U.Porto Journal of Engineering, 9:3 (2023) 1-13
ISSN 2183-6493
DOI:10.24840/2183-6493_009-003_001132

Received: 24 January, 2022
Accepted: 26 March, 2022
Published: 28 April, 2023

Investigation of Process Parameters of a Novel Magnetorheological Finishing Process for External Cylindrical Surfaces

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Abstract

The recent rise in the demand for high precision, close tolerances, and super surface finish quality of components and part assembly modules in the competitive manufacturing industrial environment for the enhanced working life and functional requirements of machines globally. Three revolving curved tip tools based on magnetorheological process has been designed and developed to fine finish the external cylindrical surfaces of soft and hard materials. The effect of the key operational machining parameters on the surface roughness of a newly developed magnetorheological process has been carried out using a one factor at a time method. The magnetizing current, revolving speed of the tools, the rotational speed of the workpiece and workpiece traverse speed are the parameters that have been considered for this purpose. The experimentation has been performed on the aluminium workpiece because of its broad applicability, such as manufacturing shafts, rods, pistons, and other circular components. The primary purpose of this study is to determine the range of essential control parameters for the newly developed finishing process. The percentage reduction in Ra, Rq, and Rz values are 69.64%, 58.21%, and 54.48%, respectively, after 60 minutes of finishing at magnetizing current 2 A, revolving speed of the tools 30 RPM, the rotation speed of the workpiece 600 RPM and feed 10 cm/min.

Author Keywords. magnetorheological finishing, M.R. fluid, surface roughness, one factor at a time, external cylindrical surface.

Type: Research Article

1. Introduction

Every part made in the industry with the help of any manufacturing process, i.e., welding, casting, forming, machining, etc., needs to be finished in the last. Usually, it is the last and necessary process to do on every part or component. Surface roughness is an important factor that significantly affects the functioning and life of the sliding or rotating components. A better surface requires accuracy, quality, and precision fits to remove irregularity in the profile of a component. The surface finish is time-consuming, tedious, labour demanding, and costly work that consumes almost 10-15% of the total production cost of the part (Mahalik 2010). Material removal in the finishing process is significantly less, only in the microchips or powder form. Presently, many finishing processes arises used for finishing the industrial parts. Machining parameters are responsible for the sub-surface defect, heat affected zone, cracks or microcracks on the surface, and change in the microstructure of the workpiece material, which is directly responsible for the working of the product and fatigue life of the product (Bayoumi and Abdellatif 1995). The finishing process is mainly classified into conventional machining processes and non-conventional machining processes. In most finishing processes, abrasive particles have been used as multi cutting tools. However, chemical or other materials are used to reduce the surface roughness in some processes. In conventional processes, abrasive particles are bound to the bonding materials, and material removal takes place due to the abrasion mechanism. There is no control over the cutting forces in the conventional processes. A large amount of heat is generated because the tool and workpiece rub each other, so that workpiece usually has minor or major surface defects when finished with these processes(Sunanta 2002; Liu et al. 2015). It only finishes or machines the workpiece of limited shapes and sizes. Many advanced processes are developed to finish the flat, cylindrical, concave, convex, spherical, 3D shapes, complex and intricate shapes workpiece without any surface defect to overcome the disadvantages of conventional processes. In some of these processes, a viscous polymer medium, chemical reaction, a mixture of abrasives, and CIP particles are used as the finishing tool. The control on the external forces acting on the workpiece by regulating the magnetic field by varying the current in the electromagnet or by varying the working gap in case of permanent magnets. Abrasive flow finishing is an advanced process used to finish concave, convex, spherical, internal, or external surfaces of complex shapes (Rhoades, Lawrence J. 1988; Lam and Smith 1997). In this process, a viscoelastic polymer is used as a medium, and abrasive particles are mixed; the viscoelastic media is extruded forth and back with the help of two vertically opposite cylinders through the cavity or over the free form surface to perform machining.

Surface finish and material removal depend on the viscosity of the medium. Chemical mechanical polishing is an advanced process; in this process, finishing occurs with chemical and mechanical action (Mori et al. 2004). Electronics industries mainly use this process to finish semiconductors or parts made from silicon or glass. The reaction products are produced when the silica slurry is applied to the workpiece removed by mechanical action (Mori et al. 1990; Peng, Guan, and Li 2014). Elastic emission machining is an ultrafine finishing process because the material is removed at an atomic level. Material removal occurs by surface energy phenomenon in which a single abrasive particle takes away many atoms from the work surface (Zantye, Kumar, and Sikder 2004; Mimura et al. 2007). The material is removed at the atomic level with the help of fine abrasives without any plastic deformation and used for finishing hard X-ray optical mirrors (Yumoto et al. 2005; Umehara et al. 2006). These advanced processes are used in industry to finish different-different parts up to the micron level, but due to no control over the cutting forces, poor surface finish or subsurface defects can be seen.

