.14 (b).

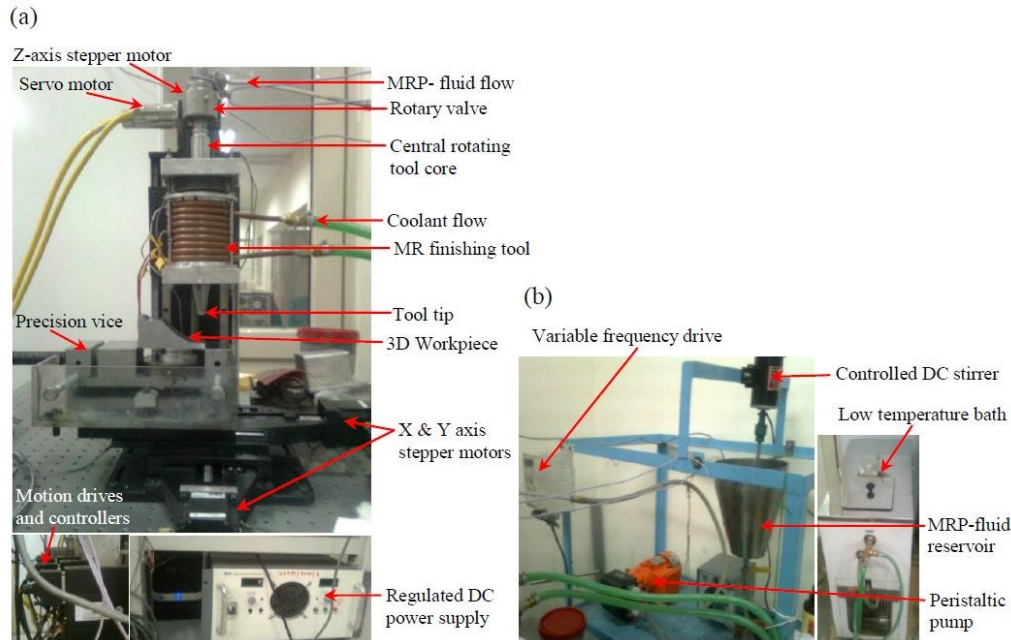


Fig. 1.14 Experimental setup of ball end type of magnetorheological finishing process and (b) MR polishing fluid delivery system (Singh *et al.*, 2012).

The carbonyl iron particles (CIPs) acquire the magnetic field strength and further combined into chains like structure for final surface finishing (Furst and Gast, 2000). The material removal takes place by the action of the shear stress between the abrasive particles and the workpiece material (Brecker *et al.*, 1969). The mechanism of particles used for material removal in ball end type magnetorheological finishing process is shown in Fig. 1.15.

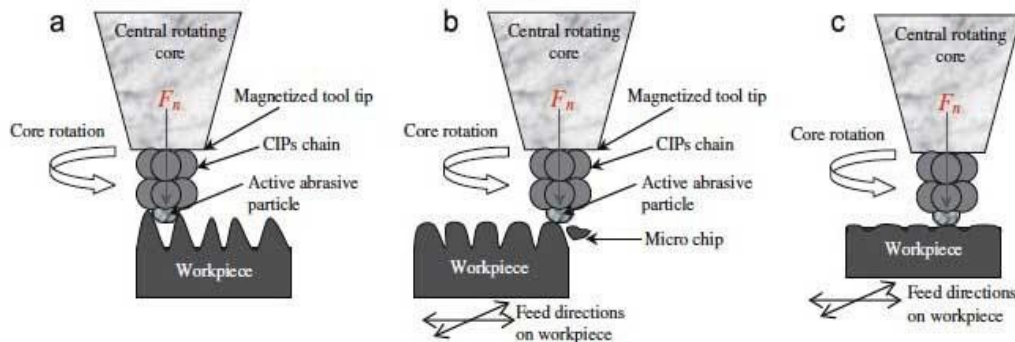


Fig. 1.15 Mechanism of particles used for material removal in ball end type of magnetorheological finishing process (Singh *et al.*, 2013).

The shear strength of engrossed abrasive particles depends upon the bonding strength provided by the CIPs chains structure which helps in better gripping of abrasive particles. The higher

shearing strength of abrasive particles is helpful in removing the roughness peaks more significantly from the workpiece surface. The abrasive particles pierce more firmly on the roughness peaks due to the higher magnetic field as shown in Fig. 1.15 (a). The high yield strength of finishing spot of MR polishing fluid rotates on the workpiece surface, the high shear strength of engrossed abrasives particles are able to cut the peaks in the form of micro-chips as shown in Fig. 1.15 (b). When the continuous feed rate is given to the workpiece than the final surface finish can be achieved after wearing of roughness peaks due to abrasion action is shown in Fig. 1.15 (c).

1.5 Advantages of magnetorheological (MR) fluid based finishing processes

-  Closer tolerances design can be achieved
-  Increase the functional and operational life of the work materials
-  Better sealing capabilities
-  Decreasing the wear and friction losses
-  Reduces the surface defects (such micro cracks, cavity etc.)

CHAPTER 2

LITERATURE REVIEW

The final surface finishing of the different manufacturing components is always owing to labour demanding and time consuming (Jain, 2009). The requirement of precise finishing on the components without any surface defects is an important consideration in today's industry. The different of traditional finishing processes such as grinding and honing operations are used for finishing of internal or external cylindrical surfaces. Grinding is most commonly used abrasive finishing process to improve surface finish. In grinding, an abrasive material rubs on the workpiece surface and removes the roughness peaks from the material. A large number of abrasive particles are bonded together to form a porous revolving body through a bonding material and material removal is provided by means of rotating abrasive wheel with respect to the workpiece surface. Honing is a finishing process performed by a honing tool, which has contains a set of three to a dozen and more bonded abrasive sticks. The sticks are mounted uniformly on the outside surface of the honing tool. They are strikes the workpiece surface with uncontrollable pressure by small springs. The honing tool is given a complex rotational and reciprocation axial motion, which forms a crosshatched lay pattern on the final finished surface. These traditional processes use a rigid type of tool to finish the workpiece surfaces. Also, the uncontrollable finishing forces provided by the rigid abrasive stones on the internal cylindrical surfaces which results in various surface defects such as deeper grooves, cavities, grooves with sharper edges and ploughed materials (Gupte *et al.*, 2008). The enhancement in surface characteristics without any defects of such ferromagnetic components is still an important challenge for the production engineer for producing a precise finish surface. To overcome this challenge the different types of advanced finishing processes based on magnetorheological (MR) fluid were developed for producing better surface quality. During these processes, the finishing forces can be externally controlled by varying the magnetizing current to the electromagnetic coil. The literature about the finishing processes (both traditional and advanced type) as discussed below.

2.1 Traditional finishing processes

The literature reviews regarding these traditional finishing processes are discussed as below.

Ye *et al.*, (2004) showed that the torn and folded metals produced on the internal surface of a cylinder bore made of A390 type aluminium alloy after the honing operation can lead to the piston scuffing wear in automotive engines. The micro-scuffing wear produced between the internal surface of the cylinder liner and the piston rings finally produces scuffing marks. During the actual running of the piston inside the cylinder liner, the generated scuffing marks on the mating surfaces create a noise due to friction in between them.

Gupte *et al.*, (2008) studied the effect of torn and folded metals induced during internal surface honing of cylindrical gray cast iron cylinder liner. The surface finish of cylinder liner (made of gray cast iron) obtained after traditional honing operation resulted in non-uniform surface finish i.e. torn and folded metals induced on the surface which generally increases a wear between the piston ring and cylinder liner. The torn and folded metal was the microscopic welded metallic debris attached to the internal surface during the traditional honing operation. This was considered as a honed surface defect and when this honed cylindrical workpiece uses in automotive industry, it affects their functional performance. The torn and folded microscopic metallic welded on the honed surface creates scuffing wear between the mating surfaces of piston rings and cylinder liner during the actual running operation. The scuffing wear resulted in scuffing marks which produced cavities or holes on the internal surface of the cylinder liner.

Dimkovski *et al.*, (2011) evaluated the finishing performance of honing stone during finishing of a gray cast iron cylinder liner. During finishing, the rigid abrasive stone approaches the internal workpiece surface which produces a non-uniform surface texture between the top region and bottom region of the cylinder liner. This is because of uncontrollable finishing forces produced by abrasive stones onto the internal surface of the cylinder liner. The non-uniformity in surface texture produces various surface defects such as deeper grooves, axial scratches and torn and folded metals. Therefore, these types of surface defects hinder the functional performance of the cylinder liner by decreasing its operational life.

El-Helieby and Rowe, (2013) studied the microstructural changes in ground EN-31 steel flat workpiece after the grinding operation. The process parameters were taken as grinding wheel speed of 30.5 m s^{-1} , table speed of 17.5 m min^{-1} and grinding fluid of emulsion Osul EH (1:2). The authors concluded that the thermal effect is important in determining the microstructural changes on the workpiece surface. During finishing, the heat flux enters into the workpiece was

mainly due to uncontrollable finishing forces produced by the rigid abrasive stone onto the workpiece surface. This finally causes surface cracks onto the workpiece surface.

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

From the above literature review, it is cleared that the required surface characteristics produced by the traditional finishing processes are likely not found effective to achieve the precise applications of internal surfaces (Zhong, 2008). The internal surface finishing of ferromagnetic cylindrical workpiece with conventional honing operation results into various surface defects such as torn and folded metals, deeper grooves, pits or cavities etc which results in decreasing the surface integrity of cylindrical components (Gupte *et al.*, 2008). The traditional finishing operations use a rigid type of tool that produced considerable normal stresses on the workpiece surface and even some time resulted in surface damage on the internal cylindrical surfaces (Jain, 2008). This is because of uncontrollable finishing forces produced by the honing stones onto the internal surface of cylindrical workpiece which finally reduces the reliability and efficiency of various machine components (Jain, 2008). Therefore, to make defect-free components, the control of finishing forces is quite necessary.

2.2 Advanced finishing processes with external control of finishing forces

The advanced finishing processes were developed for obtaining better surface characteristics on different types of workpiece materials. During these processes, the finishing forces can be easily regulated by varying the magnetic field. Under the magnetic field effect, the MR polishing fluid gets retained and stiffened at the higher magnetic flux density gradient region and is used as a finishing segment for obtaining a precise surface finish. The literature reviews regarding the advanced finishing processes with external control of forces are discussed as below.

Umehara *et al.*, (1995a) developed and compared the performance of the two different types of magnetic fluid grinding processes i.e. rotating zirconium dioxide (ZrO_2) balls type and

oscillating (ZrO_2) balls type for finishing of the internal surface of non-ferromagnetic cylindrical workpiece such as brass pipe. The authors used water-based magnetic fluid (W40) and 20% volume of SiC abrasive powder for finishing. During finishing with rotating balls type, the polishing pressure was 8 N and rotation speed of 918 rpm. During finishing with oscillating balls type, the polishing pressure was 8 N and the oscillating frequency of 2 Hz. The results concluded that for the higher material removal rate, the rotating balls type finishing was used. For finishing of small and bending tubes, the oscillating balls type was used. Further, to finish the curvature types of bending tubes made of brass, the taper type magnetic fluid grinding process was used (Umehara *et al.*, 1995b).

The high-quality lenses usually made of glass tends to break during finishing operation. To counter this limitation, the authors (Kordonski and Jacobs, 1996) developed a magnetorheological finishing process (MRF). This process completely relies on magnetorheological (MR) fluid for precise surface finishing. The MR polishing fluid consists of iron particles, CeO_2 abrasive particles dispersed in a non-magnetic carrier medium such as mineral oil, silicon oil or water etc. Under the effect of magnetic field, the MR polishing retained and stiffened at the higher magnetic flux density gradient region. Under the control of finishing forces (i.e. by changing magnetizing current), the MRF process provides a better precise finishing on the lens surface.

Kim *et al.*, (1997) used magnetic abrasive jet machining for precise finishing of the internal surface of non-ferromagnetic cylindrical workpiece (made of SUS 304 steel). During finishing, the magnetic abrasive (combined Al_2O_3 particles and pure iron particles) along with the working fluid i.e. compressed air (maximum 4 to 5 atm) was jetted through the nozzle onto the inner surface of non-ferromagnetic cylindrical workpiece. In this process, the magnetic poles arrangement lies outside the cylindrical workpiece surface. The results revealed that the surface roughness (R_a) value decreased to $0.191\text{ }\mu\text{m}$ from initial $0.485\text{ }\mu\text{m}$ with jet velocity of 20 m/sec, magnetic flux density of 0.4 T and finishing time of 30 min.

Jha and Jain, (2004) reported the effect of different magnetic flux density on the final surface finish by using magnetorheological abrasive flow finishing (MRAFF) process. In this finishing process, the electromagnet was placed outside the cylindrical workpiece and MR polishing fluid inside the cylindrical workpiece. The authors used MR polishing fluid (usually a mixture of 20%

CIPs, 20% SiC abrasive particles and 60% visco plastic base medium) for finishing of stainless steel workpiece. The experimental conditions used during finishing were magnetic flux density as 0.574 T and number of finishing cycles as 200. The authors concluded that with the increased in magnetic field strength, the surface roughness (R_a) value got decreased as shown in Fig. 2.1.

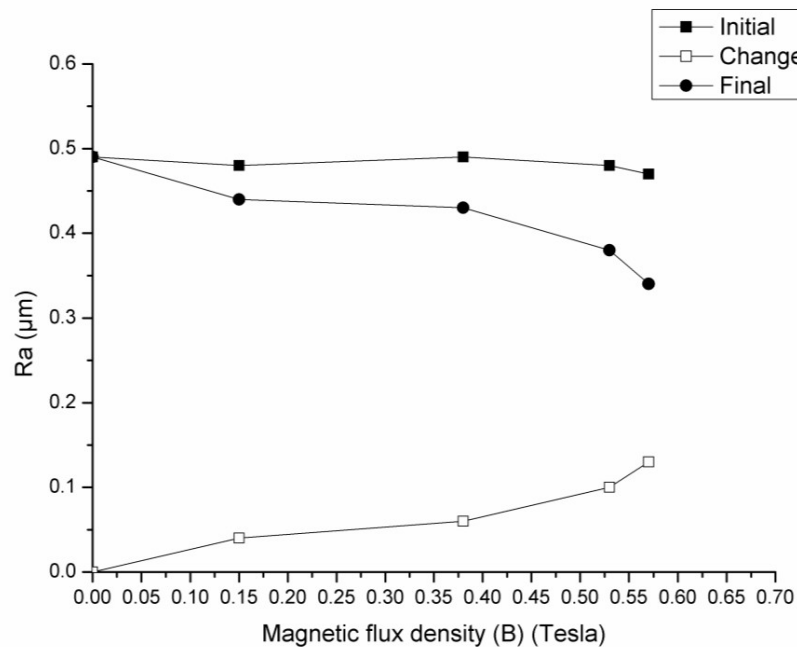


Fig. 2.1 Effect of magnetic field strength on surface roughness (R_a) value (Jha and Jain, 2004).

Yamaguchi and Shinmura, (2004) performed their experiments on the magnetic assisted finishing process for finishing of alumina ceramic tube. The experimentation was performed by using iron particles of different sizes (i.e. 150 μm , 330 μm and 510 μm), different sizes of diamond abrasive (i.e. 0-1 μm , 2-4 μm , 4-8 μm and 8-12 μm) and different lubricant (i.e. 0.1 ml, 0.2, ml 0.25 ml, 0.3 ml and 0.35 ml). The results concluded that with the use of iron particle (330 μm), diamond abrasive (0-1 μm) and soluble type barrel finishing lubricant (0.3 ml), the surface roughness (R_a) value reduced to 0.02 μm with workpiece rotation of 1800 rpm, working gap of 1 mm and magnetic flux density of 0.37 T.

Singh *et al.*, (2004) worked on magnetic abrasive finishing (MAF) process for determining the effect of different process variables on the surface finish. The polishing fluid consists of a mixture of 75% iron particles and 25% SiC abrasives. The results concluded that the % ΔR_a

value was found better with voltage applied to the electromagnet of 11.5 V, different working gaps and rotational speeds of the magnet as shown in Fig. 2.2.

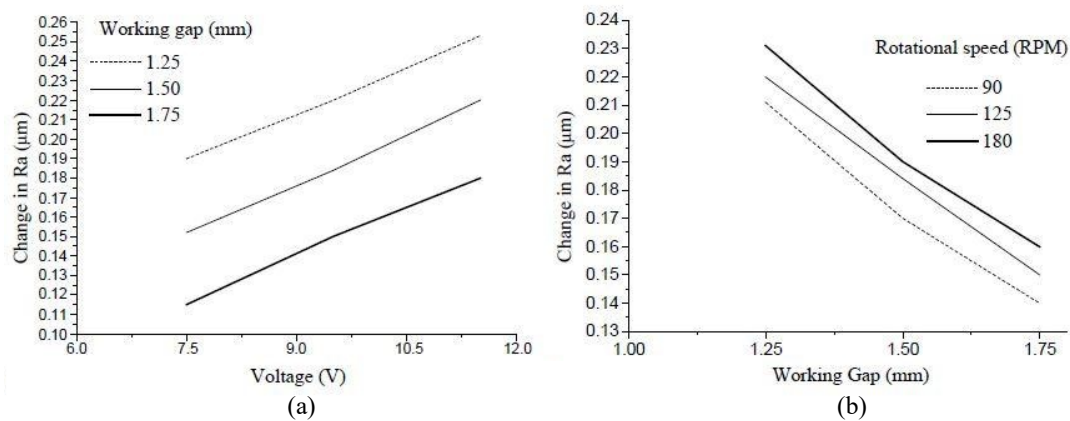


Fig. 2.2 (a) Effect of voltage on surface roughness (R_a) value having dissimilar working gaps, and (b) effect of working gap on surface roughness (R_a) value for different rotational speeds of magnet (Singh *et al.*, 2004).

Yin and Shinmura, (2004) compared the performance of surface roughness and deburring by using vibration-assisted magnetic finishing process. The finishing was carried out with the mixer of iron particles, white alumina (WA), magnetic alumina and straight oil type grinding fluid on different work materials such as magnesium alloy (AZ31B), stainless steel (SU304) and brass (C2680). The experimental conditions used during deburring were workpiece feed speed of 17 mm/min, magnetic flux density of 0.6 T, working clearance of 3 mm and finishing time of 160 s. The authors concluded that the surface finishing and deburring were performed better in magnesium alloy (AZ31B) as compared to other two materials.

The comparison of material removal rate and surface finish (MRR) with polishing time was reported by the authors (Wang and Hu, 2005). The experimentation was performed with magnetic assisted finishing (MAF) process for finishing of Ly12 aluminium alloy, 316L stainless steel and H62 brass. The experimentation was carried out with four different types of abrasive particles namely $\text{Al}_2\text{O}_3/\text{Fe}$ (20% Al_2O_3), TiC/Fe (20% TiC), TiC/Fe (35% TiC), TiC/Fe (7% TiC) along with the finishing fluid as stearic acid and transformer oil. The results concluded that the surface roughness (R_a) value of aluminium tube reduced to $0.24 \mu\text{m}$ from initial R_a value of $9.6 \mu\text{m}$.

Jha and Jain, (2006) also evaluated the effect of different grades of carbonyl iron particles (CIPs) of CS grade having a diameter of 18 μm and HS grade having a diameter of 3.5 μm and was used separately in MR polishing fluid. The authors used MR polishing fluid (a mixture of 20% CIPs, 20% SiC abrasive particles and 60% visco plastic base medium by volume) for finishing of the internal surface of stainless steel cylindrical workpiece by using MRAFF process. The authors concluded that the surface roughness (R_a) value reduced to 0.17 μm from 0.28 μm with CIPs of CS grade having diameter of 18 μm after 200 numbers of finishing cycles whereas, the surface roughness (R_a) value reduced to 0.24 μm from 0.28 μm with CIPs of HS grade having diameter of 3.5 μm after 200 numbers of finishing cycles.

Kordonski and Shorey, (2007) performed their experiments on magnetorheological jet finishing (MRJF) process for finishing of dome concave shape made of fused glass silica. The authors used MR polishing fluid which consists of a mixer of abrasive particles (CeO_2) along with liquid jet for precise surface finishing. In this process, the MR jet moves out from the injection nozzle at a very high velocity and strike the roughness peaks of workpiece surface. The authors concluded that the surface roughness (R_q) value was found as 6 nm from the initial 50.3 nm with a velocity of MR jet as 30 m/sec.

Yamaguchi *et al.*, (2007) developed magnetic abrasive finishing (MAF) process for internal cylindrical surface finishing of SUS 304 tube workpiece. The MR polishing fluid used during finishing was a mixer of 80% by weight of iron particles and 20% by weight of magnetic abrasives. During this process, a magnetic abrasive brush inside the tube was formed under the effect of magnetic field. Due to reciprocal movement of external magnetic poles and rotation movement of cylindrical non-ferromagnetic tube workpiece, the flexible magnetic abrasive brush (FMAB) performed the final surface finishing. The results showed that more than 80% reduction in the surface roughness (R_a) value on the internal surface non-ferromagnetic workpiece with workpiece rotational speed of 30,000 min^{-1} and finishing time of 16 min. This process was likely not used for finishing of ferromagnetic cylindrical workpiece because the magnetic abrasive brush gets stuck onto the internal ferromagnetic cylindrical surface during finishing.

Cheng *et al.*, (2008) worked on wheel-shaped polishing tool for finishing of K9 glass mirror. The authors used MR polishing fluid (usually a mixture of 33.84% of CIPs, 57.34% of silicone oil, 2.82% of the stabilizing agent and 6% of CeO_2 abrasive powder) for precise finishing. The

experimental studies were conducted in two sets (with/without abrasive particles) in order to ensure the polishing effectiveness. The authors concluded that the surface roughness (R_a) value decreased to 0.47 nm from initial 1.52 nm with the viscosity of 8.9 Pa.s, the voltage of 2V, polishing time of 30 min by using CeO₂ abrasive powder as shown in Fig. 2.3.

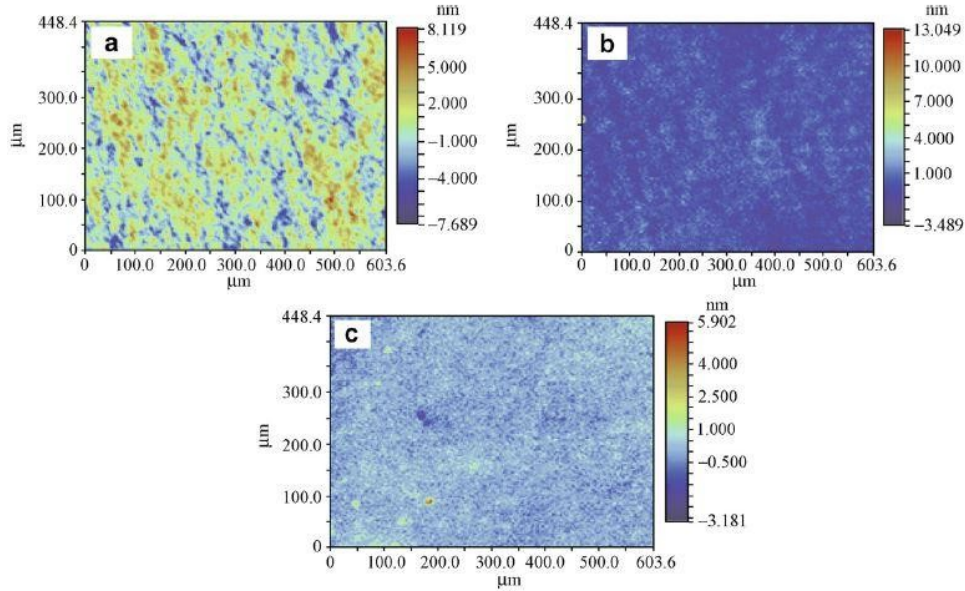


Fig. 2.3 Wyko measurement of the K9 glass test-part (a) initial surface roughness (R_a) value of 1.52 nm, (b) surface roughness (R_a) value of 0.61 nm after 10 min of polishing and (c) surface roughness (R_a) value of 0.47 nm after 30 min of polishing (Cheng *et al.*, 2008).

The effect of different finishing cycles on the final surface finish was reported by the authors (Das *et al.*, 2008). The authors performed both theoretical and experimental studies by using magnetorheological abrasive flow finishing (MRAFF) process for finishing of stainless steel workpieces. The finishing was carried with the help of MR polishing fluid (consists of 20% CIPs, 20% SiC abrasive powder with 60% visco plastic base medium by volume). The results concluded that with the increase in the number of cycles to 350, the value of surface roughness (R_a) values reduces for both experimental and theoretical cases.

The effect of material removal rate (MRR) on the surface finish was reported by the authors (Jung *et al.*, 2009). The finishing was carried with wheel type MR finishing process. The authors used MR polishing fluid (made from a water-based suspension of CIPs with 20% volume of abrasive concentration) for precise finishing of hard disc slider made of Al₂O₃-TiC material. The finishing was conducted by using different types of MR polishing fluid i.e. MR polishing fluid

having no abrasives, having carbon nano-tube (CNT) abrasives, having diamond abrasives and having sintered carbon-nano-tube (I-CNT). The results revealed that the MR polishing with I-CNT abrasives provide a better enhancement in MRR i.e. 0.036 nm/sec with working gap of 2 mm, tool rotational speed of 500 rpm and finishing time of 60 min.

The effect of magnetic field on the surface finish was reported by the authors (Sadiq and Shunmugam, 2009). The magnetorheological abrasive honing (MRAH) process was developed for finishing the external curved surfaces made of aluminium alloy (Al 6063) and austenite stainless steel. The authors used MR polishing fluid (a mixture of 30% CIPs, 25% SiC abrasive particles and natural castor oil) for precise surface finishing. The authors concluded that the surface roughness (R_a) value of aluminium alloys was found as 1.3 μm from initial 1.629 μm with the magnetic flux density of 0.633 T, workpiece rotational speed of 420 rpm and finishing time of 15 min. The surface roughness (R_a) value of austenite stainless steel was found as 0.446 μm from initial 0.696 μm with the magnetic flux density of 0.633 T, workpiece rotational speed of 450 rpm and finishing time of 15 min.

Sadiq and Shunmugam, (2010) also performed the experiments on magnetorheological abrasive honing (MRAH) process for finishing of mild steel (AISI 1020) and stainless steel (SS 316L). The authors used MR polishing fluid (a mixture of 30% CIPs, 25% SiC abrasive particles and natural castor oil by volume). The authors concluded that a very little change in surface roughness (R_a) value (6.7% at 0.65 T) was observed during finishing of the mild steel material, whereas a larger improvement in surface finish (41.7% at 0.65 T) and (43.5% at 20 min) was observed in case of non-ferromagnetic stainless steel. This was due to the distribution of maximum flux density gradient found on the mild steel workpiece surface than finishing fluid. Therefore, MR polishing fluid gets attached on the mild steel workpiece surface and due to this, there was no proper relative motion observed between the ferromagnetic workpiece surface and MR polishing fluid. Hence, the mild steel surface was found difficult to finish as there was likely no shearing action on the surface by the MR polishing fluid due to the absence of relative motion between them.

To improve the finishing performance of abrasive flow finishing (AFF) process, the authors (Shankar *et al.*, 2010) developed rotational abrasive flow finishing (R-AFF) process in which the cylindrical workpiece was rotated externally whereas, the finishing medium reciprocate inside

the cylindrical cover through hydraulic actuators. To check the effectiveness of the developed process, the preliminary experiments were carried on Al alloy, Al alloy/SiC MMC with 10% SiC and Al alloy/SiC MMC with 15% SiC. The different effect of process parameters i.e. extrusion pressure workpiece rotation and finishing medium compositions was evaluated for determining the % ΔR_a values. The authors used a finishing medium that composed of soft styrene polymer, abrasive particles and hydrocarbon oil. The results concluded that during R-AFF, the % ΔR_a values was found 44% more than AFF process while finishing of Al alloy/SiC MMC with 10% SiC substrate.

Singh *et al.*, (2011) developed ball end magnetorheological finishing (BEMRF) process and performed preliminary finishing on a flat EN-31 workpiece and three dimensional copper workpiece surfaces for examining the developed process performance. The authors used MR polishing fluid having volume concentration of 20% of SiC, 20% of CIPs and 60% of the base fluid. The results concluded that the surface roughness (R_a) value of EN-31 workpiece was found as 70 nm from initial 414.1 nm with working gap of 2 mm, tool rotational speed of 100 rpm, the magnetic field of 0.2 T and finishing time of 100 min. The surface roughness (R_a) value of 3D copper workpiece was found as 102 nm from initial 336.8 nm with working gap of 2 mm, tool rotational speed of 600 rpm, the magnetic field of 0.2 T and finishing time of 60 min.

For enhancing the performance of magnetorheological abrasive flow finishing (MRAFF) process, later the authors (Das *et al.*, 2012) made a modification in MRAFF process. This modification was made by rotating the electromagnet and hence, this process was named as rotational-magnetorheological abrasive flow finishing (R-MRAFF) process. The effect of different process parameters such as extrusion pressure, a number of finishing cycles, magnet rotational speed and CIP/SiC ratio on the percentage change in surface roughness (R_a) value was conducted during finishing of stainless steel and brass workpiece. The results concluded that the surface roughness (R_a) value of stainless steel was found as 110 nm, with electromagnet speed of 67 rpm, extrusion pressure of 38.92 bar, finishing cycles of 660 and CIP/SiC ratio of 2.3. The surface roughness (R_a) value of brass workpiece was found as 50 nm, with electromagnet speed of 73 rpm, extrusion pressure of 38 bar, finishing cycles of 690 and CIP/SiC ratio of 2.22.

The magnetorheological abrasive flow finishing process (MRAFF) (Jha and Jain, 2004) and rotational magnetorheological abrasive flow finishing process (R-MRAFF) (Das *et al.*, 2012) are

mostly found suitable for finishing of the internal non-ferromagnetic surface. But, due to its tool design structure i.e. electromagnet is kept outside the cylindrical workpiece surface. Due to this arrangement, the maximum value of magnetic flux density gradient can be obtained on the internal surface of ferromagnetic cylindrical workpiece and the lower magnetic flux density in the MR polishing fluid. Therefore, the MR polishing fluid gets stuck on the internal surface of the cylindrical ferromagnetic workpiece. This results in no relative movement of MR polishing fluid on the internal surface of ferromagnetic cylindrical workpiece. Therefore, these processes can be found likely less effective for finishing the internal surface of ferromagnetic cylindrical workpiece.

Kang *et al.*, (2012) developed a magnetic abrasive finishing (with double dipole tip set) for finishing of austenite 304 stainless steel tube. The mixed type magnetic abrasive consists of (80% iron particles and 20% magnetic abrasive) along with a soluble type barrel finishing compound was used as a finishing segment. The process parameters were magnetic flux density of 1.26 to 1.29 T, workpiece rotational speed of 500 to 30000 rpm, a processing time of 10 to 20 min and workpiece pole tip clearance of 0.3 mm. The initial surface roughness (R_a) value of SS 304 stainless steel workpiece was in the range of 2-3 μm . The results concluded that at 10000 rpm, the surface roughness (R_a) value decreased to 0.1 μm after 10 minutes of finishing.

Sidpara and Jain, (2012) performed their experiments on magnetorheological fluid based finishing process for finishing of single crystal silicon. The effects of different process parameters such as a concentration of abrasive particles, a concentration of iron particles and carrier wheel speed on the final change in surface roughness (R_a) value were studied. The authors used MR polishing fluid usually a mixture of CIPs, CeO_2 abrasive particles and 8% volume of glycerol for precise surface finishing. The authors concluded that the surface roughness (R_a) value decreased from 1300 nm to 8 nm with the volume of 39.58% of CIPs, 5.07% of CeO_2 abrasive particles, 298.36 rpm of carrier wheel speed and finishing time of 210 min, as shown in Fig. 2.4.

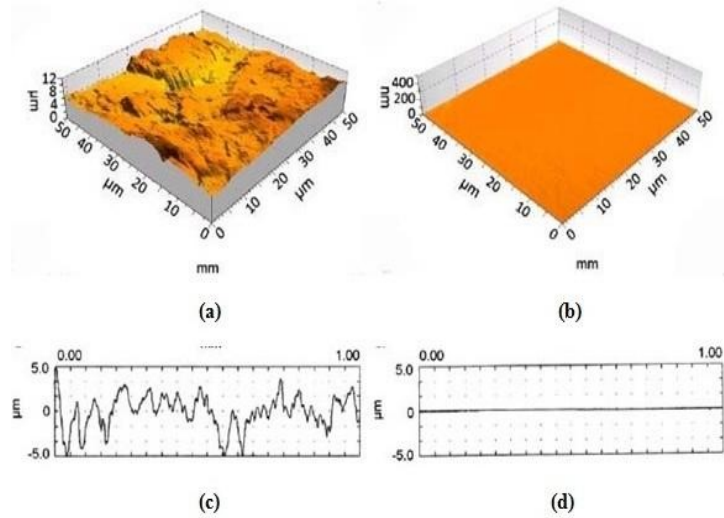


Fig. 2.4 Three dimensional topography of (a) initial surface, (b) finished surface, (c) initial surface (1300 nm) and (d) finished surface (8 nm) (Sidpara and Jain, 2012).

The theoretical and experimental analysis of normal and tangential forces by using magnetorheological fluid based finishing process was reported by the authors (Sidpara and Jain, 2012). The theoretical models of both normal force and tangential force were purposed in order to clearly visualize the mechanism of material removal during finishing of single crystal silicon. However, it was concluded that the effect of normal and tangential force increases with the increase in CIPs concentration, whereas with the increase in working gap, the effect of normal and tangential force decreases. Later, the effect of theoretical models has compared the experimental results. The results revealed that the theoretical normal, as well as tangential forces, showed a better agreement with the experimental results.

Singh *et al.*, (2012) performed the experiments on ball end type magnetorheological finishing (BEMRF) process for finishing of a typical three dimensional mild steel workpiece with different projections. The finishing operation was performed with X-Y-Z axis feed. The authors used MR polishing fluid consists by volume concentration of 20% of SiC, 20% of CIPs and 60% of the base fluid mixer. It was concluded that the surface roughness (R_a) value of flat, 30°, 45° and 50° curve surfaces reduced to 18.7 nm, 30.4 nm, 71.0 nm and 123.7 nm with a magnetizing current of 4A, working gap of 0.66 mm and 60 number of finishing passes. This is because the magnetic flux density was found almost uniform during flat surface finishing as shown in Fig. 2.5. In case

of inclined surfaces of three dimensional ferromagnetic workpiece, the distribution of magnetic flux density in working gap was not uniform as shown in Fig. 2.6.

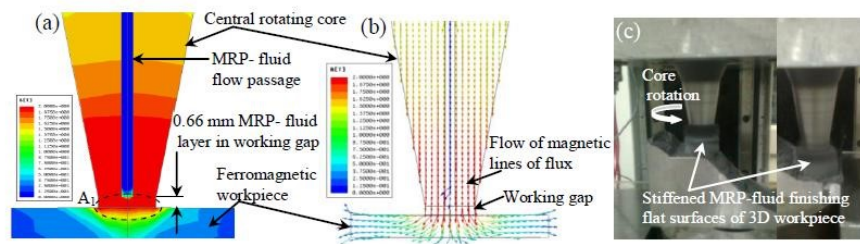


Fig. 2.5 Finite element analysis for (a) distribution of magnetic flux density, (b) flow of magnetic lines of forces in working gap of a flat surface and (c) photograph during finishing the flat surfaces of a typical three dimensional workpiece by stiffened MR polishing fluid (Singh *et al.*, 2012).

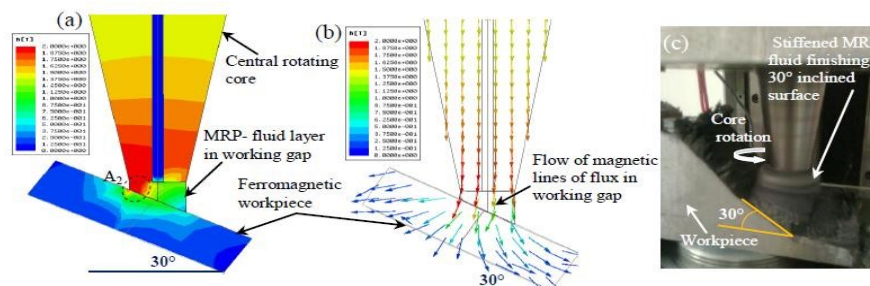


Fig. 2.6 Finite element analysis for (a) distribution of magnetic flux density, (b) flow of magnetic lines of forces in working gap of 30° inclined surface and (c) photograph during finishing the 30° inclined surfaces of three dimensional workpiece by stiffened MR polishing fluid (Singh *et al.*, 2012).

Singh *et al.*, (2013) compared the theoretical and experimental investigation on material removal rate (MRR) and different working gaps by using ball end MR finishing tool during the finishing of a flat ferromagnetic workpiece. The theoretical observation was carried out by analyzing the normal forces at different working gaps. The finishing was carried out with MR polishing fluid (a mixture of 20% CIPs, 20% SiC abrasive powder and 60% visco plastic base medium by volume). The results concluded that the surface roughness (R_a) value decreased to 0.028 μm with 0.66 mm of working gap, where the magnetic normal force of 16.35 N was acting on the workpiece surface.

Gheisari *et al.*, (2014) developed a magnetorheological (MR) finishing process for ultra-precision finishing of the external surface of aluminium cylindrical workpiece. This finishing

works were similar to wheel-type MR finishing process. The MR polishing fluid consists of a water-based suspension of micron-sized diamond abrasive particles. The process parameters such as a current of 9A and working gap of 5 mm were used. The initial surface roughness of the workpiece material was 170 nm. The experimentation was conducted in three sets. In the first case, the workpiece material speed varies from 250-1000 rpm. In the second case, the process time varies from 20-100 min. In the third case, the effect of a fast RAM on the surface roughness was considered. The results concluded that with the increase in rotational speed upto 1000 rpm, the surface roughness (R_a) value gets reduced to 40 nm with 90 minutes of finishing time.

Saraswathamma *et al.*, (2015) used a ball end magnetorheological finishing (BEMRF) process for finishing of silicon wafer workpiece. The effect of different process parameters such as tool rotational speeds, magnetizing currents and working gaps on the percentage change in surface roughness (R_a) value was evaluated. The authors used MR polishing fluid consists of 25% of CIPs, 66.75% of deionized water, 6% of ceria abrasives, 2.5% of glycerol and 0.75% of NaOH (by volume). The results concluded that the surface roughness (R_a) value reduced to 89.8 nm from initial value of 457 nm with tool rotational speed of 30 rps, magnetizing current of 3 A and working gap of 0.6 mm.

Singh *et al.*, (2017) developed magnetorheological (MR) finishing process for external cylindrical surfaces. The finishing arrangement was mounted on a lathe machine. To check the feasibility of the developed process, the authors compared the performance of two different types of tool tip surfaces i.e. flat tool tip surface and curved tool tip surface for finishing of the external surface of mild steel workpiece. The composition of MR polishing fluid used by the authors was 20% of SiC, 20% of CIPs and 60% of visco plastic base fluid (by volume). The experimentation conditions used during both sets of experiments were working gap of 0.5 mm, magnetizing current of 2 A and workpiece rotational speed of 443 rpm. The results concluded the percentage change in surface roughness (R_a) value was found as 54% by using flat tool tip, whereas in case of curved tool tip was found as 81%.

Verma *et al.*, (2017) developed magnetic abrasive finishing process (permanent magnet type) for finishing of the internal surface of stainless steel (SS 304) cylindrical workpiece. The effect of different process parameters such as rotational speed of tool, abrasive mesh size, magnetic flux density and abrasive weight percentage was carried out in order to determine the percentage

change in surface roughness (R_a) value. The authors reported that the surface roughness (R_a) value found least as 56 nm from initial 541 nm with the magnetic flux density of 0.8 T, tool rotational speed of 500 rpm, abrasive weight percentage of 20%, and abrasive mesh size of 800.

2.3 Research gaps

 The traditional internal finishing processes i.e. grinding and honing are found less suitable for achieving a fine surface finish of the internal cylindrical surface. This is due to uncontrollable finishing forces provided by the rigid abrasive stones on the internal cylindrical surface which results in various surface defects such as deeper grooves, cavities, grooves with sharper edges and ploughed materials.

