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A novel magnetorheological finishing process based on three revolving flat tip tools for external cylindrical surfaces

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Abstract: The magnetorheological finishing technique based on a stationary curved tip tool is found less effective in finishing external cylindrical surfaces. Therefore, three revolving flat tip tools-based magnetorheological finishing process which utilises the rotation of both workpiece and tools have been developed to address the issues of the existing method. Also, a feed mechanism has been built to provide the longitudinal movement to the workpiece. A workpiece of mild steel has been finished by both developed and existing methods. It has been observed that after finishing 1 hour 30 minutes with a stationary curved tip tool, surface roughness values R_a, R_q, and R_z decrease by 69.29%, 64.41%, and 61.26%, respectively. Whereas, the reduction in the surface roughness value of R_a, R_q, and R_z by 85.38%, 84.51%, and 82.7%, respectively, have been noted after finishing with the three revolving flat tip tools process at the same parameters and conditions.

Keywords: magnetorheological fluid; external cylindrical surfaces; surface roughness; magnetorheological finishing.

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1 Introduction

Precision and accuracy are critical components of product quality in today's industrial sectors. The surface finish of the product enhances the product's surface quality. High strength application life may indeed be extended by improving the quality of the surface (Jain et al., 2007). In today's world, items must be finished on a nanoscale and dimensional dimensions (Zhong, 2008). Time-consuming and expensive finishing procedures are the two most difficult challenges in attempting nano-level finishing (Singh and Jayant, 2018). A significant portion of the entire product cost is due to the costly finishing processes, accounting for between 15%–20% of the total product cost (Bedi and Singh, 2016). The finishing time directly impacts the whole manufacturing process. Cylindrical components like shafts, plungers, cylindrical punches, and cylinders provide sliding and rotating motion in machines and other equipment. Furthermore, precise finishing is required for vehicle transmission components such as vane pump shafts, armature shafts, turbocharger shafts, and transmission yoke. For external cylindrical surface finishing, there are various commercial methods available. Grinding is the most often used procedure for finishing cylindrical surfaces (Lim et al., 2002). Lack of control over the machining forces is the main flaw of the grinding process. Excessive heat is generated during the grinding process, resulting in heat-affected zones, microcracks, and thermal stresses on the formed surfaces (Alonso et al., 2015; Liu et al., 2015). To address these challenges and increase surface quality, a number of sophisticated finishing methods have been established (Singh et al., 2021). Magnetic-assisted methods are more influential among the latest finishing techniques due to more control over the finishing forces (Jain, 2009). Magnetic aided finishing technologies (Judal et al., 2013; Singh et al., 2020, 2012a; Singh and Jayant, 2020; Yousefzadeh and Safari, 2012; Grover and Singh, 2019; Natarajan, 2021) are efficiently used to finish flat and three-dimensional surfaces. The ball end magnetorheological finishing approach is preferred over the other techniques (Singh et al., 2012b; Iqbal et al., 2020) A magnetorheological polishing fluid comprising carrier fluid, carbonyl iron particles (CIPs) and abrasive particles is used in the magnetorheological finishing processes (Paswan et al., 2021). The base fluid has various compositions and CIPs of various sizes (Alam et al., 2019; Thomas and Rosén, 2009; Sidpara and Jain, 2014). Magnetorheological polishing fluid can be used to finish both hard and soft materials because of its flexibility and controllability (Niranjan et al., 2014). As a magnetic field is applied to the magnetorheological polishing fluid, stiffer chains of CIPs develop. These chains hold the abrasive particles that assist in removing material from metals and non-metals to achieve the necessary level of surface finish (Singh and Jayant, 2022a; Singh et al., 2012c; Saraswathamma et al., 2015). The viscosity of the magnetorheological fluid is increased due to increases in the magnetic field intensity. The finishing of the complicated surfaces may be done effectively because of the magnetorheological polishing fluid's rheological qualities. The amount of CIP, abrasive particles, and base fluid in a fluid determines its rheological characteristics (Singh and Singh, 2021; Sidpara and Jain, 2014; Nagdeve et al., 2018).

An improved version of the magnetorheological finishing process was proposed to fulfil the need for the external cylindrical surface's finishing (Singh et al., 2016). A stationary tool with a curved tip and flat tip face was employed in this study. The process finishing performance with a curved tip tool was superior to the flat tip tool. Additionally, the workpiece was rotated using the lathe's headstock, and the tool was stationary. Apart from that, the arrangement to feed the workpiece or tool was not built in this experimental setup.

