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Experimental investigation on magnetorheological finishing process parameters

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ABSTRACT

Magneto-rheological polishing (MRP) fluid was developed by MR fluid using a magnetic field, non-magnetic abrasives such as SiC and Al_2O_3, and carrier medium like oil. A magnetic polishing tool was developed using a super-strong permanent neodymium magnet ($Nd_2Fe_{14}B$) with 0.5-tesla magnetic intensity. This polishing tool was assembled to the vertical milling machine for the finishing workpieces. In the present research, magnetic materials (steel material) and non-ferromagnetic (copper) content were finishing using a developed MRP setup for experimental investigation. This research also investigated the parametric dependencies of different abrasives on the magneto-rheological finishing process. It determined the effect of magnetic particle concentration and abrasives on the surface roughness of ferromagnetic (stainless steel) and non-ferromagnetic material (copper). The final surface roughness value has reached 30 nm from its initial surface roughness of 800 nm for non-ferromagnetic (copper). For the magnetic material (stainless steel), the value is 50 nm from 1300 nm.

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1. Introduction

Magnetorheological (MR) fluid was developed in the 1940 s. It is a smart fluid activated in the presence of a magnetic field used in various engineering applications, such as mechanical damper, clutch, seismic isolation damper, and finishing operations [1]. The achievement of better surface quality is of paramount importance in every machining operation other than acquiring precise measurements.

Magneto-rheological finishing is an intelligent finishing process that depends on MR fluid. This process is categorized under techniques of nano finishing because the surface finish of this process is given in a nanometer (10^{-9} m) [2]. This process can be controlled externally by employing the magnetic field strength variation. Therefore, it is also categorized under the deterministic approach [3]. The surface finish, applied stress of a part is highly determined by surface integrity. Surface conditions are also critical factors affecting fatigue strength because uneven and rugged surfaces typically have poorer process parameters. With the increase of roughness of the surface, the performance is reduced due to wear, optical failure improvement, and the flow's resistance. For the exterior finishing of optical lenses at nanometer depths, MRF is used [4]. During the finishing process, it tries to control the magneto-rheological (MR) flow characteristics through external means (i.e., magnetic field) to regulate the properties of machined surfaces [5,6].

The MR fluids are magnetic particles fragments of micron size with plenty of contaminants in the medium of the viscoelastic base, such as silicone oil, glycerol, paraffin oil, and water. Such fluids demonstrate non-Newtonian behaviour, i.e., poor Bingham behaviour, in the absence of external forces. MR fluid relying on hydrocarbon oil has a reduced field viscosity of zero, around 0.6 times below the MR fluid based on silicone oil [7]. However, a water-based MR fluid can mitigate waste management issues and enable the components to be quickly recycled. Unwanted particle accumulation occurs in condensed MR fluids due to remnant magnetization of the particles [8]. As a response, it promotes the establishment of stiff sediments that are possible to disperse properly. Various methods have been suggested to reduce particle accumulation, and settling is shown in Fig. 1.

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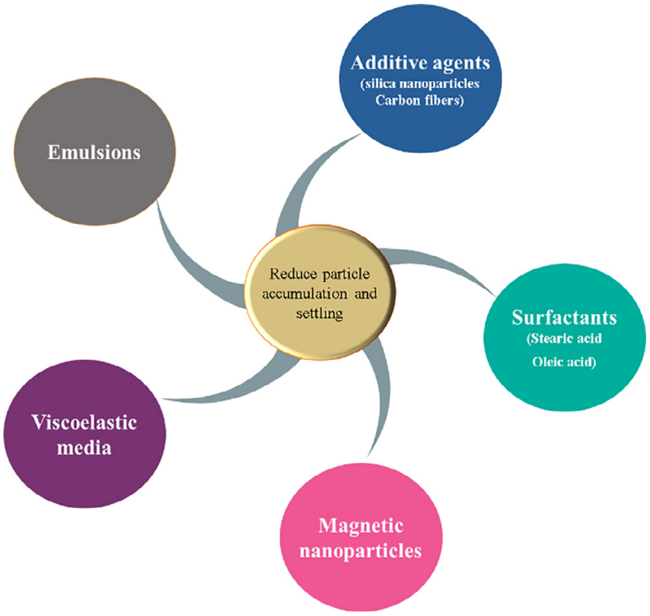

Fig. 1. Reduce particle accumulation and settling techniques.