Researchers have developed advanced finishing processes in which magnetic fields can control the cutting force. The magnetic abrasive finishing process did develop to finish the flat surfaces of the hard materials by the Soviet Union in 1987 (W.I. Kordonski and Jacobs 1996). The workpiece and tool do not directly contact each other as a gap exists between them. Due to the magnetic field, a dry mixture of abrasive particles and magnetic particles forms a flexible finishing brush and acts as multi cutting tools. The magnetic particles make the chain in the direction of the magnetic field lines and tightly hold the abrasive particles between them. Magnetic float polishing non-conventional process develops to finish the spherical surface. i.e., bearing rollers and ceramics balls using levitation force exerted by the magnetic field on the abrasives. NBD-200 Si_3N_4 balls used in the spindle of high precision machines and aircraft's jet turbines are finished by magnetic float polishing (William I. Kordonski et al. 1998; Park, Song, and Choi 2009). Magnetorheological finishing develops to finish the brittle and hard materials, i.e., optics, glass (Susan-Resiga, Bica, and Vékás 2010).

The finishing done with the help of M.R. fluid, also called smart fluid, changes its rheological properties when the magnetic field applies. M.R. fluid is the mixture of abrasive particles, carbonyl iron particles, and base fluid or carrier medium (mineral oil, water, grease Etc.) (Patel 2011; Grover and Singh 2018). Some additives, stabilizers, and surfactants do mix with fluid: to control the sedimentation of abrasives; to increase the viscosity of fluid; to control the corrosion and wear resistance. The viscosity of M.R. fluid changed with changes in the magnetic field (Kumar Singh, Jha, and Pandey 2012). Many Magnetorheological processes have been developed by different researchers for finishing different-different shapes of parts and materials. The roughness achieved by these processes is mainly in the range of 10-100 nm or less than 10 nm (Maan, Singh, and Singh 2017; M. Singh and Singh 2019). An improved version of the magnetorheological finishing process has been proposed to fulfil the need for the cylindrical surfaces' external finishing. (G. Singh, Singh, and Garg 2017). A solid core-based stationary electromagnetic tool with curved and flat tip surface have been used in this work. It was found that the finishing performance of the tool having a curved tip was superior to that of a tool with a flat tip surface. Also, the lathe's headstock was used to rotate the workpiece as the tool was stationary. The arrangement was not developed in the above process to give the feed to the workpiece or the tool.

Therefore, to address the above issue of the existing methods, the current study developed three revolving curved tip tools magnetorheological finishing process. In the developed method, the provision of rotating the tool has also been proposed along with the workpiece. The feed arrangement has been built that gives the longitudinal movement to the workpiece to interact with the finishing of the tool and workpiece. The experimentation has been conducted on a newly developed, three revolving curved tip tools magnetorheological process for an external cylindrical workpiece, to obtain the operating ranges and levels of the process parameters.

2. Materials and Methods

The experimentation has been conducted on an aluminium workpiece shown in (**Figure 1**) because of its broad applicability in the manufacturing industry. The outer surface of the workpiece requires a fine finish to achieve smooth and noiseless operation. The fine finish also reduces the friction and wear on the cylindrical shaft. A novel three revolving curved tip tools magnetorheological finishing method has been proposed to finish the shaft's outer surface for experimentation.

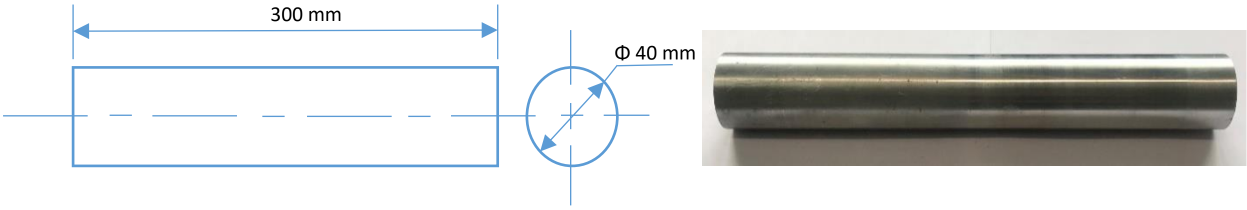


Figure 1: Drawing and actual photograph of an aluminium workpiece.

A single tip tool has been designed, and three single tip tools have been fixed on the circular plate at equal distances with the help of fixtures. The schematic figure of the MRF tool and single tip tool modelled on CAD software has been shown in (**Figure 2**)(a) and (**Figure 2**)(b), respectively. The pictorial view of the experimental setup is shown in (**Figure 3**). The workpiece is held fixed between the live center and dead center and the rotation to the workpiece is given with the help of a stepper motor. The rotational speed of the workpiece and tool and the feed rates are controlled by installing different motors such as stepper motor, D.C. motor, and A.C. synchronous motor. For instance, the stepper motor rotates the workpiece at the required speed and gives the workpiece feed. The revolving speed of the tools is controlled by the D.C. motor of 1 H.P. which is mounted with a speed controller and sensor to vary the speed.