 The existing advanced finishing process based on MR polishing fluid i.e. magnetorheological abrasive flow finishing process (MRAFF) and rotational magnetorheological abrasive flow finishing process (R-MRAFF) are found suitable for finishing the internal surface of non-ferromagnetic cylindrical workpiece. But, due to its tool design structure i.e. electromagnet is placed outside the cylindrical workpiece surface, these processes can be found likely less effective for finishing of the internal surface of ferromagnetic cylindrical workpiece.

To analyze the existing processes MRAFF and R-MRAFF for finishing of internal surfaces of ferromagnetic and non-ferromagnetic cylindrical workpieces, the magnetostatic finite element analysis (FEA) has been done by using Maxwell Ansoft V13 (student version) software to evaluate the magnetic flux density. The schematic of setup and two dimensional (2D) plots from the magnetostatic FEA where the electromagnet is placed outside the cylindrical workpiece as likely similar to MRAFF process are shown in Fig. 2.7. Fig. 2.7 (a) showed the schematic of the experimental setup when the electromagnet is placed outside the cylindrical workpiece surface and the MR polishing fluid is kept inside the cylindrical workpiece surface. The similar design principles were also used in MRAFF and R-MRAFF processes. Figs. 2.7 (b) and (c) showed the magnetostatic two dimensional plots of magnetic flux density distribution between the MR polishing fluid and the internal surface of ferromagnetic and non-ferromagnetic cylindrical workpieces. From the two dimensional plot (Fig. 2.7a), it can be clearly seen that the maximum value of magnetic flux density gradient is on the internal surface of ferromagnetic cylindrical workpiece than the MR polishing fluid.

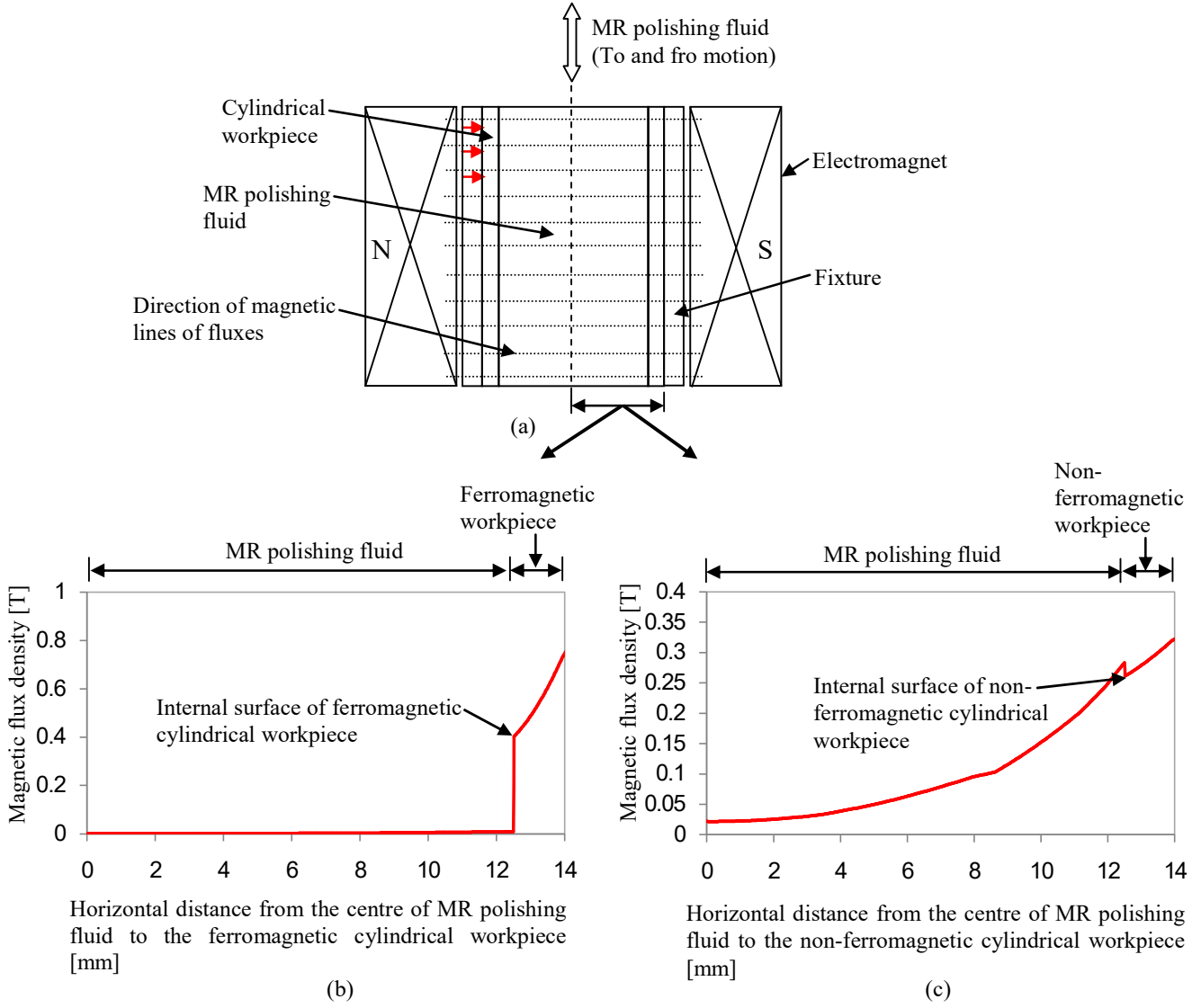


Fig. 2.7 (a) Schematic of MRAFF process, two dimensional plot of distribution of magnetic flux density from magnetostatic finite element analysis (FEA) (b) between the MR polishing fluid and surface of ferromagnetic cylindrical workpiece and (c) between the MR polishing fluid and surface of non-ferromagnetic cylindrical workpiece.

Therefore, due to this effect, the MR polishing fluid gets stuck on the internal surface of ferromagnetic cylindrical workpiece (Fig. 2.8a). This results in no relative movement of carbonyl iron particles (CIPs) chains on the internal surface of ferromagnetic cylindrical workpiece. Also, the non-magnetic abrasive particles pushed out towards the lower magnetic flux density gradient (Fig. 2.8a) and could not take part in surface finishing.

Thus, the existing MRAFF and R-MRAFF processes could not be able to perform significant finishing on the internal surface of ferromagnetic cylindrical workpiece. This is because of more gradient of magnetic flux density towards the internal surface of ferromagnetic cylindrical workpiece as compared to the MR polishing fluid (Fig. 2.7b). This is happened because of the electromagnet placed outside the cylindrical workpiece surface. But, these processes are found capable for significant finishing of non-ferromagnetic cylindrical workpiece surface as there is more magnetic flux density gradient available with MR polishing fluid (Fig. 2.8b). Also, due to non-ferromagnetic nature of workpiece surface, there is no restriction on the relative movement between the workpiece surface and MR polishing fluid (Fig. 2.8b).

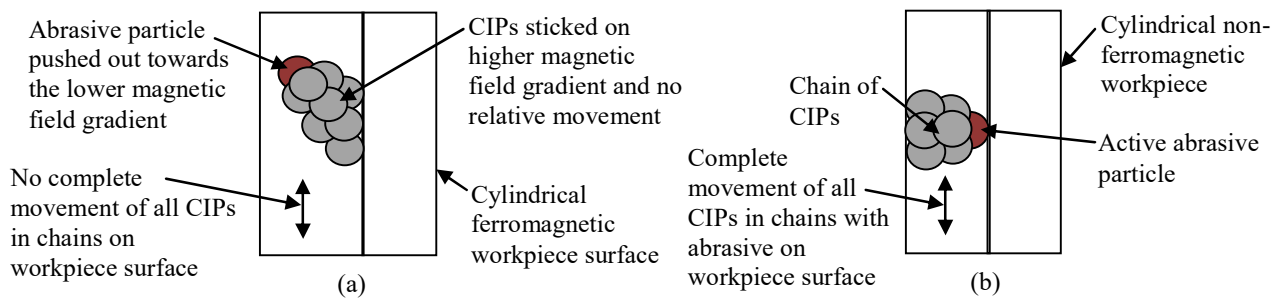


Fig. 2.8 Carbonyl iron particles (CIPs) chains with abrasive particle movement for finishing the internal surface of cylindrical (a) ferromagnetic workpiece and (b) non-ferromagnetic workpiece.

The applications of ferromagnetic cylindrical components are useful in cylindrical molds and dies, hydraulic cylinder, cylindrical barrel for injection molding etc. Therefore, these ferromagnetic cylindrical components require a highly finished internal surface for increasing its operative functional life. At present, these ferromagnetic cylindrical components are finished by using either fine surface grinding or special vertical honing machine. The finishing forces produced by the abrasive stones are less controlled during finishing and may sometimes result in different surface defects such as flakes, groove interrupt, folded metals, smudgy grooves etc. (Beyerer and Puente Leon, 1997). The requirements of uniform surface finishing and better surface characteristics on these ferromagnetic cylindrical products in today's production industry are extremely required for improving its reliability and efficiency. Therefore, a better controllable finishing tool can be made which is useful to improve the functional application of these ferromagnetic cylindrical components. This results in the reduction in wear as well as energy consumption (between the mating parts) by reducing the surface roughness values. It can

further improve the service life, maintenance of the cylindrical components as compared to traditional finishing tools.

2.4 Research objectives

-  Design and development of an experimental set-up of a novel magnetorheological honing process.
-  To synthesize and test of magnetorheological polishing fluid suitable for the developed finishing process.
-  To study the effect of process parameters (magnetizing currents, number of finishing cycles, % volume of different size of carbonyl iron particles, % volume of different size of abrasives etc.) on the process response such as surface finish improvement using response surface methodology in order to optimize the developed finishing process for better performance.
-  To analyze the finished surface characteristics and texture to understand the material removal mechanism using the developed finishing process.
-  To demonstrate finishing of some direct industrial applications of internal and blind-hole type workpiece surfaces on the developed process.

2.5 Organization of the thesis chapters

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

- Chapter 1** Introduces the different types of traditional and advanced finishing processes and their applications. This chapter correlates the overall advantages of advanced finishing processes based on magnetorheological (MR) polishing fluid for finishing of different materials as well as shape and size of the workpiece.
- Chapter 2** Reviews the literature related to various techniques used for finishing of the different kind of surfaces in the meant area of research. This chapter also gives an overview of the requirements of present work in industries as compared to the existing magnetorheological finishing processes. The chapter ends with the main objectives of the present research work and organization of the thesis chapters.
- Chapter 3** Reports the design and development of magnetorheological (MR) honing setup for finishing of the internal surface of ferromagnetic cylindrical workpiece. In this chapter, the comparative performance of two different magnetorheological (MR) honing tools using Maxwell Ansoft V13 (student version) software is reported.

Based on the results obtained from magnetostatic finite element analysis (FEA), the designs of the MR honing tools are discussed.

- Chapter 4** Deals with the synthesis of different MR polishing fluids. The rheological behavior of synthesized MR polishing fluid as per the composition given is discussed. The preliminary experiments to examine the finishing performance of the present developed setup with the two newly designed MR honing tools are reported.
- Chapter 5** States the detailed study regarding the statistical design (plan of experiments) conducted for better finishing of the internal surface of ferromagnetic EN-24 cylindrical workpiece. The regression model to analyze the effect of different process parameters on the percentage change in surface roughness (R_a) or % ΔR_a values is discussed. The optimization of the regression model to maximize the % ΔR_a values is also discussed.
- Chapter 6** Discuss the demonstration of finishing of the internal surface of cylindrical materials such as gray cast iron used in cylinder liner and hardened EN-24 steel used in injection barrel using MR honing tool with rectangular shaped core. This chapter also deals with the internal surface finishing of hardened EN-31 steel used as blind-hole type workpiece.
- Chapter 7** Reflects with the conclusions and important findings of the present research work and also the scope of the future work.

CHAPTER 3

DESIGN AND DEVELOPMENT OF MAGNETORHEOLOGICAL HONING PROCESS

As discussed in research gap, the magnetorheological (MR) fluid based finishing processes such as MRAFF (Jha and Jain, 2004) and R-MRAFF (Das *et al.*, 2012) are likely not found suitable for finishing of the internal cylindrical surface made of ferromagnetic material due to their tool design structure. Therefore, to overcome the challenges for significant finishing of the internal surface of ferromagnetic cylindrical workpiece, a magnetorheological (MR) honing process has been developed.

The design requirement in the present magnetorheological (MR) fluid based finishing process is to finish the internal surface of ferromagnetic cylindrical workpiece significantly as similar to conventional honing tool movement with the controlled magnetic field. To get such requirement, a new MR honing tool along with electromagnet has been designed and made to move together inside the cylindrical ferromagnetic workpiece surface (Fig. 3.1). The present designed tool ensures that the maximum magnetic flux density always obtained on outer tool core surface than the internal surface of ferromagnetic or non-ferromagnetic cylindrical workpiece. This result in MR polishing fluid always retains or sticks on the outer tool core surface rather than the internal surface of the ferromagnetic cylindrical workpiece. When the tool surface with retained MR polishing fluid has relative motion with respect to the internal surface of ferromagnetic cylindrical workpiece, the retained MR polishing fluid shear the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece (Fig. 3.1). Thus, the internal surface of ferromagnetic cylindrical workpiece is being finished by the present designed tool. The schematic of present thought of magnetorheological (MR) honing tool for finishing of the internal and blind hole surface of the cylindrical ferromagnetic workpiece are shown in Fig. 3.1 (a) and (b), respectively, with the two dimensional plot (magnetostatic finite element analysis) for distribution of magnetic flux density in the working gap. The magnetostatic finite element analysis (FEA) has been conducted with Maxwell Ansoft V13 software (student version). The magnetic flux density distribution at 0.6 mm working gap (filled with MR polishing fluid) was analyzed. The lower working gap provides a maximum distribution of magnetic flux density

between the tool outer surface and the inner surface of the cylindrical workpiece (Singh et al., 2012). As the working gap increases, the effect of magnetic flux density reduces. Therefore, 0.6 mm working gap has been chosen on the basis of available literature (Singh et al., 2012).

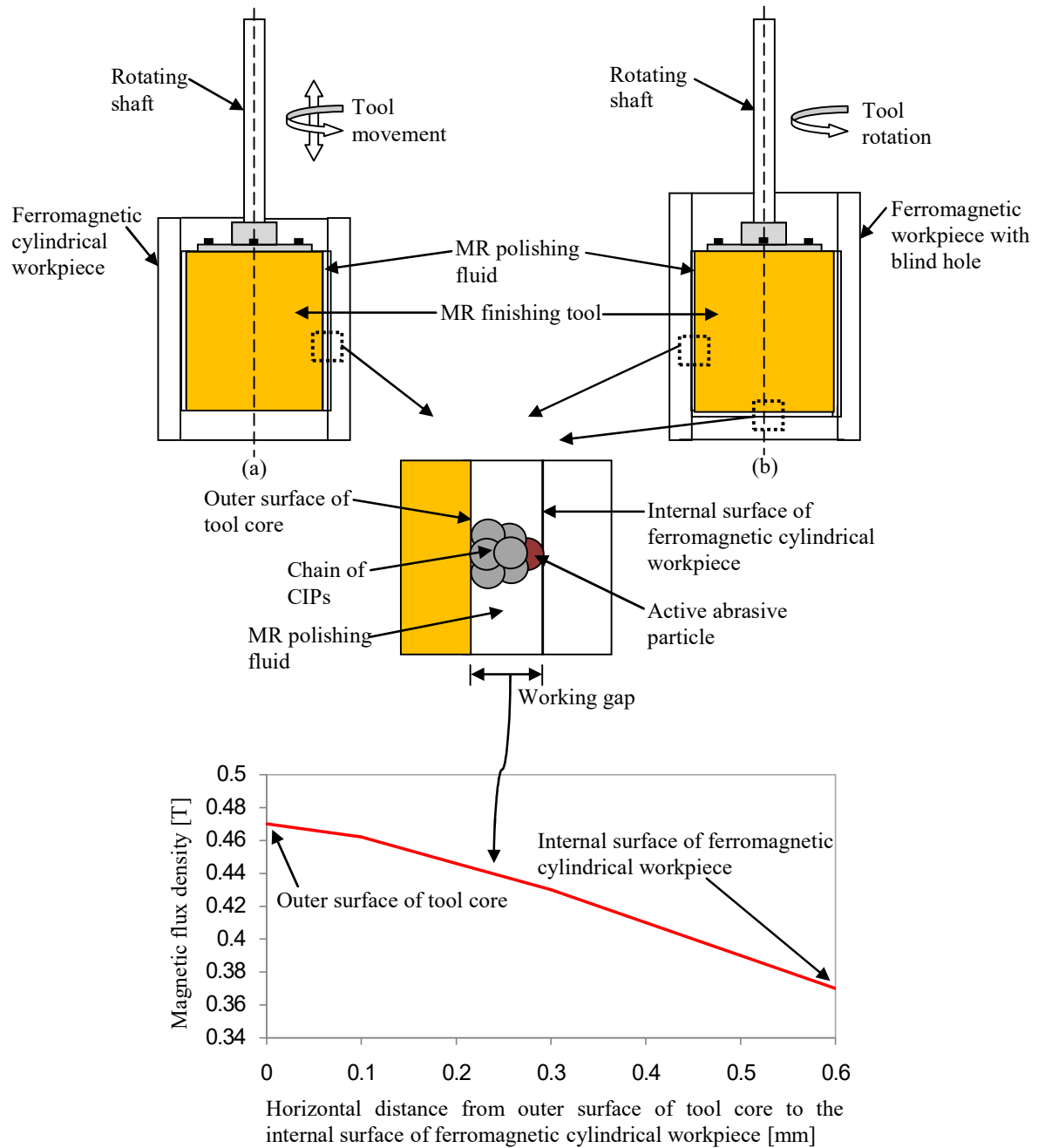


Fig. 3.1 Schematic of the present thought of magnetorheological (MR) honing tool during finishing of the internal ferromagnetic surface of (a) cylindrical type workpiece and (b) blind-hole type workpiece.

For the magnetostatic FEA, the assigned material to the electromagnetic model of the present tool design is given in Table 3.1. The values of relative permeability of different materials were taken from the existing literature review (Singh et al., 2013). The relative permeability of stainless steel as 1.003 is taken as an actual value. The current value as 2A and number of turns as 700 were taken as per the different trials performed for electromagnet size in Maxwell Ansoft V13 software.

Table 3.1 Assigned process parameters to the electromagnetic model of the present proposed tool design.

Parameters	Materials	Relative Permeability	Current	Number of turns
Electromagnet coil	Copper (20 standard wire size)	0.999991	1.3 A	700
Tool core	Mild steel	600		
Finishing medium	MR polishing fluid	5		
Ferromagnetic workpiece for both cylindrical and blind hole type	Mild steel	600		
Rotating shaft	Stainless steel	1.003		

It can be seen from Fig. 3.1 (2D plot of magnetic flux density) that the present thought to design a new finishing tool can ensure the higher magnetic flux density always available on the outer tool core surface than the internal surface of ferromagnetic cylindrical workpiece. As a result, MR polishing fluid always remains on the outer tool core surface and not sticks on the internal cylindrical ferromagnetic workpiece surface. Thus, the proper relative motion can be possible between the MR polishing fluid and ferromagnetic workpiece surface during the finishing operation. As the higher magnetic flux density present on the outer surface of tool core, therefore the CIPs forms chains like structure over the outer tool core surface and strongly pushes the entrapped active abrasives towards the internal surface of ferromagnetic cylindrical workpiece which has lower magnetic flux density. When these stiffened CIPs chains with entrapped active abrasives move on the internal surface of ferromagnetic cylindrical workpiece as similar to the conventional honing operation, the material removal takes place from the workpiece surface.

Thus, the present thought of developing a new finishing tool can be found relevant for finishing of internal as well as blind-hole type surfaces of ferromagnetic cylindrical workpiece.

3.1 Development of magnetorheological (MR) honing setup

A magnetorheological (MR) fluid based finishing with programmable logic controller (PLC) setup is developed for the finishing of internal surface of ferromagnetic cylindrical workpiece. The schematic and actual photograph of the present developed MR honing setup is shown in Figs. 3.2 and 3.3, respectively.

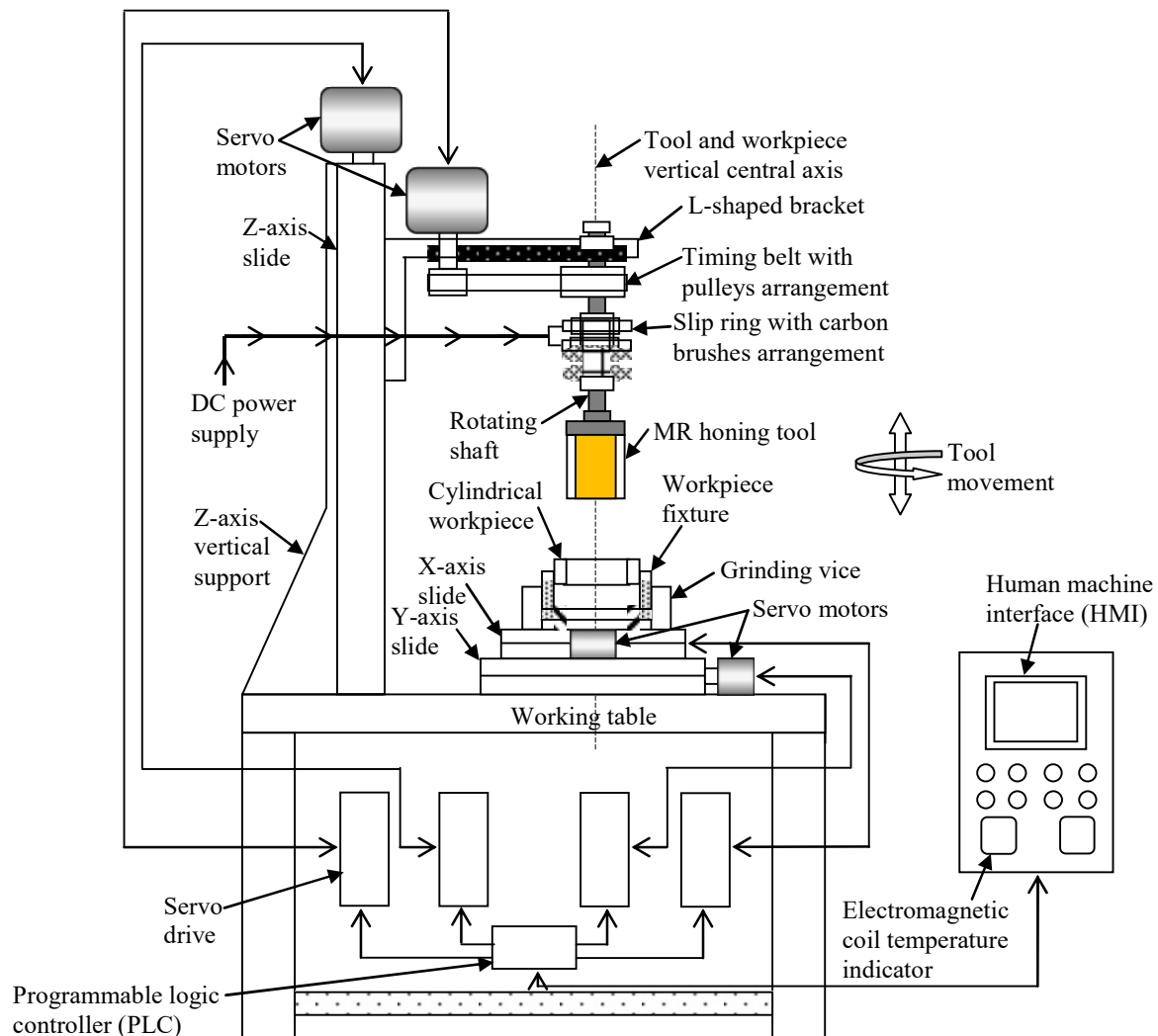


Fig. 3.2 Schematic of a newly developed magnetorheological (MR) honing setup.

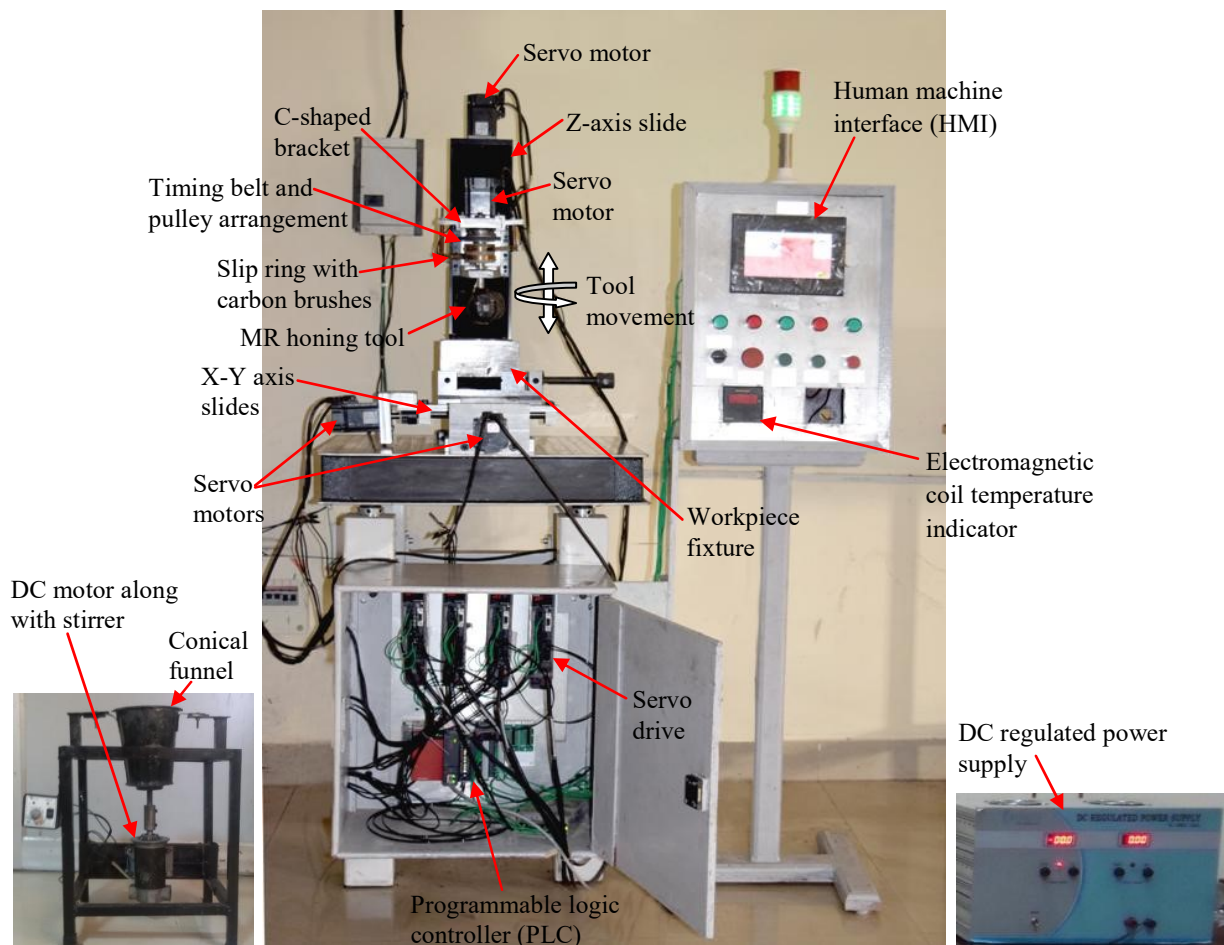


Fig. 3.3 Actual photograph of a newly developed magnetorheological (MR) honing setup.

The MR honing tool is placed on a Z-axis slide by means of the C-shaped aluminium bracket. The MR polishing fluid is applied externally on the outer finishing surface of tool core and depicts the formation of stiffened MR polishing fluid when direct current (DC) power is supplied to the electromagnet. The C-shaped aluminium bracket is attached to the vertical surface of Z-axis slide such that the outer finishing surface of tool core along with retained MR polishing fluid moves over the internal surface of ferromagnetic cylindrical workpiece. This is driven with the help of a servo motor through timing belt and pulleys arrangement. The timing belt and pulleys is an arrangement to provide the rotational movement to the MR honing tool through the servo motor. The motion controller is integrated with programmable logic controller (PLC) to control the movement (both rotational as well as reciprocation simultaneously) of the present

developed tool through a human-machine interface (HMI). The slip ring and carbon brushes are attached to the rotating shaft in order to transmit a continuous direct current (DC) power supply to the electromagnet of the present MR honing tool. The cylindrical workpiece along with the fixture is fixed with the help of a grinding vice and are further mounted on X-Y axis linear slides. The movements of X-Y axis linear slides are made through servo motors. The X-Y axis linear slides help to accomplish the centering of the axis of the cylindrical workpiece with the central vertical axis of the present MR honing tool. This results in a uniform working gap between the outer finishing tool surface and the inner surface of the cylindrical workpiece.

The servo motor is also attached to the Z-axis slide for controlling the movement of the tool in the vertical direction. For synthesizing the MR polishing fluid indigenously, a mixing chamber has been fabricated which comprises of a cone-shaped funnel along with a DC motor controlled stirrer.

3.1.1 Design and fabrication of magnetorheological (MR) honing tool with I-shaped core

Design and fabrication of the MR honing tool have been done on the basis of magnetostatic finite element analysis (FEA) for determining the variation in magnetic flux density between the outer finishing tool core surface and the ferromagnetic cylindrical workpiece surface. The magnetic flux density is an important significant parameter in MR fluid based finishing process because the strength of MR polishing fluid depends upon the magnetic flux density. Since the present developed process is also based on MR fluid, therefore the analysis of magnetic flux density is realized as the most important factor to achieve the required process performance. Hence, the present MR honing tool with I-shaped core has been designed for getting the maximum magnetic flux density on the outer finishing tool core surface than the ferromagnetic cylindrical workpiece surface as shown in Fig. 3.4. The dimensions of MR honing tool with I-shaped core are selected on the basis of different trials for getting the maximum magnetic flux density on its core outer surface through Maxwell Ansoft V13 software. The final dimensions of present MR honing tool are obtained as inner core diameter (d_1) of 10 mm, upper/lower core diameter (d_2) of 70 mm, length of upper/lower part of tool core (l_1 or l_3) of 8 mm, length of middle part of tool core (l_2) of 40 mm and thickness of middle part of tool core (t) of 2 mm as shown in Fig. 3.4 (a). The standard wire size (SWG) is selected for the electromagnet coil as 20 (or 0.914 mm diameter). The schematic and actual fabricated photograph of MR honing tool with I-shaped core are shown

in Figs. 3.4 (b) and (c), respectively, where the finishing tool along with the electromagnet is made to rotate and reciprocate inside the ferromagnetic cylindrical workpiece surface. The assigned parameters to the electromagnetic model of MR honing tool with I-shaped core are given in Table 3.2.

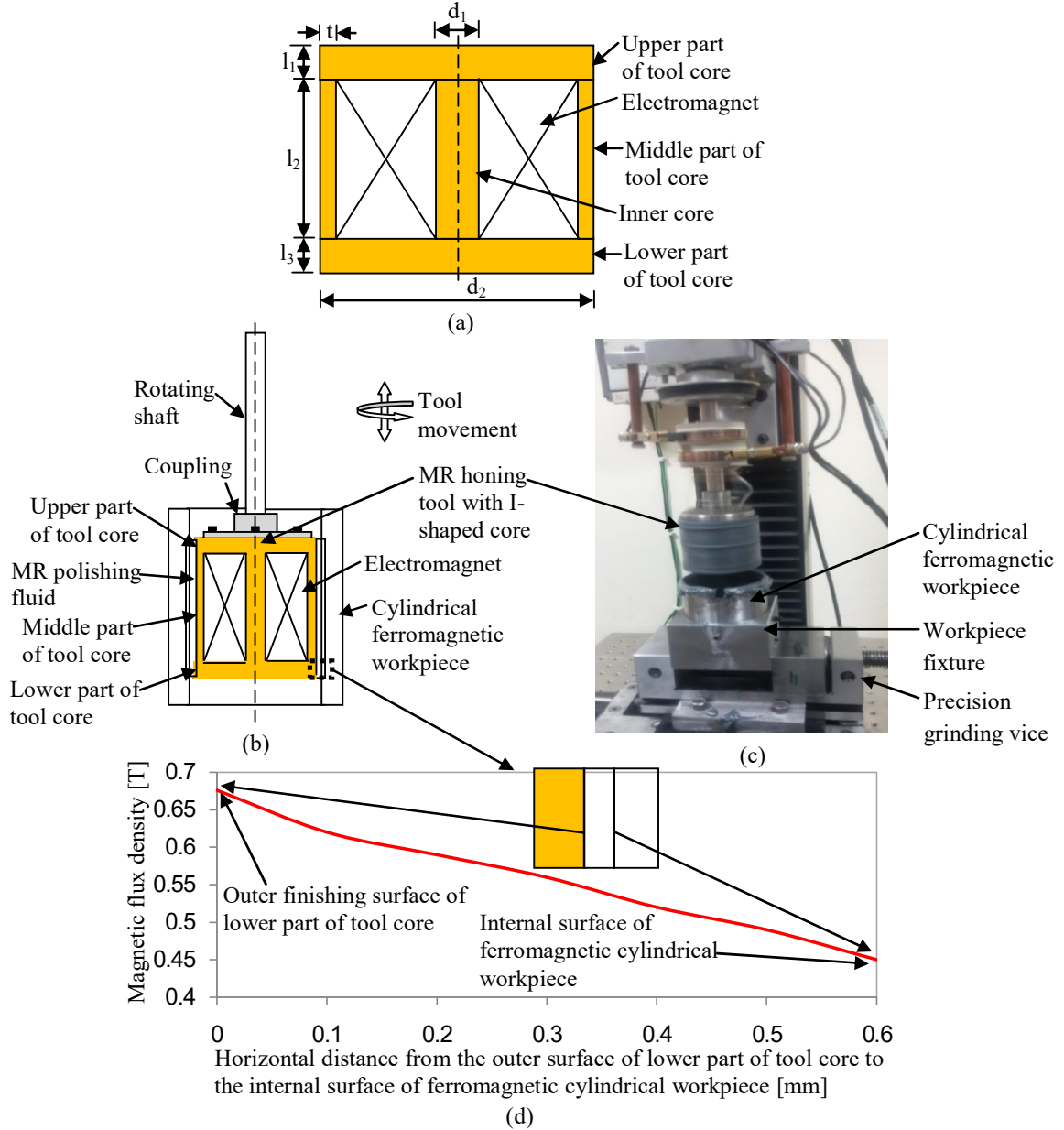


Fig. 3.4 (a) Schematic representing the dimensions of MR honing tool with I-shaped core, (b) schematic of designed MR honing tool with I-shaped core during finishing of internal surface of ferromagnetic cylindrical workpiece, (c) photograph of developed tool with I-shaped core and (d) two dimensional plot of distribution of magnetic flux density distribution within the working gap.

The magnetic flux density distribution at 0.6 mm working gap (filled with MR polishing fluid) is analyzed. Fig. 3.4 (d) shows the two dimensional plot from the magnetostatic FEA which clearly revealed that the maximum magnetic flux density gradient obtained on the outer finishing surface of tool core than the internal surface of ferromagnetic cylindrical workpiece.

Table 3.2 Assigned parameters to the electromagnetic model of the present MR honing tool with I-shaped and rectangular shaped cores.

Parameters	Materials	Relative permeability	Current	Number of turns on each core
Electromagnet coil	Copper	0.999991	2A	700
Rotating core (I-shaped core and rectangular shaped core)	Mild steel	600		
Finishing medium	MR polishing fluid	5		
Cylindrical ferromagnetic workpiece	Mild steel	600		
Rotating shaft	Stainless steel	1.003		

The two dimensional plot of variation in magnetic flux density on the outer finishing surface of tool core vertically from its upper part to the lower part is also obtained from magnetostatic FEA. The schematic of different parts of I-shaped finishing tool core and two dimensional plots of magnetic flux density obtained from magnetostatic FEA on the outer finishing surface of tool core vertically from its upper part to the lower part is shown in Figs. 3.5 (a) and (b), respectively. It can be seen from Fig. 3.5 (b), that the outer finishing surface of upper and lower part of the I-shaped tool core obtained a maximum magnetic flux density than it's the middle part. The non-uniform distribution of magnetic flux density along the outer finishing surface of the I-shaped tool core can also be seen from the result of magnetostatic simulation as shown in Fig. 3.5 (c). As a result, MR polishing fluid retained always more strongly on the outer finishing surface of upper and lower part of the I-shaped tool core than its middle part. Hence, the outer finishing surface of upper and lower part of the I-shaped tool core can be contributed more for finishing of the internal surface of ferromagnetic cylindrical workpiece than its middle part. Also, the

carbonyl iron particles (CIPs) formed strong chains on the outer finishing surface of upper and lower part of I-shaped tool core and maintained better strength to hold the active abrasives on its surface during finishing operation. The outer finishing surface of middle part of I-shaped tool core obtained comparatively lower magnetic flux density (Fig. 3.5b and c).

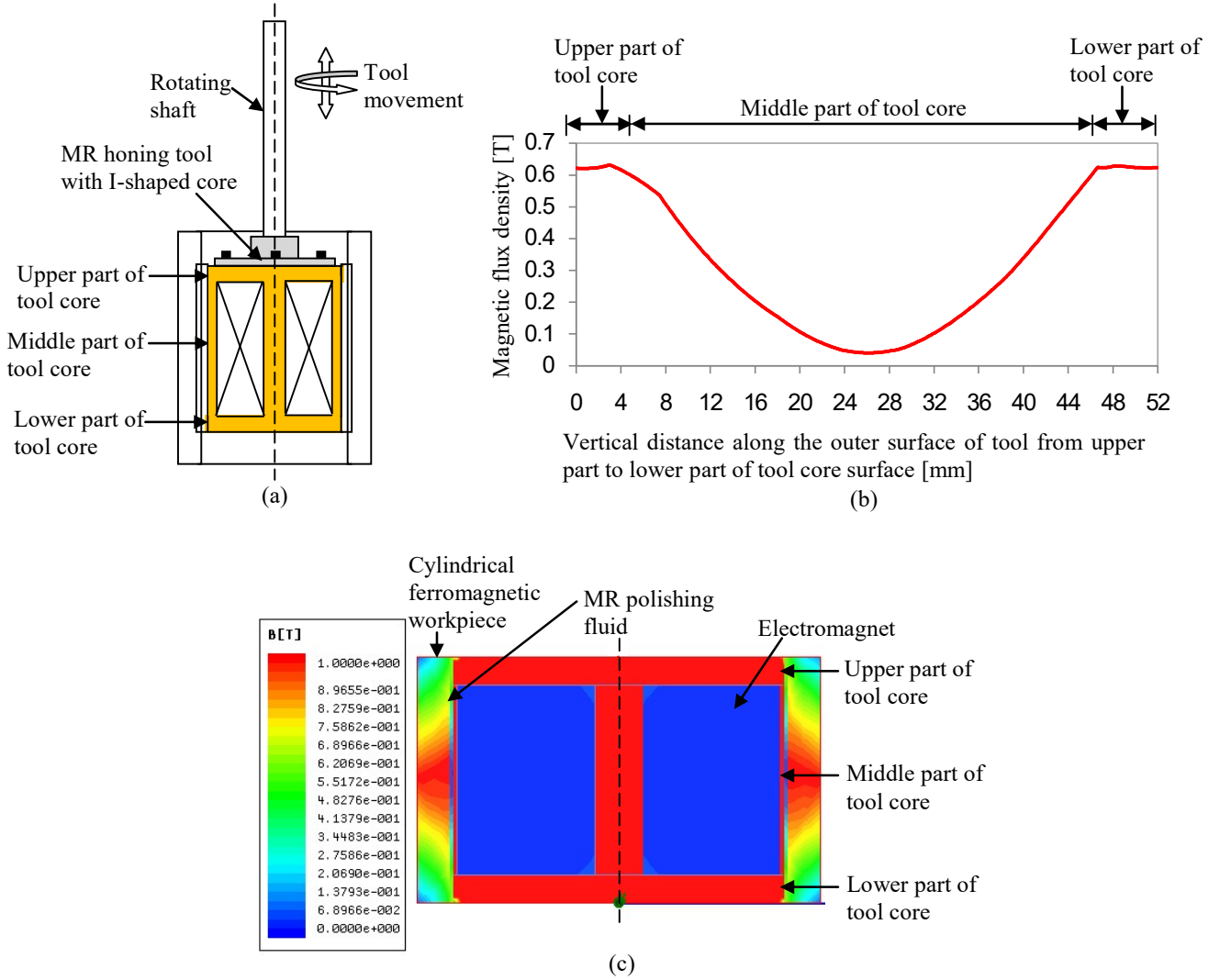


Fig. 3.5 (a) Schematic of different parts of I-shaped tool core, (b) two dimensional plot of distribution of magnetic flux density obtained from magnetostatic finite element analysis (FEA) vertically along the outer surface of the tool from upper part to the lower part of tool core and (c) magnetostatic simulation for distribution of magnetic flux density on tool with the I-shaped core along with cylindrical ferromagnetic workpiece and MR polishing fluid in working gap.