To solve the difficulty mentioned above with existing approaches, the current work offers a new magnetorheological finishing method for exterior cylindrical surfaces that improve surface tolerance while reducing finishing time. Three newly designed flat tip tools revolve around the rotating workpiece in this process. Also, a feed system has been built to provide longitudinal movement to the workpiece to produce more interaction among the tools and the workpiece. As a result, the improved magnetorheological process based on three flat tip tools is more efficient for external cylindrical surfaces than the existing finishing method based on a stationary curved tip tool.

2 Material and method

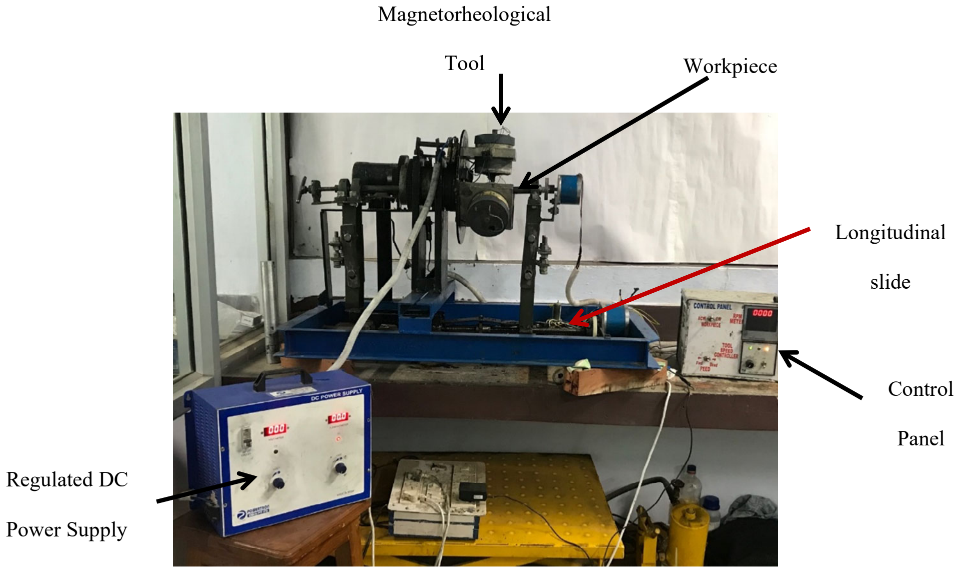
A stepped cylindrical shaft made of mild steel was used for the experimentation. This mild steel cylindrical shaft is a component of the macaroni machine. Table 1 details the composition of workpiece material. The external surface of the shaft workpiece should be completed correctly to enable silent and smooth operation. The outside surface of the shaft has been finished using a single stationary curved tip tool and three revolving flat tip tools magnetorheological finishing methods.

Table 1 Composition of workpiece material

Elements	*Fe*	*Mn*	*C*	*Si*	*Cr*	*Cu*	*Ni*	*S*	*Pb*	*P*	*W*	*Ti*	*Mo*
%	98.1	0.56	0.28	0.21	0.124	0.18	0.14	0.0743	0.05	0.041	0.025	0.021	0.01