Initially, the gap has been provided between the workpiece and the curved tip tool to avoid contact. Further, this gap is maintained by filling the gap with MRP fluid. This fluid also helps in removing the micro-chips during the finishing operation. In starting, the M.R. polishing fluid has been applied to the face of the tooltip. The DC current has been supplied to the electromagnet, which generates the magnetic field on the tooltip. In the presence of the magnetic field, the carbonyl particles present in the M.R. fluid arrange themselves in the direction of the magnetic force lines and, while arranging themselves, hold the abrasive particles in between them to remove the micro-chips through its relative movement.

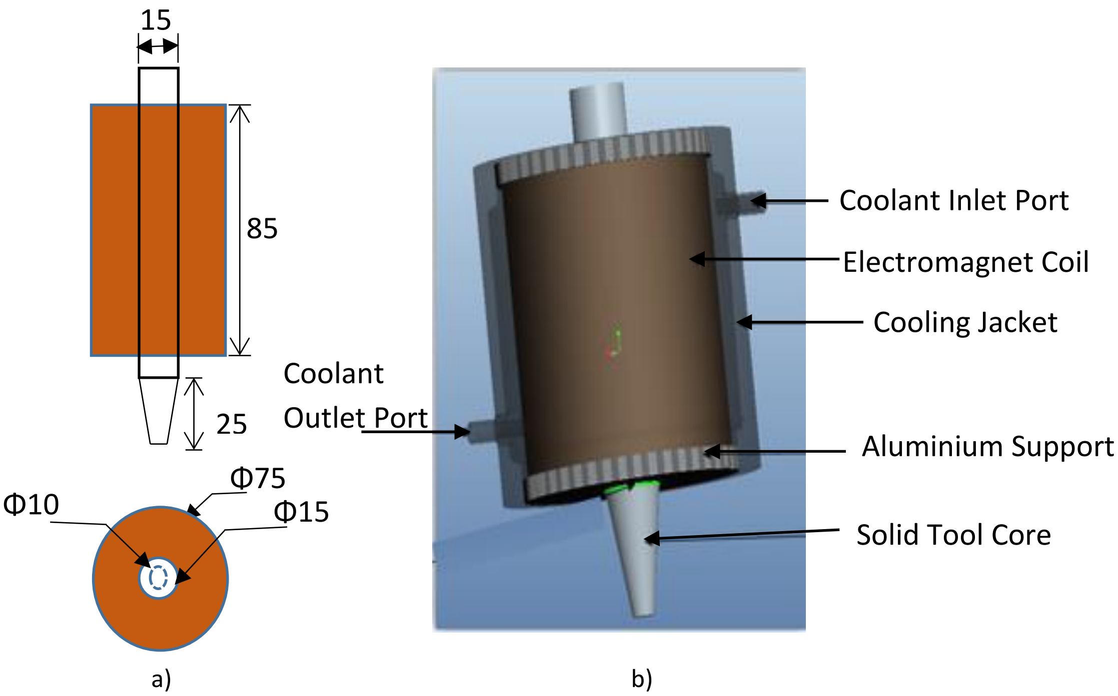


Figure 2: (a) Schematic diagram and (b) 3D CAD model of single tip MRF tool.

The magnetorheological polishing fluid has been prepared by mixing 20% of the aluminum oxide abrasive particles (600 mesh size), 20% of the carbonyl iron particles (CIPs) (400 mesh size) and 60% of the carrier fluid (paraffin oil 80% and AP3 grease 20% by weight) by volume, in the present study. The variation in the magnetic field is done by varying the electric current that also varies the viscosity of the M.R. polishing fluid. As the magnetic field intensity increases, the fluid's viscosity also increases, the carbonyl iron particles (CIPs) are attracted towards the tool that forces the abrasive particles towards the workpiece and thus stacked between the chains of CIPs that helps in finishing (G. Singh, Singh, and Garg 2017).