Therefore, the CIPs formed weak chains on its surface and maintained poor strength to hold the active abrasives on the surface during finishing. Thus, the CIPs chains cannot maintain a uniform strength on the outer finishing surface of the I-shaped tool core. This can even rub the finished surface which is being already finished by strong held active abrasives with CIPs chains during the finishing cycles and finally, it may cause a non-uniform surface finishing. Hence, to get uniform finishing on the internal surface of cylindrical workpiece, another finishing tool with the core needs to be designed for obtaining the uniform magnetic flux density on the outer finishing surface of the MR honing tool.

3.1.2 Design and fabrication of magnetorheological (MR) honing tool with rectangular shaped core

As the uniform distribution of magnetic flux density over the outer finishing tool core surface plays a high priority role for uniform finishing of workpiece surface, therefore, another new finishing tool with rectangular shaped core has been designed for obtaining the uniform magnetic flux density over its finishing surface as shown in Fig. 3.6. The dimensions of MR honing tool with rectangular shaped core are selected on the basis of different trials for getting the maximum magnetic flux density on its core surface using Maxwell Ansoft V13 software. The final dimensions of present MR honing tool are taken as rectangular core tool height (h_1) of 25 mm, electromagnet height (h_2) of 75 mm, rectangular tool core width (w_1) of 5 mm, electromagnet width (w_2) of 30 mm, rectangular tool core length (l_1) of 30.31 mm, electromagnet length (l_2) of 27.81 mm, upper portion shaft diameter (d_1) of 15 mm and lower portion shaft diameter (d_2) of 20 mm as shown in Figs. 3.6 (a) and (b), respectively. The standard wire size (SWG) selected for the electromagnet coil was 23 (or 0.610 mm diameter). The schematic and actual fabricated photographs of new MR honing tool with rectangular shaped core are shown in Figs. 3.6 (c), (d) and (e), respectively.

The three rectangular cores are equally inclined with the electromagnet on the rotating shaft whose outer surface are made in circular cross-section as same as cylindrical workpiece surface as shown in (Fig. 3.7a). The rectangular cores are tightened on a central rotating shaft through screws and easily replaceable as per the finishing required on the different sizes of the internal surface of ferromagnetic workpiece. Hence, the present MR honing tool with rectangular shaped core is designed to obtain a uniform magnetic flux density over its outer finishing tool core

surface for obtaining a uniform finishing on the internal surface of ferromagnetic cylindrical workpiece. The assigned parameters to the electromagnetic model of present MR honing tool with rectangular cores are also given in Table 3.2.

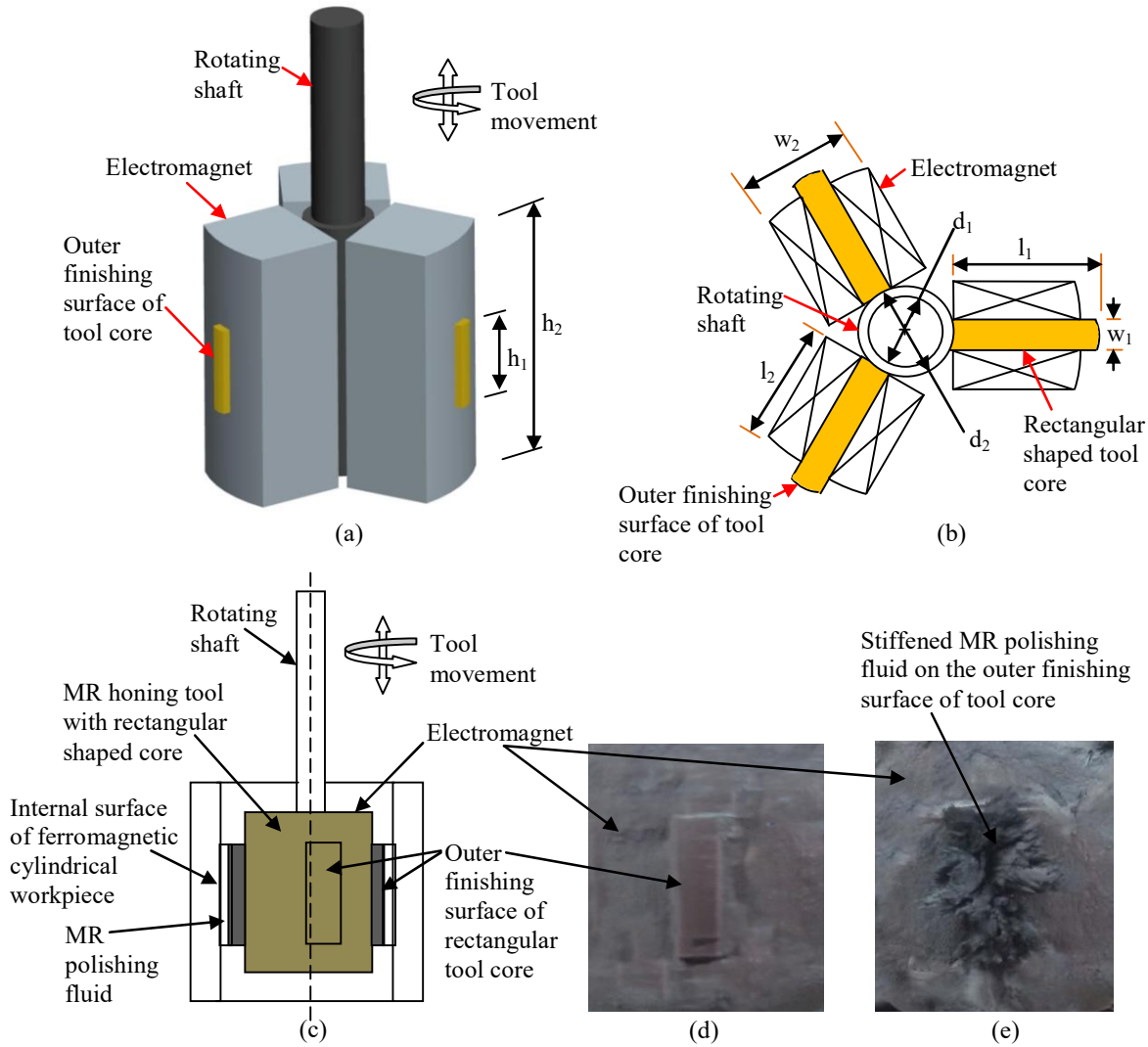


Fig. 3.6 (a) CAD model of MR honing tool with rectangular shaped core, (b) schematic representing the dimensions of MR honing tool with rectangular shaped core, (c) schematic front view of MR honing tool with rectangular shaped core, (d) with no MR polishing fluid on outer finishing surface of tool core and (e) with stiffened MR polishing fluid on the outer finishing surface of tool core under effect of magnetizing current.

The magnetic flux density distribution at 0.6 mm working gap (filled with MR polishing fluid) is analyzed. The total three number of solid rectangular tool cores design has been selected after

analyzing the different trials of design with the different number of rectangular cores in Maxwell ansoft V13 software for getting higher and uniformly magnetic flux density on its outer finishing tool core surface. The magnetostatic FEA with three numbers of rectangular cores is shown in Figs. 3.7 (b-d).

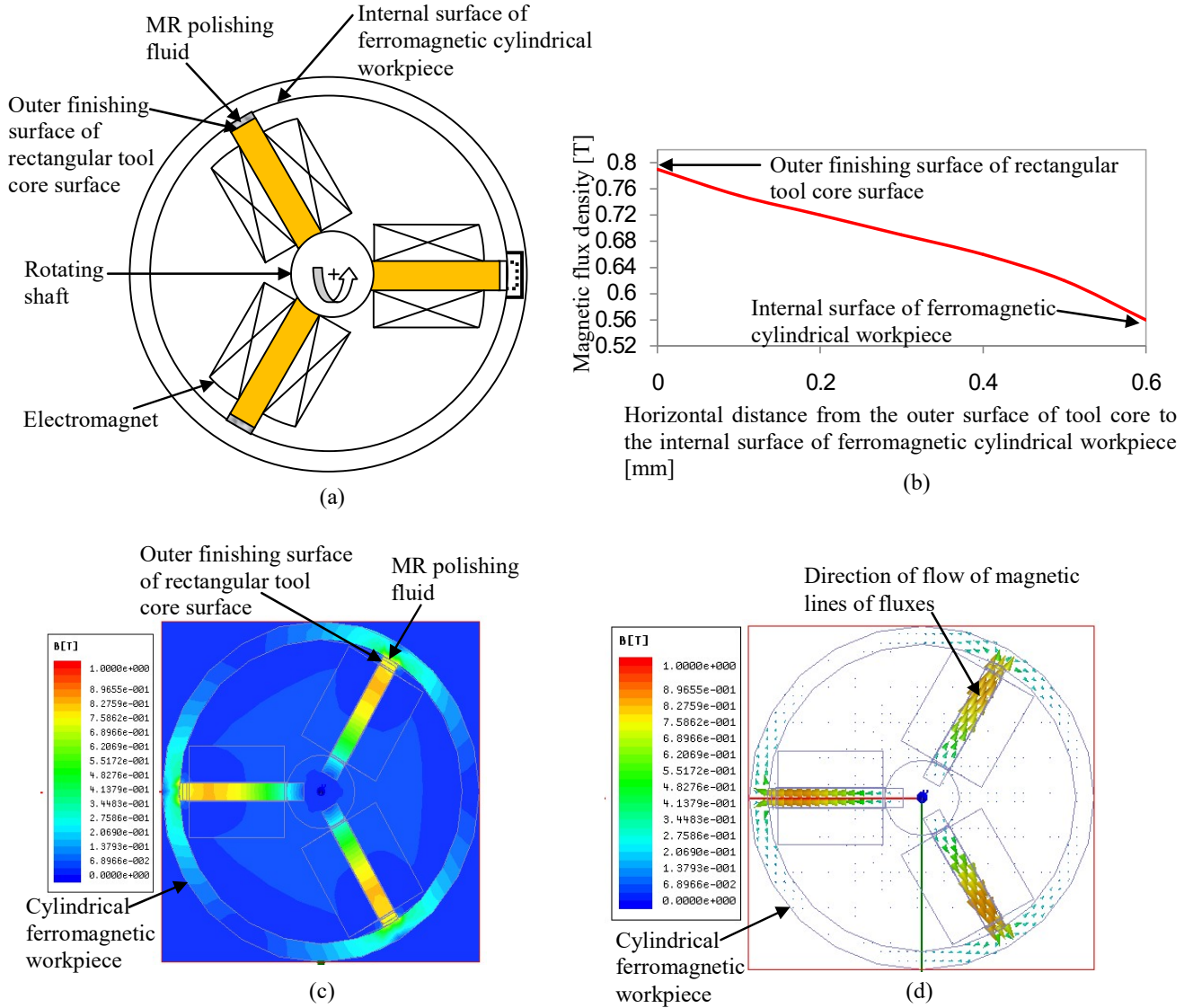


Fig. 3.7 (a) Schematic top view of MR honing tool with rectangular shaped core during finishing of the internal surface of ferromagnetic cylindrical workpiece, (b) two dimensional plot of distribution of magnetic flux density from magnetostatic finite element analysis (FEA) between the working gap, (c) magnetostatic simulation of tool with rectangular shaped core along with cylindrical ferromagnetic workpiece and MR polishing fluid in working gap and (d) direction of flow of magnetic lines of fluxes from the outer surface of rectangular tool core.

The two dimensional plot and magnetostatic simulation of magnetic flux density from magnetostatic FEA have clearly revealed that the outer finishing surface of rectangular tool core obtained maximum magnetic flux density than the internal surface of ferromagnetic cylindrical workpiece (Fig. 3.7b). Fig. 3.7 (c) shows the magnetostatic simulation of MR honing tool with rectangular shaped core along with cylindrical ferromagnetic workpiece and MR polishing fluid in working gap. Also, Fig. 3.7 (d) shows the direction of magnetic lines of fluxes from the outer finishing surface of rectangular tool core.

As maximum flux density gradient found on the outer finishing surface of rectangular tool core than the internal surface of ferromagnetic cylindrical workpiece, therefore the CIPs of MR polishing fluid gets attached on the outer finishing surface of tool core (higher magnetic flux density gradient) and not to the internal surface of ferromagnetic cylindrical workpiece (lower magnetic flux density gradient). The repulsive forces from the CIPs chains of higher magnetic flux density gradient push the abrasive particles towards the internal surface of ferromagnetic cylindrical workpiece of lower magnetic flux density gradient. These abrasive particles perform finishing when it moves on the internal surface of ferromagnetic cylindrical workpiece. Further to verify whether the magnetic flux density is uniform or not on the entire outer finishing surface of rectangular tool core, the magnetostatic FEA has been carried out vertically on its outer surface.

Figs. 3.8 (a) and (b) shows the magnetostatic simulation of MR honing tool with the rectangular shaped core, and two dimensional plot (from magnetostatic FEA) of magnetic flux density measured vertically on the outer finishing surface of rectangular tool core. This confirmed that the outer finishing surface of rectangular tool core obtained uniform magnetic flux density. Now, the carbonyl iron particles (CIPs) are able to form strong chains with uniform strength on the entire finishing surface of rectangular tool core. The whole CIPs chains maintained proper uniform strength with active abrasives during the finishing operation. Thus, the new designed MR honing tool with rectangular shaped core can be found more useful for uniform finishing on the internal surface of ferromagnetic cylindrical workpiece than finishing by MR honing tool with I-shaped core.

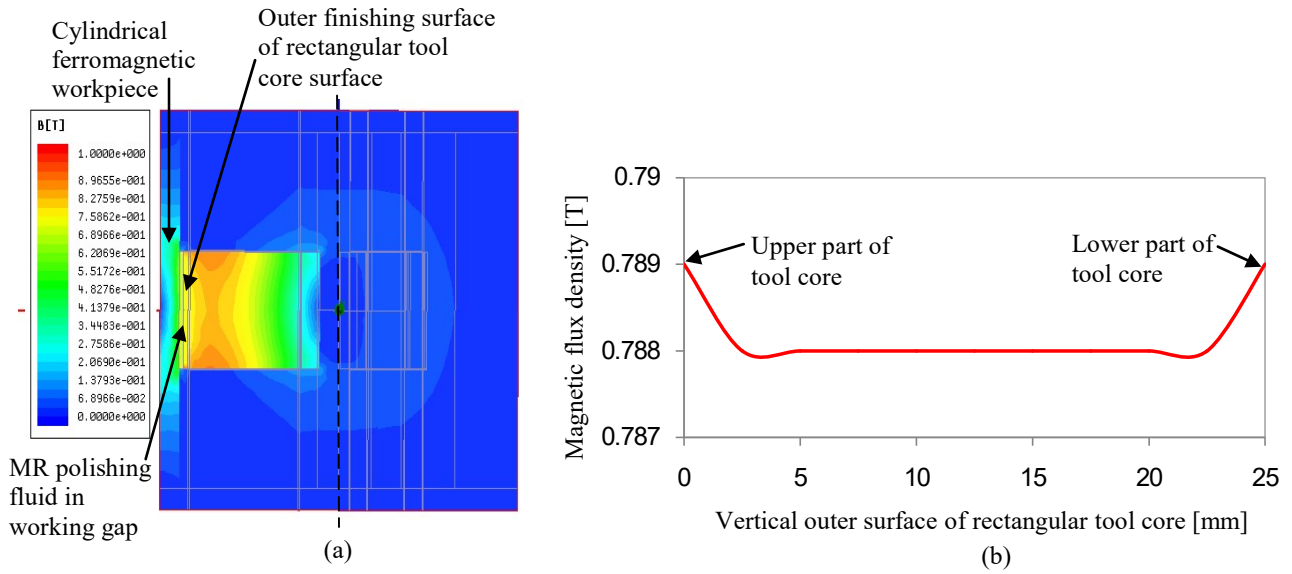


Fig. 3.8 (a) Magnetostatic simulation of MR honing tool with rectangular shaped core along with cylindrical ferromagnetic workpiece and MR polishing fluid in working gap (front view) and (b) two dimensional plot of distribution of magnetic flux density from magnetostatic finite element analysis (FEA) measured vertically along the outer surface of rectangular tool core.

3.1.3 Finite element methods (FEM) analysis of L-shaped bracket to hold magnetorheological (MR) honing tool

The design of L-shaped bracket is analyzed by FEM analysis in ANSYS 14.5 software in order to determine the static structural and pre-stress modal analysis of a bracket. To avoid the leakage of the magnetic field from the tool core to the L-shaped bracket, the non-ferromagnetic material was chosen for designing and fabrication of L-shaped bracket. Therefore, the material taken for L-shaped bracket was aluminium.

The material used in the L-shaped bracket design is given in Table 3.3.

Table 3.3 Materials used in L-shaped bracket design.

Component name	Material
L-shaped bracket	Aluminium
Tool holder shaft	Stainless steel
Tool	Mild steel

The different forces acting on the bracket during the structural analysis of bracket were considered on the following basis:

 Gravitation force acting due to the weight of the MR honing tool

 Gravitational force acting due to the weight of the servo motor

 Combined forces acting at the central axis of rotating MR honing tool

Both static structural and pre-stress modal analysis are carried out while designing a bracket. The hexahedral and tetrahedral meshes of the bracket assembly are generated with the number of nodes as 1,07,805. The initial boundary condition of the bracket assembly is shown in Fig. 3.9. The fixed support (C) is mounted to the Z-axis vertical slide through a cylindrical support (D). The standard earth gravity (B) is applied by considering the self-weight of the bracket assembly. The rotational velocity (A) is given to the tool holder shaft and the motor weight is given by the remote force as shown by the symbol (E).

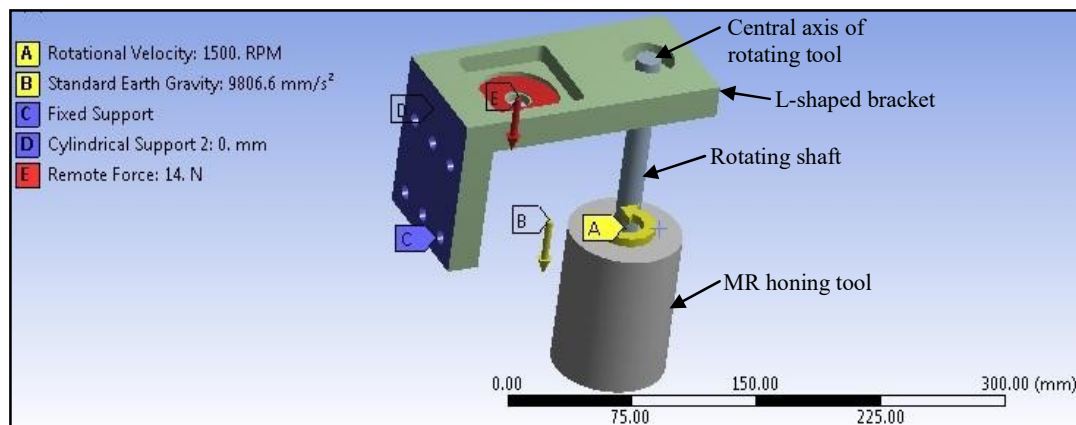


Fig. 3.9 Finite element method (FEM) analysis of L-shaped bracket used for holding the MR honing tool.

From the iteration, it clearly observed that the design is safe in term of deformation. The maximum deformation and stress acting on the bracket assembly are shown in Figs. 3.10 (a) and (b). The ultimate yield strength of the aluminium is 145 MPa and the maximum stress acting on the bracket is 3MPa which results in a higher value of the factor of safety. Therefore, the design is ultra safe under the static condition. The pre-stress (static structural) analysis is carried out in order to calculate the natural frequency of the bracket. The value of deformation from the modal analysis is shown in Fig. 3.10 (c).

The natural frequency of the bracket from the pre-stress (static structural) modal analysis is calculated as 55 Hz.

The natural frequency is obtained through the following Eq. (3.1).

$$\text{Natural frequency} = \frac{\sqrt{\frac{E \cdot I}{m \cdot L^3}}}{60} \quad (3.1)$$

As rotation speed of tool whose rotating shaft is in contact with bracket is 1500 rotation per minute. Therefore, using above relation, the natural frequency of bracket assembly is obtained as 25 Hz. While, the natural frequency of the bracket assembly is 25 Hz which did not match with the frequency calculated in modal analysis. Hence the design is found to be safe.

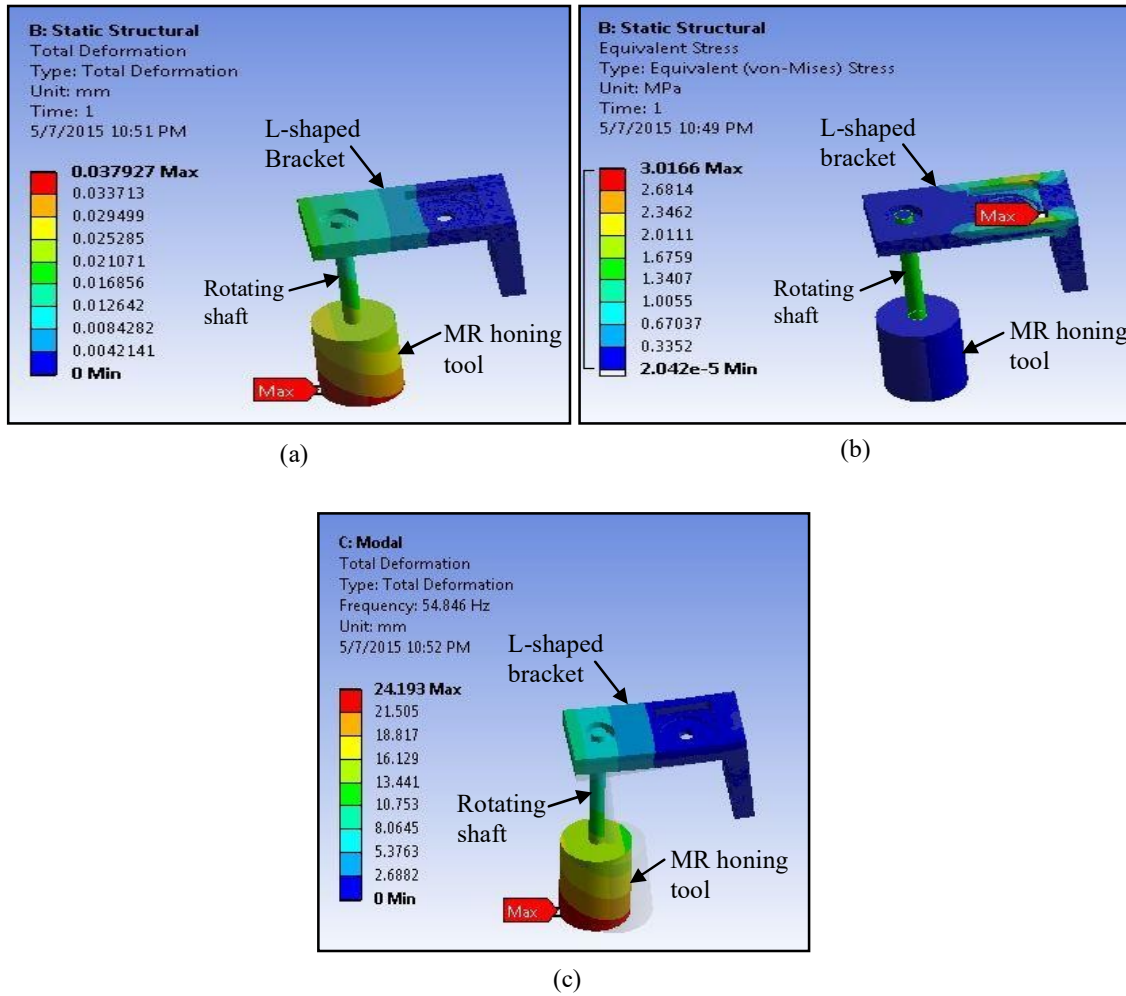


Fig. 3.10 Finite element method (FEM) analysis for (a) maximum deformation of a bracket, (b) maximum value of von-misses stresses and (c) modal analysis of L-shaped bracket.

3.2 Material removal mechanism in present developed finishing process

The material removal during magnetorheological (MR) honing process is caused by micro-cutting due to mechanical abrasion. The finishing capability of MR polishing fluid depends upon the ability of active abrasives to be in contact with the internal surface of ferromagnetic cylindrical workpiece. The schematic representation of the flow of magnetic repulsive forces from outer finishing tool core surface towards the internal surface of ferromagnetic cylindrical workpiece is shown in Fig. 3.11.

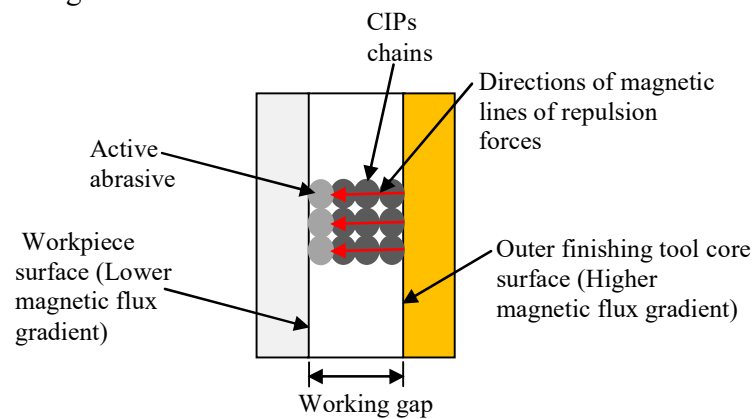


Fig. 3.11 Schematic representation of the flow of magnetic lines of repulsive forces from outer finishing tool core surface to the internal surface of ferromagnetic cylindrical workpiece.

The distance between the outer finishing tool core surface and internal surface of ferromagnetic cylindrical workpiece represents the thickness of MR polishing fluid. The thickness of MR polishing fluid represents the layer of MR polishing fluid within the working gap. When the finishing tool magnetized, the MR polishing fluid retained and became stiffened at the outer finishing tool core surface. This is because of the higher magnetic flux density gradient found at the outer finishing tool core surface than the ferromagnetic workpiece surface. With the influence of magnetic field, the carbonyl iron particles (CIPs) of MR polishing fluid attracted towards the magnetized outer finishing tool core surface and its repulsive forces pushes the SiC active abrasives outwards on the ferromagnetic workpiece surface. The active abrasives gripped by the CIPs chains on the internal surface of ferromagnetic cylindrical workpiece are responsible for finishing the surface by its movement over the internal surface. In the present tool design (both I-shaped and rectangular shaped tool core), the optimum value of magnetizing current was taken as 2A. Correspondingly, the better distribution of magnetic flux density was found within

the working gap is shown in Fig. 3.4 (d) and Fig. 3.7 (b). Due to the decrease in the gradient of magnetic flux density from outer tool core surface to the internal surface of the ferromagnetic cylindrical workpiece, the MR polishing fluid has been retained and stiffened on the outer surface of tool core. As the magnetizing current of 2A provided maximum magnetic flux density on the outer surface of the tool core, therefore, MR polishing fluid has got maximum rigidity on it. This rigidity of MR polishing fluid is further used to perform finishing on the internal surface of the ferromagnetic cylindrical workpiece by its rotational and reciprocation movements along with the tool. Depending upon the hardness of workpiece, the amount of rigidity of MR polishing fluid can be controlled by controlling the magnetizing current to the electromagnetic coil.

The schematic of finishing action due to rotational and reciprocation movement of gripped active abrasives on the internal surface of ferromagnetic cylindrical workpiece are shown in Figs. 3.12 (a), (b) and (c), respectively. Due to the effect of magnetic field and tool movement as similar to conventional honing tool process, the finishing force is induced. The rotational and reciprocation movement of the tool exerts an axial force (F_{ax}) along the axial path of the cylindrical ferromagnetic workpiece. Due to the effect of magnetizing current, the active abrasives entrapped by the CIPs chains exert a radial force (F_{ra}) on it. The depth of indentation of active abrasive particles entrapped by the CIPs chains onto the workpiece depends mainly on radial force (F_{ra}). The combined effect of axial force (F_{ax}) and tangential force (F_{ta}) is an important parameter for shearing the uneven peaks from the internal surface of ferromagnetic cylindrical workpiece. Due to the rotational and reciprocational movement of tool, the active abrasive is responsible for removing the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece as shown in Figs. 3.12 (b) and (c).

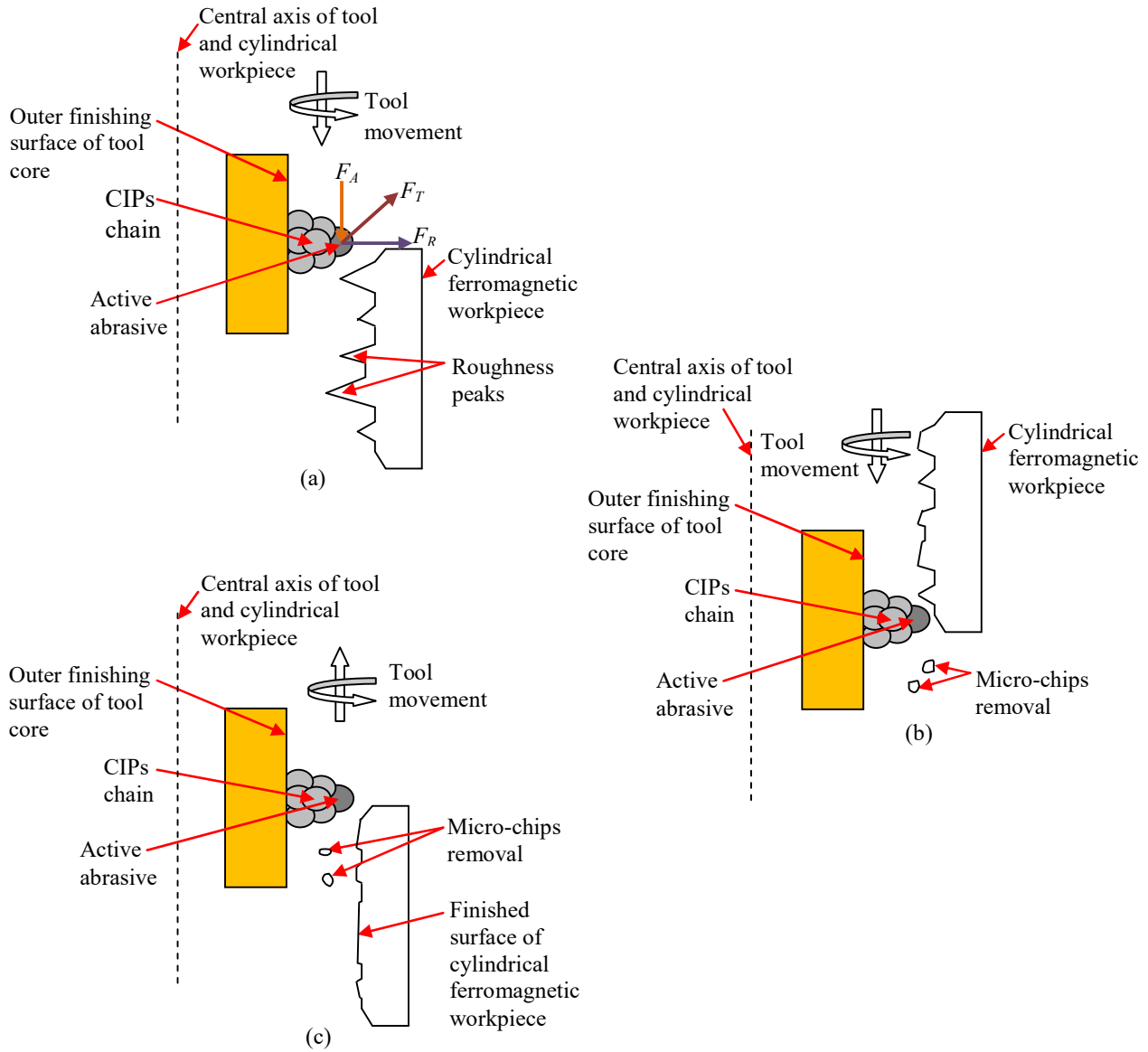


Fig. 3.12 Mechanism of material removal by MR honing tool with I-shaped core as well as rectangular shaped core (a) when the tool about to enter inside the cylindrical ferromagnetic workpiece, (b) when the tool moved fully downward and (c) when the tool again moved upward.

3.3 Conclusions

The following conclusions are drawn after the design and development of magnetorheological (MR) honing process.

-  The present new finishing process based on magnetorheological (MR) fluid demonstrated successfully for finishing the internal surface of ferromagnetic cylindrical workpiece as similar to honing operation with the controlled magnetic field.
-  In the present tool design, the higher magnetic flux density gradient obtained on the present designed outer finishing tool core surface than the internal surface of ferromagnetic cylindrical workpiece which clearly disclosed that the MR polishing fluid is always retained on the outer finishing tool core surface and does not stick on the internal surface of ferromagnetic workpiece of low gradient magnetic flux density during the finishing operation.
-  The newly designed MR honing tool with rectangular shaped core provided a uniform magnetic flux density than the MR honing tool with I-shaped tool core which is more advantageous to provide a uniform level of surface finishing on the internal surface of ferromagnetic cylindrical workpiece.

CHAPTER 4

SYNTHESIS OF MAGNETORHEOLOGICAL POLISHING FLUIDS AND PRELIMINARY EXPERIMENTATION

The magnetorheological (MR) fluids are commonly known as smart fluids that exhibit a change in viscosity under the change of magnetizing current (Rabinow, 1948). The apparent viscosity changes significantly from 10^5 to 10^6 times within the milliseconds under the effect of the magnetic field (Kordonski *et al.*, 1996). When the no magnetic field is applied to MR polishing fluid, the apparent viscosity gets reduced but when the magnetic field is applied to MR polishing fluid, the apparent viscosity of fluid increases and the fluid becomes stiffened. Due to this, magnetic iron particles are responsible for forming a chains type structure as per the direction of magnetic lines of fluxes as shown in Fig. 1.4 (Chapter 1). The chains structure of iron particles resists a certain level of shear stress without breakage. When the shear stress increases beyond the apparent yield stress, the iron particles chains structure breaks and finally these particles began to flow. The MR fluid behaves as a Bingham plastic model, which means that it exhibits a non zero shear stress value for a zero shear rate, behaving more like a solid than like a liquid (Macosko, 1994; Spaggiari, 2013). Later, the MR polishing fluids have been developed for finishing of different kinds of materials ranging from optical glass to the hardest material (Kordonski and Jacobs, 1996). MR polishing fluid is an important part of MR finishing processes which shows a change in magnetorheology due to change in magnetic field. MR polishing fluid is basically a suspension of non-magnetic abrasive particles such as silicon carbide and magnetic particles such as carbonyl iron particles (CIPs) and these are dispersed in a carrier medium such as mineral oil, silicone oil, or water (Jain 2009; Sidpara *et al.*, 2009). Under the magnetic field effect, the CIPs forms chains type structure which finally gripped and pushes the abrasive particles towards the lower magnetic flux gradient region. The gripped abrasive particles on the workpiece surface commonly known as active abrasives are responsible for precise surface finishing.

At present, the synthesis of MR polishing fluids has been made indigenously as per the requirement of different experimental conditions. The abrasive particles in MR polishing fluid are responsible for finishing in present developed MR honing process. The controllable behaviour of MR polishing fluid results in better process control during finishing by controlling

the magnetizing current. The synthesis of MR polishing fluid was carried out with the help of a specially made DC controlled mixing chamber as shown in Fig. 4.1.

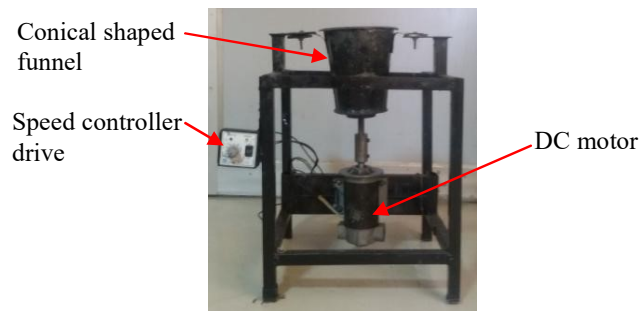


Fig. 4.1 Photograph of a DC controlled mixing chamber for synthesising the MR polishing fluid.

DC controlled mixing chamber is used for synthesizing the MR polishing as per the required composition. It consists of a conical shaped funnel, speed controller drive, stirrer and DC motor. The control of speed can be accomplished by using a speed controller drive. The MR polishing fluid was mixed thoroughly in a conical shaped funnel by the continuous rotation of stirrer.

4.1 Synthesis of required MR polishing fluid

The synthesis of MR polishing fluid was carried out with the help of a mixing chamber as discussed above. The MR polishing fluid compositions along with the different sizes of SiC abrasive particles and carbonyl iron particles (CIPs) with the percentage (%) volume concentration as per given in Table 4.1 to 4.4, were synthesized and which were further used for different experiments in this present research work. The MR polishing fluid was synthesized with the similar composition was already reported (Singh *et al.*, 2012). This synthesized MR polishing fluid was used as a finishing medium in this preliminary experimentation.

Table 4.1 MR polishing compositions used in preliminary experiments for internal finishing of cylindrical mild steel workpiece and cylindrical gray cast iron material used in cylinder liner.

Ingredients	Percentage volume concentration	Mesh sizes
SiC abrasive particles	20	800
Carbonyl iron particles (CIPs)	20	600
Base fluid (80% of heavy paraffin oil + 20% of AP3 grease by weight)	60	

Table 4.2 MR polishing compositions used in plan of experiments using central composite design technique for the internal surface finishing of EN-24 cylindrical workpiece.

Ingredients	Percentage volume concentration	Mesh sizes
SiC abrasive particles	20	400, 600, 800, 1000, 1200
Carbonyl iron particles (CIPs)	20	200, 300, 400, 500, 600
Base fluid (80% of heavy paraffin oil + 20% of AP3 grease by weight)	60	

Table 4.3 MR polishing compositions used for finishing of the internal surface of hardened EN-24 cylindrical material used in injection barrel.

Ingredients	Percentage volume concentration	Mesh sizes
SiC abrasive particles	20	800
Carbonyl iron particles (CIPs)	20	500
Base fluid (80% of heavy paraffin oil + 20% of AP3 grease by weight)	60	

Table 4.4 MR polishing compositions used for finishing of the internal surface of hardened EN-31 blind-hole type ferromagnetic workpiece.