The water-based fluid use glycerol and surfactants as stabilizers. Alkaline tends to boost the susceptibility to decay and sustainability to increase the performance of MAF, and it was suggested to use a new medium of magnetic abrasive through using the gel of silicone for mixing with the silicon-carbon and steel grits [9,10]. This one-dimensional quasi-static design investigates magneto-rheological materials' structural and magnetic characteristics by creating a process in which the magnetic flux density is dispersed inside the composite material. Jha et al. created a hydraulic controlled capillary rheometer to describe the MR polishing fluid rheological behavior and three models, Casson fluid (CF), Herschel-Bulkley (HB), and Bingham plastic (BP) [11]. The characterization analysis for water-based MR polishing fluid was conducted using a parallel plate magneto rheometer. Their results indicate that shear thinning is accompanied by MRP fluid and is the best model to match the flow curve design Herschel-Bulkley [3]. Although some attempts have been made to address this issue, it is still under investigation on the effect of concentration with different compositions of the polishing fluid with MR. The presented manuscript investigates the parametric dependencies of other abrasives on the magneto-rheological finishing process. The concentration of magnetic particles and abrasives, the rotational speed of the magnetic finishing tool, and surface roughness and machining time was observed.

A setup has been developed to investigate the behavior of MR Polishing fluid by assembling a magnetic finishing tool (permanent magnet) on a pillar drilling machine. Copper and Ferromagnetic workpieces (Stainless steel) were used for the experiment.

MR fluid is the crucial element of all MR fluid-based finishing procedures. MR fluids were initially designed for suspension systems, clutches, and vibration isolators, even without abrasive particles. However, few researchers described MR fluids as the polishing medium for glass. Presently, finishing processes based on MR-fluid are becoming an inevitable aspect of precision processing [12,13].

1.1. MR polishing fluid compositions

The MR fluid composition greatly influences a workpiece's finished surface. Robust MR flow conditions such as homogeneity, temperature, and apparent viscosity are essential for regulating substance withdrawal. The standard MR fluid comprises magnetic carbonyl iron particles with a micron (CIPs) size, polishing abrasives that are non-magnetic and embedded in a carrier solvent and some stabilizers. The CIPs can produce muscular strength for the MR fluid in the applied magnetic field. For elevated material removal rate (MRR), polishing abrasive particles is required. The carrier liquid decreases solid particle sedimentation and increases fluid stability [14]. The MR fluids compositions which are used to finish various materials are shown in Table 1.

They are some essential characteristics of an MR polishing, like under the magnetic field, it has a high yield stress value. MR fluid has good stability under the static sedimentation effect with low off-state viscosity. MR Polishing have good dispersibility and corrosion resistance. The optimum concentration of the abrasive particles and the magnetic particles. It has high efficiency for polishing (the finishing rate increases without causing damage to the surface) with less agglomeration [15].

1.2. The parameters of the process in MRF

Magnetic particles combine as small and fragile links at low volume concentrations that cannot sustain the abrasive during finishing correctly. However, the chains expand both in length and width as the density of the magnetic particles increases. These chains then accumulate in the shape of an MR fluid ribbon which is solid and dense. The materials are removed effectively by the abrasives, tightly held by the effect of the magnetic particle chains [5]. Nevertheless, the finishing quality is reduced by the concentration of the magnetic particle above a certain threshold. It is also stated that the overall concentration of solid particles (abrasive particles and magnetic particles) does not surpass 45–50% by volume. Many strong particles have few concerns associated with high off-state viscosity (the MR fluid has low fluidity) [16]. Circulating the MR fluid through pipes and pumps is difficult. Remixing the MR fluid is difficult due to low dispersibility [16].

1.3. Effect of abrasive particle concentration

In finishing using MR fluid, the mechanism is affected by the variation of the concentration of the abrasive particles. Instead of CIPs for the magnetic particle, electrolyte iron force is chosen to have better visibility and the perception of the CIPs chain structure combined with the abrasive particles. Larger magnetic particles and abrasive particles are chosen, and for the abrasive, aluminum oxide (Al_2O_3) is selected [17]. The CIPs chain combination includes both high and low abrasive particles distribution. Therefore, the abrasive particles are not equally dispersed. In the structure of the CIP chain, a few abrasives are stuck at a trim level of these particles. So, under the magnetic field, fewer CIP irregular chains are identified. CIP chains are thus able to grip abrasive particles during the finishing action more tightly. With the increase of the concentration of the abrasive particle, the abrasive volume entangled in CIP chains is also increased, which affects decreasing the fluid pressure under shear flow [18]. Magnetic interaction force is given below [19],

Table 1
Constituents of MR polishing fluids.