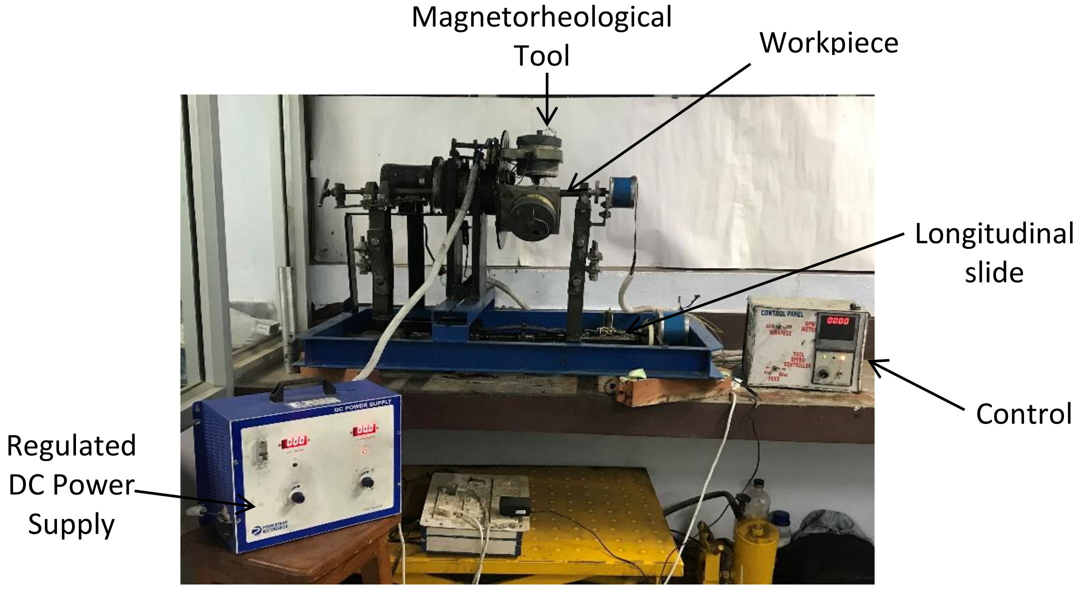


Figure 3: Photograph of three revolving curved tip tools based magnetorheological finishing setup.

The core material should have an excellent magnetic property. Therefore, mild steel of 2000 relative permeability is selected to make the solid core of the tool. Two aluminium supports are used with the core to hold the copper coil properly. The snap rings help in holding the aluminium supports. The 18-gauge copper wire of 0.99999 relative permeability has been used for coiling purposes. The 1700 turns of copper wire have been wound on each tool.

A regulated D.C. supply source has been used to give current to the electromagnet coils. The temperature of the electromagnetic tool rises linearly with time due to the constant flow of current through it. High temperatures can affect the workpiece's surface accuracy and quality (Mishra et al. 2014; Mulik, Srivastava, and Pandey 2012). Therefore, jacketing of transformer oil has been provided to Electromagnetic tools to address said issue. This MRF process is based on a cylindrical finishing operation in which the tool and workpiece are both rotated. The axis of the workpiece and tool are correctly aligned to maintain a high level of finishing. Taylor Hobson Surtronic 25 with a cutoff length of 0.25 mm has been used to measure the surface roughness of the workpiece. Table 1 lists the experimental parameters and conditions based on one factor at a time approach.

3. Experimentation

The experimentation has been conducted on the three revolving curved tip tools magnetorheological finishing process with one factor at a time approach to obtain the operating ranges and levels of process parameters. The cylindrical workpiece of the aluminium (non-ferromagnetic) workpiece has been used for finishing operation. A working gap of 0.8 mm has been maintained between the workpiece and tools.

4. Results and Discussion

The effect of different parameters such as magnetizing current, revolving speed of the tools, rotating speed of the workpiece, reciprocating speed of workpiece on the percentage reduction of roughness value (%ΔRa) of the surface have been observed, which are discussed as follows:

S.No	Current (A)	Tool (RPM)	Workpiece (RPM)	Feed (cm/min)	Average Initial Surface Roughness (µm)	Average Final Surface Roughness (µm)	Percentage Change in Surface Roughness
1	2	**20**	100	10	0.52	0.36	**30.76**
2	2	**30**	100	10	0.51	0.26	**48.54**
3	2	**40**	100	10	0.53	0.25	**52.32**
4	2	**50**	100	10	0.53	0.38	**13.46**
5	1	30	100	10	0.52	0.42	**26.92**
6	**2**	30	100	10	0.53	0.27	**49.12**
7	**3**	30	100	10	0.54	0.25	**53.70**
8	**4**	30	100	10	0.52	0.33	**36.53**
9	2	30	**200**	10	0.54	0.28	**48.76**
10	2	30	**400**	10	0.56	0.24	**58.62**
11	2	30	**600**	10	0.56	0.17	**69.64**
12	2	30	**800**	10	0.54	0.21	**60.25**
13	2	30	100	**10**	0.53	0.27	**48.25**
14	2	30	100	**13.5**	0.52	0.25	**52.24**
15	2	30	100	**18**	0.51	0.23	**54.12**
16	2	30	100	**22.5**	0.52	0.33	**35.76**

Table 1: Plan of experiments according to one factor at a time approach

4.1. Effect of electromagnet current (A)

The magnetizing current increases the magnetic field density at the tooltip, which helps to make the strong chains of CIP's and strong chains hold the abrasives tightly, resulting in more percentage change in the roughness. Increasing magnetizing current increases radial force, which helps to more impingement of abrasive in the workpiece and results in the material removal. (**Figure 4**) shows that the percentage change in surface roughness has been increased with an increase in the magnetizing current.