Ingredients	Percentage volume concentration	Mesh sizes
SiC abrasive particles	20	800
Carbonyl iron particles (CIPs)	20	400
Base fluid (80% of heavy paraffin oil + 20% of AP3 grease by weight)	60	

4.2 Rheological behaviour of MR polishing fluid

The rheological behaviour in terms of flow stability of MR polishing as per the composition is given in Table 4.1, was carried out with the help of magnetorheometer with shear mode (Antar Paar modular compact rheometer MRC 301). During testing stage, the average working gap of 1 mm was taken in order to determine the viscosity and shear rate at different magnetizing current

(0 to 4 A). During the rheological behavior testing of MR polishing fluid, the gap was maintained as 1 mm which can be considered as a similar situation when different MR finishing processes used to be conducted. The cooling temperature during testing was maintained at 25°C around the MR polishing fluid. The plot between viscosity and shear rate of synthesized MR polishing fluid at different magnetizing current is shown in Fig. 4.2. The synthesized MR polishing fluid was found stable for the shearing rate between the 50 to 1000 s^{-1} with different magnetizing currents (1 to 4 A). The variations in the viscosity of MR polishing fluid against different magnetizing currents was shown almost constant during the shear rates between 50 to 1000 s^{-1} . Also, the synthesized MR polishing fluid was found little less stable for magnetizing current 0.5 A for the same shear rates as variation in viscosity was not shown constant during the shear rate 50 to 1000 s^{-1} . This may be due to the lesser magnetic field. At 0 A current, as there no magnetic field was applied. Therefore, the rheological behaviour of present synthesized MR polishing fluid found was unstable as shown in Fig. 4.2. Hence, the synthesized MR polishing fluid can be found useful for finishing application in the present developed process for shearing rates 50 to 1000 s^{-1} with magnetizing currents (1 to 4 A), as it showed good rheological behaviour of MR polishing fluid.

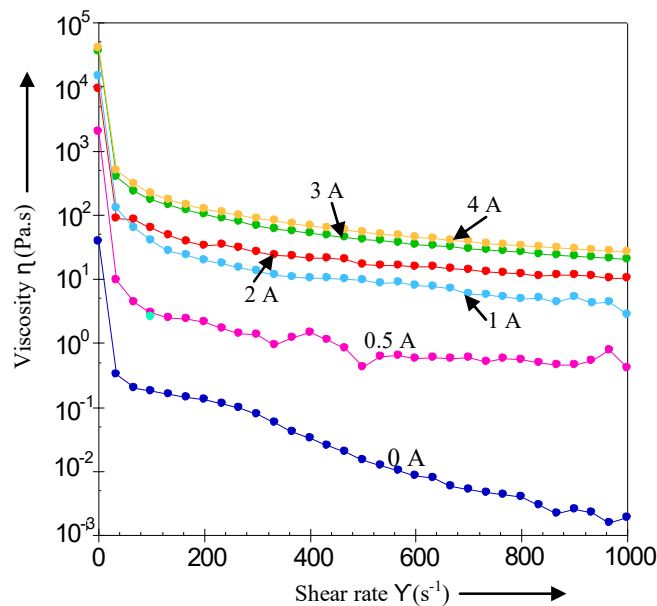


Fig. 4.2 Plot between viscosity versus shear rate of synthesized MR polishing fluid at different magnetizing current (0 to 4 A).

4.3 Preliminary experimentation

To analyze the finishing performance of two newly developed finishing tools with I-shaped and rectangular shaped cores, the preliminary experimentation were carried out on the internal surface of ferromagnetic cylindrical workpiece (made of mild steel) for investigating the change in surface roughness (R_a) values with different finishing time. The synthesized MR polishing fluid as given in Table 4.1, was used for finishing of internal surface of ferromagnetic cylindrical workpiece. The CAD model of a cylindrical ferromagnetic workpiece representing the different surface roughness measuring points is shown in Fig. 4.3 (a).

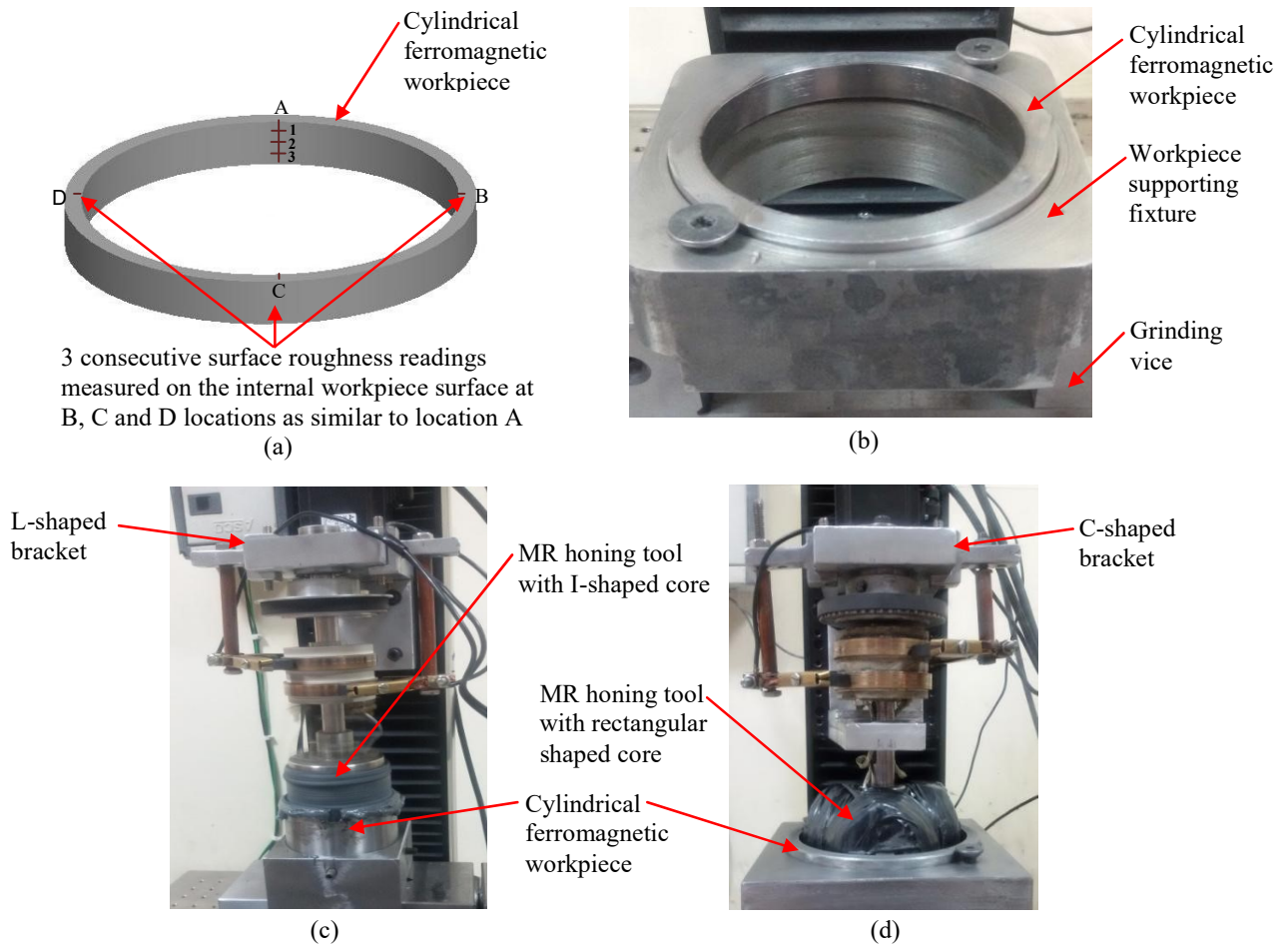


Fig. 4.3 (a) CAD model of cylindrical ferromagnetic workpiece representing the different surface roughness measuring points, (b) photograph of the arrangement of cylindrical ferromagnetic workpiece with supporting fixture for finishing of internal surface of ferromagnetic cylindrical workpiece, photograph of finishing of internal surface of ferromagnetic cylindrical workpiece using MR honing tool with (c) I-shaped core and (d) rectangular shaped core.

The cylindrical ferromagnetic workpiece was fixed to precision grinding vice by means of supporting fixture as shown in Fig. 4.3 (b). The centering of cylindrical workpiece axis along the tool vertical axis was done with help of the X-Y axis slides for maintaining a uniform working gap of 0.6 mm between the outer finishing tool core surface and the internal surface of ferromagnetic cylindrical workpiece and further a dial gauge was used to check the proper alignment of tool axis with respect to the axis of cylindrical workpiece surface. The dial gauge reading showed zero error i.e. the axis of tool coincided with the axis of the cylindrical workpiece surface. As a result, the uniform working gap was maintained between the outer finishing surface of tool core and the internal surface of ferromagnetic cylindrical workpiece for obtaining a uniform surface finishing throughout the entire internal cylindrical surface. The photograph of MR honing tool with the I-shaped core and rectangular shaped core during the internal surface finishing of ferromagnetic cylindrical workpiece are shown in Figs. 4.3 (c) and (d), respectively. The initial ground and final surface roughness values were measured with surfest SJ-400 (Mitutoyo) with cut off length as 0.25 mm and the number of intervals as 5. The surface roughness value (R_a) at different locations (A, B, C and D) on the internal surface of ferromagnetic cylindrical workpiece was measured. Each location consists of 3 consecutive readings (Fig. 4.3a). The total 12 readings of surface roughness values were measured on the internal surface of ferromagnetic cylindrical workpiece to represent the average roughness of the whole surface. The DC power was supplied to the electromagnetic coil through slip ring and carbon brushes in order to get the magnetic flux density on outer finishing tool core surface. The average magnetic flux density on the outer finishing tool core surface was measured with the help of gauss meter. As there is a continuous movement of abrasive particles over the internal surface of ferromagnetic cylindrical workpiece, the cutting edges of abrasive particles get eroded. These abrasive particles can be considered as blunted abrasive particles. As a result, the cutting ability of these abrasive particles can be reduced. In order to avoid the movement of blunted abrasive particle within the MR polishing fluid, the renewal of fresh MR polishing fluid after every 30 minutes of finishing takes place for achieving better finishing performance.

The statistical quantification for both initial and final surface roughness profiles for the mean or average (μ) and standard deviation (σ) are given by Eqs (4.1) and (4.2) as

$$\mu = \frac{\frac{f_{\mu 1}}{f_1} + \frac{f_{\mu 2}}{f_2} + \frac{f_{\mu 3}}{f_3} \dots \dots \dots + \frac{f_{\mu N}}{f_N}}{f_{\mu}} \quad (4.1)$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (R_a - \mu)^2} \quad (4.2)$$

where, μ be the mean or average of total 12 surface roughness (R_a) values, $x_1, x_2, x_3, \dots, x_n$ be the different surface roughness (R_a) values on the internal surface of ferromagnetic cylindrical workpiece, N be the total number of surface roughness (R_a) readings on the internal surface of ferromagnetic cylindrical workpiece, σ be the standard derivation with respect to mean (μ) and x_i be the individual surface roughness (R_a) value.

The experimental conditions were used for finishing of the internal surface of ferromagnetic cylindrical workpiece by using MR honing tool with I-shaped core and rectangular shaped core as per given in Table 4.5.

Table 4.5 Experimentation conditions taken for preliminary trials.

Parameters	For MR honing tool	
	With I-shaped core	With rectangular shaped core
Total finishing time	150 minutes	90 minutes
Tool rotational speed	500 rpm	500 rpm
Tool vertical linear speed	40 cm/min	40 cm/min
Working gap	0.6 mm	0.6 mm
DC power supply to electromagnetic coil	36.5 V, 3 A	24.2 V, 2 A
Average magnetic flux density on outer finishing tool surface	0.397 T	0.405 T

4.3.1 Observations and discussion on experimentation with I-shaped core of finishing tool

The preliminary experimentation was carried out on the internal surface of ferromagnetic cylindrical workpiece (made of mild steel) for investigating the change in surface roughness (R_a) values with different finishing time. The dimensions of cylindrical ferromagnetic workpiece were taken as the internal diameter of 72 mm and the external diameter of 86 mm. The initial surface roughness value (R_a) was in the range of 532-573 nm which was obtained after internal surface grinding. The mean (μ) of 12 initial surface roughness (R_a) values were calculated as 554 nm and the standard deviation with respect to mean (μ) was calculated as 13.

The change in surface roughness (R_a) values after 150 minutes of finishing by using MR honing tool with I-shaped core is shown in Fig. 4.4 (a). The final surface roughness values obtained with

the I-shaped core was in the range of 120-201 nm. The mean (μ) of the 12 final surface roughness (R_a) values obtained by the I-shaped tool core was calculated as 155 nm and the standard deviation with respect to the mean (μ) was calculated as 24. The percentage change in the surface roughness (R_a) or $\% \Delta R_a$ values after 150 minutes of finishing by using tool with I-shaped was found in the range of 65-78% as shown in Fig. 4.4 (b). The variation in $\% \Delta R_a$ values from 65% to 78% on the finished internal surface of ferromagnetic cylindrical workpiece shows the non-uniform surface roughness by using MR honing tool with I-shaped core. The non-uniformity in surface roughness values on the finished surface in terms of standard deviation (σ) was calculated as 24 which were more than the 13 as calculated for the initial ground surface.

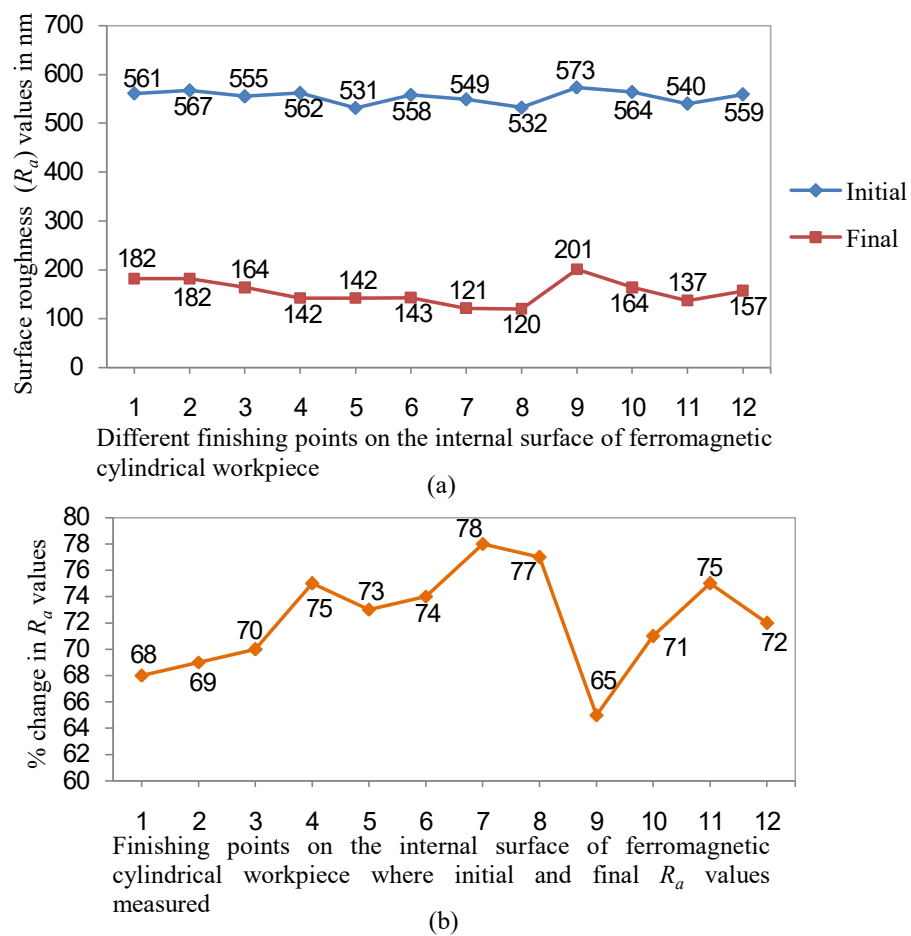


Fig. 4.4 (a) Plot between the change in surface roughness (R_a) values from initial to final and (b) percentage change in surface roughness (R_a) values at that points where initial and final R_a measured after 150 minutes of finishing by using MR honing tool with I-shaped core.

This may be due to the I-shaped MR honing tool core having a non-uniform distribution of magnetic flux density over its surface (Fig. 3.5b of Chapter 3). More magnetic flux density was found on its upper and lower parts than the middle part. Therefore, CIPs formed weak chains on the middle part of the I-shaped tool core and did not maintain better strength with active abrasives during finishing. When the finishing tool with an I-shaped core rotated and reciprocated inside the cylindrical ferromagnetic surface, the retained and stiffened MR polishing fluid due to the effect of magnetizing current also moved along with the tool. Though the MR polishing fluid along the outer finishing surface of the upper and lower parts of the tool core performed better finishing, but due to the movement of weak CIPs chains with loose active abrasives as supported by the outer finishing surface of the middle part of the tool core, the finished surface during the finishing cycle. Thus, the present designed MR honing tool with an I-shaped core was not found more competent for achieving uniform finishing with uniform $\% \Delta R_a$ values due to non-uniform magnetic flux density on its outer surface.

4.3.2 Preliminary experimentation with rectangular shaped core of finishing tool

The preliminary experimentation was also carried out on the internal surface of ferromagnetic cylindrical workpiece (made of mild steel) for investigating the change in surface roughness (R_a) values with different finishing time. The dimensions of the cylindrical ferromagnetic workpiece were taken as the internal diameter of 82 mm and the external diameter of 96 mm. The initial surface roughness value (R_a) was in the range of 520-597 nm which was obtained after internal surface grinding. The mean (μ) of 12 initial surface roughness (R_a) values was calculated as 568 nm and the standard deviation with respect to mean (μ) were calculated as 23. The experimental conditions used during the internal surface finishing of ferromagnetic cylindrical workpiece are given in Table 4.5. The experimentation was carried out for 90 minutes of finishing. The change in surface roughness (R_a) values after 90 minutes of finishing by using MR honing tool with rectangular shaped core is shown in Fig. 4.5 (a). The final surface roughness values obtained with rectangular shaped core were in the range of 101-132 nm. The mean (μ) of the 12 final surface roughness (R_a) values obtained by the rectangular shaped tool core was calculated as 120 nm and the standard deviation with respect to mean (μ) was calculated as 10. The percentage change in surface roughness (R_a) or $\% \Delta R_a$ values after 90 minutes of finishing on the internal surface of ferromagnetic cylindrical workpiece was found in the range of 78% to 81% as shown in Fig. 4.5 (b). The variation in $\% \Delta R_a$ values from 78% to 81% on the finished surface shows

almost uniform surface roughness was achieved on the finished internal surface of cylindrical ferromagnetic. The better uniformity in surface roughness values on the finished surface in terms of standard deviation (σ) was calculated as 10 which were less than the 23 as calculated for the initial ground surface. This is due to the rectangular shaped MR honing tool core has a uniform distribution of magnetic flux density over its surface (Fig. 3.8b of Chapter 3). The carbonyl iron particles (CIPs) of MR polishing formed strong chains with uniform strength on the entire surface of rectangular tool core. When the MR honing tool with rectangular shaped core rotated and reciprocated inside the cylindrical ferromagnetic surface, the uniform stiffened MR polishing fluid over its surface also moved and performed uniform finishing on the internal surface of ferromagnetic cylindrical workpiece.

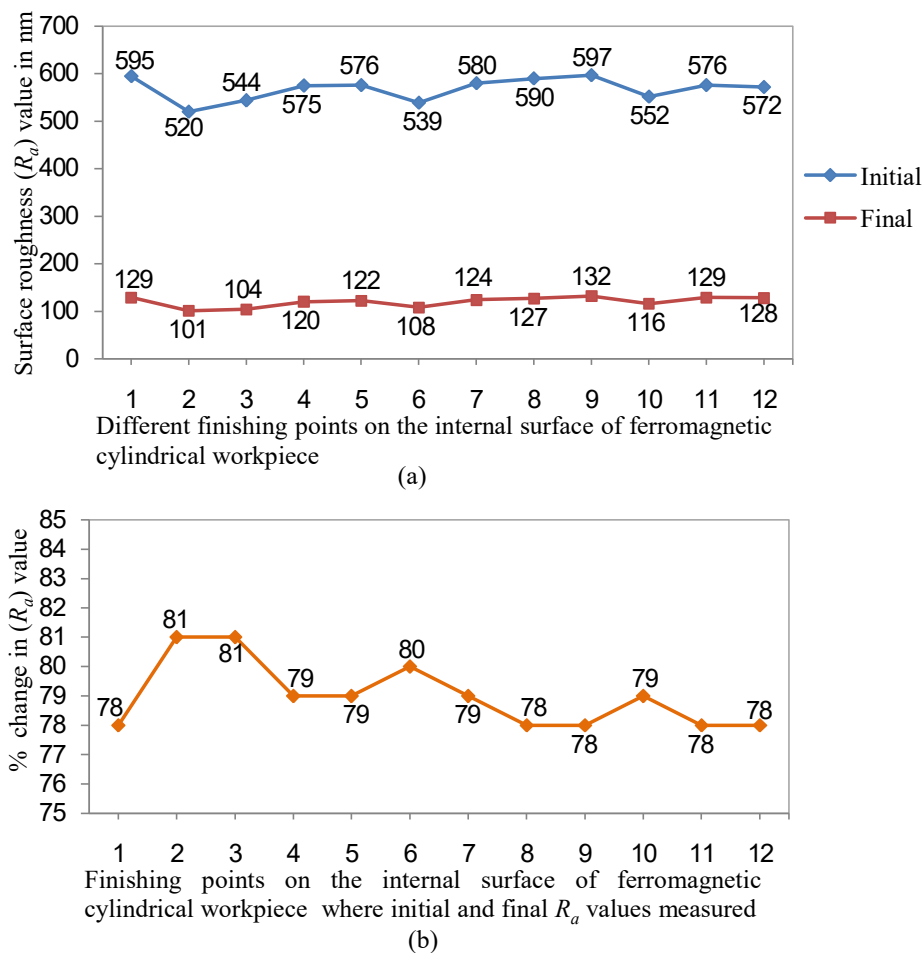


Fig. 4.5 (a) Plot between the change in surface roughness values (R_a) from initial to final and (b) percentage change in (R_a) values at that points where initial and final R_a measured after 90 minutes of finishing by using MR honing tool with rectangular shaped core.

The initial and final finished surface roughness profiles (at point 8 of location “C” in Fig. 4.3a) by using the MR honing tool with I-shaped core after 150 minutes of finishing are shown in Figs. 4.6 (a) and (b), respectively.

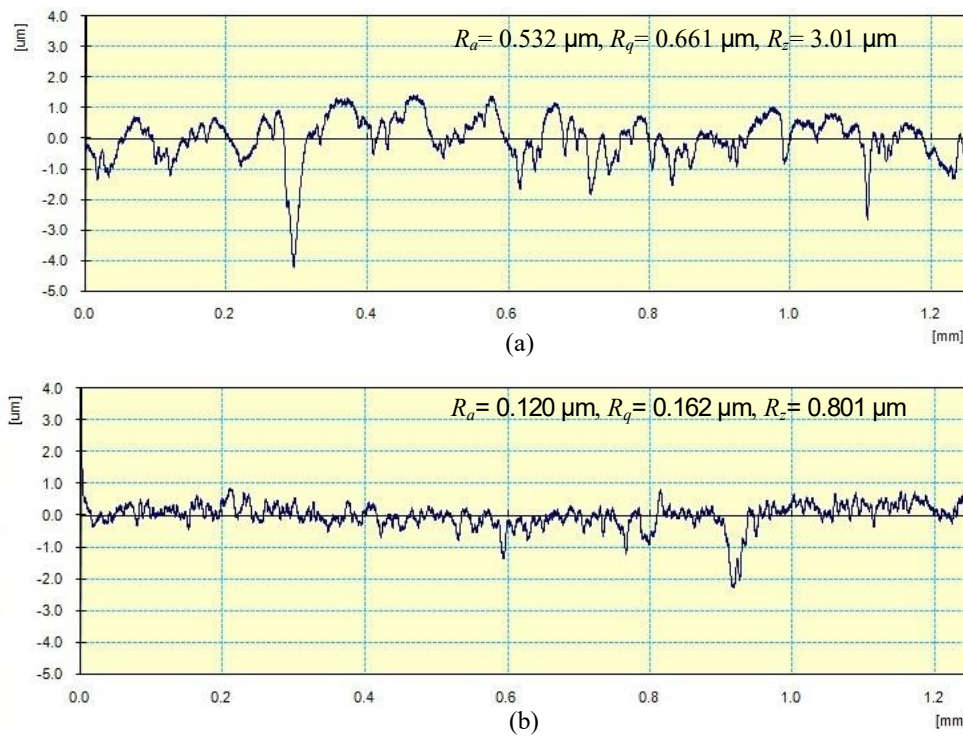


Fig. 4.6 Surface roughness profiles of (a) initial ground surface and (b) finished surface of ferromagnetic cylindrical surface (at point 8 of location “C”) after 150 minutes of finishing by using MR honing tool with I-shaped core.

The initial and final finished surface roughness profiles (at point 2 of location “A” in Fig. 4.3a) by using the MR honing tool with rectangular shaped core after 90 minutes of finishing are shown in Figs. 4.7 (a) and (b), respectively. The scanning electron microscopy (SEM) at x1000 magnification was also carried out to know the surface texture of initial and finished surface after 90 minutes of finishing by using MR honing with rectangular shaped core as shown in Figs. 4.8 (a) and (b), respectively. The $\% \Delta R_a$ values in the range of 78% to 81% after 90 minutes of finishing with rectangular shaped tool core was found better as compared to 65% to 78% after 150 minutes of finishing with I-shaped tool core.

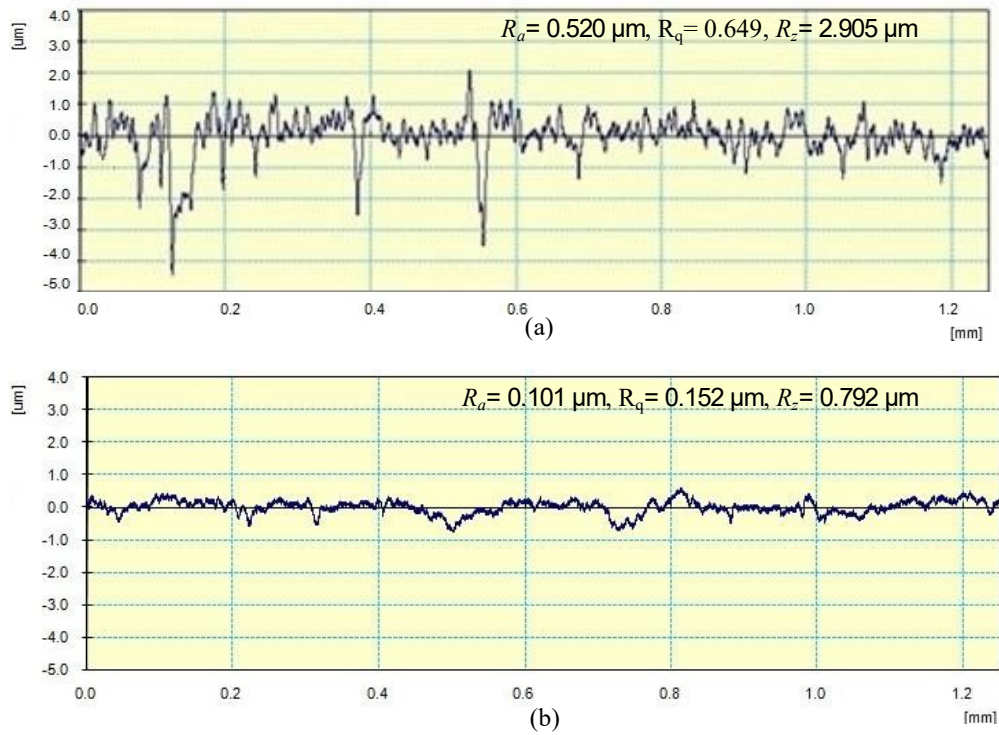


Fig. 4.7 Surface roughness profiles of (a) initial ground surface and (b) finished surface of ferromagnetic cylindrical surface (at point 2 of location “A”) after 90 minutes of finishing by using MR honing tool with rectangular shaped core.

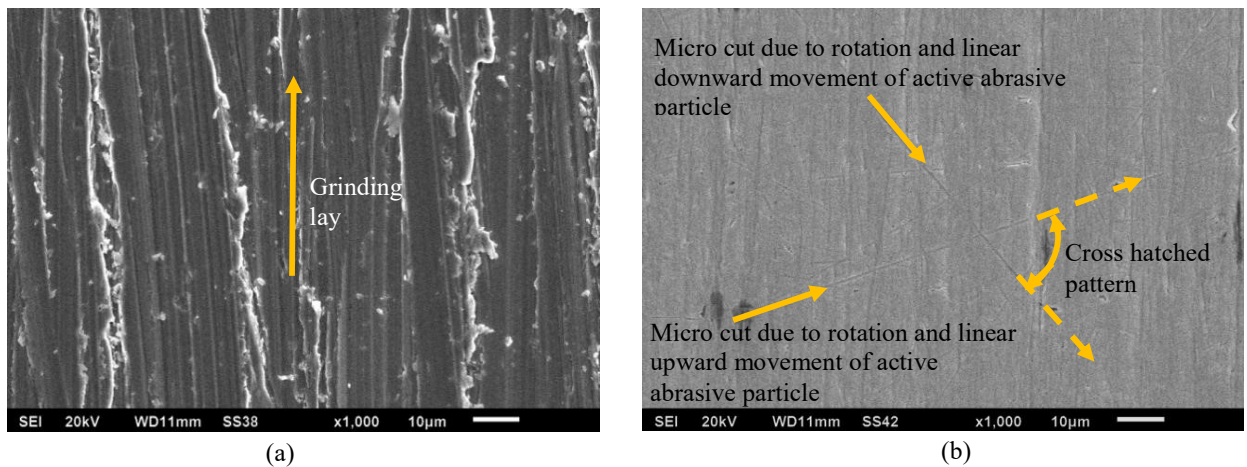


Fig. 4.8 Scanning electron microscopy (SEM) images of ferromagnetic cylindrical workpiece (a) initial ground surface and (b) finished surface at x1000 after 90 minutes of finishing by using MR honing tool with rectangular shaped core.

Also, better improvement in surface texture which clearly revealed that the present developed finishing tool with rectangular shaped core is more effective for significant finishing of the

internal surface of ferromagnetic cylindrical workpiece. Also, the MR honing tool with rectangular shaped core can be found more competent for more efficient and uniform surface finishing on the internal surface of ferromagnetic cylindrical workpiece than the MR honing tool with I-shaped core. This is useful to provide better in close tolerance design, higher bearing load capacity and longer service life of the components. The overall results showed that the finishing performance of the present designed MR honing tool with rectangular shaped core was found better as compared to the tool designed with I-shaped core.

4.4 Conclusions

The following conclusions are drawn after synthesis of MR polishing fluid and preliminary experimentation with MR honing setup having I-shaped tool core and rectangular shaped tool core for finishing of the internal surface of ferromagnetic cylindrical workpiece.

- FM
81 The synthesis of different MR polishing fluids were carried out indigenously in order to check the feasibility of the present developed process in achieving better surface characteristics on the internal cylindrical surface made of ferromagnetic materials.
- FM
81 The rheological behaviour of MR polishing fluid as per composition is given in Table 4.1, clearly revealed that the synthesized MR polishing fluid was found stable for the shearing rate between 50 to 1000 s^{-1} with different magnetizing currents (1 to 4 A). The variations in the viscosity of MR polishing fluid against applied magnetizing currents was showed almost constant during the shear rates between 50 to 1000 s^{-1} .
- FM
81 From the preliminary experimental results, the percentage change in surface roughness (R_a) values in the range of 78% to 81% after 90 minutes of finishing with the newly designed rectangular shaped tool core was found more efficient as compared to the percentage change in surface roughness (R_a) values as 65% to 78% after 150 minutes of finishing with I-shaped tool core. This is because of the MR honing tool with rectangular shaped core provided a uniform magnetic flux density at its outer finishing tool core surface.
- FM
81 The overall results concluded that MR honing tool with rectangular shaped core can be used for achieving a uniform level of finishing on the internal ferromagnetic cylindrical surface of different industrial cylindrical components such as cylinder liner, injection barrel, cylindrical molds and dies etc.

CHAPTER 5

PARAMETRIC STUDY OF MAGNETORHEOLOGICAL HONING PROCESS

The present magnetorheological (MR) honing process with rectangular shaped core was found appropriate for obtaining a uniform level of surface finishing on the internal cylindrical surface made of ferromagnetic materials. In this chapter, the detailed parametric study using the statistical design of experimentation was conducted for finishing of the internal surface of ferromagnetic cylindrical workpiece by the present MR honing process with rectangular shaped tool core. To increase the productivity and performance of the present developed process, the optimum process parameters were identified. Response surface methodology was carried out to plan and evaluate the effect of mesh sizes of SiC abrasive particles, mesh sizes of carbonyl iron particles (CIPs), magnetizing currents, tool rotational speeds and tool linear speeds on the percentage change in surface roughness (R_a) or ($\% \Delta R_a$) values. The experimental analysis indicated that the higher $\% \Delta R_a$ values were mostly determined by the magnetizing currents followed by tool linear speeds, mesh sizes of CIPs, tool rotational speeds and mesh sizes of SiC abrasive particles. The surface roughness (R_a) values were found as low as 96 nm from initial 401 nm after 90 minutes of finishing by using optimum process parameters. The optimum process parameters were found as SiC abrasive particles of 800 mesh size, CIPs of 400 mesh size, magnetizing current of 1.2 A, tool rotational speed of 500 rpm and tool linear speed of 50 cm/min. Further, to study the difference in surface morphology of initial and final finished surface, the scanning electron microscopy was also conducted. The surface defects such as deeper grooves and sharp edges were completely removed after 90 minutes of finishing.

5.1 Magnetorheological (MR) honing process variables

Magnetorheological (MR) honing process is a new finishing process which is useful for fine finishing of the internal cylindrical surface made of ferromagnetic material. On the basis of experimentations, the process variables (both controllable and uncontrollable type) are identified as given in Table 5.1. For the parametric study, the controlled variables (independent in nature) are taken and are discussed as below.

Table 5.1 Magnetorheological (MR) honing process variables.

Independent controlled variables	Dependable uncontrolled variable
Mesh sizes of SiC abrasive particles	Ambient temperature
Mesh sizes of carbonyl iron particles (CIPs)	
Magnetizing currents	
Tool rotational speeds	
Tool linear speeds	
Initial values of surface roughness	
Material properties of cylindrical workpiece	

5.1.1 Mesh sizes of SiC abrasive particles (S)

The different sizes of SiC abrasive particles are helpful in removing the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece surface during actual finishing operation. The coarser size of abrasive particles is better suited for removing the higher peaks of roughness profiles, whereas the finer size of abrasive particles is suited for fine finishing of waviness type of roughness profiles. The material removal takes place through abrasive particles is in form of micro-chips. The experimentations are conducted by using different mesh sizes of SiC abrasive particles that varies from 400 mesh size to 1200 mesh size. These mesh sizes of SiC abrasive particles are the standard size used in industry. The 400 mesh size of abrasive particles is of course type, whereas 1200 mesh size of abrasive particles is of fine type.

5.1.2 Mesh sizes of carbonyl iron particles (C)

The different sizes of carbonyl iron particles (CIPs) are an important process variable which is taken into account during the finishing performance. The micro-chips removed from the internal surface of ferromagnetic cylindrical workpiece through the SiC abrasive particle totally depends upon the bonding forces in between each CIP. The CIPs due to its magnetic nature forms a chains structure along the magnetic lines of fluxes, which finally holds the SiC abrasive particles by its chains structure. The amount of indentation of SiC abrasive particles totally depends on the rigidity in CIPs chains structure. The experimentations are conducted by using different mesh sizes of CIPs that varies from 200 mesh size to 600 mesh size.

5.1.3 Magnetizing current (I)

The rheological property of MR polishing fluid mainly depends upon the strength of magnetic flux density. The strength of magnetic flux density in terms of Tesla [T] and it can be increased

or decreased by changing the magnetizing current to the electromagnetic coil through DC power supply. The stiffness of MR polishing fluid depends upon the strength of magnetic field which can be varied by changing the magnetizing current to the electromagnetic coil. The experimentations are conducted by using the different magnetizing currents range that varies from 0.4 A to 2.0 A. These ranges of magnetizing currents are selected between low and high range as per the design of electromagnetic coil.

5.1.4 Tool rotational speed (R)

The rotational speed of the tool with the retained MR polishing fluid over the outer finishing surface of rectangular tool core helps to remove the roughness profiles from the internal surface of ferromagnetic cylindrical workpiece. The shearing force induced by the SiC abrasive particles due to the tool rotational movement. This is helpful for material removal in form of micro-chips because of mechanical abrasion. The experimentations are conducted by using the different tool rotational speed that varies from 200 rpm to 600 rpm. These ranges are taken on the basis of preliminary experimental trials.

5.1.5 Tool linear speed (L)

The continuous vertical (to and fro) motion of SiC abrasive particles on the internal surface of ferromagnetic cylindrical workpiece is necessary for achieving better finishing results. Also, to uniformly remove the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece, the tool linear speed is one of the most effective process parameter. On the basis of preliminary experimental trials, the different range of tool linear speeds are selected and are varies from 10 cm/min to 50 cm/min.

5.2 Design of experiments

To examine the influence of different process parameters on the percentage change in surface roughness (R_a) or ($\% \Delta R_a$) values, the design of experiments was used. The experiments were conducted on the developed magnetorheological (MR) honing process as shown in Fig. 5.1. The material used for finishing the internal cylindrical surface is EN-24 steel (ferromagnetic in nature) which is mainly used in injection barrels. The cylindrical EN-24 workpiece consists of a four key slots arrangement as shown in Fig. 5.2. For measuring the surface roughness as well as better observations of surface morphology under scanning electron microscopy, a key type workpiece parts were made in such a way that it can be easily attached and remove from the cylindrical workpiece surface by means of interference fit.

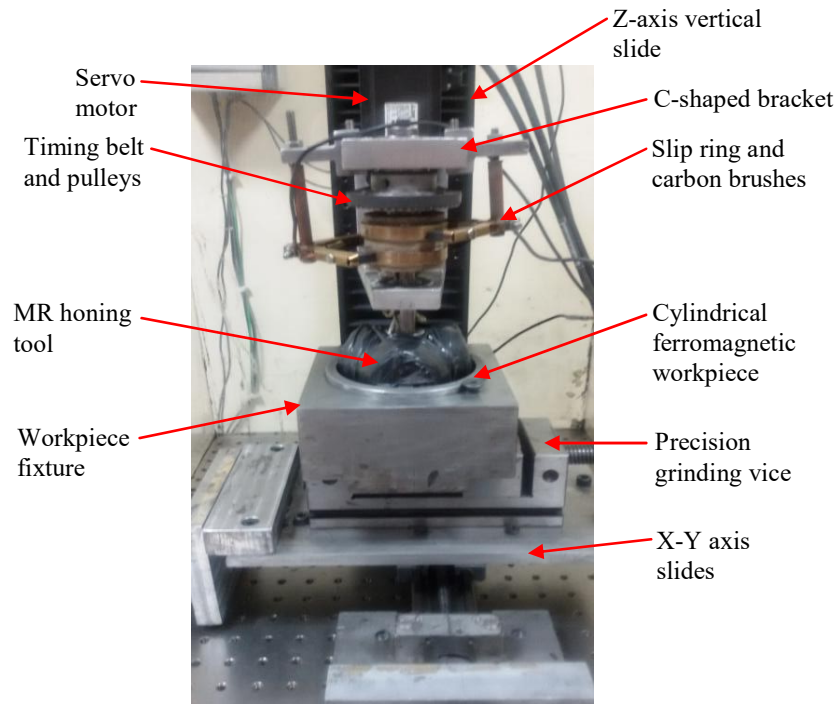


Fig. 5.1 Photograph of magnetorheological (MR) honing setup during internal surface finishing of ferromagnetic cylindrical workpiece parts.