Magnetic Particle	Abrasive Particle	Carrier fluid	Stabilizers
Carbonyl iron particle	Cerium oxide	Water	Glycerol
Electrolyte iron powder	Diamond powder	Oil	Grease
Iron-cobalt alloy powder	Aluminum Oxide		Oleic acid
	Silicon carbide		Xanthan gum
	Boron carbide		

$$F = \mu_0 \pi / 144 (D^2 CM/S)^2 \tag{1}$$

(Where μ_0 represents the free space permeability, D represents the CIP diameter, S represents the distance between the two CIPs centers, M represents the magnetization intensity, and C is a constant.)

With the increased intensity between magnetic particles (S), the magnetic interaction force decreases, which means the interval between the CIPs increases, and F reduces if some of the abrasive particles are stuck between the CIPs.[3]. If the size of the abrasive particles is bigger relative to a small abrasive particle, the drop in F is stronger. That's because F is low, and the bonding power between the CIP is reduced, and the abrasives were not effectively grasped. In addition, F is decreased if there is any stuck of greater abrasive in the chain of CIP. More chains become discontinuous with the abrasive concentration, which reduces the magnetic interaction power (F). Therefore, MRR and finishing rate decline below an optimal of the particles of the abrasive concentration, and the disparity in finishing the surface (’Ra = original Ra value - final Ra value) achieved during the specified period becomes smaller. The influence on the abrasive percentage volume's reaction parameters, initial surface roughness percentage volume, and the wheel's rotation [20]. Ghosh et al. have investigated the residual stress and surface roughness to finish the oxygen-free high conductivity (OFHC) copper using a magneto-rheological finishing process. The results showed that surface roughness was reduced to 15.5 nm and residual compressive stress reached 6.9 MPa [21]. Aggarwal et al. have proposed a novel magneto-rheological finishing process using grinding wheel type single magnetic too to improve the surface finish of cylindrical blind holed (CBH) parts. The results showed that the surface roughness was reduced from60 from 230 nm on the flat end surfaces and 240 to 90 nm on the longitudinal surface [22]. Arora et al. have developed a novel magnetic finishing process, namely a novel magneto-rheological bevel gear finishing (MRBGF) process to finish polymer bevel gears (BGs). They concluded that the surface roughness was reduced from 0.38 μm to 0.10 μm in the duration of 40 min [23]. Prakash et al. used the magneto-rheological finishing process to improve the surface finish of b-phase Ti-Nb-Ta-Zr (b-TNTZ alloy) based orthopaedic implant. The surface roughness was reduced to the lowest 9 nm by around 97.68% improvement, and the material removal rate was highest at 65 mg [24]. Gupta et al. have done the experimental investigation magneto-rheological finishing process to the fused silica.

The authors used ball end type MRF (BEMRF) for the nano finishing of the fused silica, and the results showed that the surface roughness was reduced to 0.165 nm [25]. Arora et al. have proposed a novel magneto-rheological finishing process to finish the straight bevel (SB) gears. The study proved that the surface roughness was reduced to 90 nm [23]. Kumar et al. have used the magneto-rheological finishing process to finish the miniature gear teeth profiles. They used the novel finishing technique, namely uniform restrictor. The results showed the surface roughness was reduced to 23.9 nm [5]. Singh et al. have finished the variable diametric external surface of the tapered cylindrical parts using a magneto-rheological finishing process. The results showed that the surface roughness was reduced from 0.8410 μm to 0.2057 μm by 97.28% of improvement [26]. Ghosh et al. have used a magneto-rheological finishing process to finish the HVOF sprayed WC- Co coating. The results showed that the surface roughness of the WC- Co coating was reduced to 130 nm [4]. Singh et al. proposed a magneto-rheological finishing process to improve the surface quality of copper cylindrical roller of printing machine. The initial surface roughness was 190 nm reduced to 25 nm after 4 hrs. finishing [27]. Paswan et al. have done the experimental investigation of the magneto-rheological finishing process to finish the internal surface of the cast-iron cylindrical moulds. The results showed that the surface roughness was reduced from its initial values 0.420 μm, 2.4 μm, and 0.52 μm to the final values 0.05 μm, 0.4 μm, and 0.07 μm respective [28]. Rana et al. have developed a novel magneto-rheological finishing setup using permanent magnets (made up of neodymium NdFe35) to finish the stepped cylindrical parts of aluminum. The results showed that the surface roughness Ra was reduced to 62 nm [29].