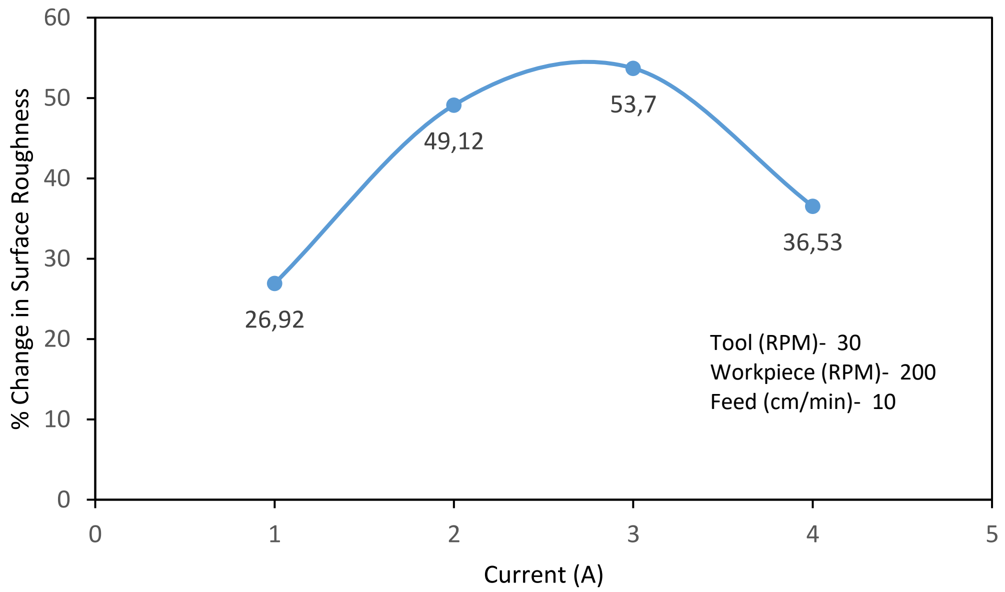


Figure 4: Effect of electromagnet current on the surface finish.

At the low range of magnetizing current, i.e., 1 A, the CIPs chains do not provide a better bonding strength on each CIP, i.e., forming the structure of loose chains. The abrasive particles gripped by the structure of the loose chain of CIPs do not provide better finishing results because the abrasive particles move out from the loose CIPs chains during the finishing operation. At 3A magnetizing current, the CIPs were made strong chains along the magnetic lines and strongly gripped the abrasive particles. As a result, the percentage change in surface roughness increased, but at 4A magnetizing current, the CIPs have formed rigid chain structure. The structure of the rigid chain provides a higher indentation force on the workpiece surface via abrasive particles. Further, these abrasive particles have been indenting into the cylindrical workpiece's internal surface and produced cavities or micro-scratches on the workpiece surface, resulting in a decrement of %ΔRa values.

4.2. Effect of the revolving speed of the tools

The tool's revolving speed also has a considerable effect on the finishing surface of the cylindrical workpiece. The tool's revolving speed provides a tangential cutting force on the active abrasives and increases the interaction between the tool and workpiece. Both factors are important to shear the roughness peaks from the cylindrical workpiece (**Figure 5**) indicates that at a low revolving speed of the tools, i.e., 20 RPM, the % variation in surface roughness value was also less. As the revolving speed of the tools increased, the percentage change in surface roughness value also increased. However, as the revolving speed of the tools was increased above 40 RPM, the percentage change in the surface roughness value began to decrease. It happened because, after the 40 RPM tool revolving, the centrifugal force acting on the M.R. fluid weakens the magnetic force so that the bonding strength of the M.R. polishing fluid was insufficient to shear material from the cylindrical workpiece. As a result, at the high revolving speed of the tools, the M.R. fluid was moved from the tool tip's face and accumulate around the tool tip, resulting in less reduction in surface roughness values.