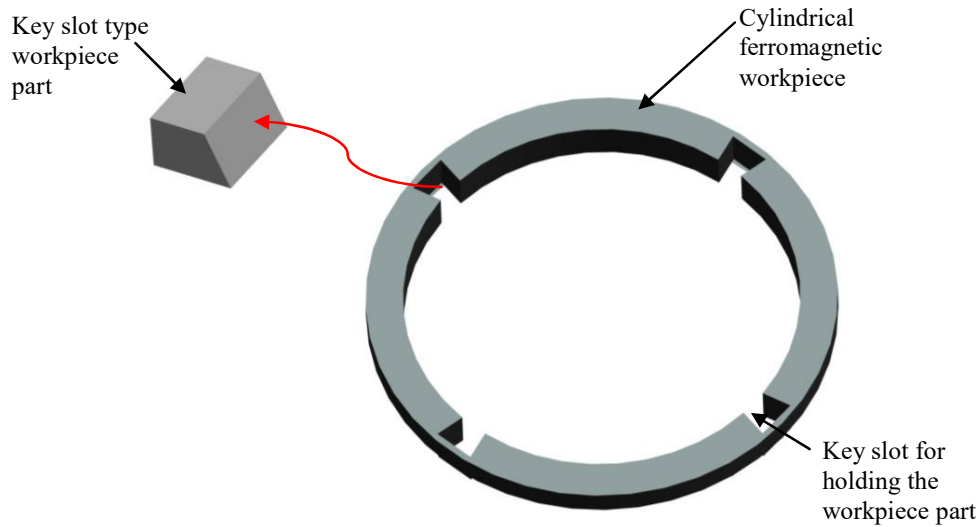


Fig. 5.2 CAD model of ferromagnetic cylindrical workpiece with key slot type workpiece part.

Initially, an internal surface grinding was performed on these key type workpiece parts along with the main cylindrical ferromagnetic workpiece surface. The initial surface roughness (R_a) values of the key type workpieces were found in the range of 669-692 nm which were measured

by SJ-210 surftest. The value of 0.25 mm was taken as cut off length during surface roughness measurements. The initial values of surface roughness (R_a) values were not similar for all key type workpieces, therefore, this fluctuation in surface roughness (R_a) values was considered by taking the % ΔR_a values as a final response as given by Eq. 5.1.

$$\% \text{ 粗糙度} = \frac{(\text{平均粗糙度} - \text{平均粗糙度})}{(\text{平均粗糙度})} \times 100 \quad (5.1)$$

In the cylindrical ferromagnetic workpiece, the 4 different key slot holes were made. The key slot type workpieces are attached individually to the main cylindrical ferromagnetic workpiece through an interference fit. The cylindrical workpiece was fixed in the workpiece fixture which was further mounted on the precision grinding vice. The X-Y axis slides movement along with precision grinding vice was used to maintain a proper working gap between the outer finishing surface of rectangular tool core and the internal cylindrical workpiece surface.

The response surface methodology (RSM) is the combination of both numerical and statistical data which is helpful for analyzing the engineering models. RSM determines the relation between the independently controlled variables and the final response surfaces. At present, five factors and five levels with six central and axial runs were selected for experimentations. The regression analysis was carried by using central composite design (CCD). Further, from the analysis of variance (ANOVA), the F -test was performed to determine the consequence of regression equation. The regression equation helps to evaluate the relationship among independent controllable variables and the improvement in surface finish. The effect of five process variables was examined on the % ΔR_a values by the full factorial design. The process parameters represented by its coded levels and along with its actual values used for finishing of the internal surface of ferromagnetic cylindrical workpiece by using MR honing setup is given in Table 5.2. During regression analysis, the alpha was taken as 2 which represent the equal interval of process parameters. With the help of alpha, the coded level i.e. -2 to +2 represents the lower most and upper most values of the process parameters.

The experimentation conditions used during finishing of the internal surface of ferromagnetic cylindrical workpiece are given in Table 5.3. The synthesized MR polishing fluid as given in Table 4.2, was used for finishing of the internal surface of cylindrical ferromagnetic workpiece.

Table 5.2 Actual values of process parameters along with its coded levels.

Sr. No	Process parameters	Units	Coded levels				
			-2	-1	0	1	2
1.	Mesh sizes of SiC abrasive particles (S)	Mesh size	400	600	800	1000	1200
2.	Mesh sizes of CIPs (C)	Mesh size	200	300	400	500	600
3.	Magnetizing currents (I)	A	0.4	0.8	1.2	1.6	2.0
4.	Tool rotational speeds (R)	Rpm	200	300	400	500	600
5.	Tool linear speeds (L)	cm/min	10	20	30	40	50

Table 5.3 Experimentation parameters and conditions.

Parameters	Conditions
Working gap	0.6 mm
Total finishing time	45 minutes
Cylindrical workpiece material	EN-24 die steel

The experimentation was performed for finishing of the internal ferromagnetic surface (cylindrical type) as per the plan of experiments as given in Table 5.4.

Table 5.4 Plan of experiments.

Std order	Run order	Mesh sizes of SiC abrasive particles (S)	Mesh sizes of CIPs (C)	Magnetizing currents (I)	Tool rotational speeds (R)	Tool linear speeds (L)
1	37	600	300	0.8	300	20
2	9	1000	300	0.8	300	20
3	43	600	500	0.8	300	20
4	22	1000	500	0.8	300	20
5	20	600	300	1.6	300	20
6	24	1000	300	1.6	300	20
7	45	600	500	1.6	300	20
8	18	1000	500	1.6	300	20
9	36	600	300	0.8	500	20
10	48	1000	300	0.8	500	20
11	23	600	500	0.8	500	20
12	15	1000	500	0.8	500	20

13	39	600	300	1.6	500	20
14	31	1000	300	1.6	500	20
15	44	600	500	1.6	500	20
16	35	1000	500	1.6	500	20
17	11	600	300	0.8	300	40
18	17	1000	300	0.8	300	40
19	28	600	500	0.8	300	40
20	19	1000	500	0.8	300	40
21	49	600	300	1.6	300	40
22	27	1000	300	1.6	300	40
23	16	600	500	1.6	300	40
24	13	1000	500	1.6	300	40
25	25	600	300	0.8	500	40
26	2	1000	300	0.8	500	40
27	29	600	500	0.8	500	40
28	10	1000	500	0.8	500	40
29	40	600	300	1.6	500	40
30	42	1000	300	1.6	500	40
31	14	600	500	1.6	500	40
32	47	1000	500	1.6	500	40
33	6	400	400	1.2	400	30
34	38	1200	400	1.2	400	30
35	46	800	200	1.2	400	30
36	41	800	600	1.2	400	30
37	1	800	400	0.4	400	30
38	32	800	400	2	400	30
39	5	800	400	1.2	200	30
40	7	800	400	1.2	600	30
41	33	800	400	1.2	400	10
42	8	800	400	1.2	400	50
43	12	800	400	1.2	400	30
44	30	800	400	1.2	400	30
45	34	800	400	1.2	400	30
46	21	800	400	1.2	400	30
47	50	800	400	1.2	400	30
48	26	800	400	1.2	400	30
49	4	800	400	1.2	400	30
50	3	800	400	1.2	400	30

5.2.1 Response surface regression analysis

The responses in terms of percentage change in surface roughness (R_a) or ($\% \Delta R_a$) values during each set of experimentation are given in Table 5.5. The responses in terms of $\% \Delta R_a$ values were analyzed by using Eq. (5.1).

Table 5.5 Response summary.

Std order	Run order	S	C	I	R	L	Initial R_a values (nm)	Final R_a values (nm)	Response ($\% \Delta R_a$)
1	37	600	300	0.8	300	20	686	474	31
2	9	1000	300	0.8	300	20	679	462	32
3	43	600	500	0.8	300	20	685	438	36
4	22	1000	500	0.8	300	20	686	425	38
5	20	600	300	1.6	300	20	681	407	40
6	24	1000	300	1.6	300	20	675	401	41
7	45	600	500	1.6	300	20	676	392	42
8	18	1000	500	1.6	300	20	678	366	46
9	36	600	300	0.8	500	20	685	421	39
10	48	1000	300	0.8	500	20	669	461	31
11	23	600	500	0.8	500	20	685	425	38
12	15	1000	500	0.8	500	20	682	420	38
13	39	600	300	1.6	500	20	681	397	42
14	31	1000	300	1.6	500	20	676	394	42
15	44	600	500	1.6	500	20	683	391	43
16	35	1000	500	1.6	500	20	692	389	44
17	11	600	300	0.8	300	40	684	415	39
18	17	1000	300	0.8	300	40	670	445	34
19	28	600	500	0.8	300	40	684	418	39
20	19	1000	500	0.8	300	40	678	423	38
21	49	600	300	1.6	300	40	675	388	43
22	27	1000	300	1.6	300	40	676	403	40
23	16	600	500	1.6	300	40	676	381	44
24	13	1000	500	1.6	300	40	683	391	43
25	25	600	300	0.8	500	40	684	376	45
26	2	1000	300	0.8	500	40	689	433	37
27	29	600	500	0.8	500	40	681	376	45
28	10	1000	500	0.8	500	40	681	415	39
29	40	600	300	1.6	500	40	679	369	46
30	42	1000	300	1.6	500	40	676	386	43
31	14	600	500	1.6	500	40	679	361	47
32	47	1000	500	1.6	500	40	678	370	45
33	6	400	400	1.2	400	30	691	380	45
34	38	1200	400	1.2	400	30	677	395	42

35	46	800	200	1.2	400	30	681	377	45
36	41	800	600	1.2	400	30	679	341	50
37	1	800	400	0.4	400	30	675	519	23
38	32	800	400	2	400	30	680	421	38
39	5	800	400	1.2	200	30	676	369	45
40	7	800	400	1.2	600	30	674	338	50
41	33	800	400	1.2	400	10	671	345	49
42	8	800	400	1.2	400	50	674	310	54
43	12	800	400	1.2	400	30	685	332	52
44	30	800	400	1.2	400	30	672	315	53
45	34	800	400	1.2	400	30	686	349	49
46	21	800	400	1.2	400	30	671	326	51
47	50	800	400	1.2	400	30	681	330	52
48	26	800	400	1.2	400	30	679	329	52
49	4	800	400	1.2	400	30	677	335	51
50	3	800	400	1.2	400	30	681	327	52

The sequential sum of squares was evaluated to choose the elevated order of the polynomial. In this the extra terms are regarded as significant and model is not aliased. The sequential sum of square determined the provisions of rising complication contribute to the entire model as given in Table 5.6. The lack of fit for the entire models was also evaluated and is given in Table 5.7. The quadratic model was selected from Tables 5.6 and 5.7. The analysis of variance (ANOVA) for the entire model is given in Table 5.8. At present, the significant level i.e. $\alpha = 0.05$ was taken for the given hypothesis for which a p-value which is ≤ 0.05 is considered as significant. The F -value as 39.43 for the given model revealed that the model is considered as significant i.e. the value of Prob>F is <0.0001 which is less than 0.05.

Table 5.6 Sequential sum of square.

Source	Sum of squares	df	Mean square	F -Value	p-value Prob > F	Remarks
Mean vs Total	91848.98	1	91848.98			
Linear vs Mean	594.00	5	118.80	3.49	0.0096	
2FI vs Linear	115.75	10	11.57	0.28	0.9803	
Quadratic vs 2FI	1327.43	5	265.49	140.38	< 0.0001	Suggested
Cubic vs Quadratic	18.37	15	1.22	0.47	0.9203	Aliased
Residual	36.47	14	2.61			
Total	93941.00	50	1878.62			

Table 5.7 Lack of fit tests.

Source	Sum of squares	df	Mean Square	<i>F</i> -value	p-value Prob > <i>F</i>	Remarks
Linear	1488.02	37	40.22	28.15	<0.0001	
2FI	1327.27	27	50.82	35.48	<0.0001	
Quadratic	44.85	22	2.04	1.43	0.3288	Suggested
Cubic	26.47	7	3.78	2.65	0.1112	Aliased
Pure Error	10.00	7	1.43			

From the Table 5.8, the terms such as S, C, I, R, L, S^2 , C^2 , I^2 , R^2 , SC, SI, SR, SL and IL are significant. If the p-value is > 0.05 then the terms are considered as not significant. If there are insignificant terms in the model, then the model can further be improved by eliminating the insignificant terms. The *F*-value in case of lack of fit is 1.64 which clearly implies that there is 26.09% chance that the lack of fit *F*-value could happen because of noise.

Table 5.8 ANOVA for % ΔR_a values.

Source	Sum of square	df	Mean square	<i>F</i> -value	Prob> <i>F</i>	
Model	204.30	25	81.69	39.43	<0.0001	Significant
S	12.10	1	12.10	5.84	0.0236	
C	22.50	1	22.50	10.86	0.0030	
I	96.10	1	96.10	46.39	<0.0001	
R	19.60	1	19.60	9.46	0.00252	
L	28.90	1	28.90	13.95	0.0010	
S^2	182.41	1	182.41	88.05	<0.0001	
C^2	61.61	1	61.61	29.74	<0.0001	
I^2	1017.00	1	1017.00	490.91	<0.0001	
R^2	61.61	1	61.61	29.74	<0.0001	
E^2	4.81	1	4.81	2.32	0.1408	
SC	15.13	1	15.13	7.30	0.0124	
SI	15.13	1	15.13	7.30	0.0124	
SR	18.00	1	18.00	8.69	0.0070	
SL	28.13	1	28.13	13.58	0.0012	
CI	1.13	1	1.13	0.54	0.4683	
CR	4.50	1	4.50	2.17	0.1535	
CL	6.13	1	6.13	2.96	0.0984	
IR	4.50	1	4.50	2.17	0.1535	
IL	15.13	1	15.13	7.30	0.0124	
RL	8.00	1	8.00	3.86	0.0611	
S^3	0.10	1	0.10	0.048	0.8280	
C^3	0.000	1	0.000	0.000	1.000	

I ³	4.90	1	4.90	2.37	0.1371	
R ³	0.025	1	0.025	0.012	0.9134	
L ³	0.10	1	0.10	0.048	0.8280	
Residual	49.72	24	2.07			
Lack of Fit	39.72	17	2.34	1.64	0.2609	Not significant
Pure Error	10.00	7	1.43			
Cor Total	2092.02	49				

Regarding the ANOVA, the other parameters are given in Table 5.9. The R^2 value determines the closeness of experimental data points with the regression fit line. The R^2 for the given model is 0.9762. This means that the model determines a good response input. The adequate precision (A ratio) is the measure of signal to noise ratio. The A ratio in this model is 29.868 which is greater than 4, hence the model is desirable i.e. this model can use to steer the design space.

Table 5.9 Other ANOVA parameters.

Std. Dev.	1.44	R^2	0.9762
Mean	42.86	Adj R^2	0.9515
C.V. %	3.36	Pred R^2	-0.1992
PRESS	2508.85	Adeq precision	29.868

The confidence interval (CI) of 95% low values and 95% high values are the lower and upper bound of 95% CI that enclosed the coefficient approximate for the factor (Singh *et al.*, 2012). Table 5.10 represents that the accurate factor coefficients should be found 95% of the time. The variance inflation factor (VIF) of the model measures how the variance is magnified by the need of orthogonality in the design. If the value of VIF is 1.00, then the factor is orthogonal to other factors within the model. If the value of VIF is <10 , then the factors are not independent of each other.

If the p-value is > 0.05 , then the model is regarded as not significant. There are eleven insignificant terms in the model (Table 5.8). These terms are L^2 , CI, CR, CL, IR, RL, S^3 , C^3 , I^3 , R^3 and L^3 . Therefore, to improve the model design, these insignificant terms can be eliminated. The ANOVA after eliminating the insignificant terms is given in Table 5.11.

Table 5.10 Factor coefficients (coded form).

Factor	Coefficient estimate	df	Standard error	95% CI low	95% CI high	VIF
Intercept	51.81	1	0.50	50.78	52.84	
S	-0.92	1	0.38	-1.70	-0.13	2.78
C	1.25	1	0.38	0.47	2.03	2.78
I	2.58	1	0.38	1.80	3.37	2.78
R	1.17	1	0.38	0.38	1.95	2.78
L	1.42	1	0.38	0.63	2.20	2.78
S ²	-2.39	1	0.25	-2.91	-1.86	1.00
C ²	-1.39	1	0.25	-1.91	-0.86	1.00
I ²	-5.64	1	0.25	-6.16	-5.11	1.00
R ²	-1.39	1	0.25	-1.91	-0.86	1.00
L ²	-0.39	1	0.25	-0.91	0.14	1.00
SC	0.69	1	0.25	0.16	1.21	1.00
SI	0.69	1	0.25	0.16	1.21	1.00
SR	-0.75	1	0.25	-1.28	-0.22	1.00
SL	-0.94	1	0.25	-1.46	-0.41	1.00
CI	-0.19	1	0.25	-0.71	0.34	1.00
CR	-0.38	1	0.25	-0.90	0.15	1.00
CL	-0.44	1	0.25	-0.96	0.088	1.00
IR	-0.38	1	0.25	-0.90	0.15	1.00
IL	-0.69	1	0.25	-1.21	-0.16	1.00
RL	0.50	1	0.25	-0.025	1.03	1.00
S ³	0.042	1	0.19	-0.35	0.43	2.78
C ³	0.000	1	0.19	-0.39	0.39	2.78
I ³	0.29	1	0.19	-1.00	0.68	2.78
R ³	0.021	1	0.19	-0.37	0.41	2.78
L ³	-0.042	1	0.19	-0.43	0.35	2.78

Table 5.11 ANOVA for % ΔR_d values after eliminating the insignificant terms.

Source	Sum of squares	df	Mean square	F-value	Prob > F	Remarks
Model	2008.12	14	143.44	59.84	<0.0001	Significant
S	28.90	1	28.90	12.06	<0.0001	
C	62.50	1	62.50	26.07	<0.0001	
I	372.10	1	372.50	155.23	<0.0001	
R	57.60	1	57.60	24.03	<0.0001	
L	72.90	1	72.90	30.41	<0.0001	
S ²	182.41	1	182.41	76.09	<0.0001	
C ²	61.61	1	61.61	25.70	<0.0001	
I ²	1017.01	1	1017.01	424.26	<0.0001	

R ²	61.61	1	61.61	25.70	<0.0001	
SC	15.13	1	15.13	6.31	0.0168	
SI	15.13	1	15.13	6.31	0.0168	
SR	18.00	1	18.00	7.51	0.0096	
SL	28.13	1	28.13	11.73	0.0016	
IL	15.13	1	15.13	6.31	0.0168	
Residual	83.90	35	2.40			
Lack of Fit	73.90	28	2.64	1.85	0.2042	Not Significant
Pure Error	10.00	7	1.43			
Cor Total	2092.02	49				

The model *F*-value is 59.84 suggests that the model is significant i.e. the value of Prob>F is less than 0.05 which clearly indicates that the model terms are considered as significant. The R² for the given model is 0.9599 as given in Table 5.12.

Table 5.12 Other ANOVA parameters after reduction in model.

Std. Dev.	1.55	R ²	0.9599
Mean	42.86	Adj R ²	0.9439
C.V. %	3.61	Pred R ²	0.8994
PRESS	210.52	Adeq precision	36.968

A ratio of 36.968 (i.e. greater than 4), is considered as desirable. The factor coefficients representation after reduction in the model is given in Table 5.13. The factor coefficient represents a range that the accurate coefficient should be initiated 95% of the time.

Table 5.13 Factor coefficients representation in coded form after reduction in model.

Factor	Coefficient estimate	df	Standard error	95% CI low	95% CI high	VIF
Intercept	51.50	1	0.49	50.51	52.49	
S	-0.85	1	0.24	-1.35	-0.35	1.00
C	1.25	1	0.24	0.75	1.75	1.00
I	3.05	1	0.24	2.55	3.55	1.00
R	1.20	1	0.24	0.70	1.70	1.00
L	1.35	1	0.24	1.85	1.85	1.00
S ²	-2.39	1	0.27	-1.83	-1.83	1.00
C ²	-1.39	1	0.27	-0.83	-0.83	1.00
I ²	-5.64	1	0.27	-5.08	-5.08	1.00

R ²	-1.39	1	0.27	-0.83	-0.83	1.00
SC	0.69	1	0.27	1.24	1.24	1.00
SI	0.69	1	0.27	1.24	1.24	1.00
SR	-0.75	1	0.27	-0.19	-0.19	1.00
SL	-0.94	1	0.27	-0.38	-0.38	1.00
IL	-0.69	1	0.27	-0.13	-0.13	1.00

The following equation (5.2) and (5.3) represents the quadratic equations which define the empirical relations between the process parameters.

The final equation as per the coded factors is represented in Eq. (5.2).

$$\% \Delta R_a = +51.50 - 0.85X_1 + 1.25X_2 + 3.05X_3 + 1.20X_4 + 1.35X_5 - 2.39X_1X_2 - 1.39X_1X_3 - 5.64X_1X_4 - 1.39X_1X_5 + 0.69X_2X_3 + 0.69X_2X_4 - 0.75X_2X_5 - 0.94X_3X_4 - 0.69X_3X_5 - 0.13X_4X_5 \quad (5.2)$$

The final equation as per the actual factors is represented in Eq. (5.3).

$$\% \Delta R_a = -111.62500 + 0.096250X_1 + 0.096000X_2 + 90.46875X_3 + 0.15300X_4 + 0.71625X_5 - 0.0000596875X_1X_2 - 0.000138750X_1X_3 - 35.23438X_1X_4 - 0.000138750X_1X_5 + 0.0000343750X_2X_3 + 0.00859375X_2X_4 - 0.0000375000X_2X_5 - 0.000468750X_3X_4 - 0.17187X_3X_5 \quad (5.3)$$

The contribution of each process parameters on percentage change in surface roughness (R_a) values ($\% \Delta R_a$) values are given in Table 5.14.

Table 5.14 Contribution of process parameters (in percentage) in final R_a response.

Source	Sum of squares	Percentage contribution
S	28.90	1.43
C	62.50	3.09
I	372.10	18.34
R	57.60	2.85
L	72.90	3.61
S ²	182.14	9.03
C ²	61.61	3.05
I ²	1017.1	50.39
R ²	61.61	3.05
SC	15.13	0.74
SI	15.13	0.74
SR	18.00	0.89
SL	28.13	1.39
IL	15.13	0.74

5.3 Results and discussion

After the regression analysis, the Eq. (5.3) was obtained depending upon the experimentation results. The consequence of different process parameters such as mesh sizes of SiC abrasive particles, mesh sizes of carbonyl iron particles (CIPs), magnetizing currents, tool rotational speeds and tool linear speeds were observed. The effects of independent controlled variables and their interactions were found to be significant and are discussed as follows.

5.3.1 Effect of mesh sizes of SiC abrasive particles

The effect of mesh sizes of SiC abrasive particles in removing the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece is an important requirement in analyzing the performance of the developed process. The larger size of SiC abrasive particles is having higher cutting edges, whereas the smaller size of SiC abrasive particles is having smaller cutting edges. The effect of mesh sizes of SiC abrasive particles on $\% \Delta R_a$ values is shown in Fig. 5.3.

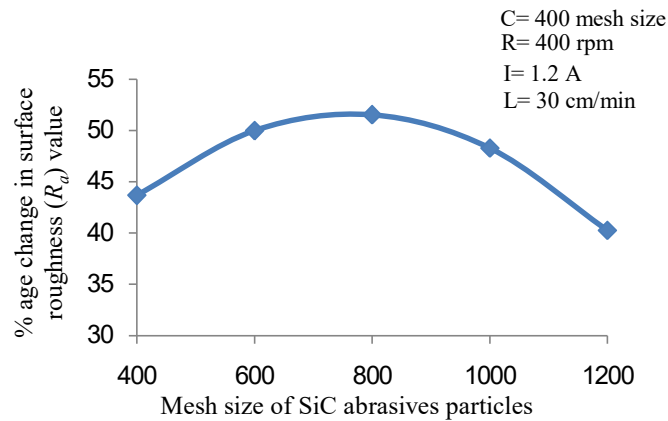


Fig. 5.3 Effect of mesh sizes of SiC abrasive particles on percentage change in surface roughness (R_a) values.

During finishing with 800 mesh size of SiC abrasive particles, the $\% \Delta R_a$ value increases significantly. This is because the SiC abrasive particles of 800 mesh size provided the sufficient gripping of abrasive particles with 400 mesh size of CIPs. There is a sufficient cutting edges of the SiC abrasive particles for removing the roughness peaks from the workpiece surface. When the mesh sizes of SiC abrasive particles increases from 800 to 1200, the $\% \Delta R_a$ value starts reducing. The reason is that the size of SiC abrasive particles changed to a very finer one. The cutting ability of SiC abrasive particles is not enough to remove the roughness peaks from the workpiece surface having same initial roughness. As a result, the $\% \Delta R_a$ value decreased continuously. When the mesh sizes of SiC abrasive particles decreased from 800 to 400, the $\%$

ΔR_a value also decreased. This is because of improper gripping of SiC abrasive particles does not provide better cutting of roughness peaks from the workpiece surface. This is the main reason for the hump in the curve.

5.3.2 Effect of mesh sizes of carbonyl iron particles (CIPs)

The effect of mesh sizes of carbonyl iron particles (CIPs) on $\% \Delta R_a$ values is shown in Fig. 5.4. The CIPs plays a significant task in gripping the SiC abrasive particles. The selection of the particular size of SiC abrasive particles with 800 mesh size was found important factor for gripping it CIPs chain structure. The gripped abrasive particles are further helpful in removing the roughness peaks from the internal surface of ferromagnetic cylindrical workpiece.

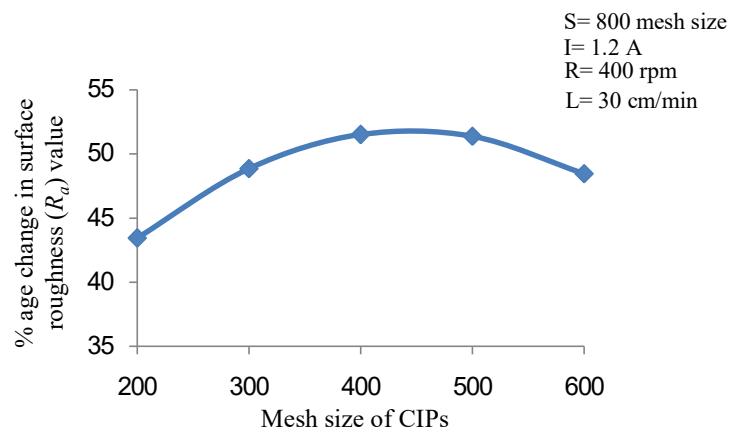


Fig. 5.4 Effect of mesh sizes of CIPs on percentage change in surface roughness (R_a) values.

The higher size of CIPs i.e 200 mesh size provides a strongly bonded CIPs chains strength under the effect of magnetizing current. This is because the higher size of each CIP particles provided the higher magnetic field for the same applied magnetizing current of 1.2 A. Therefore, for 200 mesh sizes of CIPs, the CIPs chains can be provided very strong rigid support for gripping the abrasive particles onto the workpiece surface during finishing operation. Thus, the more rigidly gripped active abrasive particles with 200 mesh size of CIPs chains structure, it may create micro-scratches on the workpiece surface rather than performing proper finishing. As a result, the smaller reduction in $\% \Delta R_a$ values was found. When the CIPs size decreased (i.e. 600 mesh size), the higher strength was required for strongly bonding these CIPs chains. But, due to less size of CIPs, it provided a lesser magnetic field for the same magnetizing current of 1.2 A. Therefore, the CIPs chains structure of 600 mesh size provided lesser strength due to a low

magnetic field for the same magnetizing current. Thus, a lesser strength of CIPs chains structure with 600 mesh sizes may provide comparatively lesser support for gripping the abrasive particles. This is because the small size of CIPs was obtained lesser magnetic field and could not maintain a required strength to grip the abrasive particles. As a result, the smaller $\% \Delta R_a$ values take place. With 400 mesh size of CIPs, the SiC abrasive particle gripped by these CIPs chain structure provided a feasible or gentle indentation of gripped SiC abrasive particles onto the internal surface of ferromagnetic cylindrical workpiece. This result in higher $\% \Delta R_a$ values from the internal surface of ferromagnetic cylindrical workpiece.

5.3.3 Effect of magnetizing currents

The effect of magnetizing currents on $\% \Delta R_a$ values is shown in Fig. 5.5.

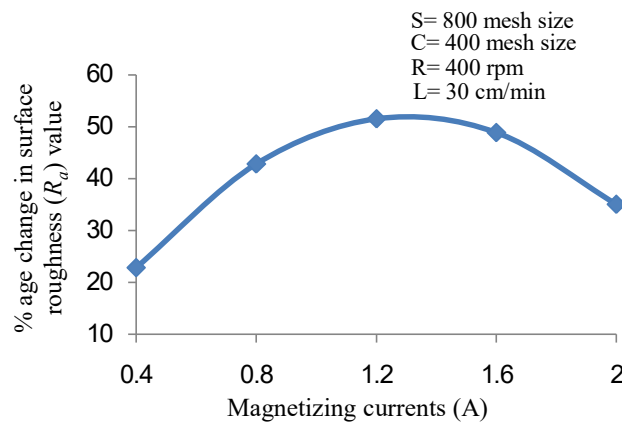


Fig. 5.5 Effect of magnetizing currents on percentage change in surface roughness (R_a) values.

Under the lower range of magnetizing current i.e. 0.4 A, the CIPs chains do not provide a better bonding strength on each CIP i.e. forming a loose chains structure. The SiC abrasive particles gripped by the loose chains structure of CIPs do not provide better finishing results. This is because the SiC abrasive particles move out from the loose CIPs chains during finishing operation. At 1.2 A magnetizing current, the CIPs provided strong bonding chain strength. This further helps to grip the abrasive particles more strongly by the strong bonding strength of each CIPs chains structure. As a result, the $\% \Delta R_a$ values increased. At 2 A magnetizing current, the CIPs forms a more rigid chains structure. This rigid chains structure provides a higher indentation force on the workpiece surface via abrasive particles. Further, these SiC abrasive particles indent into the internal surface of ferromagnetic cylindrical workpiece and produce cavities or micro scratches on the workpiece surface. This results in decreased the $\% \Delta R_a$ values.

5.3.4 Effect of tool rotational speeds

The effect of tool rotational speeds on % ΔR_a values is shown in Fig. 5.6. At lower tool rotational speed i.e. 200 rpm, the tangential shearing force provides by the SiC abrasive particles was lower which results in a smaller % ΔR_a values. The tangential shearing force increases with the higher tool rotational speed. The % ΔR_a value increased gradually upto a tool rotational speed of 400 rpm. At 500 rpm, the % ΔR_a values were likely almost constant. This is because; the effect of centrifugal force withstood by the strongly bonded CIPs chains upto 500 rpm of tool rotational speed. With the decrease in velocity, the stiffness of MR polishing fluid is also decreased (Sidpara and Jain, 2013). As a result, the % ΔR_a value got reduced. Beyond 500 rpm of tool rotational speed, the centrifugal force of CIPs increases which tends to decrease the normal magnetic force. Also, with the increased in tool rotational speed beyond the optimum value of 500 rpm, the yield strength of MR polishing fluid got decreased. The yield strength of MR polishing fluid decreases with increase in the shear rate (Goncalves *et al.*, 2005).

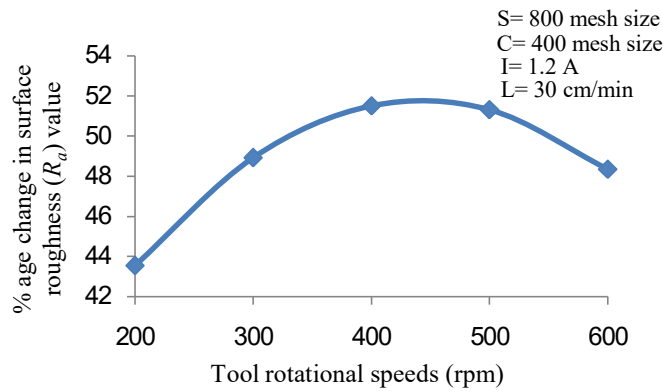


Fig. 5.6 Effect of tool rotational speeds on percentage change in surface roughness (R_a) values.

5.3.5 Effect of tool linear speeds

The tool linear speed increases the axial shearing capability of SiC abrasive particles in removing the roughness peaks from the internal surface of cylindrical ferromagnetic workpiece. The effect of tool linear speeds on % ΔR_a values is shown in Fig. 5.7.

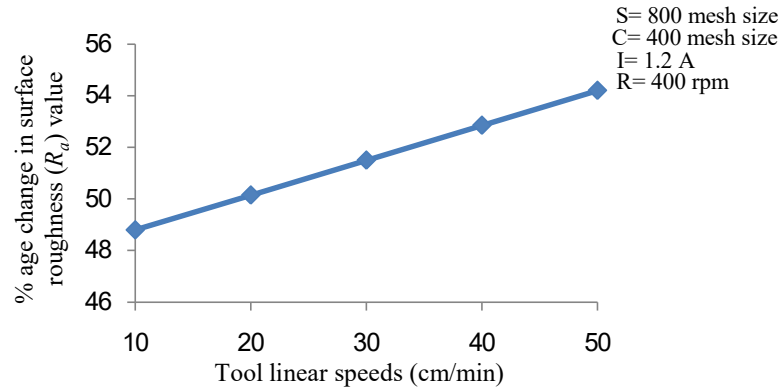


Fig. 5.7 Effect of tool linear speeds on percentage change in surface roughness (R_a) values.

5.3.6 Effect of interaction of mesh sizes of SiC abrasive particles with the CIPs mesh sizes

The effect of interaction of mesh sizes of SiC abrasive particles with the CIPs mesh sizes is shown in Fig. 5.8.

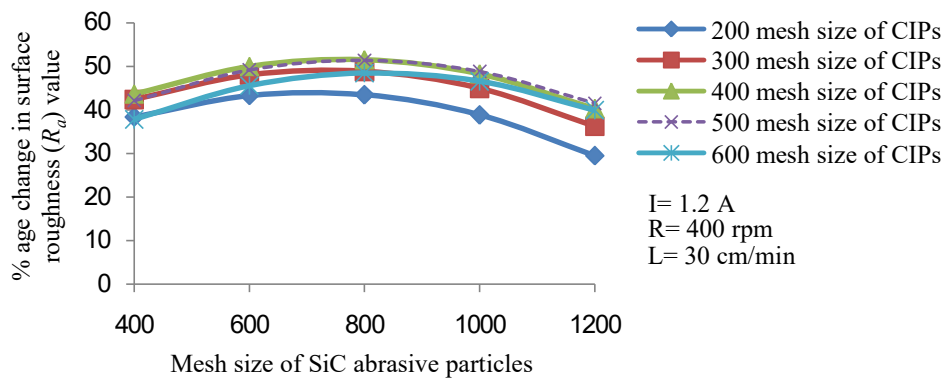


Fig. 5.8 Effect of interaction of various mesh sizes of SiC abrasive particles with various mesh sizes of CIPs on percentage change in surface roughness (R_a) values.

The mesh sizes of SiC abrasive particles in MR polishing fluid is an important consideration in actual surface finishing. For obtaining better finishing results, the size of abrasive particles should be such that it can be easily gripped by the CIPs chains structure. If the size of CIPs was smaller than the SiC abrasive particles size i.e. SiC abrasive particles of 400 mesh size and CIPs of 600 mesh size, then there was no sufficient gripping of abrasive particles by the CIPs chains. If the size of CIPs was almost doubled than the SiC abrasive particles size i.e. SiC abrasive particles as 800 mesh size and CIPs as 400 mesh size, then there was a proper locking of abrasive particles by the chains structure of CIPs. If the size of CIPs was very larger as compared

to the SiC abrasive particles size i.e. SiC abrasive particles of 1200 mesh size and CIPs of 200 mesh size, then the abrasive particles may have the lesser surface finishing tendency. This is because of smaller size of SiC abrasive particles which is having a smaller cutting edge surface. Therefore, the 800 mesh size of SiC abrasive particles with 400 mesh size of CIPs provides better finishing results.

5.3.7 Effect of interaction of magnetizing currents with the mesh sizes of CIPs

The effect of the interaction of magnetizing currents with the mesh sizes of CIPs is shown in Fig. 5.9. This interaction was taken at 800 mesh size of SiC abrasive particles, 400 rpm of tool rotational speed and 30 cm/min of tool linear speed. The interaction was found better with 1.2 A magnetizing current and 400 mesh size of CIPs. The magnetizing currents play an important role in achieving a better finishing performance.

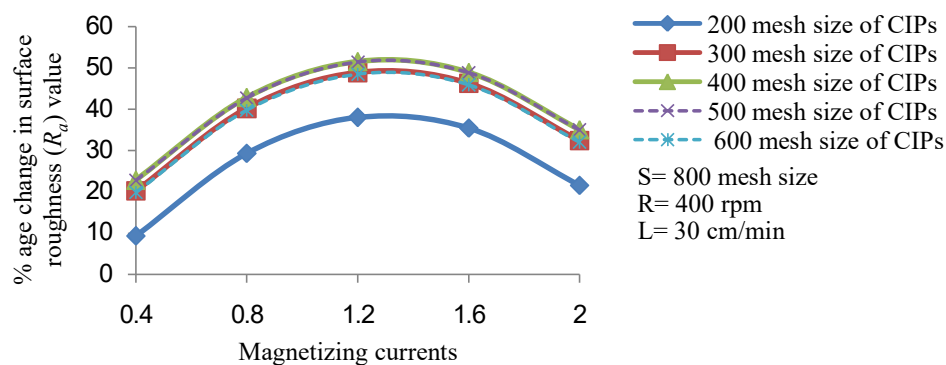


Fig. 5.9 Effect of interaction of magnetizing currents with various mesh sizes of CIPs on percentage change in surface roughness (R_a) values.

The schematic mechanism of material removal during finishing of the internal surface of ferromagnetic cylindrical workpiece at different magnetizing currents is shown in Fig. 5.10. At the low magnetizing current of 0.4 A, the CIPs formed a loose chains structure. This is because the magnetic field strength was low at the outer finishing surface of rectangular tool core. As a result, the SiC abrasive particles were gripped by the loosely formed CIPs chains. The bonding force between each CIP was not enough to maintain a required strength to grip the abrasive particles. During finishing, only the upper most roughness peaks was cut off by the SiC abrasive particles due to its lower shear strength. As the strength of base peaks increases after the first cut of its upper most peaks, the gripped SiC abrasive particles do not have the required strength to cut off the further roughness peaks. Thus, no finishing may take place as shown in Fig. 5.10 (a). At moderate magnetizing current of 1.2 A, the CIPs maintain a required strength to retain at the

outer finishing surface of rectangular tool core. The CIPs forms to chains structure along the magnetic lines of fluxes which were used to grip the SiC abrasive particles. This gripped SiC abrasive particles when moved on the internal ferromagnetic surface, the material removal in form of micro-chips takes place as shown in Fig. 5.10 (b). At high magnetizing current of 2 A, the CIPs form a dense chains with very high strength structure. The SiC abrasive particles finally gripped very tightly by the dense CIPs chains structure. During finishing, the CIPs chains provide a higher indentation force onto the internal surface of ferromagnetic cylindrical workpiece via SiC abrasive particles. Thus these abrasive particles produce a cavity into the internal workpiece surface as shown in Fig. 5.10 (c). Therefore, the interaction of 1.2 A of magnetizing current with 400 mesh size of CIPs provided better finishing results.