This research investigated the parametric dependencies of different abrasives on the magneto-rheological finishing process. The effect of magnetic particle concentration and abrasives on surface roughness of ferromagnetic (stainless steel) and non-ferromagnetic material (copper) have been investigated.

2. Material and methods

Magneto-rheological finishing (MRF) is a relatively new approach to acquiring super finished freeform surfaces. MRF is an innovative finishing procedure in which the magnetic field controls the grinding power. A magneto-rheological fluid controls MRF content removal. This fluid primarily consists of particulate abrasives additives, carrier fluids, and carbonyl iron (CI). The MRF method can produce a surface finish in a nanometer range. These functions work as an abrasive brush, which is magnetic and lightweight, responsible for the finishing action, and a magneto-rheological solvent is used in the procedure. The relative movement between the finishing medium and the workpiece can be accomplished by either rotating the finishing medium or spinning the workpiece [30].

A rig was built for MRF application that used a pillar drilling system in the current job. Trials were performed using the established design to complete free-form assignments of copper material. Impacts of various variables of the method, viz. MR fluid structure, rotational work speed, MR fluid, the size distribution of surface finish abrasives, and machining time were studied. The approach of the MRF relies on the Magnetorheological (MR) fluid which is an intelligent fluid. Magnetizable objects such as CIPs, abrasive objects (such as aluminum oxide, cerium oxide, silicon carbide, etc.), additives (such as grease), carrier medium which is non-magnetic (such as mineral oil, silicone oil, etc.). In the carrier fluid, the particles of the iron are aggregated into chains. These chains are oriented in the direction of the field upon the introduction of the external magnetic field. A tube glass is used to calculate the percentage amount of CI fragments, abrasives, and engine oil. The pure iron sawdust, the powder of fine carbonyl iron (CI), is gathered by sieving. The composition of prepared MR polishing fluid is shown in Table 2.

Total sample of MR fluid prepared = 1000 cm^3

- CIP by volume = 200 cm^3 = 200 × 7.8gm/cm^3 = 1560 gm
- SiC by volume = 200 cm^3 = 200 × 3.22 gm/cm^3 = 644 gm
- volume of base fluid = 600 cm^3 = 600 × 0.64 gm/cm^3 = 384 gm

For the experiment, the MR fluid is prepared by mixing these three components. The machine of pillar drilling is used to develop an MRF setup. The primary purpose is to get a basic structure and place on which it can be erected, and second, it is also used to obtain the relative motion between the MR fluid and the workpiece

Table 2
Sample of MR polishing fluid Preparation.

Constituent	Density (gm/cm^3)	%Volume
Base fluid	0.64	20%
CIPs	7.8	20%
SiC	3.22	60%

contained in the vessel. The experimental configuration of the MRF mechanism is illustrated in Fig. 2, which represents a graphical diagram where the fluid is expelled to the carrier spinning wheel. That form a flexible ribbon. A non-magnetic substance is used to protect the permanent magnet. The fixture, in addition to the framework of the fixture, is known as the carrier wheel. Under the effect of the field of the MR magnetic, the fluid ribbon becomes rigid, and it works as a viscoelastic fluid. The CIPs are drawn to the magnet by the magnetic field's gradient towards the carrier wheel's side. The abrasive is also forced towards the surface of the workpiece. The MR fluid is pulled across the distance between the wheel and the workpiece by the wheel movement. The association between MR fluid and the workpiece surface, which induces material degradation, creates substantial shear and regular forces. The parameters used for the experiment are given in Table 3.