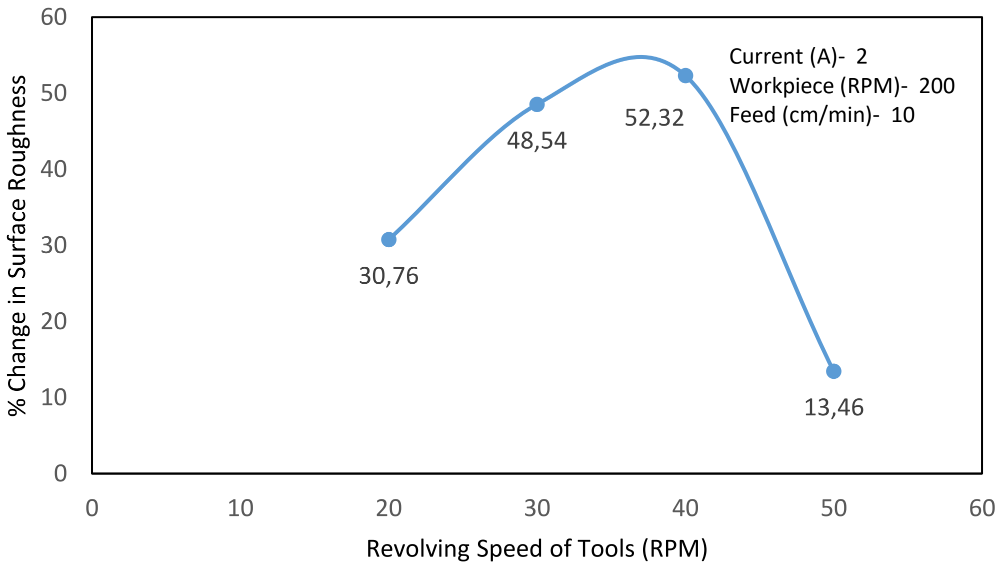


Figure 5: Effect of the revolving speed of tools on the surface finish.

4.3. Effect of reciprocating speed of the workpiece

The reciprocating speed of the workpiece provides the axial force, which helps to shear the roughness peaks from the workpiece surface. As soon as the reciprocating speed of the workpiece increases, active abrasives easily erode the material from the workpiece. As shown in (**Figure 6**), the percentage change in surface roughness was initially less at the workpiece's reciprocating speed (10 cm/min). After that, as the reciprocating speed of the workpiece increase, the percentage change in surface roughness also increases. The percentage change in surface roughness increased only up to 18 cm/min reciprocating speed of the workpiece. Beyond this reciprocating speed (18 cm/min) the percentage change in the surface roughness value drops. Because above this speed limit, the abrasive particles on the workpiece surface become unstable because of the high axial force acting on the CIP particle chains. At a high reciprocating speed, 22.5 cm/min, the CIP particle chains begin to break due to the high axial force imposed on them and cannot hold the abrasives properly. As a result, the abrasives cannot finish the cylindrical workpiece effectively and begin rolling across the surface. As a result, the percentage variation in the surface roughness value reduces after the workpiece reciprocates at 18 cm/min speed.

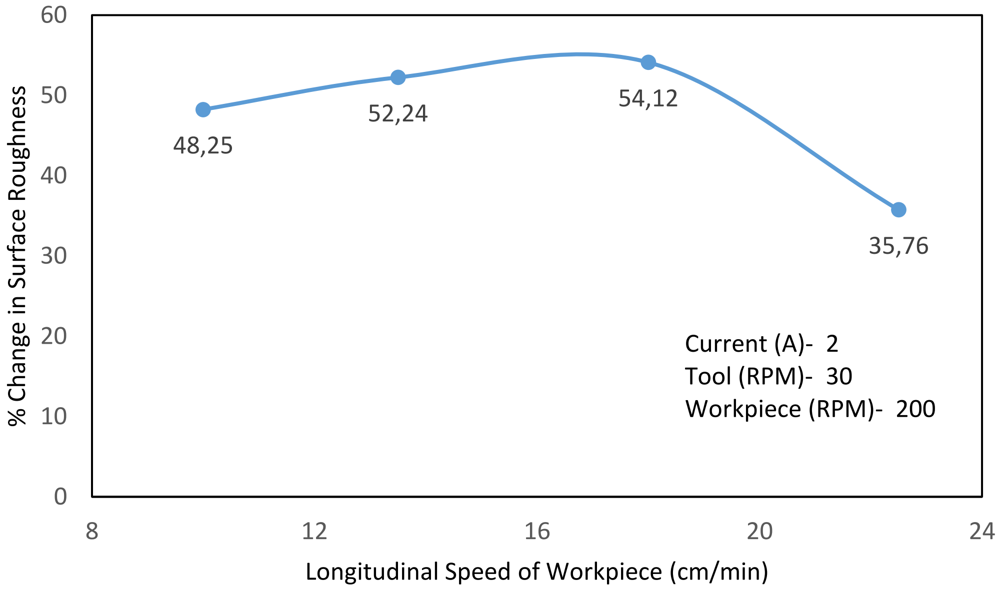


Figure 6: Effect of reciprocating speed of workpiece on the surface finish.