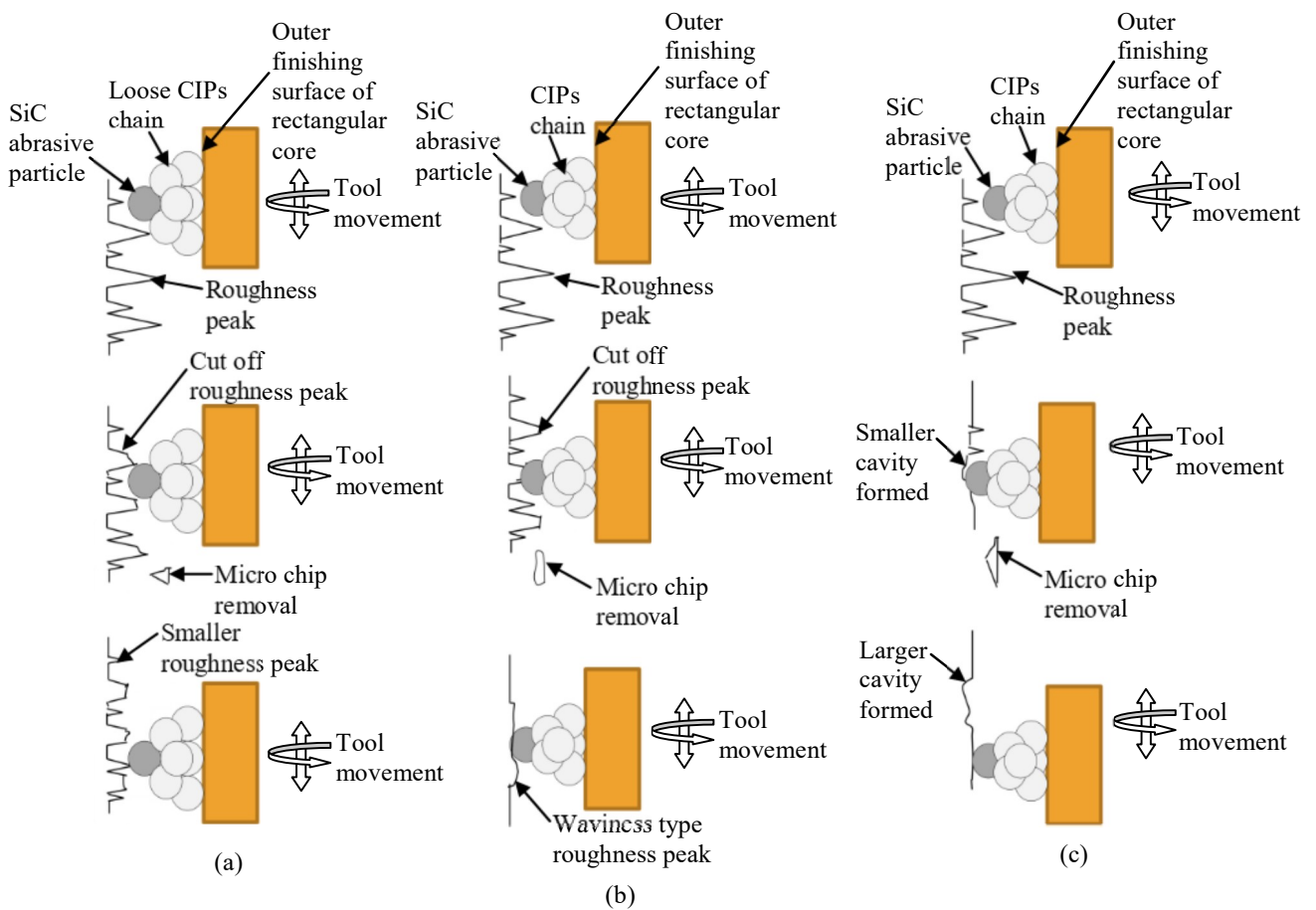


Fig. 5.10 Schematic mechanism of material removal during finishing at (a) 0.4 A of magnetizing current, (b) 1.2 A of magnetizing current and (c) 2 A of magnetizing current.

5.3.8 Effect of interaction of tool linear speeds with various magnetizing currents

The effect of the interaction of tool linear speeds with various magnetizing currents is shown in Fig. 5.11. This interaction was taken at 800 mesh size of SiC abrasive particles, 400 mesh size of CIPs and 400 rpm of tool rotational speed. From the interaction plot, it can be seen very clearly that with the increase in tool linear speed, the percentage change in surface roughness (R_a) values also increase. This was due to the continuous rotation of SiC abrasive particles at 400 rpm when it also reciprocated on the internal cylindrical ferromagnetic surface, the higher axial force (F_{axial}) due to reciprocation results into a better shearing of the roughness peaks from the internal ferromagnetic surface. At a magnetizing current of 1.2 A, the finishing performance was found better. At a magnetizing current of 2 A, a slight decrease in percentage change in surface roughness (R_a) values as due to the high current which results in the formation of cavities or scratches on the internal ferromagnetic surface. These types of surface defects were due to high indentation force of SiC abrasive particles provided by dense CIPs chains on the internal ferromagnetic surface as already discussed in Fig. 5.10 (c). The two dimensional contour and three dimensional plot of the interaction of tool linear speeds at various magnetizing currents on % ΔR_a values is shown in Fig. 5.12 (a) and (b), respectively. Therefore, the interaction of 1.2 A magnetizing current with higher tool linear speed of 50 cm/min provided better finishing results.

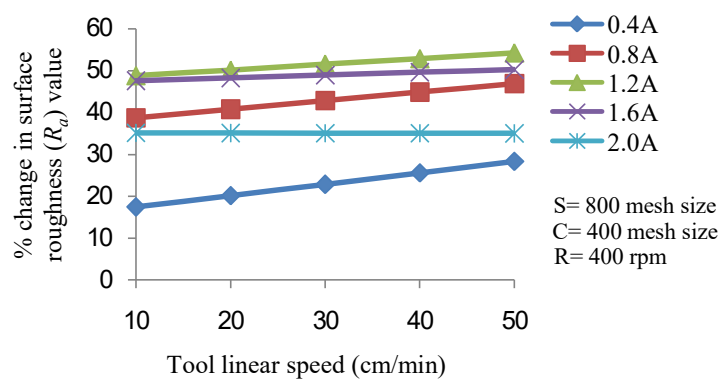


Fig. 5.11 Effect of interaction of tool linear speeds with various magnetizing currents on percentage change in surface roughness (R_a) values.

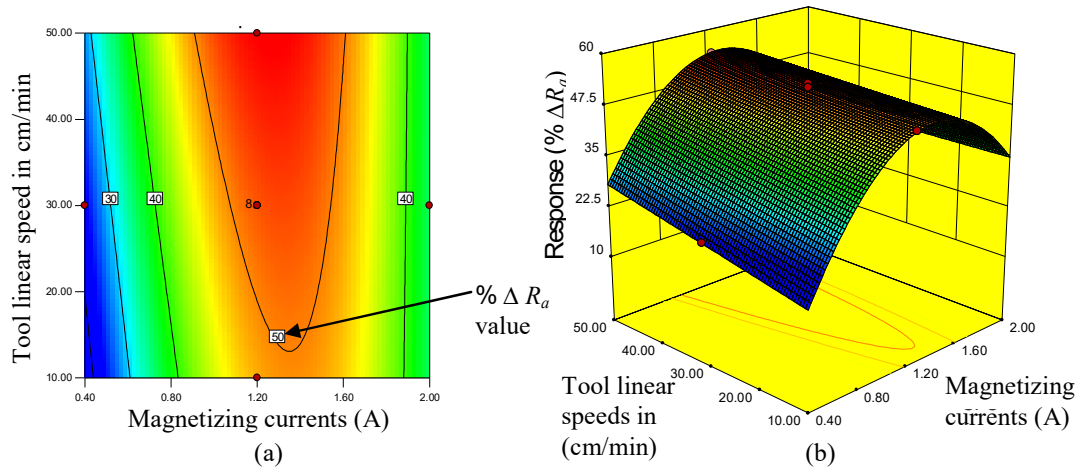


Fig. 5.12 (a) Two dimensional contour and (b) three dimensional plot of the interaction of tool linear speeds with various magnetizing currents on percentage change in surface roughness (R_a) values.

5.3.9 Effect of interaction of mesh sizes of CIPs at various tool rotational speeds

The effect of interaction of mesh sizes of CIPs at various tool rotational speeds is shown in Fig. 5.13.

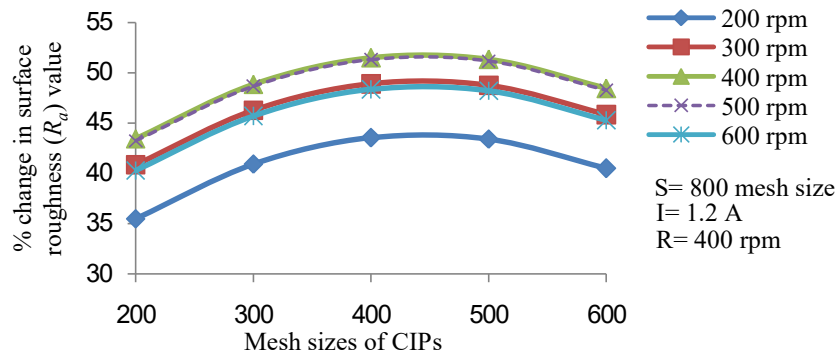


Fig. 5.13 Effect of interaction of various mesh sizes of CIPs with various tool rotational speeds on percentage change in surface roughness (R_a) values.

This interaction was taken at 800 mesh size of SiC abrasive particles, 1.2 A of magnetizing current and 30 cm/min of tool linear speed. With the increase in tool rotational speed from 200 rpm to 500 rpm, the $\% \Delta R_a$ values were also increased. At 400 rpm to 500 rpm, the $\% \Delta R_a$ value was almost similar because the centrifugal force slowly increases at 500 rpm. Further increase in the tool rotational speed at 600 rpm, the $\% \Delta R_a$ was reduced. This was due to the effect of the centrifugal force acting on CIPs which begins to increase beyond the attraction of magnetic force on the these CIPs. Therefore, at a rotational speed of 600 rpm, the normal magnetic force

decreases. The reason for the decrease in the normal magnetic force was because of the centrifugal force acting on the CIPs chains structure at higher rotational speed. This result in decrease in magnetic normal force and CIPs chains structure may start decreasing their bonding strength. Due to this, the SiC abrasive particles may disperse from the CIPs chains structure or loosely gripped with the CIPs chains structure. When these loosely gripped abrasive particles comes in contact with the internal ferromagnetic surface, these loosely gripped abrasive particles can even rub or roll over the surface without finishing which further reduced $\% \Delta R_a$ values.

5.3.10 Effect of interaction of mesh sizes of SiC abrasive particles at various tool linear speeds

The effect of interaction of mesh sizes of SiC abrasive particles at various tool linear speeds is shown in Fig. 5.14.

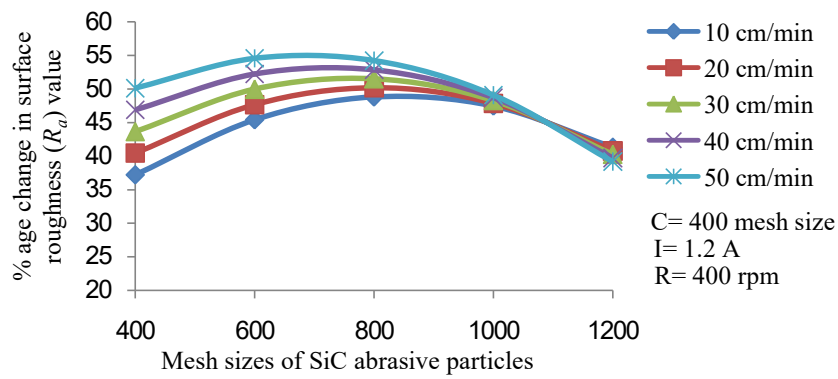


Fig. 5.14 Effect of interaction of various mesh sizes of SiC abrasive particles with various tool linear speeds on percentage change in surface roughness (R_a) values.

This interaction was taken at 400 mesh size of CIPs, 1.2 A of magnetizing current and 400 rpm of tool rotational speed. From the interaction plot, it is cleared that at higher tool linear speed, the $\% \Delta R_a$ values also increased. This was because of the formation of higher shearing force due to continuous reciprocation movement of SiC abrasive particles which helps to remove the roughness peaks significantly from the internal surface of cylindrical ferromagnetic workpiece. At a lower tool linear speed i.e. 10 cm/min, the effect of shearing force to remove the roughness peaks was lesser. With increase in the size of SiC abrasive particles from 400 mesh size to 800 mesh size, the $\% \Delta R_a$ values got increased. Beyond 800 mesh size of SiC abrasive particles, the $\% \Delta R_a$ values decreased. This is because the size of abrasive particles was small as compared to the size of CIPs. Therefore, the cutting edge of abrasive particles was also small which results in no finishing of the internal ferromagnetic cylindrical surface take place. Also, due to the smaller size of abrasive particles, these abrasive particles during finishing may move inside the CIPs

chains structure rather than gripped and move outwards towards the internal cylindrical ferromagnetic surface. Therefore, the interaction of 800 mesh size of SiC abrasive particles with 50 cm/min of tool rotational speed provided better finishing results.

5.3.11 Effect of interaction of mesh sizes of SiC abrasive particles at various magnetizing currents

The effect of interaction of mesh sizes of SiC abrasive particles at various magnetizing currents is shown in Fig. 5.15.

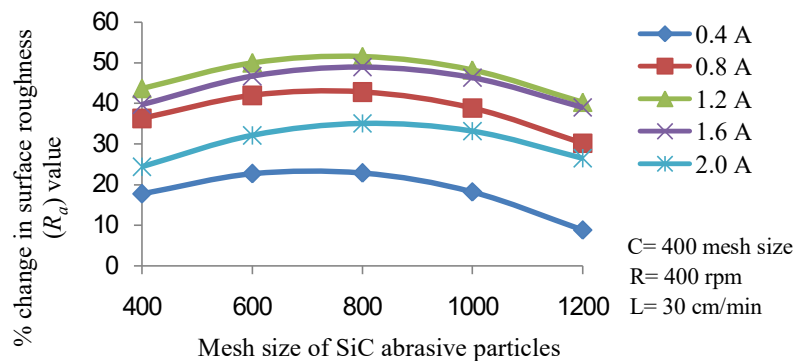


Fig. 5.15 Effect of interaction of various mesh sizes of SiC abrasive particles with various magnetizing currents on percentage change in surface roughness (R_a) values.

This interaction is taken at 400 mesh size of CIPs, 400 rpm of tool rotational speed and 30 cm/min of tool linear speed. At the magnetizing current of 1.2 A and 800 mesh size of SiC abrasive particles, the % ΔR_a values was found higher. This was because at 1.2 A of magnetizing current, a better gripping of abrasive particles by the CIPs chains takes place. During the reciprocation and rotational movement of SiC abrasive particles over the internal surface of ferromagnetic cylindrical workpiece, the sharp edges of SiC abrasive particles cut the roughness peaks from the internal cylindrical ferromagnetic surface. At 0.4 A of magnetizing current, the abrasive particles was loosely gripped by the CIPs chains structure. From the loosely CIPs chains structure, the abrasive particles move out from the chain structure. As a result, these randomly distributed abrasive particles do not take part in cutting the roughness peaks from the internal ferromagnetic cylindrical surface. At 2 A of magnetizing current, the SiC abrasive particles were strongly gripped by the CIPs chains structure. During the reciprocation and rotational movement of SiC abrasive particles over the internal surface of cylindrical ferromagnetic workpiece, the CIPs chains structure provides a higher indentation force to the SiC abrasive particles during the finishing operation. The cutting of roughness peaks takes place by the SiC abrasive particles.

Also due to higher indentation force, these SiC active abrasive also indent into the workpiece surface and finally produces cavities on the workpiece surface. As a result, the % ΔR_a values got decreased. Therefore, the interaction of 800 mesh size of SiC abrasive particles with 1.2 A magnetizing current provided better finishing results.

5.4 Confirmatory experiments for validation of model

The five different experiments were conducted to confirm the validity of the regression model as obtained in Eq. 5.3, with the experimental results as % ΔR_a values. The verification tests and their similarity with the predicted designed for % ΔR_a values are given in Table 5.15. From this analysis, the percentage error (%) among the experimental and predicted data lies within -5.71% to 5.40%. The results found to be in good agreement with each other.

5.5 Optimization of process parameters

As the lowest surface roughness (R_a) value of final finished surface was required, therefore, to provide a higher % ΔR_a values, the optimization of the quadratic model can be done from the results obtained. The optimization was performed based on the effect of each process parameters on % ΔR_a values. After least square regression model analysis, the optimum process parameters were found and are given in Table 5.16.

Table 5.15 Confirmatory experiments to validate the results.

Sr No.	Process parameters					Experimental (% ΔR_a) value	Predicted (% ΔR_a) value	Error (%)
	S	C	I	R	L			
1	1000	500	0.5	500	20	35	37	-5.71
2	600	300	0.8	500	40	45	44	2.22
3	800	400	0.4	400	30	22	23	-4.54
4	800	400	2	400	30	37	35	5.40
5	800	400	1.2	400	50	53	54	-1.88

Table 5.16 Optimum process parameters.

Parameters	Values
Size of SiC abrasive particle	800 mesh size
Size of CIPs	400 mesh size
Magnetizing current	1.2 A
Tool rotational speed	500 rpm
Tool linear speed	50 cm/min

To check the feasibility of optimum process parameters by using MR honing process, the experimentation was conducted on EN-24 steel key type cylindrical workpiece (similar type of workpiece as used in the plan of experiments) by using optimum process parameters (Table 5.16). The initial surface roughness (R_a) value of EN-24 key type workpiece was found as 401 nm. The experimentation was carried with 90 minutes of finishing. The MR polishing fluid was renewed after 30 minutes of finishing on the outer surface of rectangular tool cores for obtaining better finishing results. The surface roughness (R_a) value was found as least as 96 nm from initial 401 nm after 90 minutes of finishing. The change in surface roughness (R_a) value against finishing time is shown in Fig. 5.16. The initial ground and final profiles of surface roughness are shown in Fig. 5.17. The surface morphology observed by scanning electron microscopy (SEM) images of initial ground and final finished surface are shown in Fig. 5.18. The surface defects like deeper groove, sharp edges were found on the initial SEM image (Fig. 5.18a). After MR finishing, the surface defects were completely removed and can be clearly seen by SEM image (Fig. 5.18b).

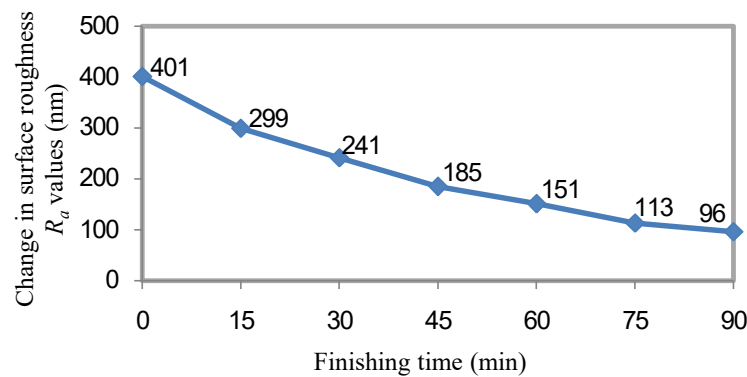


Fig. 5.16 Change in surface roughness (R_a) values with respect to finishing time.

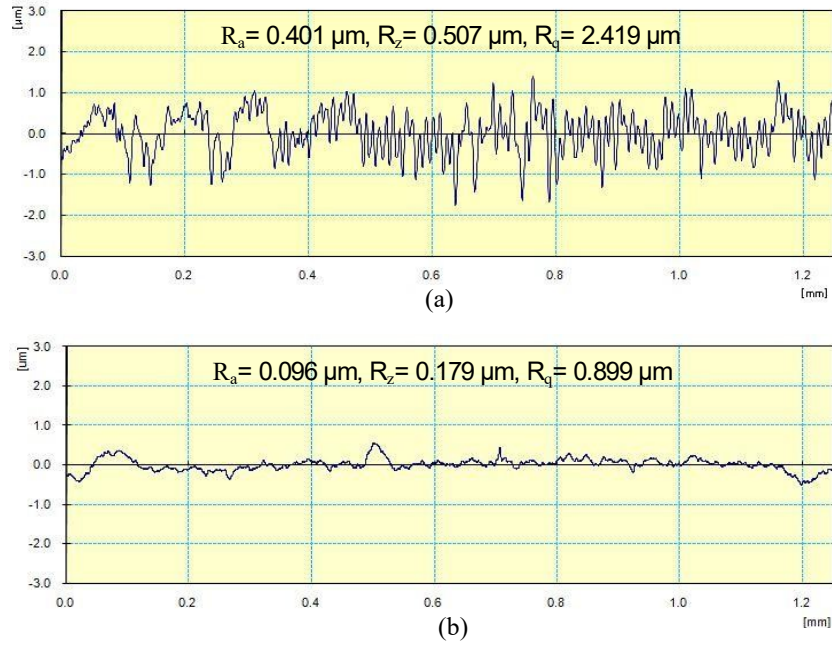


Fig. 5.17 Surface roughness profiles of (a) initial ground surface and (b) final finished surface after 90 minutes of finishing (at S= 800 mesh size, C= 400 mesh size, I= 1.2 A, R= 500 rpm and L= 50 cm/min).

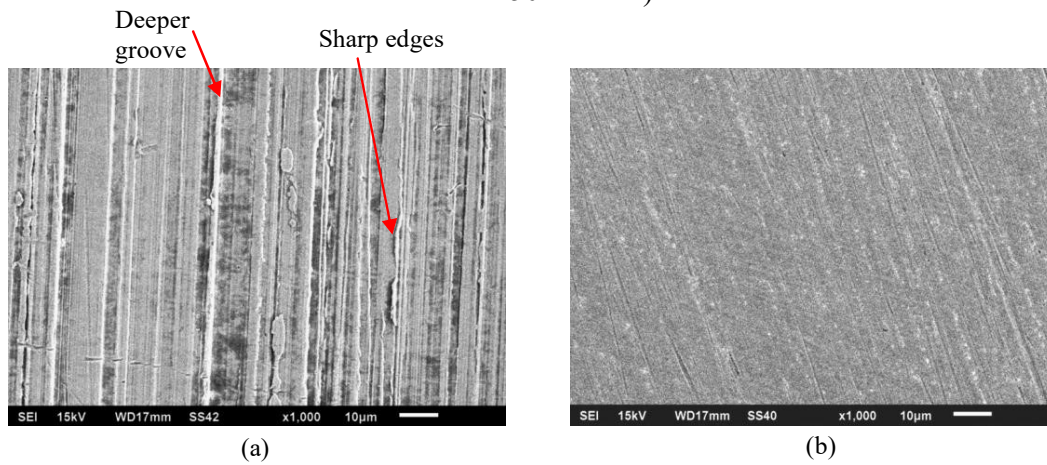


Fig. 5.18 Scanning electron microscopy images at 1000x of (a) initial ground surface and (b) final finished surface after 90 minutes of finishing (at S= 800 mesh size, C= 400 mesh size, I= 1.2 A, R= 500 rpm and L= 50 cm/min).

5.6 Conclusions

The following conclusions are drawn from the parametric study of magnetorheological (MR) honing process during the internal surface finishing of EN-24 steel cylindrical workpiece.

 From the response surface regression analysis, the maximum contribution was made by magnetizing currents followed by tool linear speeds, mesh sizes of CIPs, tool rotational speeds and mesh sizes of SiC abrasive particles.

 The lowest surface roughness (R_a) value was found as 96 nm from 401 nm after 90 minutes of finishing with optimum parameters as 800 mesh size of SiC abrasive particles, 400 mesh size of CIPs, 1.2 A of magnetizing current, 500 rpm of tool rotational speed and 50 cm/min of tool linear speed.

 The surface defects such as deeper grooves and sharp edges left out on the internal surface after grinding operation were completely removed by the present MR honing process which is correlated with the scanning electron microscopy images at 1000x.

CHAPTER 6

DEMONSTRATION OF THE FINISHING CAPABILITY OF DEVELOPED MAGNETORHEOLOGICAL HONING PROCESS ON THE INDUSTRIAL APPLICATIONS

In today's industries, several ferromagnetic cylindrical components such as cylinder liner, injection barrel of molding machine, cylindrical molds and dies, hydraulic cylinder etc. as well as non-ferromagnetic component such as pneumatic cylinder requires better surface finishing even after traditional grinding or honing process for its better functional applications. Hence, the present magnetorheological (MR) honing process has the capability to improve the functional applications of initial ground or honed cylindrical components (ferromagnetic or non-ferromagnetic) by reducing its further surface roughness values and improving the surface quality. This results in more wear and friction resistance, load bearing capacity, less energy utilization between the mating parts during its functional applications as compared to initial ground cylindrical components. Based on the industrial applications, the internal surface finishing of different components such as cylinder liner, injection barrel of moulding machine and blind-hole type mould cavity was carried out. The detail studies regarding finishing of these internal cylindrical components are presented as follows.

6.1 Demonstration of the developed process for finishing of internal cylindrical surface material used in cylinder liner

The cylinder liner made of ferromagnetic gray cast iron material is commonly used in engine block assembly of an automobile industry. The common method used for internal surface finishing of the cylinder liner (gray cast iron) is the traditional honing process. The nominal composition measured in gray cast iron as Fe= 91.1%, C= 3.6%, Si= 2.3%, Mn= 0.779%, Cr= 0.45%, Mo= 0.41%, Ni= 0.24%, S= 0.13% and P= 0.12%. The various surface defects like deeper grooves, honing grooves with sharp edges, torn and folded metals, cavities or holes etc (Gupte *et al.*, 2008) are commonly induced after the traditional honing operation, which decreased the surface characteristics of the cylinder liner. Therefore, for improving the surface characteristics of honed surface of cylinder liner made up of gray cast iron, the experimentation was performed with help of a magnetorheological (MR) honing process. The dimensions of the traditionally honed cylindrical gray cast iron were taken as internal diameter of 96 mm, outer

diameter of 110 mm and height of 13 mm. The magnetic flux density distribution in working gap between the outer finishing surface of rectangular tool core and cylindrical ferromagnetic workpiece surface was carried out with Maxwell Ansoft V13 software (student version). The magnetic flux density distribution at 0.6 mm working gap (filled with MR polishing fluid) was analyzed. For the magnetostatic finite element analysis (FEA) material assigned to the electromagnetic model of MR honing tool during internal surface finishing of cylindrical cast iron workpiece is given in Table 6.1. The values of relative permeability of copper and MR polishing fluid were taken from the existing literature review (Singh et al., 2012). The actual standard value relative permeability was taken for cold rolled iron as 1500, gray cast iron as 1500 and stainless steel as 1.003. The value of current 1A and number of turns 2400 were taken as per the different trials performed in Maxwell Ansoft V13 (student version) software for getting the maximum flux density on the outer finishing tool core surface.

Table 6.1 Assigned process parameters to the electromagnetic model of the MR honing tool during the internal surface finishing of cylindrical gray cast iron workpiece.

Parameters	Materials	Relative Permeability	Current	Number of turns
Electromagnet coil	Copper (26 standard wire size)	0.999991	1A	2400
Tool core	Cold rolled iron	1500		
Finishing medium	MR polishing fluid	5		
Ferromagnetic cylindrical workpiece	Gray cast iron	1500		
Rotating shaft	Stainless steel	1.003		

The magnetic simulation results clearly revealed that the magnetic flux density was found higher at the outer finishing surface of rectangular tool core than the internal surface of ferromagnetic cylindrical workpiece (Fig. 6.1a). The direction of magnetic lines of fluxes in the outer finishing surface of rectangular tool core is shown in Fig. 6.1 (b). The decrease in magnetic flux density from the outer finishing surface of rectangular tool core to the internal surface of ferromagnetic cylindrical workpiece can be clearly seen in 2D magnetic field report as shown in Fig. 6.1 (c). This result in MR polishing fluid always retained at the outer finishing surface of rectangular tool core than the internal surface of ferromagnetic cylindrical workpiece. Hence, there was no

any possibility of MR polishing to stick on the internal surface of ferromagnetic cylindrical workpiece during finishing. This was the necessary requirement for finishing the internal surface of ferromagnetic cylindrical workpiece. Therefore, when the outer finishing surface of rectangular tool core along with electromagnet was moved simultaneously with reciprocation and rotation inside the cylindrical ferromagnetic surface, the finishing on the internal surface of ferromagnetic cylindrical workpiece was taken place with the present MR honing process.

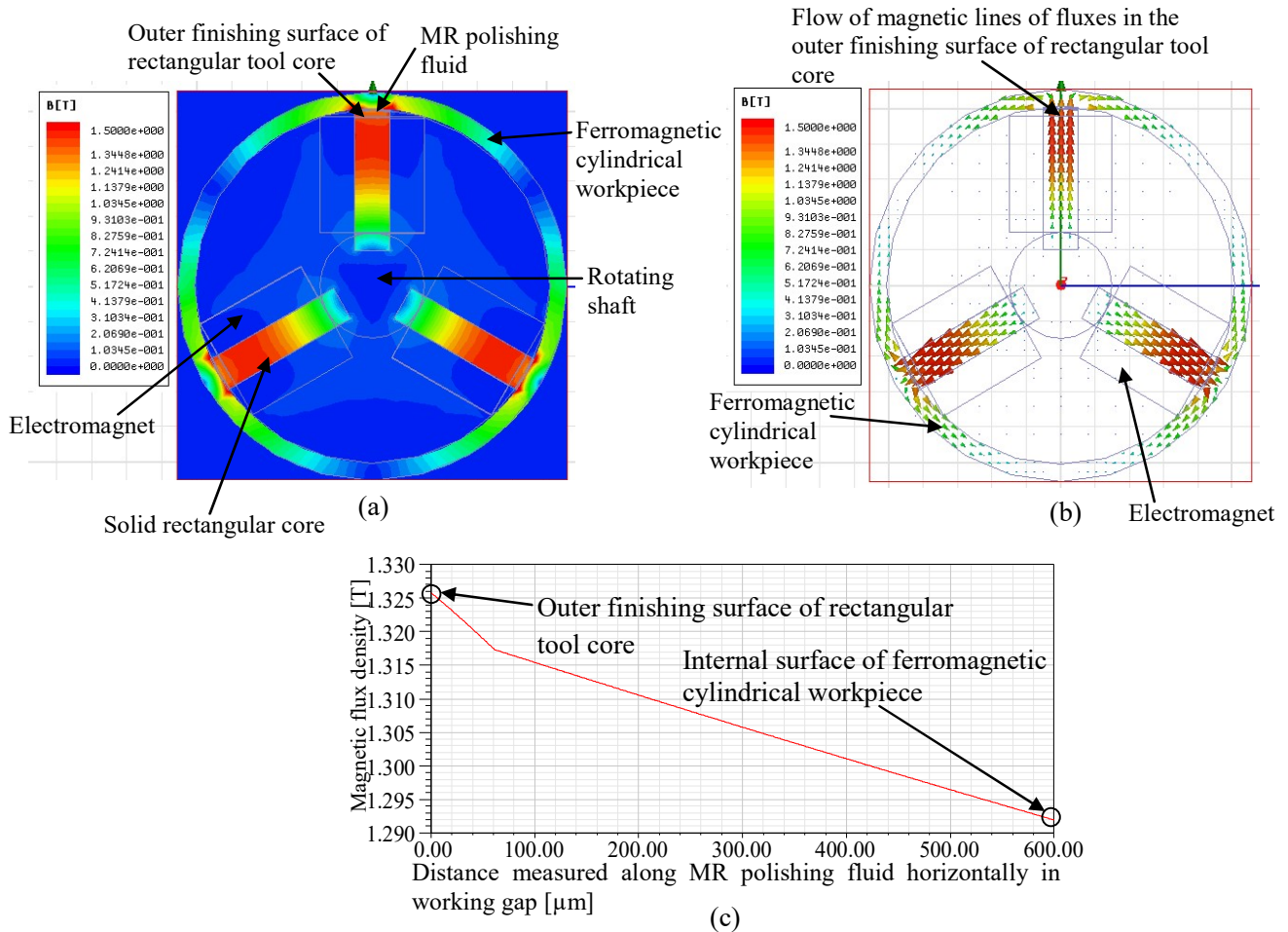


Fig. 6.1 (a) Magnetostatic FEA of MR honing tool with cylindrical ferromagnetic workpiece and MR polishing fluid within the working gap (top view), (b) flow of magnetic lines of fluxes in the outer finishing surface of rectangular tool core (top view) and (c) two dimensional plot of magnetic flux density distribution within the working gap from FEA (with number of turns of electromagnetic coils on each solid rectangular core as 2400 and current of 1A).

The experimentation was carried out with the present MR honing process for improving the surface characteristics of the ferromagnetic honed cylinder (made of gray cast iron). The surface roughness profiles was measured by a contact mode type surfest SJ-400 (make Mitutoyo) with

diamond stylus tip of radius= $0.5\mu\text{m}$, cone angle of diamond stylus tip= 90° , cut off length= 0.25 mm and digital filter as Gaussian. The surface roughness profiles were measured at four different locations on the internal surface of ferromagnetic cylindrical workpiece in order to analyze the uniformity in surface roughness throughout the internal cylindrical surface. Each location consists of three consecutive readings as shown in Fig. 6.2 (a).

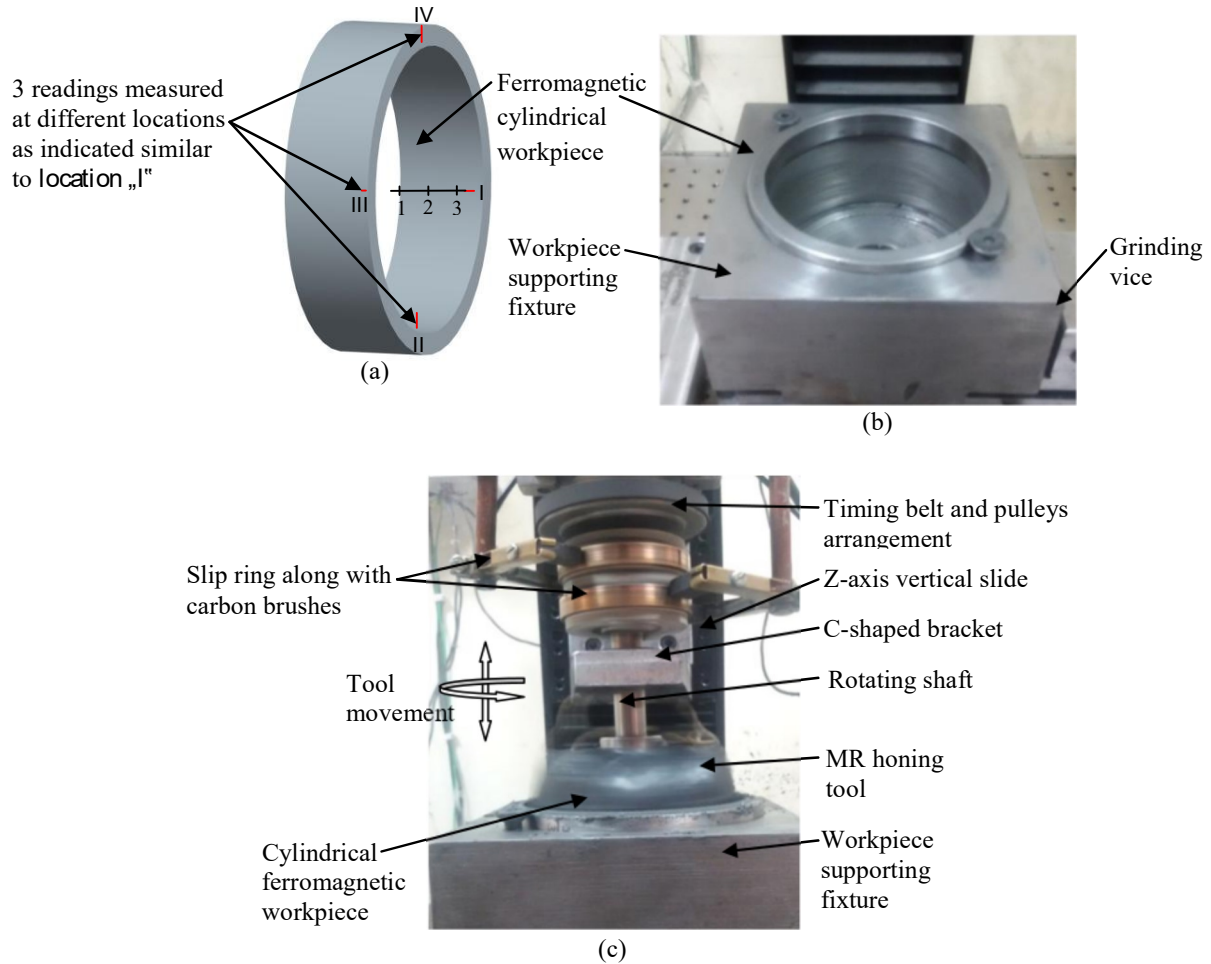


Fig. 6.2 (a) CAD model of a cylindrical ferromagnetic workpiece representing different measurement points for the surface roughness values, (b) photograph of a cylindrical ferromagnetic honed gray cast iron workpiece along with workpiece supporting fixture and (c) photograph of the MR honing tool during finishing of the internal surface of honed gray cast iron cylindrical workpiece.

Therefore, there are total 12 points on the internal cylindrical honed surface, where roughness values were measured. The variation in measured initial surface roughness values among 12 points on the internal cylindrical honed surface were found as $R_a = 368\text{ nm}$ to 375 nm , $R_q = 486\text{ nm}$ to 499 nm and $R_z = 2910\text{ nm}$ to 3315 nm . The cylindrical ferromagnetic workpiece was fixed

to a supporting fixture of rectangular type as shown in Fig. 6.2 (b). The synthesized MR polishing fluid as given in Table 4.1, was used for finishing of the internal cylindrical cast iron workpiece surface. The actual experimentation photograph during finishing of the internal gray cast iron cylindrical surface with the present MR honing tool is shown in Fig. 6.2 (c).

Before the start of finishing, the MR polishing fluid at the outer finishing surface of rectangular tool cores was applied manually with the help of steel spoon. The DC power was supplied to the electromagnetic coil to make the MR polishing fluid retain and stiffen on the outer finishing surface of tool core surface. The experimentation conditions used during finishing of cylindrical gray cast iron workpiece are given in Table 6.2. The different parameters were chosen as per the initial trials experimentation. The parameters which were given the better results had been chosen as per given in Table 6.2

Table 6.2 Experimentation conditions used for finishing of the internal surface of grey cast iron cylindrical workpiece.

Parameters	Conditions
Rotational speed of finishing tool	500 rpm
Reciprocational speed of finishing tool	70 cm/min
Working gap	0.6 mm
Total finishing time	90 min
Each finishing step	30 min
DC power supply to electromagnet	1 A
Magnetic flux density produced at the outer finishing tool core surface	0.591 T

These experimental parameters have been chosen according to the results obtained from preliminary experimentation. The magnetizing current of 1A has been selected which produce a magnetic flux density of 0.591T (measured with digital gauss meter) at the outer finishing surface of rectangular tool core. For analyzing the geometry throughout the entire finished surface (from top region to bottom region of the internal cylindrical surface), the parallelity, roundness and concentricity were measured by using coordinate measuring machine. The straightness and cylindricity were measured by dial gauge. For microscopy study, the scanning

electron microscopy (SEM) was performed on both initial honed surface and finished surface with the present MR honing process.

6.1.1 Observation and discussion on experimentation during internal surface finishing of cylindrical gray cast iron workpiece

To clearly describe the mechanism of surface improvement of the ferromagnetic cylindrical honed surface with the present MR honing process, the experiments were conducted on the traditionally honed surface made up of the gray cast iron material. The surface roughness parameters i.e. R_a , R_q and R_z on the internal surface of gray cast iron cylindrical workpiece with respect to finishing time were measured at 12 different points. The variation in measured surface roughness values at 12 different points after 90 minutes of finishing on internal cylindrical surface were found as R_a = 83 nm to 85 nm, R_q = 145 nm to 148 nm and R_z = 810 nm to 814 nm. This clearly revealed that the variation in roughness values at 12 different points on the finished surface after 90 minutes of finishing with the present MR honing process was almost uniform. The change in surface roughness values R_a , R_q and R_z with 90 minutes of finishing are shown in Fig. 6.3.

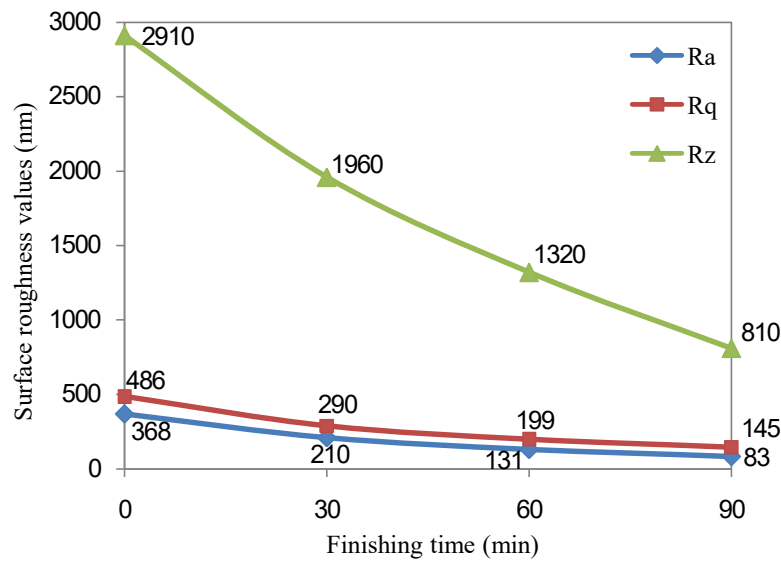


Fig. 6.3 Plot between surface roughness values (nm) versus finishing time (minutes).