2.1. Working on the MRF experimental setup

The workpiece is rotated in an MRF solution to obtain the required surface finish to machine external surfaces. In the present work, at the same time between the magnetic tool fixture and the workpiece, the MR fluid is filled. Magnetic tool fixture rotated by drilling machine motor. A magnetic brush is formed on magnetic fixtures that remove the material from the workpiece in Nano or microchips. A smooth mirror finished surface can be achieved in comparatively less time. The CAD model of the proposed MRF setup is shown in Fig. 3.

3. Results and discussions

Summarises the results obtained at various stages of the research by carefully examining the data. It is found that the surface finish is dependent on the size of the abrasive particles and concentration, the CIPs particles the size and concentration, type of Abrasive particles, rotational tool speed, and type of workpiece material. Most parameters are investigated during the finishing process and compared with previous work done by Jain et al. and Brinksmeier et al. [31,32]. Primary parameters effects abrasive size on machining time and the effects concentration of the abrasive particles on the machining, also tool rotational affects speed on machining time, the concentration of the abrasive particles on surface roughness (Raf), the concentration of the CIPs particles on surface roughness (Raf), and type of workpiece material.

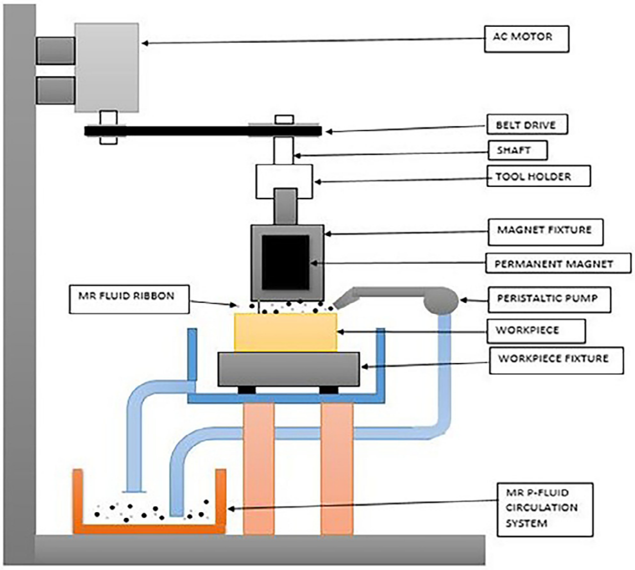

Fig. 2. Schematic of Experiment setup of MRF Process.

Table 3
Parameters used for Experimentation.

Parameters	Condition
The rotational speed of the tool	500 rpm
Magnet type and flux density	Nd-Fe-B (0.5 T)
Working gap	0.5 mm
Workpiece material	Ferromagnetic (stainless steel), non-ferromagnetic (copper)

The four independent process parameters are chosen for the current experimental investigation. These parameters are the rotational tool speed (R), CIPs concentration (C), volume, and abrasive (A). The limitation of production results in a significant difference in the roughness of the surface of silicon work parts. Therefore, the surface roughness (Rai) is considered as an independent variable. In the MR fluid preparation, the glycerol concentration is kept steady (8 per cent vol); the amount of the abrasive and CIPs may vary, although the deionized water is part of the MR fluid. For the reaction parameters, machining time and surface roughness are chosen. 60 min required to cover the entire workpiece surface is considered as a duty cycle. For each workpiece, 180 min. (3 cycles are required). It has been observed that the MR fluid consistency decreases with each phase (in terms of viscosity and yield stress). After each run, MR fluid is replaced with a new one. The current analysis keeps the distance at 0.5 mm to produce a larger magnetic field. The material removal is determined by measuring the workpiece after and before the process. The roughness of the surface is obtained using Federal Surf analyzer 5000 instruments, and to filter waviness, a cut-off value of 0.6 mm is chosen. The final surface roughness (Raf) and the initial roughness (Rai) are measured using a template and averaged out. Each input variable, randomized experiments, and response parameters response are given in Figs. 4 to 11.

3.1. Effect of abrasive size on machining time

The machining time decreases with increasing the size of abrasive particles up to 15 μm. But after an optimum size, machining time increases because when the particle size increases, it decreases the magnetic field intensity. It is shown in Fig. 4.

3.2. Effect of the percentage of CIP particles (Vol %) on machining time

The machining time decreases with increasing CIP particles' share. The increase in the rate of CIP particles increased the magnetic field intensity due to the buildup of a thick and long chain of CIP particles. It is shown in Fig. 5.