4.4. Effect of workpiece rotation speed

The rotating speed of the workpiece plays a significant role in the finishing of the cylindrical workpiece. The rotating speed of the workpiece provides a tangential cutting force that increases the interaction between the workpiece and the tool. As observed in (**Figure 7**), the increment in the rotation speed of the workpiece increases the percentage change in surface roughness up to 600 RPM. After 600 RPM, the percentage change in surface roughness reduces. Because, at the higher rotational speed of the workpiece, the centrifugal force increases on the workpiece, whose amplitude is much more than the magnetic force at the tip. Due to this, the fluid will not be stable in the working gap. Normal magnetic force helps to impinge the abrasive particles in the workpiece, and the rotation speed of the workpiece (cutting force) is responsible for removing the material. At the higher rotational speed of the workpiece, the centrifugal force is much higher than the normal magnetic force. Due to normal magnetic force, abrasive impinge in the workpiece. However, because of higher centrifugal force, the CIP's chains cannot hold the abrasive and break before the material removes from the workpiece. Therefore, to maximize the percentage reduction in the surface roughness, the medium rotational speed of the workpiece is required.

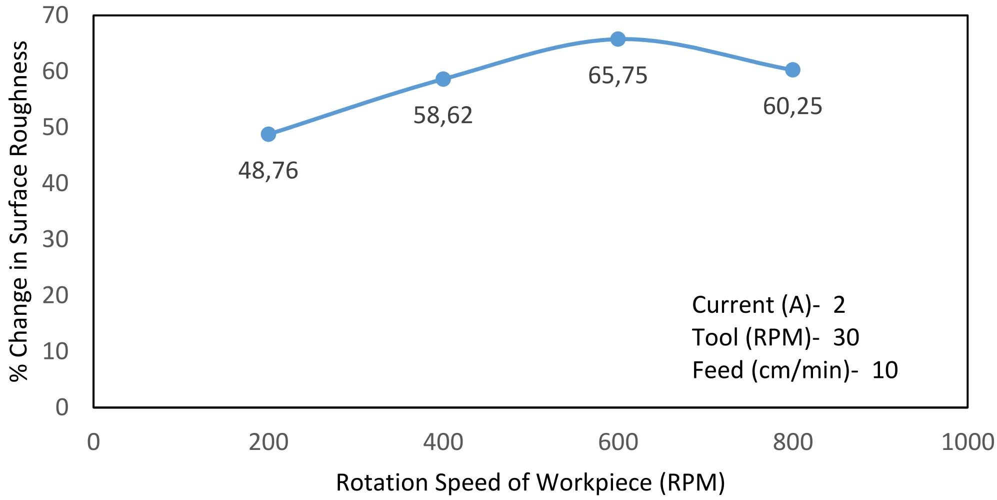


Figure 7: Effect of the rotation speed of the tool on the surface finish.

The Ra profiles of the cylindrical workpiece surface before and after MR finishing operation are demonstrated in (**Figure 8**)(a) and (**Figure 8**)(b). The MR finishing was carried out for 60 mins duration. R_a, R_q, and R_z are decreased from 0.56 µm, 0.706 µm, and 4.1 µm to 0.17 µm, 0.295 µm, and 1.85 µm, respectively. The percentage reduction in R_a, R_q, and R_z values are 69.64%, 58.21%, and 54.48%, respectively, after 60 minutes of finishing at magnetizing current 2 A, the revolving speed of the magnetorheological tools 30 RPM, the rotation speed of the workpiece 30 RPM and feed 10 cm/min. Also, the induced magnetic field gradient in the working gap is sufficient to maintain the MR polishing fluid rigidly on the tip surface of the tool. This demonstrated the achievement of the proposed approach for fine finishing the external surfaces of cylindrical workpieces.