The initial honed and final finished surfaces roughness profiles (for point 3 of location „I“ in Fig. 6.2a) are shown in Figs. 6.4 (a) and (b), respectively. From the roughness profiles, it clearly revealed that the surface roughness values reduced from R_a = 368 nm, R_q = 486 nm and R_z = 2910

nm to final $R_a = 83$ nm, $R_q = 145$ nm and $R_z = 810$ nm with 90 minutes of finishing. During the experimentation, the finishing was carried in three different steps. Each finishing step consists of 30 minutes. The fresh MR polishing fluid was conditioned after every 30 minutes of finishing step in order to maintain the fresh active abrasives during finishing on the traditionally honed surface using the present process. This may consider as one of the important factor for material removal stability in every 30 minutes of finishing step. After every 30 minutes of finishing step, the surface roughness values were measured and are shown in Fig. 6.3.

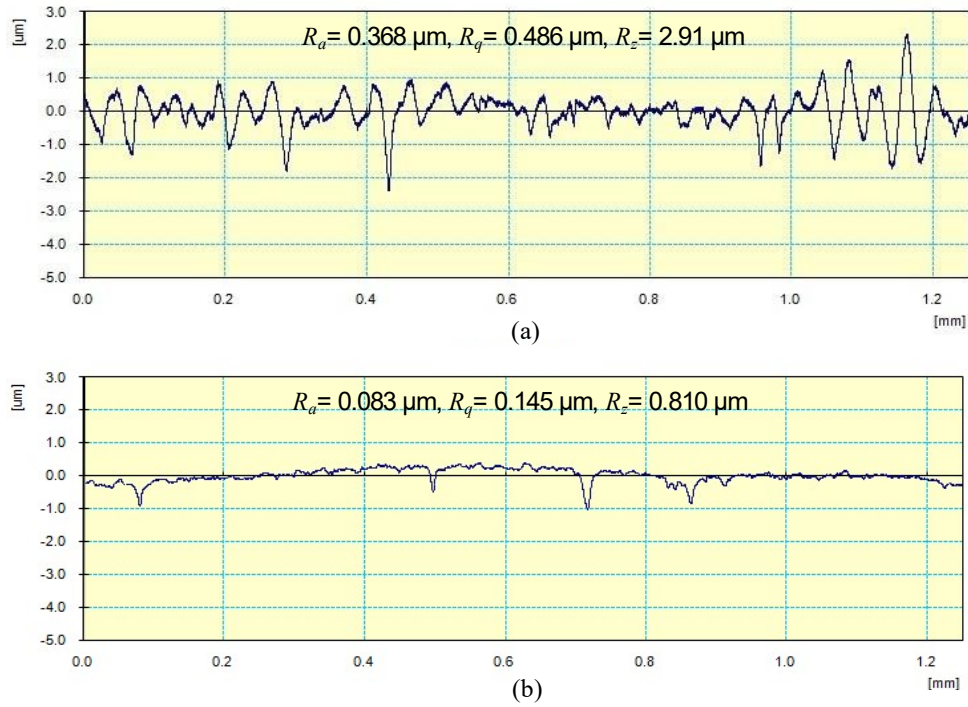


Fig. 6.4 Surface roughness profiles of (a) initial traditionally honed internal surface of cylindrical gray cast iron workpiece and (b) finished internal honed surface (at point 3 of location „I“) after 90 minutes of finishing with the present MR honing process.

The significant finishing on the internal surface of gray cast iron cylindrical workpiece was found. This is due to the uniform magnetic flux density obtained along the width of outer finishing surface of rectangular tool core (Fig. 6.1a). Also, the at the outer finishing rectangular tool core surface, the magnetic flux density was higher (Fig. 6.1c). Thus, the carbonyl iron particles (CIPs) of MR polishing fluid get stuck towards it and simultaneously pushing the non-magnetic abrasive particles towards the internal ferromagnetic surface (Fig. 6.5a).

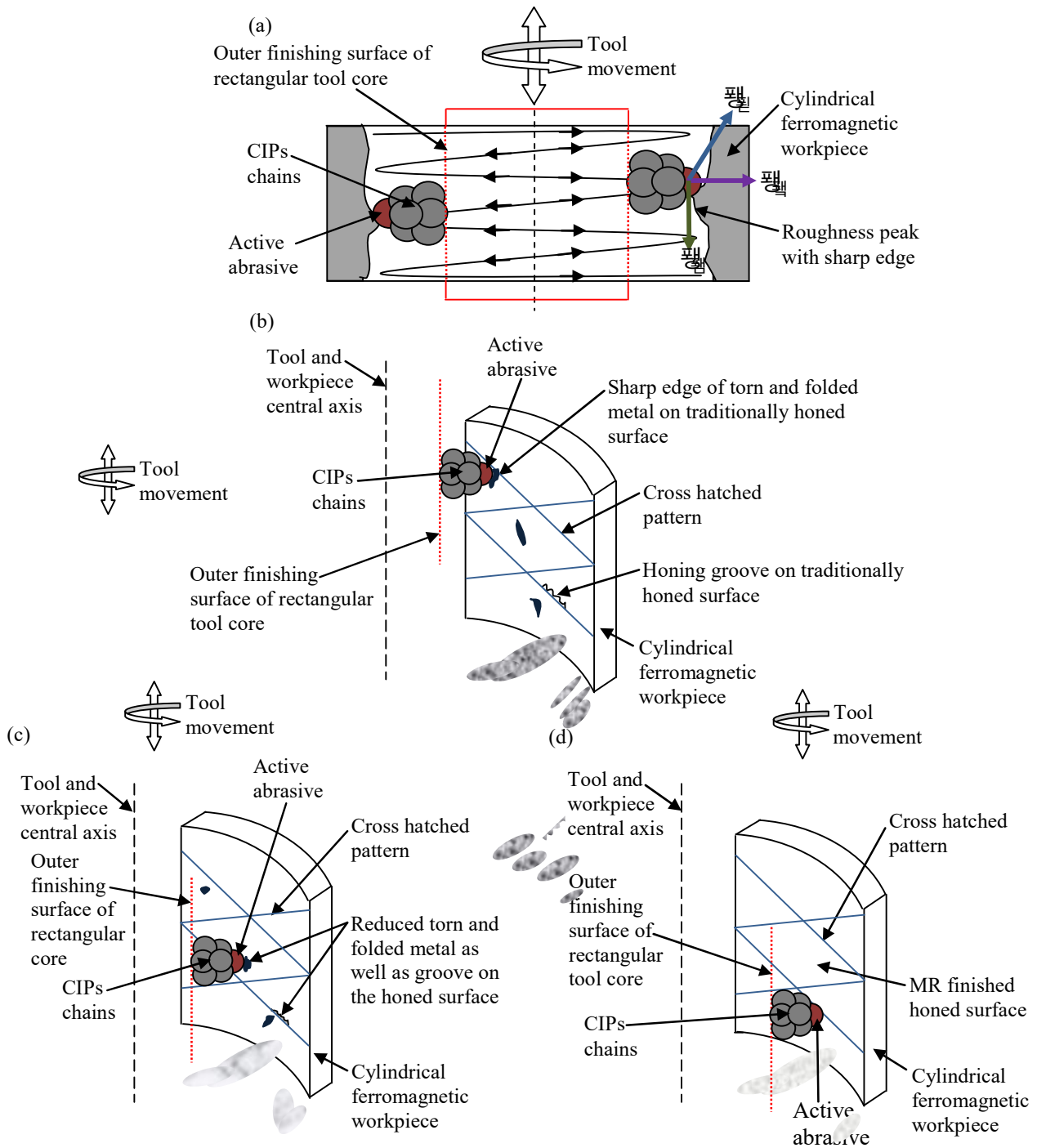


Fig. 6.5 Schematic of (a) the active abrasive locked strongly by carbonyl iron particles (CIPs) chains approaching the roughness peaks of the internal surface of initially honed gray cast iron cylindrical workpiece, removal of various honed surface defects in (b) first finishing step, (c) second finishing step and (d) third finishing step with the present MR honing process.

The CIPs make chains as per the trends followed by the magnetic lines of fluxes and grip the abrasives on the internal gray cast iron cylindrical surface. The locked abrasives within the CIPs chains on the internal surface are called as active abrasives (Fig. 6.5a). Also, the CIPs give a repulsive force to the active abrasives which make them indent on the internal gray cast iron cylindrical surface. The indented abrasives which gripped by CIPs chains when rotated as well as reciprocated along with the finishing tool, the irregular peaks gets eroded from the internal gray cast iron cylindrical surface. The mechanism of material removal during each step of finishing is shown by the schematic representation in Figs. 6.5 (b), (c) and (d). During the first step of finishing, the active abrasives approached to the grooves of sharp edges of torn and folded metals due to the effect of indentation force (F_{indent}). These indented abrasives, when rotate and reciprocate along with the outer finishing surface of rectangular tool core strikes the sharp edges of torn and folded metals as well as honing grooves of the initial honed surface (Fig.6.5b). As initially, the shearing strength of sharp edges of torn and folded metals as well as honing grooves was low, therefore the removal of these sharp edges taken place easily due to the combined effect of tangential force (F_{tan}) and axial force (F_{ax}). The surface roughness values were decreased from $R_a = 368$ nm, $R_q = 486$ nm and $R_z = 2910$ nm to $R_a = 210$ nm, $R_q = 290$ nm and $R_z = 1960$ nm after 30 minutes of finishing (Fig. 6.3). After the first step of finishing, the sharp edges of torn and folded metal, as well as honing grooves, were reduced in a smaller range as shown in Fig. 6.5 (c).

During the start of the second set of finishing (i.e. after 30 minutes), the MR polishing fluid was conditioned on the outer finishing surface of rectangular tool core in order to avoid the blunted active abrasives along with the micro-chips as removed from the sharp edges of torn and folded metals of the initial honed surface. The indented abrasives during second set of finishing again approached to the already reduced edges of the torn and folded metals after 30 minutes of finishing. This further reduced the edges of the torn and folded metals due to the combined effect of tangential force (F_{tan}) and axial force (F_{ax}) when finishing tool core surface reciprocated as well as rotated simultaneously. The surface roughness values got reduced to $R_a = 131$ nm, $R_q = 199$ nm and $R_z = 1320$ nm from $R_a = 210$ nm, $R_q = 290$ nm and $R_z = 1960$ nm after next 30 minutes second set of finishing (Fig. 6.3).

Again, before start of third set of finishing (i.e. after 60 minutes), the MR polishing fluid was renewed on the outer finishing surface of rectangular tool core and magnetic field switched ON

so that MR polishing fluid stiffened on the outer finishing surface of rectangular tool core. When the finishing tool core surface with the stiffened MR polishing fluid reciprocated as well as rotated simultaneously inside the honed surface, the left out tiny torn and folded metals were completely removed due to the combined effect of tangential force ($\frac{F_{\text{tang}}}{F_{\text{axial}}}$) and axial force ($\frac{F_{\text{axial}}}{F_{\text{tang}}}$) (Fig. 6.5 d). The surface roughness values further got reduced to $R_a=83$ nm, $R_q=145$ nm and $R_z=810$ nm from $R_a=131$ nm, $R_q=199$ nm and $R_z=1320$ nm after third set of finishing (Fig. 6.3). The overall percentage change in roughness values (R_a , R_q and R_z) of the cylindrical honed surface made up of gray cast iron were decreased to 77.44%, 70.16% and 72.16% respectively, after 90 minutes of finishing with the present process.

Further, to inspect the form error on the finished internal surface of honed cylindrical workpiece after 90 minutes of finishing with the present process, the coordinate measuring machine and dial gauge were used. The form error in terms of parallelity, concentricity, cylindricity and straightness measured from top region to bottom region on the finished internal honed surface was found as zero. The roundness error was found within 2 microns. These results were more evidenced that the new MR honing process is liable for removing the various defects from the surface of traditionally honed cylindrical workpiece with better geometrical accuracy.

In order to clearly visualize the internal surface texture of cylindrical honed gray cast iron cylindrical workpiece before and final finished with the present MR honing process, the microscopic study was carried out by using scanning electron microscopy (SEM) at x500. The SEM image of the initial cylindrical honed surface (Fig. 6.6a) of cylindrical gray cast iron clearly visualize the different types of surface defects found after the traditional honing process.

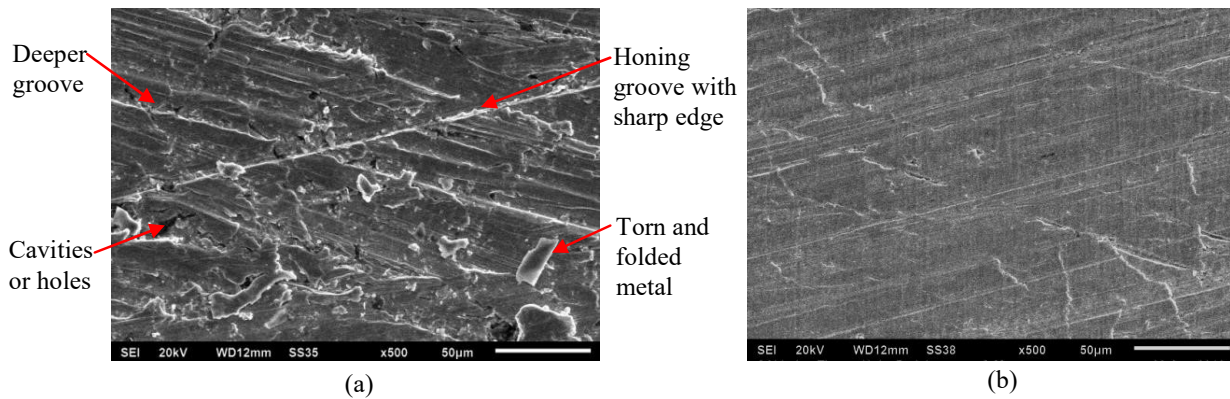


Fig. 6.6 Surface morphology using scanning electron microscopy (SEM) at x500 of (a) initial traditionally honed internal surface of cylindrical gray cast iron workpiece and (b) finished internal honed surface after 90 minutes of finishing with the present MR honing process.

The various surface defects like deeper grooves, honing grooves with sharp edges, torn and folded metals, cavities or holes were seen on the initial honed surface (Fig. 6.6a). The SEM image of the final finished surface after 90 minutes of finishing with the present process is shown in Fig. 6.6 (b). From SEM images, it can be clearly visualized that the finished surface of cylindrical honed workpiece with the present MR honing process has better surface texture than the initial traditionally finish honed surface. The surface defects such as torn and folded metals as well as honing grooves with sharp edges as found on the initial honed surface were completely removed by the present MR honing process. This results in a better operational life of finished cylindrical honed surface with the present MR honing process. In case of the initial honed surface, the surface defect such as torn and folded metals was produced which resulted in scuffing wear and created scuffing marks, cavities or holes on the matching surface during operation. This scuffing mark created by scuffing wear between the mating surfaces sometime creates a noise during the actual running of the piston inside the cylinder liner. Also, the torn and folded metals on the traditionally honed surface used to remove micro-chips from the matching surface. These removed micro-chips entered into the deeper grooves on the traditionally honed surface. These hidden micro-chips sometime moved out from the deeper grooves during the actual running operation and this result in friction between the mating parts. Hence, the present MR honing process can find its applications in automotive industry to improve the operational life of traditionally honed surface after removing the aforesaid surface defects. Therefore, the final MR finished cylindrical liner surface with better characteristics requires less energy consumption between the mating parts during the actual running of a piston inside the cylinder liner. Hence, this results in wear and friction resistance, high load bearing capacity, fatigue strength and more operational life during its functional applications as compared to traditionally honed cylindrical components.

6.2 Demonstration of the developed process for finishing of internal cylindrical surface material used in injection barrel

The better surface qualities of various rubber or plastic products manufactured by moulding operation are in greater demand. The moulding operations of such products are done through the injection moulding machine. The cylindrical injection barrel is the important component used in injection moulding machine. The molten rubber or plastic material injected into the mould cavity through cylindrical injection barrel and screw barrel arrangement. The traditional grinding

process with rigid abrasives stones is commonly used for finishing of internal injection barrel surfaces. The unmanageable finishing forces produced by rigid abrasives stones on the internal injection barrel surfaces produces axial scratches, cavities etc. on its surface. Hence, it may also result in a non-uniform surface roughness throughout the entire internal cylindrical barrel surface. If the internal surface of injection barrels has non-uniform surface roughness then the molten plastic or rubber material of first colour (say black) gets entered into the axial scratches or cavities of internal barrel surface. During the flow of second colour (say blue), a problem of intermixing of molten plastic or rubber of second colour (say blue) with the first colour (say black) is taken place. The second colour molten material along with the intermixing of first colour molten material finally pours into the mould through injection nozzle for obtaining the required shape. This results into the rejection of final made component (because of intermixing of differently coloured materials) which overall reduces the efficiency of injection molding machine (Vishwas *et al.*, 2017). In order to increase the production efficiency of injection molding machine, the internal surface finishing of injection barrel requires a better finished surface (defect-free surface) even after traditional grinding process for obtaining the better operative performance of injection moulding machine. Moreover, the material used for cylindrical injection barrel is hard and it makes the process of internal surface finishing a monotonous task.

The preliminary experimentaion was conducted on internal ferromagnetic barrel type surface (cylindrical type) with the MR honing process. The cylindrical ferromagnetic workpiece used for finishing was taken as hardened EN-24 steel with approximately 55 rockwell hardness in “C” scale (HRC). The CAD model representing the arrangement of cylindrical workpiece on workpiece fixture and MR honing process during internal surface finishing is shown in Fig. 6.7. The cylindrical ferromagnetic workpiece consists of key-type workpiece parts of hardened EN-24 material represented by its CAD model is shown in Fig. 6.7 (a). These ferromagnetic key-type workpiece part can be easily fitted or removed from the cylindrical ferromagnetic workpiece surface. The cylindrical ferromagnetic workpiece along with the key-type ferromagnetic workpiece parts (made of same material) were fixed to the precision grinding vice through workpiece fixture. The initial and final surface roughness profiles were measured by using SJ-210 surfest (made by Mitutoyo). On each ferromagnetic key-type workpiece part, the surface

roughness (R_a) values with 0.25 mm as cut off length were taken at three different points (Fig. 6.7a).

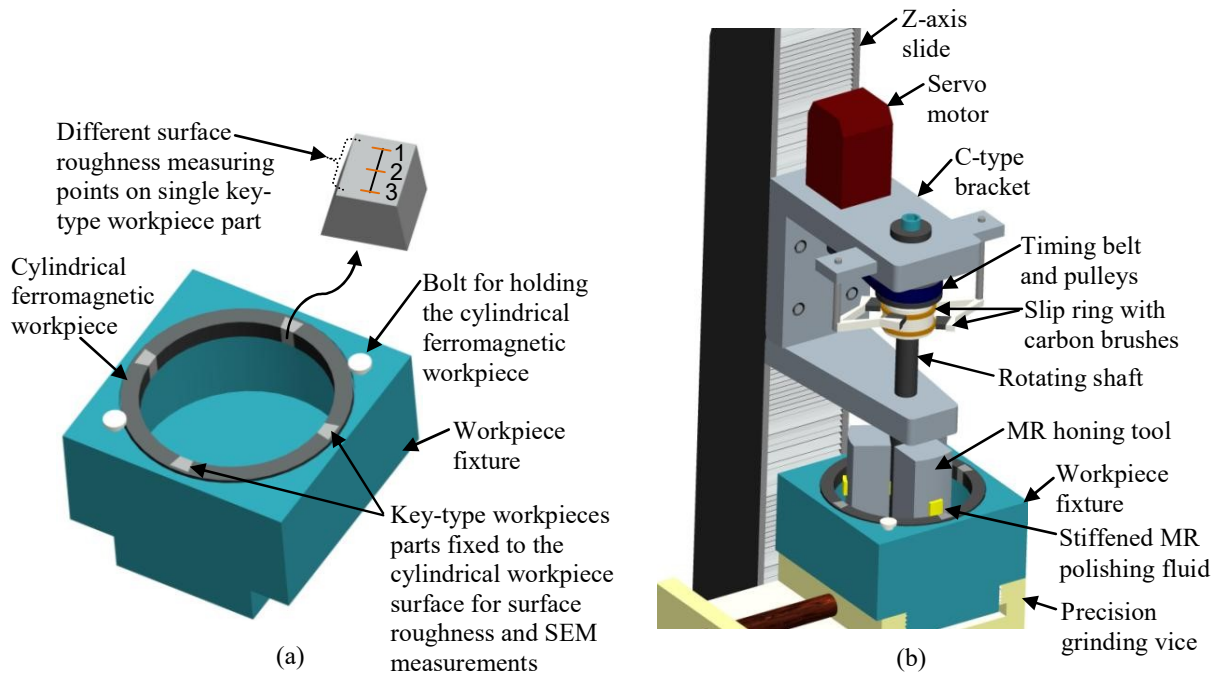


Fig. 6.7 (a) Cylindrical ferromagnetic workpiece attached to the workpiece fixture representing the position of different key-type EN-24 steel workpiece part and (b) actual experimentation during finishing of internal surface of EN-24 steel cylindrical workpiece.

Correspondingly, the surface roughness (R_a) values on the remaining key-type workpiece parts were also taken with three different readings. Scanning electron microscopy (SEM) images at x500 were also taken for analyzing the difference in surface characteristics of both initial and final finished surface. The synthesized MR polishing fluid as given in Table 4.3, was used for finishing of the internal surface of EN-24 steel cylindrical workpiece. The CAD model representing the actual finishing of the internal surface of EN-24 steel cylindrical workpiece by the MR honing process is shown in Fig. 6.7 (b). The experimentation conditions used during finishing of the internal surface of EN-24 steel cylindrical workpiece by using MR honing process is given in Table 6.3. The different parameters were chosen as per the initial trials experimentation. The parameters which were given the better results had been chosen as per given in Table 6.3.

Table 6.3 Experimentation conditions used during finishing of the internal surface of EN-24 steel cylindrical workpiece.

Parameters	Conditions
Rotational speed of finishing tool	800 rpm
Reciprocational speed of finishing tool	10 cm/min
Working gap	0.6 mm
Total finishing time	90 min
Each finishing segment	30 min
DC power supply to electromagnet	1.5 A

6.2.1 Observation and discussion on experimentation during internal surface finishing of cylindrical EN-24 steel

The initial surface roughness (R_a) values after the internal surface grinding of EN-24 steel cylindrical workpiece were found in the range of 346-432 nm. These surface roughness values were measured on total twelve points of four different key-type ferromagnetic workpiece parts. The MR honing process was carried out in three segments. Each finishing segment consists of 30 minutes of finishing. Before every finishing segment, the MR polishing fluid was applied at the outer finishing surface of rectangular tool core with the help of steel spoon. The renewal of MR polishing fluid was done to eliminate the movement of removed micro-chips from internal workpiece surface within the polishing fluid. When the magnetizing current was given to electromagnet, the MR polishing remains retained at the outer finishing surface of rectangular tool core and finally becomes stiffened. This was due to higher magnetic flux density at the finishing surface of rectangular core as can be clearly shown in Fig. 6.1. The active SiC abrasives gripped by rigid CIPs structure moved over the internal surface grinding of EN-24 steel cylindrical workpiece are liable for better surface finishing. The reductions in surface roughness (R_a) values with respect to different finishing cycles are shown in Fig. 6.8. The final surface roughness (R_a) values after MR finishing of the internal surface grinding of EN-24 steel cylindrical workpiece were found in the range of 103-123 nm. The better uniformity in surface roughness values was found in case of MR finished surface than the initial ground surface.

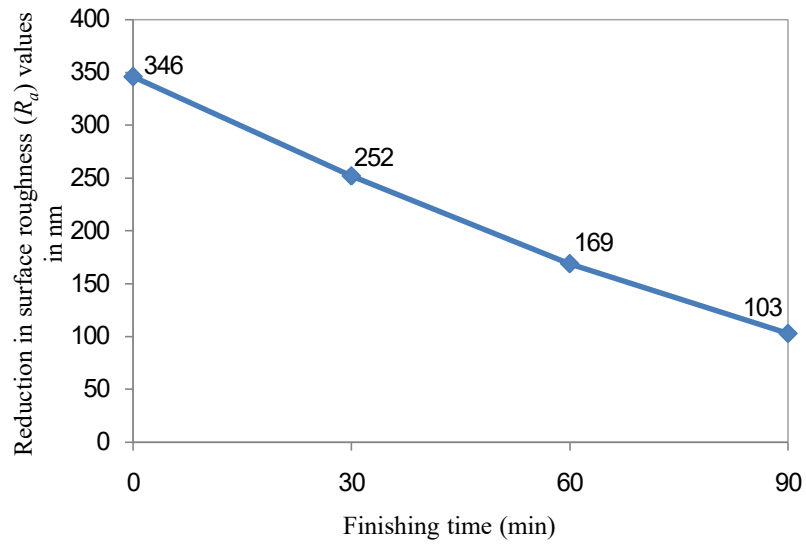


Fig. 6.8 Reduction in surface roughness (R_a) values with respect to finishing time.

The initial and MR final finished surface roughness profiles are shown in Fig. 6.9. These surface roughness profiles were taken as the lowest value of surface roughness (R_a) among the twelve different surface roughness (R_a) values of both initial and final MR finished surface.

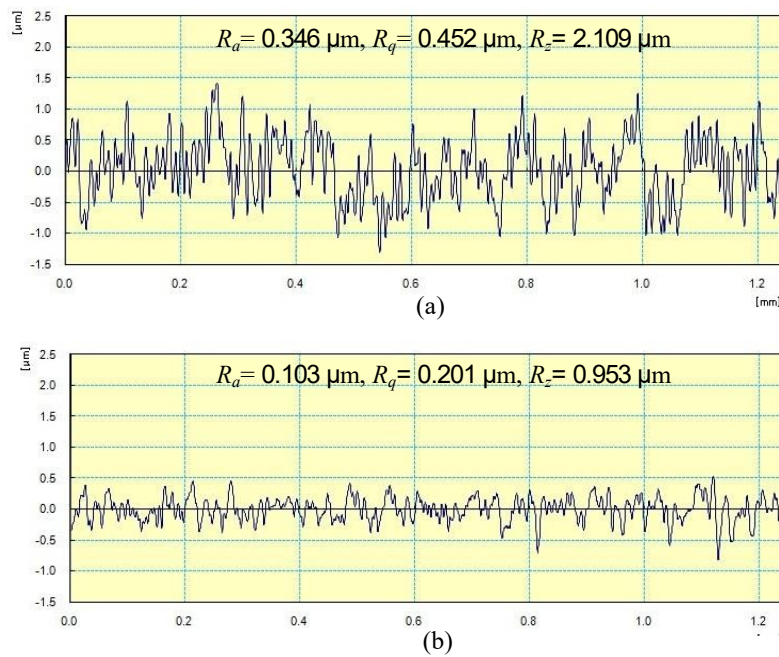


Fig. 6.9 Surface roughness profiles of (a) initial ground surface and (b) final finished surface after 90 minutes of finishing.

In order to clearly understand the reduction in surface roughness (R_a) values during different finishing cycles, it becomes important to clearly relate the difference in surface characteristics before each finishing segment as shown in Fig. 6.10.

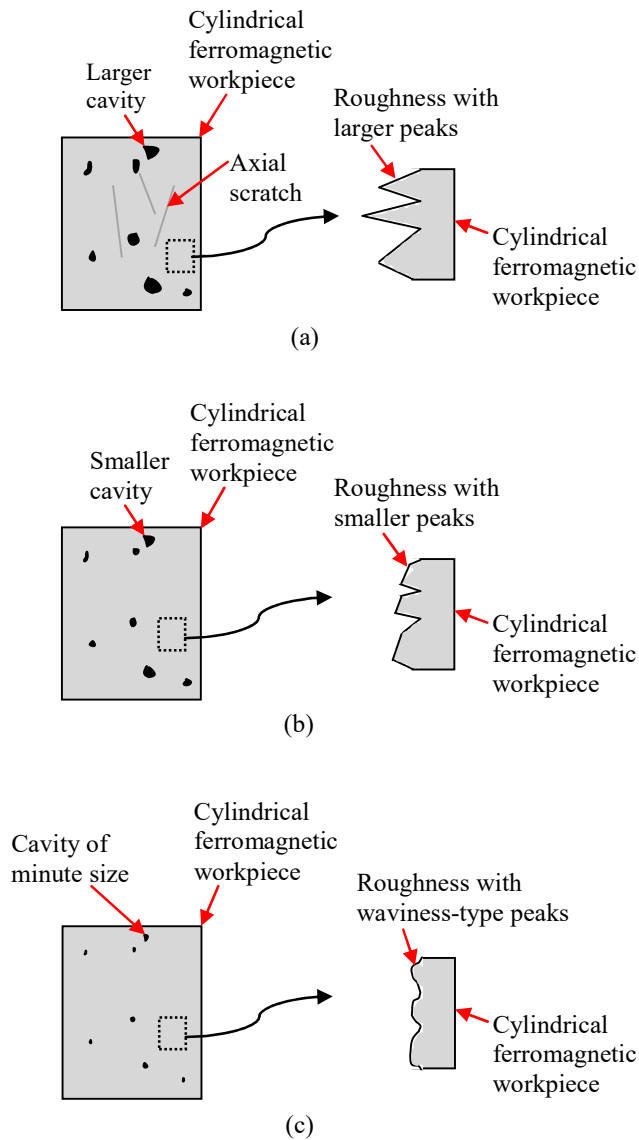


Fig. 6.10 Schematic representation of difference in surface characteristics of the internal surface finishing of EN-24 steel cylindrical workpiece before (a) Ist finishing segment, (b) IInd finishing segment and (c) IIIrd finishing segment.

The schematic of initial ground internal surface grinding of EN-24 steel cylindrical workpiece consists of various surface defects such as axial scratch, larger cavity on its surface (Fig. 6.10a). The similar surface defects can also be seen by SEM image as shown in Fig. 6.11 (a). After Ist finishing segment (i.e. after 30 minutes of finishing), the surface roughness (R_a) value decreased

to 252 nm from initial 346 nm. The fall in surface roughness (R_a) value is due to the removal of larger peaks from the internal workpiece surface. Also, these larger roughness peaks were removed easily because the shear strength of larger roughness peaks against the shearing force applied by the active SiC abrasive was very low. Due to continuous removal of material in micro chips form, the larger cavity changed to smaller cavity and axial scratch got eliminated completely after Ist finishing segment.

The MR finished surface before IInd finishing segment consists of smaller roughness peaks with smaller cavity as shown in Fig. 6.10 (b). In IInd finishing segment, the finishing was again conducted for next 30 minutes of finishing. The surface roughness (R_a) value got reduced to 169 nm from 252 nm. After this finishing segment, the smaller roughness peaks reduced to waviness-type roughness peaks. The smaller cavity got eroded and converted to minute size cavity. Before IIIrd finishing segment, the surface with waviness-type roughness peaks along with minute size of cavity was formed as shown in Fig. 6.10 (c). For finishing of internal cylindrical ferromagnetic surface again 30 minutes of finishing was performed during IIIrd finishing segment. The surface roughness (R_a) value was found as 103 nm after IIIrd finishing segment.

The waviness-type roughness peaks got eroded and also the minute size cavity got completely removed. The final MR finished surface was formed with reduced waviness-type roughness peaks as can be clearly seen by SEM image (Fig. 6.11b).

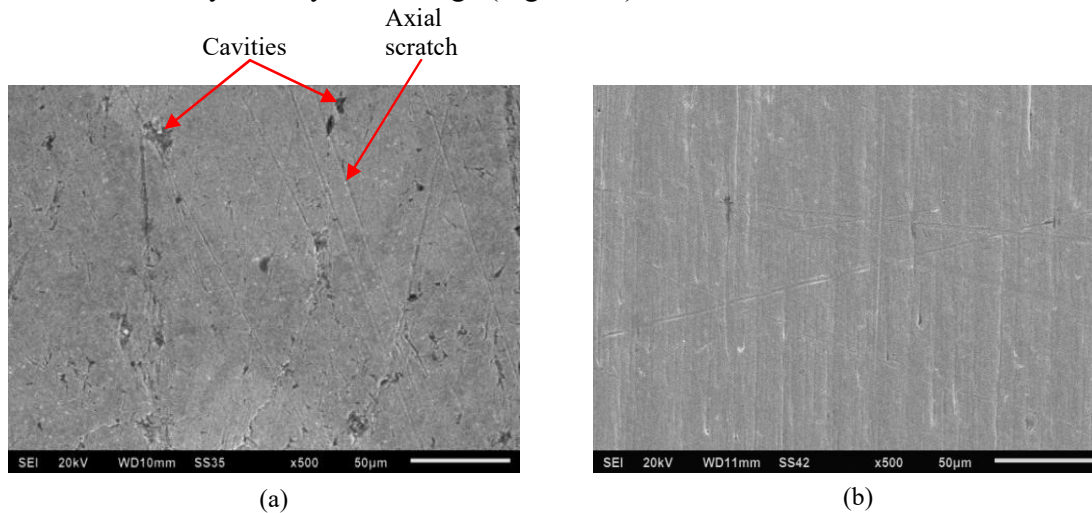


Fig. 6.11 Scanning electron microscopy (SEM) images at x500 of (a) initial ground surface and (b) final finished surface after 90 minutes of the present MR finishing.

Thus, the MR honing process is helpful for obtaining better surface characteristics on the internal cylindrical barrel type surface made of hardened EN-24 steel. The MR finished injection barrel type surface when used in the injection moulding machine would increase the production efficiency of the final made plastic or rubber products with the defect-free surface.

6.3 *Demonstration of the developed process for finishing of internal blind-hole type surface material used in mould cavity*

The precise finishing of the internal surface of ferromagnetic blind-hole type mold cavities is highly demanded in today's manufacturing industries for producing a better quality of final-made products with proper geometrical accuracy and longer service life. The manufacturer requires a huge investment for producing a precise surface finish on such blind-hole type mold cavities. The application of such blind-hole type mold cavity is generally found in the manufacturing of a plastics bottle caps (Maan *et al.*, 2017). The process of manufacturing of plastics bottle caps is done with the help of injection molding machine. The molten plastics from the injection molding machine are injected into the permanent blind-hole type mold cavity through an injection nozzle. The final-made product quality produced from the injection molding machine mainly depends on the initial surface characteristics of the blind-hole type mold cavity. The surface characteristics of these mold cavities are of primary importance as it affects the functional capability and appearance of the final-made plastic products. The finishing method used for finishing of such blind-hole type mold cavities is the internal surface grinding. The internal blind-hole type surface grinding is carried with the help of jig grinding machine. The finishing is carried out in two steps; one is by coarse abrasive pins and second is by fine abrasive pins. The abrasive pins used in surface grinding operation are typically a rigid in nature. The abrasive pins are also called as abrasive bits. Hence, this rigid tool when comes in contact with the internal surfaces during finishing operation may sometimes produces various surface defects on the blind-hole type surface such as deep-seated groove, cavity, axial scratch, ploughed material etc. (Dimkovski *et al.*, 2011). This is because of uncontrollable finishing forces applied by abrasive pins on the internal ferromagnetic blind-hole type surface. Another application of blind-hole type mold cavity is also found in pneumatic or hydraulic actuators or valve seats etc.

The better finishing of internal surface of blind-hole mould cavities is important concern to increase the operational life the components. The present developed MR honing tool with I-shaped core has the limitation of non-uniformity in magnetic flux density at the outer finishing

tool surface. Only the bottom surface can be finished by the I-shaped tool core. Also, in case of MR honing tool with rectangular shaped core, only the internal lateral surfaces can be finished. There is no possibility to finish the whole lateral surface of blind-hole type workpiece by using rectangular shaped tool core. This is because the electromagnet along with the rotating shaft can touch the internal bottom blind-hole type surface during lateral surface finishing. Therefore, to finish the internal lateral and bottom surfaces of blind-hole type cylindrical ferromagnetic workpiece, the two different magnetorheological (MR) finishing tools with the permanent magnets were made. The MR lateral finishing tool was made for internal lateral cylindrical surface finishing whereas, the MR bottom finishing tool was made for internal bottom surface finishing. These finishing tools use rectangular-type permanent magnets made of N52-Neodymium. The present MR lateral finishing tool kinematic movement was made similar to the traditional honing tool movement (i.e. rotation and translation motion). During internal lateral surface finishing, the constant working gap was made for obtaining a uniform-level of surface finishing. The working gap was filled by MR polishing fluid. The present MR bottom finishing tool kinematic movement was made similar to the traditional grinding wheel movement (i.e. only rotation motion). During internal bottom finishing, the constant working gap was made throughout the entire bottom surface for obtaining uniform-level of surface finishing. During finishing, the higher magnetic field was found at the tools lateral end and lower end surfaces as compared to the internal surface of blind-hole type ferromagnetic or non-ferromagnetic workpiece. As a result, the carbonyl iron particles (CIPs) of MR polishing fluid got retained at the tools end a surface only whereas, the active SiC abrasives due to its non-magnetic behaviour held by CIPs chains structure pushes towards to the internal blind-hole type workpiece surface. During the movement of present tools, the active abrasives also moves onto the internal blind-hole type workpiece surface which in turn helpful for obtaining a precise surface finish. The present finishing tools were made more useful for precise finishing of internal blind-hole type surface even after the jig grinding pins operation. Because during finishing of internal blind-hole type surface by jig grinding operation, only the point contact of grinding pin was made with the internal workpiece surface. This may results in the non-uniform surface finish on the internal cylindrical workpiece surface and hence results into various surface defects. In case of the present process, the constant working gap was maintained by the present finishing tools which result into a better surface finishing throughout the entire internal surface. The present process

has the advantage to improve the surface characteristics of internal ferromagnetic (or even non-ferromagnetic) blind-hole type cylindrical workpiece surface which results into the smoother surface, better geometry, defect-free surface and closer tolerance design.

The permanent blind-hole type mold cavity of ferromagnetic EN-31 work material with 62 Rockwell hardness in “C” scale measurement (HRC) is mainly used in the manufacturing of blind-hole type plastic bottle caps. For checking the feasibility of the present process, the similar EN-31 blind-hole type workpiece was taken with an internal diameter of 50 mm and bore length of 48 mm. The chemical composition of blind-hole type workpiece surface was measured by spectrometer and found as Fe= 93.6%, C= 0.8-1.2%, Cr= 1.1-1.7%, Si= 0.1-0.33%, Mn= 0.32-0.76%, S= 0.05%, P= 0.06%. The surface treatment of initial EN-31 blind type workpiece was made by heat treating at 800-850°C in the furnace followed by quenching in oil as cooling bath. After quenching, the workpiece becomes hard, brittle and internally stressed. Therefore, to reduce these internal stresses, the workpiece was tempered at 150-200°C. After tempering, the hardness of blind-hole type EN-31 workpiece was found as 62 HRC. Before the experimentation, the internal ferromagnetic blind-hole type workpiece was finished by internal surface grinding pins. The surface defects such as a deep-seated groove, cavity, axial scratch, axial groove, ploughed material etc. were generally induced after the jig grinding operation (Maan *et al.*, 2017). To further increase the surface characteristics of this initial ground ferromagnetic blind-hole type workpiece surface, the experimentation was performed with the present magnetorheological (MR) finishing process.

The main important part of the present process was the MR finishing tools. These finishing tools were mounted on the present developed MR honing setup by means of a C-shaped bracket. The MR finishing tools consist of a tool frame body (made of aluminium) and permanent magnets (made of Nd52-Neodymium). The MR finishing tool along with vertical rotating shaft was attached to the C-shaped bracket.

The magnetic field distribution in case of MR fluid based finishing processes is an important concern because the finishing reliability of the stiffened MR polishing fluid directly depends on it. The magnetic field distribution is measured in terms of magnetic flux density [T]. In present work, the magnetostatic finite element analysis (FEA) was done for determining the magnetic flux density distribution within the working gap by using Maxwell Ansoft V13 software (student version). The assigned process parameters to the electromagnetic model of the two present

finishing tools are given in Table 6.4. The different parameters were chosen as per the initial trials experimentation. The parameters which were given the better results had been chosen as per given in Table 6.4.