3.3. Effect of the percentage of abrasives (Vol %) on machining time

The machining time decreases by increasing the rate of abrasive particles up to the optimum 50%. But it was reduced after 20% of abrasive particle concentration because when the abrasive particle concentration increased, it decreased the distance between two CIP particles. Due to this reason, the magnetic field intensity was reduced along the chain of CIP particles and machining time increased. It is shown in Fig. 6.

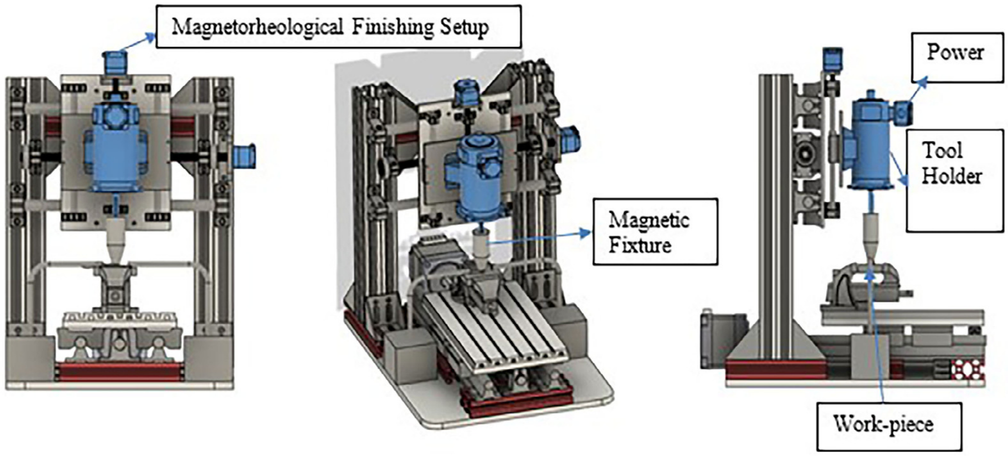

Fig. 3. Three-dimensional (3D) model for the MRF machine setup.

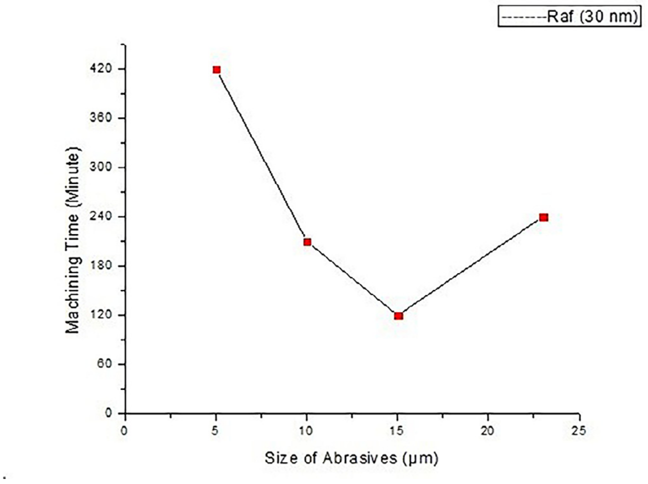

Fig. 4. Responses of the repeated experiments on size of abrasives vs machining time.

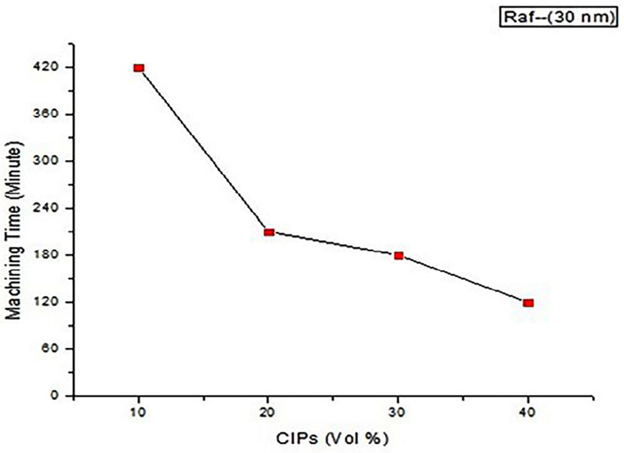

Fig. 5. Responses of the repeated experiments on CIP particles (Vol %) vs machining time.