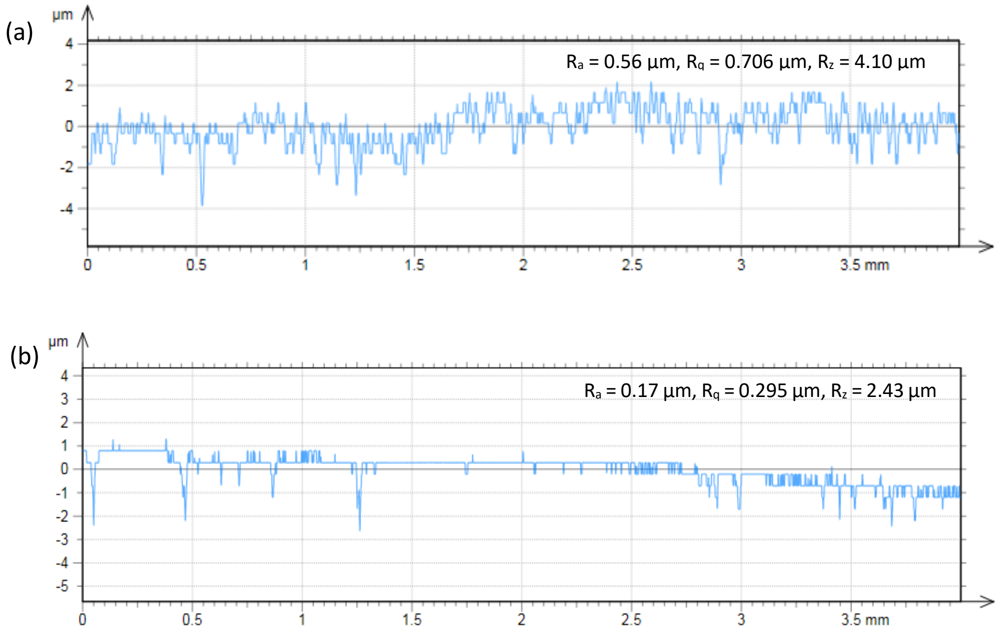
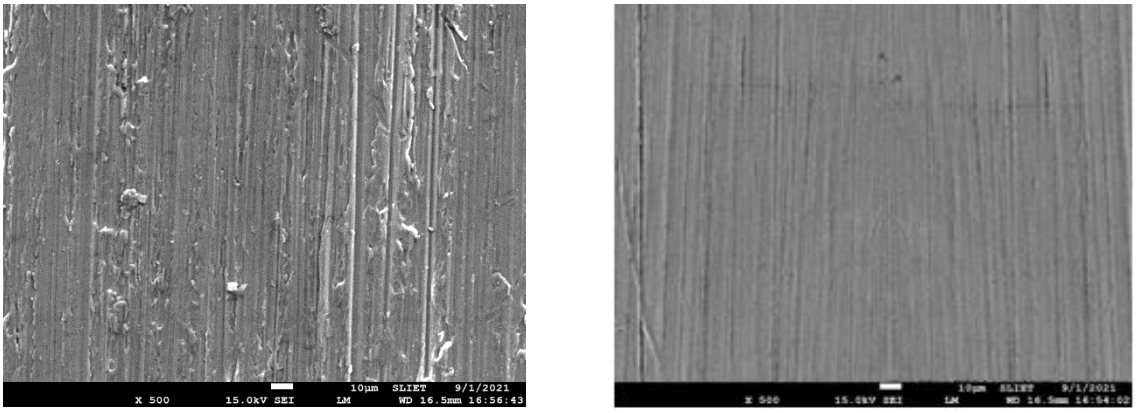


Figure 8: Roughness profiles of the cylindrical surface of the aluminium workpiece (a) before and (b) after 60 minutes of finishing at magnetizing current 2 A, the revolving speed of the magnetorheological tools 30 RPM, the rotation speed of the workpiece 30 RPM, and feed 10 cm/min.

The topography of the initial and finished external cylinder surface has been taken at a 500X optical scale on a 20 mm length of the cylindrical workpiece as shown in (**Figure 9**)(a) and (**Figure 9**)(b) to demonstrate the surface topography before and after MR finishing. The high normal force occurring on the surface during the grinding process leads to grinding lay lines on the surface, as illustrated in (**Figure 9**)(a). The external surface of the cylindrical workpiece obtained after 60 min of MR finishing is depicted in (**Figure 9**)(b) via an SEM photograph. After 60 minutes of MR finishing, the grinding lay lines has been reduced, and a smooth surface is obtained, as shown in the SEM image. The reason for the same is that the MR finishing operation provides a less magnetic normal force on the external surface cylindrical workpiece in comparison to regular grinding operation. SEM and surface roughness profile analysis demonstrated that MR finishing operation enhances the surface finish of the cylindrical workpiece. As a result, the present improvement in MR finishing is more applicable to fine finishing of the exterior surface of cylindrical workpieces such as punches, cylindrical shafts, and rods for improved functionality in industries.



(a) (b)

Figure 9: SEM micrograph at 500x (a) initial and (b) after finishing for 60 minutes at magnetizing current 2 A, revolving speed of the magnetorheological tools 30 RPM, the rotation speed of the workpiece 30 RPM and feed 10 cm/min.

5. Conclusions

Magnetorheological processes based on the three revolving curved tip tools have been successfully developed to finish external cylindrical surfaces. The following are the findings from the experimentation analysis.

• The kinetic energy of the abrasive particles in conjunction with the revolving speed of tools considerably influences the rate of material removal and finish quality.

• The R_a value is decreased from 0.56 µm to 0.170 µm using three revolving curved tip tools magnetorheological process after 60 minutes of finishing.

• The maximum surface reduction has been achieved for magnetizing current 2 A, revolving speed of the tools 30 RPM, the rotation speed of workpiece 600 RPM, and feed 10 cm/min.

• Images taken with SEM and surface roughness profile confirmed the significant improvement in surface finish.

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