Table 6.4 Assigned process parameters to the electromagnetic model of the two present MR finishing tools.

Parameters	Materials	Relative Permeability
Magnet	Permanent magnet	1.009
Tool body	Aluminium	1
Finishing medium	MR polishing fluid	5
Ferromagnetic cylindrical workpiece	Mild steel	1500
Rotating shaft	Stainless steel	1.003

The dimensions of the rectangular permanent magnet were taken as 40 x 20 x 10 mm. The schematic representation of MR lateral finishing tool during finishing of the internal ferromagnetic lateral cylindrical surface of blind-hole type workpiece is shown in Fig. 6.12 (a). The working gap between the tool lateral end surfaces and the internal ferromagnetic workpiece surface was taken as 2 mm. The retained MR polishing fluid on the tool end surfaces were filled within the working gap. From the two dimensional finite element plot, the magnetic flux density was higher at the tool lateral end surfaces (i.e. 0.508 T) and at the internal ferromagnetic lateral workpiece surface was lower (i.e. 0.431 T) as shown in Fig. 6.12 (a). The schematic representation of MR bottom finishing tool during ferromagnetic internal bottom surface finishing of blind-hole type workpiece is shown in Fig. 6.12 (b). The working gap between the tool bottom end surface and the internal ferromagnetic bottom surface was also taken as 2 mm. The retained MR polishing fluid on the tool bottom end surface was filled within the working gap. From the two dimensional finite element plot, the magnetic flux density was higher at the tool bottom end surface (i.e. 0.612 T) and at the ferromagnetic internal bottom surface was lower (i.e. 0.588 T) as shown in Fig. 6.12 (b). Hence, the higher magnetic flux density gradient at the tools end surface and lower at internal ferromagnetic blind-hole type workpiece surfaces, which

clearly confirms that the tool end surfaces have the capability to retain the MR polishing fluid on its end surfaces during the finishing operation.

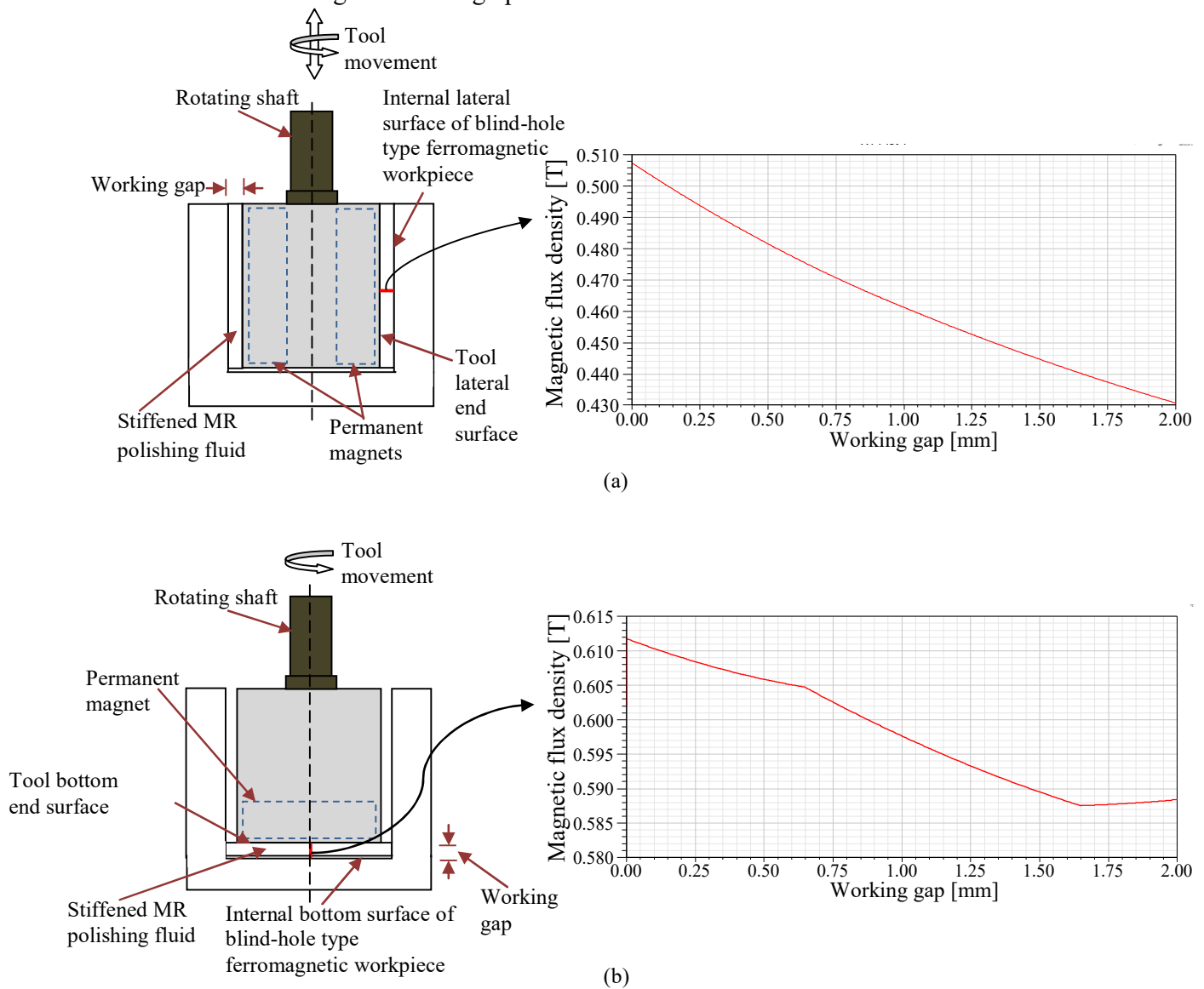


Fig. 6.12 Schematic and finite element two dimensional field report in working gap between the tool end surface and the internal ferromagnetic blind-hole type workpiece surface during (a) lateral surface finishing and (b) bottom surface finishing.

As the magnetic flux density gradient was at higher at the end surfaces of the tool, therefore the carbonyl iron particles (CIPs) of MR polishing fluid form a rigid structures i.e. chains formed over its surface. The magnetic normal force (F_{mn}) applied by the chains structure of CIPs finally hold and pushes the non-magnetic active abrasives to the lower magnet flux gradient region (internal ferromagnetic blind-hole type workpiece surface). These active abrasives are further

liable for removing the roughness peaks from the internal ferromagnetic blind-hole type workpiece surface during finishing operation.

The experimentation was conducted with the presently made two different MR finishing tools on the internal ferromagnetic blind-hole type workpiece surface (made up of EN-31 die steel). Firstly, the experimentation was carried out for finishing of the internal lateral surface of blind-hole type ferromagnetic cylindrical workpiece. Secondly, the experimentation was carried out for finishing of the internal bottom surface of blind-hole type ferromagnetic cylindrical workpiece. The surface roughness profiles were measured with surftest SJ-400 (Mitutoyo made) with stylus tip radius of $0.5\text{ }\mu\text{m}$, cut off length of 0.25 mm . The ferromagnetic blind-hole type workpiece was made in such a way that it contains one vertical slot on its lateral cylindrical surface as shown in Fig. 6.13 (a). With the help of this vertical lateral slot, the surface roughness (R_a) values at the internal bottom surface were easily measured. The initial and final surface roughness (R_a) values were measured on both internal lateral cylindrical surface and internal bottom surface of the present blind-hole type cylindrical ferromagnetic workpiece. The total five readings were taken at both the surfaces (i.e. internal lateral cylindrical surface and internal bottom surface) to visualize the uniformity in surface roughness on the ferromagnetic blind-hole type workpiece surface. The actual photograph to start of the experimentation for finishing the internal blind-hole type ferromagnetic workpiece surface is shown in Fig. 6.13 (b) and (c), respectively. The synthesized MR polishing fluid as given in Table 4.4, was used for finishing of internal surface finishing of EN-31 blind-hole type cylindrical workpiece. The MR polishing was applied at the tool end surfaces manually before the start of finishing operation. The MR polishing fluid becomes stiffened and retained at the tool end surfaces due to higher magnetic field gradient effect. The experimental conditions for performing the two different phases of finishing operations are given in Table 6.5. These conditions were taken depending upon the literature survey as well as different preliminary experimental trials. To clearly relate the surface characteristics of initial and final finished surface, the scanning electron microscopy images (at x500 magnification) were also conducted.

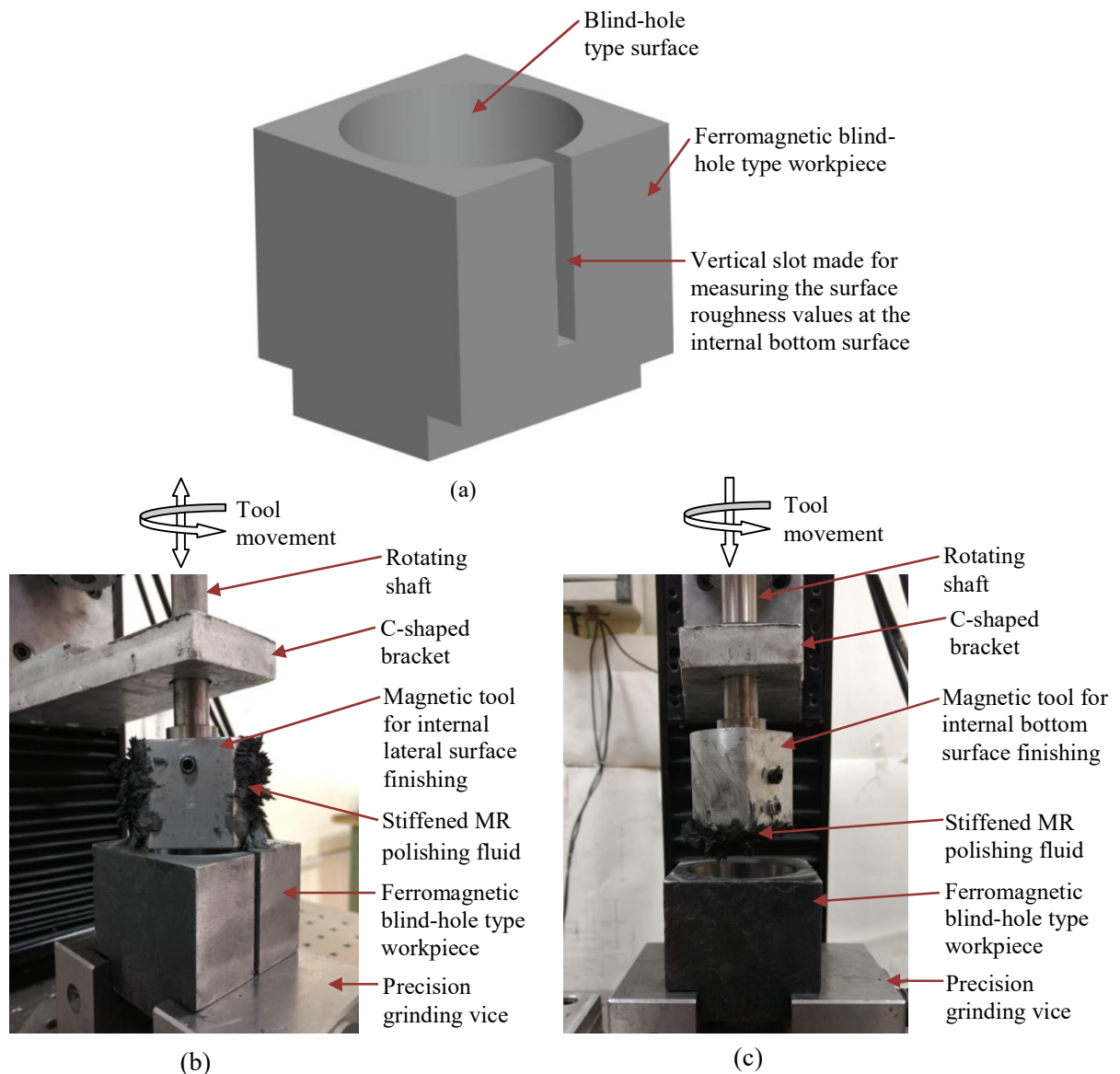


Fig. 6.13 (a) CAD model of ferromagnetic blind-hole type workpiece, stiffened MR polishing fluid retained at the (b) MR lateral finishing tool surface and (c) MR bottom finishing tool surface to start the finishing on the lateral as well as bottom surfaces of ferromagnetic blind-hole type workpiece.

Table 6.5 Experimental conditions used during the internal surface finishing of ferromagnetic blind-hole type cylindrical workpiece.

Parameters	Conditions	
	For internal lateral surface finishing	For internal bottom surface finishing
Rotational tool speed	800 rpm	800 rpm
Translational tool speed	10 cm/min	--
Working gap	2 mm	2 mm
Total finishing time	90 minutes	90 minutes
Total finishing steps	3	3
Each finishing step	30 minutes	30 minutes

6.3.1 Observation and discussion on experimentation during internal surface finishing of cylindrical blind-hole type EN-31 steel

For precise finishing of the internal ferromagnetic blind-hole type workpiece surface, the MR finishing process was used in two different phases. In the first phase, the internal lateral cylindrical surface was finished by using the MR lateral finishing tool surface. In the second phase, the internal bottom surface was finished by using the MR bottom finishing tool. As the material i.e. EN-31 die steel of blind-hole type workpiece surface was hard, the resultant higher finishing forces were required to finish the internal blind-hole type workpiece surface by the active abrasives. This was only possible by taking the higher tool rotational speed with higher strength of stiffened MR polishing fluid in order to shear the roughness peaks from the internal ferromagnetic blind-hole type workpiece surface. The surface roughness (R_a) value of the initial ground internal lateral cylindrical surface was found as 471 nm. The surface roughness (R_a) value of the initial ground internal bottom surface was found as 476 nm. Before the start of the first phase of experimentation for finishing the lateral surface of ferromagnetic blind-hole type workpiece, the MR polishing fluid was applied to the lateral end surfaces of the tool. As the lateral tool end surfaces contained a higher magnetic flux density gradient region, the MR polishing fluid gets retained at its end surfaces only. The internal lateral surface finishing was carried out in 3 different finishing steps. Each finishing step consists of 30 minutes of finishing. The renewal of fresh MR polishing fluid was done at the lateral end surfaces of the tool after every finishing step for avoiding the movement of removed micro-chips within the stiffened MR

polishing fluid. The internal ferromagnetic lateral cylindrical workpiece surface roughness (R_a) value reduced to 152 nm from 471 nm after 90 minutes of finishing.

Before the start of second phase of experimentation for finishing the bottom surface of the ferromagnetic blind-hole type workpiece, the MR polishing fluid was applied at the bottom tool end surface. As the bottom tool end surface contained a higher region of magnetic flux density gradient, the MR polishing fluid was retained at the end surface of tool. In this phase also, the experimentation was carried out in 3 different finishing steps. Each finishing step consists of 30 minutes of finishing. The renewal of fresh MR polishing fluid was done at the bottom tool end surface after every finishing step. The internal ferromagnetic bottom workpiece surface roughness (R_a) value reduced to 145 nm from 476 nm after 90 minutes of finishing. The decreased in surface roughness (R_a) values during internal lateral and internal bottom surfaces of finishing with the effect of finishing time is shown in Fig. 6.14.

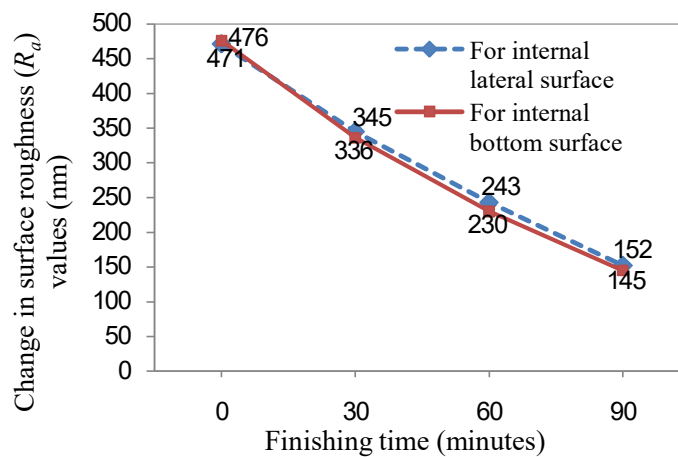


Fig. 6.14 Change in surface roughness (R_a) values with respect to finishing time.

The initial and final finished surface roughness profiles of internal lateral surface and internal bottom surface of ferromagnetic blind-hole type workpiece are shown in Fig. 6.15. The initial ground internal lateral surface consists of various defects such as deep-seated groove, axial-seated groove, axial scratch, cavity, ploughed material as shown by scanning electron microscopy (SEM) image in Fig. 6.16 (a). The similar defects were also clearly visible with the help of schematic representation as shown in Fig. 6.17 (a).

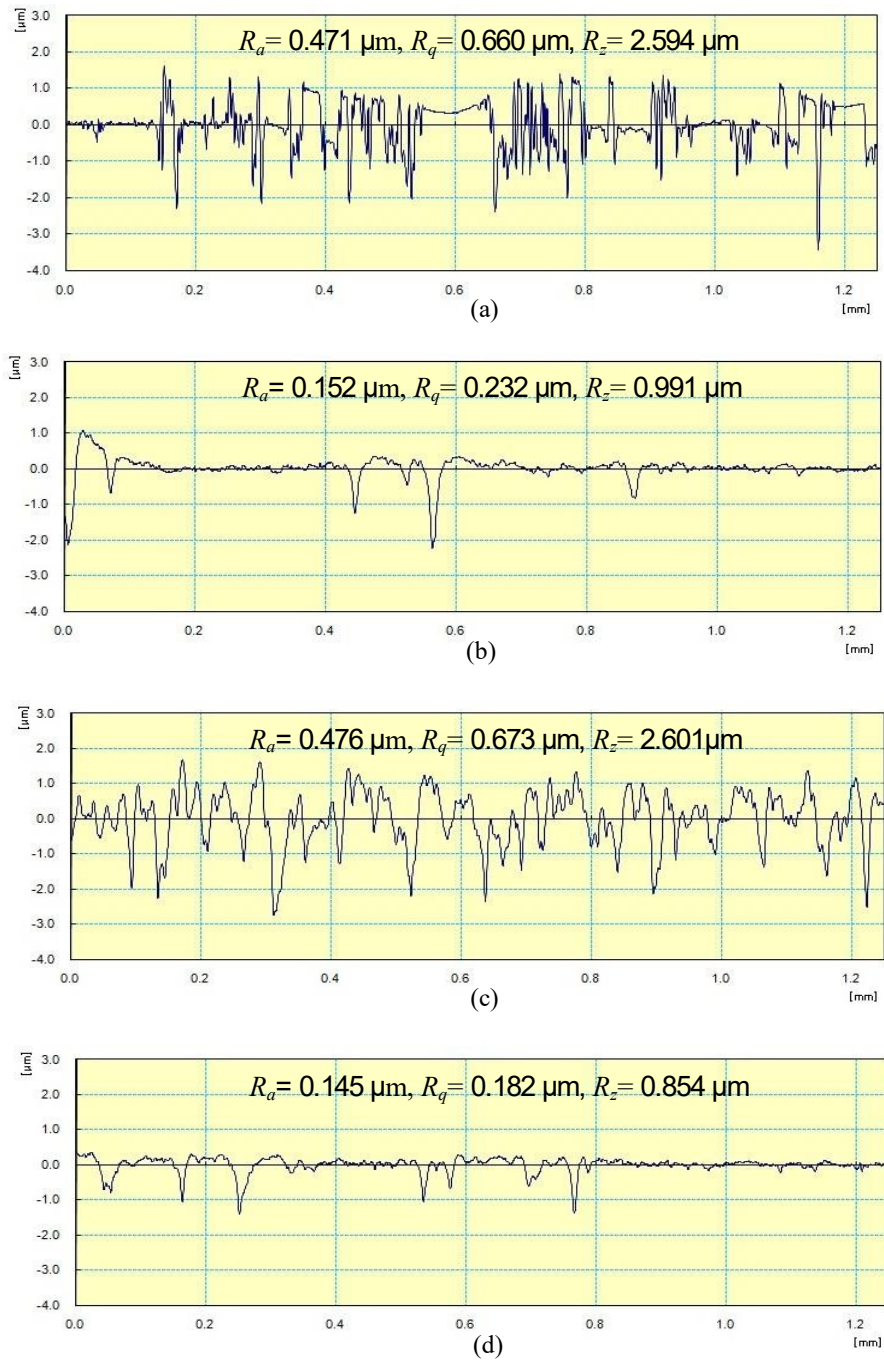


Fig. 6.15 Surface roughness profiles of (a) initial ground internal lateral surface, (b) finished internal lateral surface, (c) initial ground internal bottom surface and (d) finished internal bottom surface of ferromagnetic cylindrical blind-hole type workpiece after 90 minutes of finishing.

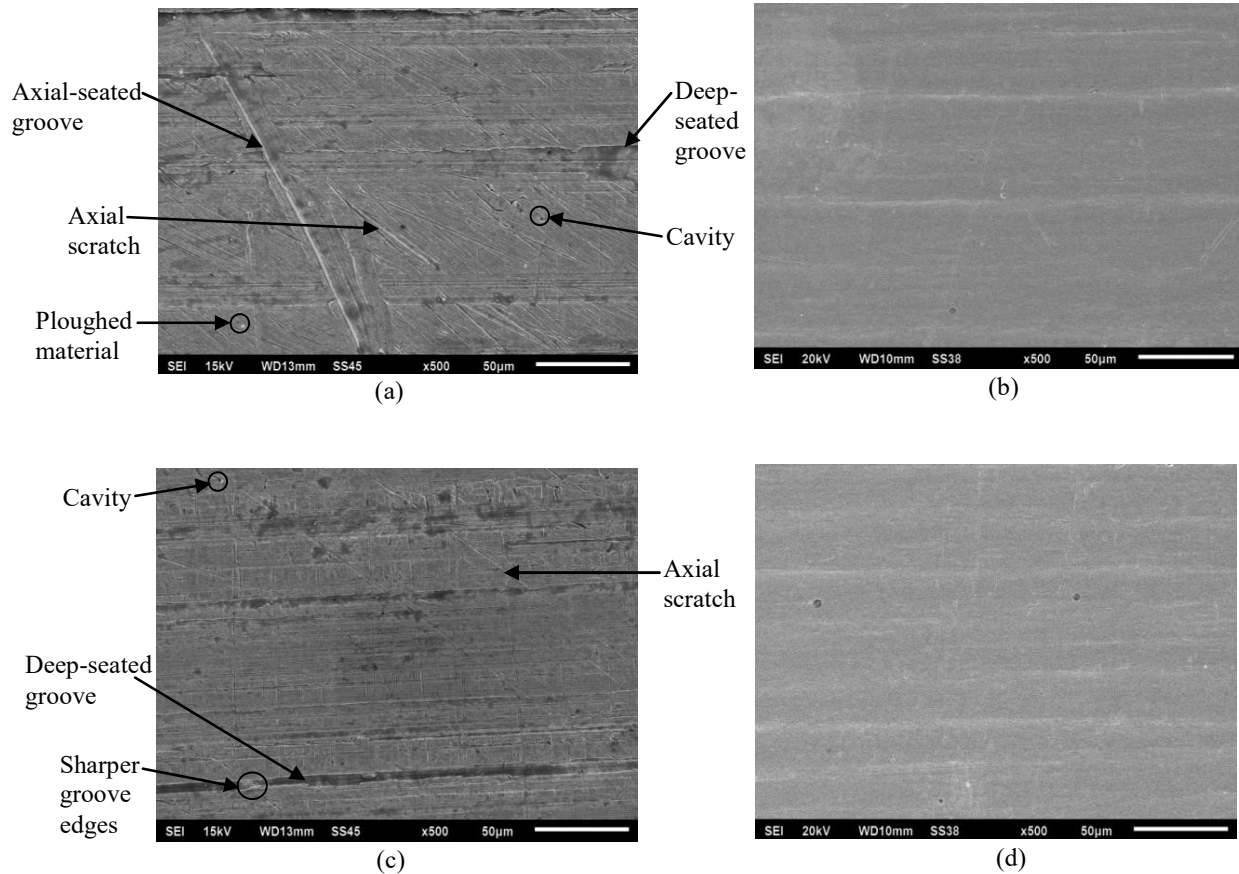


Fig. 6.16 Scanning electron microscopy (SEM) images at x500 of (a) initial ground internal lateral surface, (b) finished internal lateral surface, (c) initial ground internal bottom surface and (d) finished internal bottom surface of ferromagnetic cylindrical blind-hole type workpiece after 90 minutes of finishing.

These surface defects were produced due to the uncontrollable finishing forces produced during the rotational and translation movement of abrasive pins onto the internal lateral surface of ferromagnetic blind-hole type cylindrical workpiece. In the first phase of experimentation, the MR polishing at the lateral tool end surfaces was applied manually. Under the magnetic field effect, the MR polishing fluid retained at the tool lateral end surfaces. The active abrasives due to its rotational and translational movement eroded the initial higher roughness profiles into the smaller roughness profiles during the Ist finishing step. The ploughed material settled between the initial higher roughness profiles was removed. The axial scratch got completely eliminated and cavity got converted to smaller cavity. Also, during finishing, the deep-seated groove got converted to the small-seated groove because of the continuous movement of active abrasives particles on the internal surface ferromagnetic cylindrical workpiece as shown in Fig. 6.17 (a).

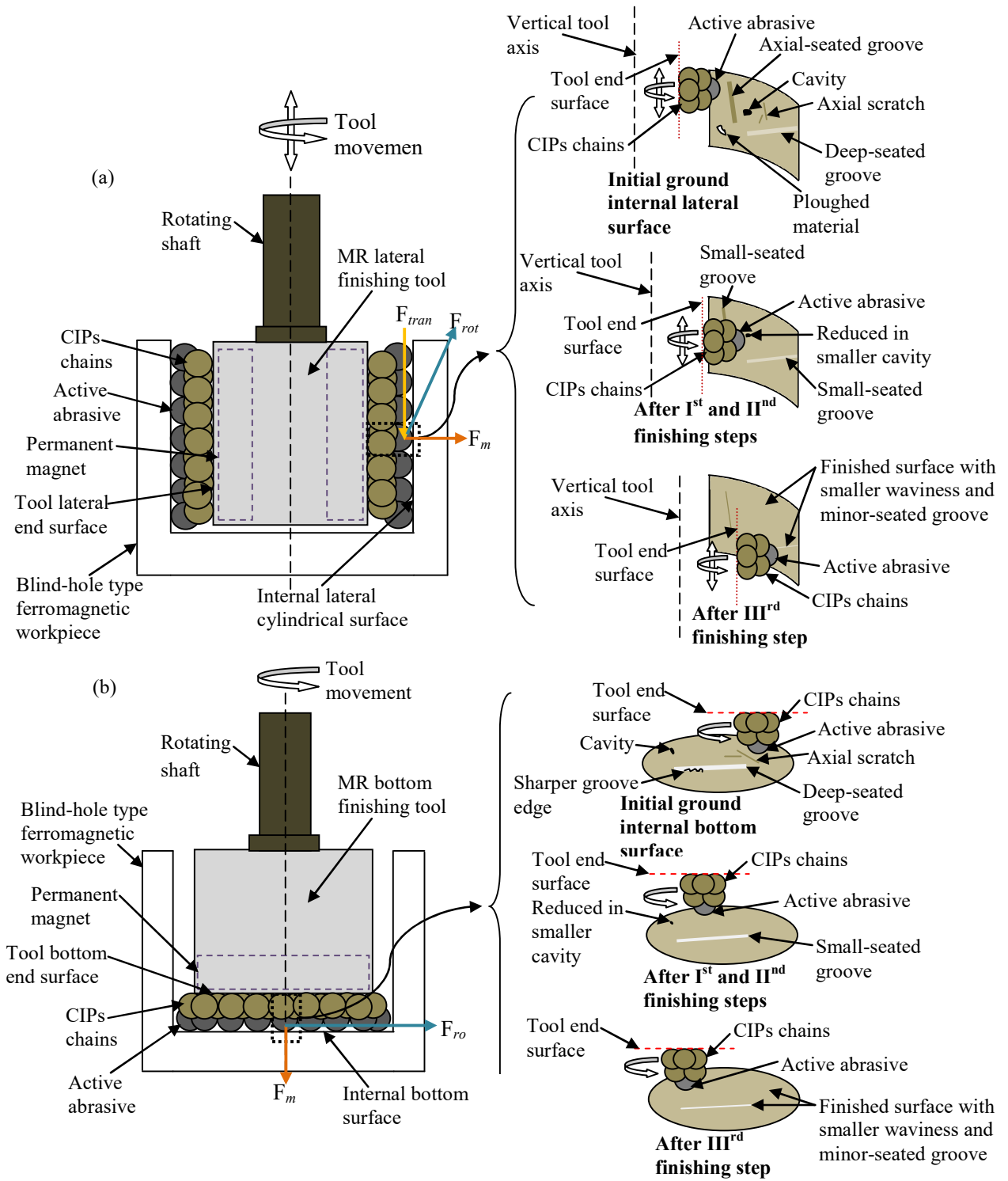


Fig. 6.17 Schematic of material removal mechanism during finishing of (a) internal lateral surface and (b) internal bottom surface of blind-hole type ferromagnetic workpiece.

After Ist step of finishing, the surface roughness (R_a) value got reduced to 345 nm from initial 471 nm. The fresh MR polishing fluid was conditioned at the lateral tool end surfaces before the start of IInd finishing step. The surface roughness values after this finishing step got reduced to 243 nm. This decreased in surface roughness (R_a) value was due to further removal of smaller roughness profiles on the internal lateral surface of blind-hole type cylindrical workpiece (Fig. 6.17a). Again, the fresh MR polishing was conditioned at the lateral tool end surfaces before starting of IIIrd finishing step. The surface roughness (R_a) value after IIIrd finishing step reduced to 152 nm i.e. the better finished surface was formed with smaller waviness along the minor-seated groove. The better surface characteristics (i.e with no surface defects) on the internal lateral cylindrical surface of blind-hole type workpiece after 90 minutes of finishing (i.e. after IIIrd finishing step) is clearly shown in the SEM image in Fig. 6.16 (b).

Similarly, the initial ground internal bottom cylindrical surface consists of various surface defects such as deep-seated groove, axial scratch, cavity and sharper groove edges as shown by the SEM image in Fig. 6.16 (c). The similar defects were also clearly visible with the help of schematic representation as shown in Fig. 6.17 (b). These surface defects were also generated due to the uncontrollable finishing force generated by the rotational as well as horizontal movement of abrasive pin onto the internal bottom surface of ferromagnetic blind-hole type cylindrical workpiece. In the second phase of experimentation, the MR polishing at the bottom tool end surface was applied manually. Under the magnetic field effect, the MR polishing fluid retained at the tool bottom end surface. During Ist finishing step, the active abrasives due to its rotational movement eroded the initial higher roughness profiles into the smaller roughness profiles. Also, the deep-seated groove got changed to smaller-seated groove due to continuous rotation of active abrasives. The shaper groove edges got totally eliminated. The axial scratch got completely eliminated and cavity on surface got converted to the smaller cavity as shown in Fig. 6.17 (b).

The surface roughness (R_a) value after Ist finishing step got reduced to 336 nm from initial 476 nm after 30 minutes of finishing. Before the start of IInd finishing step, the fresh MR polishing was renewed at the bottom tool end surface. The surface roughness (R_a) value after this finishing step got reduced to 230 nm after 30 minutes of IInd finishing step. This decrease in surface roughness (R_a) value was also due to the further removal of smaller roughness profiles on the internal bottom surface of blind-hole type cylindrical workpiece (Fig. 6.17b). The MR polishing

fluid was renewed again at the bottom tool end surface before the start of IIIrd finishing step. In this finishing step, the better finished surface was formed with smaller waviness along minor-seated groove (Fig. 6.17b). The surface roughness profiles finally got reduced to 145 nm after IIIrd finishing step. The better finished surface with smaller waviness along with the minor-seated grooves was obtained. The improved internal bottom surface of blind-hole type ferromagnetic workpiece after 90 minutes of finishing is shown by the SEM image (Fig. 6.16d). The overall results reported that the present process is advantageous in today's manufacturing industry for improving the surface characteristics of the internal ferromagnetic (or non-ferromagnetic) blind-hole type mould cavities.

6.4 Conclusions

The following conclusions are drawn after demonstrating the finishing capability of the developed magnetorheological (MR) honing process on the different industrial applications.

 A new MR honing process was used for improving the surface characteristics of traditionally honed ferromagnetic cylindrical components made of gray cast iron (used as cylinder liner in the automobile industry). The experimental results determined that the percentage variation in surface roughness (R_a , R_q and R_z) values reduced by 77.44%, 70.16% and 72.16%, respectively after 90 minutes of finishing. The improvement in surface textures as obtained in SEM analysis exhibited improvement in the surface quality of traditionally honed ferromagnetic cylindrical workpiece by removing its various surface defects such as torn and folded metal, honing grooves with sharper edges, cavities or holes etc.

 The experimentation was also performed on the internal injection barrel type surfaces (made of ferromagnetic hardened EN-24 material) by using MR honing process. The surface roughness (R_a) values of final MR finished surface was found in the range of 103-123 nm as compared to initial ground surface roughness (R_a) values in range of 346-432 nm. The lowest surface roughness (R_a) value was found as 103 nm from 346 nm (i.e. % change in R_a value as 70.23%) after 90 minutes of finishing. From SEM analysis, the better surface characteristics (defect-free surface) on the internal ferromagnetic barrel type surface were found as compared to the initial ground surface.

 The present process was used for fine finishing of the internal lateral and the internal bottom surfaces of cylindrical blind-hole type ferromagnetic workpiece. The two finishing tools based on MR polishing fluid were developed and found more effective for precise finishing of

internal lateral and internal bottom surfaces of ferromagnetic blind-hole type cylindrical workpiece. The percentage change in surface roughness (R_a) values for internal lateral and internal bottom surfaces of ferromagnetic blind-hole type cylindrical workpiece were reduced by 67.7% and 69.5%, respectively after 90 minutes of finishing. The SEM analysis revealed the significant improvement in surface characteristics with almost negligible surface defects on final finished surfaces as compared to the initial ground surfaces of ferromagnetic blind-hole type cylindrical workpiece after 90 minutes of finishing.

CHAPTER 7

CONCLUSIONS AND SCOPE OF FUTURE WORK

7.1 Conclusions

A new finishing process based on MR fluid was developed for finishing the internal surface of ferromagnetic cylindrical workpiece as similar to conventional honing operation with the controlled magnetic field. The finishing tool was designed along with electromagnet and made to move together inside the cylindrical ferromagnetic workpiece surface. The tool finished the surface by its rotational and reciprocation movement as similar to honing tool movement. Hence this process was named as MR honing process. The following results as evidence showed that the present developed process with newly designed finishing tools was competent and capable to resolve the challenges produced in existing MR fluid based processes for finishing the internal surface of ferromagnetic cylindrical workpiece. Based on the results as obtained from the present research work, the following conclusions have been drawn.

- From the magnetostatic finite element analysis (FEA), the higher magnetic flux density gradient was obtained on the present designed tools core surface than the internal surface of ferromagnetic cylindrical workpiece which clearly revealed that the MR polishing fluid was always retained on the outer surface of finishing tool and could not stick on ferromagnetic workpiece surface of low gradient magnetic flux density during finishing. This fulfilled an important requirement to perform the precise finishing on the internal ferromagnetic cylindrical surface.
- The rheological results of synthesized MR polishing fluids showed the good stability against the increased in shear rate with the magnetizing currents from 1 to 4A which is an important requirement for precise finishing of the internal surface of ferromagnetic cylindrical workpiece.
- From the preliminary experimental results, the percentage reduction in surface roughness (R_a) values in the range of 78-81% after 90 minutes of finishing with the newly designed rectangular shaped tool core was found more efficient as compared to percentage reduction in surface roughness (R_a) as 65-78% after 150 minutes of finishing with I-shaped tool core.
- The newly designed finishing tool with rectangular shaped core provided a uniform level of finishing as its entire outer finishing surface obtained a uniform magnetic flux density. This is

more useful for finishing in providing the better in closer tolerance design, higher bearing load capacity and longer service life in various cylindrical machine components.

 The analysis of experimental data using response surface methodology showed that the percentage change in surface roughness was more contributed by magnetizing currents followed by tool linear speed, mesh size of carbonyl iron particles (CIPs), tool rotational speed and mesh size of SiC abrasive particles during finishing of internal surface of EN-24 steel cylindrical workpiece.

 Using optimum parameters such as 800 mesh size of SiC abrasive particles, 400 mesh size of CIPs, 1.2 A of magnetizing current, 500 rpm of tool rotational speed and 50 cm/min of tool linear speed, the lowest surface roughness (R_a) value was found as 96 nm from 401 nm after 90 minutes of finishing on the internal surface of ferromagnetic EN-24 die steel cylindrical workpiece.

 The experimental results in terms of significant reduction in uniform surface roughness values and improvement in surface characteristics on finishing of the internal surface of cylindrical materials such as gray cast iron used in cylinder liner, hardened EN-24 steel used in injection barrel and hardened EN-31 steel used in blind-hole type mould cavity clearly demonstrated that the present developed finishing process was effective in improving the surface characteristics on the internal surface of different industrial components.

 The significant improvement in surface quality on the internal surface of ferromagnetic cylindrical workpiece as seen from SEM images confirmed the effectiveness and usefulness of the present developed process with rectangular shaped core of finishing tool in today's advanced machine tool industries.

 The present MR honing process can also find its extensive applications for enhancing the functional capability of various components used in manufacturing industries like hydraulic cylinder, connecting rod, bearing, cylindrical molds and dies, valve seat, etc. and also for non-ferromagnetic components such as air bearing, pneumatic actuators etc.

7.2 Scope of future work

The present newly developed MR honing process has already shown its capability in achieving the precise surface finishing on internal ferromagnetic surfaces. The following are some of the scopes of future work by which the finishing performance of the present MR honing process can be improved further.

-  The cooling chamber can be incorporated in the present MR honing process which helps to maintain the constant temperature of the electromagnetic coil during finishing operation. This would help in reducing the overall finishing time taken during the experimentation.
-  Rotational-magnetorheological honing process can be made in which a rotational movement can also be given to the cylindrical ferromagnetic workpiece. Due to continuous rotational movement of both tool as well as the cylindrical ferromagnetic workpiece, better finishing can be expected.
-  In case of blind-hole type MR finishing tool, the combined tool (for both lateral as well as bottom surface finishing) can be made to increase its production efficiency. Further, higher and uniform magnetic flux density gradient at the tool outer end surfaces can be obtained in the improvement of tool design for finishing of blind-hole type surfaces.
-  The preliminary experimental results on the internal surface finishing of ferromagnetic cylindrical workpiece materials for industrial applications revealed that the present newly developed MR honing process is effective in the precise internal surface finishing of ferromagnetic cylindrical workpiece. But, optimization of process performance can be done further for better process performance and productivity. This results in optimization of productivity by reducing the finishing rate.
-  The detailed study on rheological properties of MR polishing fluid is required before and after the certain finishing cycle time. This study may determine the exact time required to renew the MR polishing fluid during the different finishing cycles.

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LIST OF PUBLICATIONS AND PATENT

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1. **Bedi, T.S.;** Singh, A.K. (2017) Development of magnetorheological fluid based finishing process for finishing of ferromagnetic cylindrical workpiece. *Machining Science and Technology*, doi: 10.1080/10910344.2017.1336631.
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2. **Bedi, T.S.;** Singh, A.K. (2017) Magnetorheological finishing of ferromagnetic blind-hole type surfaces. *Materials and Manufacturing Processes*, doi: 10.1080/10426914.2017.1328120.
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2. **Bedi, T.S.**; Singh, A.K. (2017) Magnetorheological finishing on injection barrel type surface of moulding machine, 39th International MATADOR Conference on Advanced Manufacturing, July 5-7th 2017, held at The University of Manchester, United Kingdom.

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