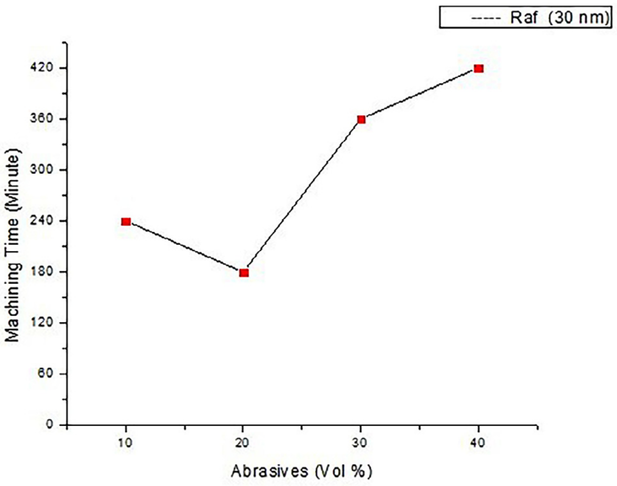

Fig. 6. Responses of the repeated experiments on abrasives (Vol %) vs machining time.

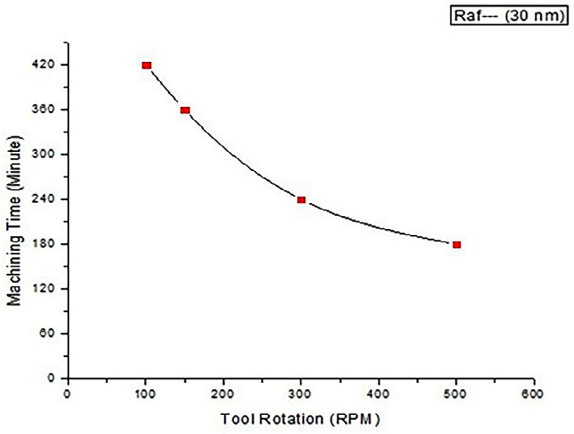

Fig. 7. Responses of the repeated experiments on tool rotation (RPM) vs machining time.

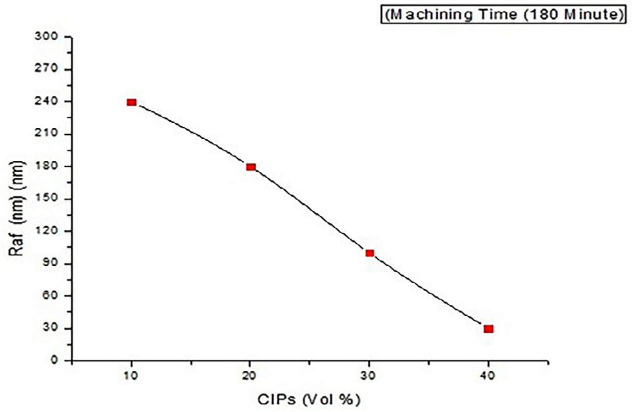

Fig. 8. Responses of the repeated experiments on CIP particles (Vol %) vs Raf.

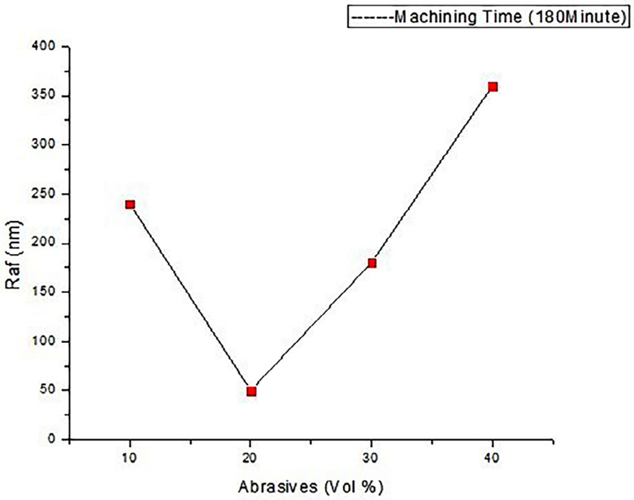

Fig. 9. Responses of the repeated experiments on abrasives (Vol %) vs Raf.

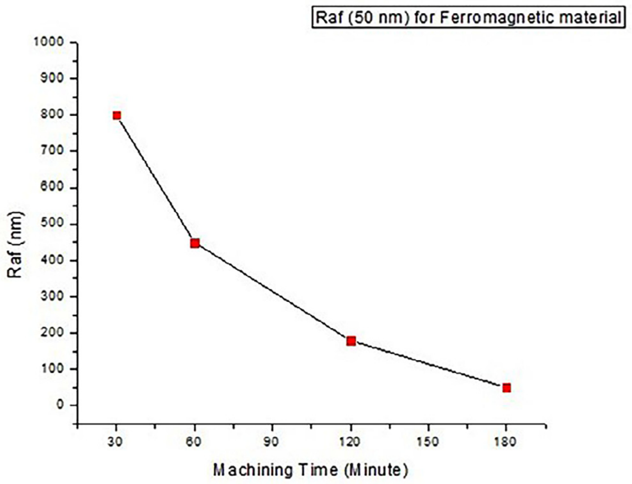

Fig. 10. Responses of the repeated experiments on machining time for the ferromagnetic material.

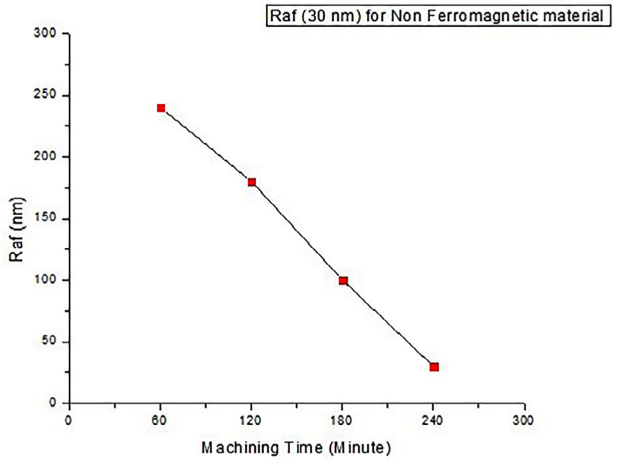

Fig. 11. Responses of the repeated experiments on machining time for non-ferromagnetic material.

3.4. Effect of tool rotation (RPM) on machining time

The machining time is decreased with increasing the rpm of tool rotation. When the tool rotation increased, it increased the shear force along the finished surfaces. Due to this reason, the machining time decreased. It is shown in Fig. 7.

3.5. Effect of the percentage of CIP particles (Vol %)) on final surface roughness (Raf)

The absolute surface roughness *(Raf)* was decreased with increasing *rate of CIP particles (Vol %))*. Due to the reason of increased the magnetic force along the chain of CIP particles. It is shown in Fig. 8.

3.6. Effect of the percentage of abrasives (Vol %) on final surface roughness (Raf)

The absolute surface roughness (Raf) decreased with an increasing rate of abrasives (Vol %) up to the optimum level of percentage 20%. After the 20%, The roughness increased because of a higher percentage of abrasive beyond the optimum value; it unevenly rubs the surfaces and ultimately reduces the final surface roughness. It is shown in Fig. 9.

3.7. Effect of ferromagnetic material on machining time

The machining time rapidly decreases for ferromagnetic material, i.e., stainless steel. Because of the magnetic nature of the workpiece material, it attracts the magnetic field of the tool towards the workpiece so that it increases the finishing force towards the finishing surface. It is shown in Fig. 10.

3.8. Effect of non-ferromagnetic material on machining time

The machining time for the non-ferromagnetic material, i.e., copper, increases. Because of the non-magnetic nature of the workpiece material, it repels the magnetic field of the tool from the workpiece, reducing the finishing forces towards the finishing surface. But the finishing forces can be adjusted by keeping a strong magnet at the base of the workpiece. So, the finishing forces increases towards the finishing surface. It is shown in Fig. 11.

4. Conclusion and future scope

This research work has paved the way towards the understanding of parametric dependency of the magneto-rheological finishing process. Several experiments could be observed that surface finish as an essential outcome of this finishing process depends on various factors like abrasive particles and iron particles. It depends on their respective concentrations in polishing fluid. The abrasive used affected the surface finish of the test specimen. The maximum surface finish has been found at 30 nm for non-ferromagnetic material (copper) and 50 nm for the ferromagnetic material (steel). The flow of magneto-rheological polishing fluid can also be analyzed in the future related to their viscosity, flow parameters, and shear strength to understand the process better.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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