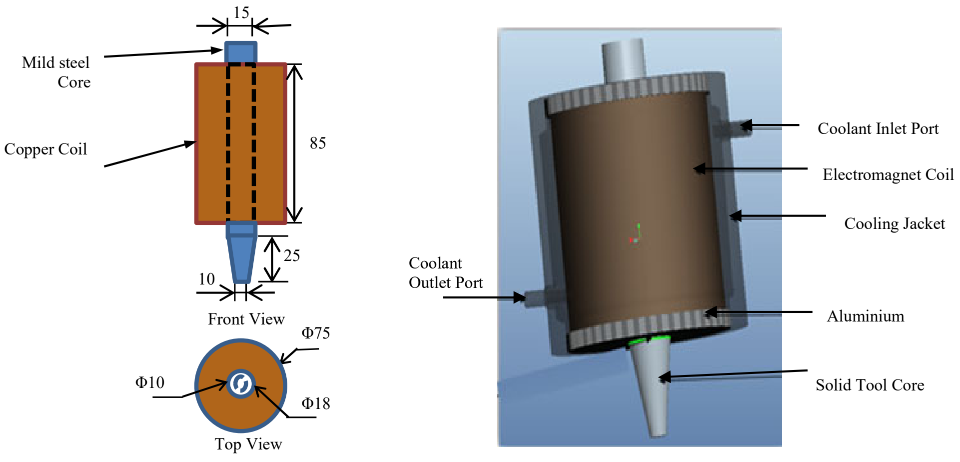
A newly fabricated experimental setup that includes a stationary curved tip tool and the three revolving flat tip tools as shown in Figure 1. A stationary curved tip electromagnetic tool is used in the existing experimental setup, whereas three flat tip electromagnetic tools have been used in the proposed setup. A flat tip tool has been designed, and three tools are fixed on the circular plate at equal distances with the help of the fixtures. The tool's tip has been tapered to concentrate magnetic lines on a small region and produce the strongest magnetic field at the tooltip's face. The schematic and 3D model of the flat tip tool obtained by CAD software is shown in Figure 2. The finite element analysis (FEA) of the flat tip type tool using MAXWELL ANSOFT V13 (student version) is shown in Figure 3. The influence of magnetic flux density in the working gap and on the tool tip surface for a flat tip tool is studied through FEA. The working gap between the flat tip tool and workpiece has been kept at 0.7 mm throughout the performance study. The flux density gradient is a critical need for all MR finishing processes. As a result, the iron particles (IPs) are attracted to the magnetic tool tip's surface. It generates a levitation force that pulls the abrasive particles to the workpiece surface. These abrasive particles act as a chipping tool, removing the roughness peaks from the surface. Figures 4(a) and 4(b) show the side view of the existing and proposed methods. The workpiece is fixed between the live and dead centre, and a stepper motor has been used to rotate the workpiece. The rotational speed of the workpiece, tools, and feed rates are controlled by installing different motors such as stepper motor, DC motor, and AC synchronous motor. For instance, the stepper motor rotates the workpiece at the required speed, and the AC synchronous motor gives the feed. The revolving speed of the tools has been controlled by the DC motor of 1 HP, which is mounted with a speed controller and sensor to vary the speed.

Figure 1 Photograph of revolving wheel type magnetorheological setup (see online version for colours)



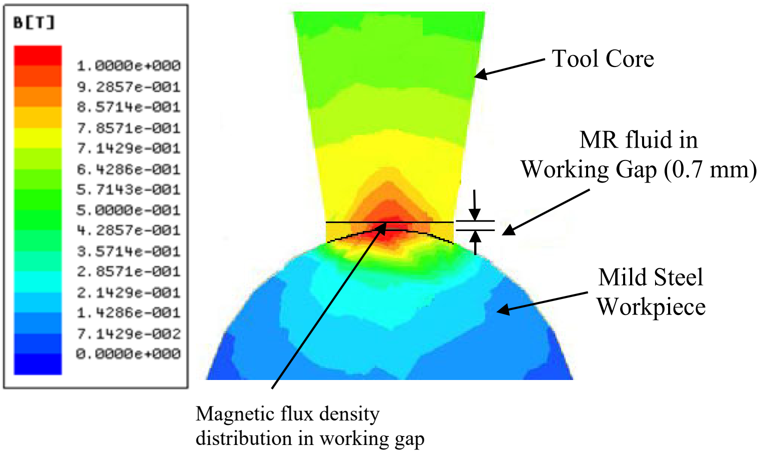
Initially, the gap has been provided between the workpiece and the tip tool, so that both do not come in contact with each other. Further, this gap maintains by filling the gap with magnetorheological fluid. This fluid helps to remove the material in the form of microchips while finishing the workpiece. In starting, the magnetorheological fluid has been applied to the face of the tooltip. The electromagnet that generates the magnetic field on the tooltip receives a DC supply. The carbonyl particles in the magnetorheological fluid organise themselves in the direction of the magnetic force lines and hold the abrasive particles between them as the MR fluid is exposed to a magnetic field, resulting in a flexible abrasive brush to finish the workpiece. The core material should have an excellent magnetic property. Therefore, mild steel of 2,000 relative permeability has been selected to make the solid core of the tool. Two aluminium supports have been used with the core to hold the copper coil properly. The 18-gauge copper wire of 0.99999 relative permeability has been used for coiling purposes. A total of 1,700 turns of copper wire have been winded on each tool's core. Taylor Hobson Surtronic-40 with a cut-off length of 0.8 mm is utilised to measure the surface roughness of the finished workpiece. A regulated DC supply source has been used to provide 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 surface accuracy and quality (Singh and Jayant, 2022b; Maan et al., 2016). For cooling purposes, a jacket has been provided around the electromagnetic coil of the tool and filled with the transformer oil.

Figure 2 (a) Schematic diagram and (b) 3D CAD model of single tip magnetorheological tool (see online version for colours)



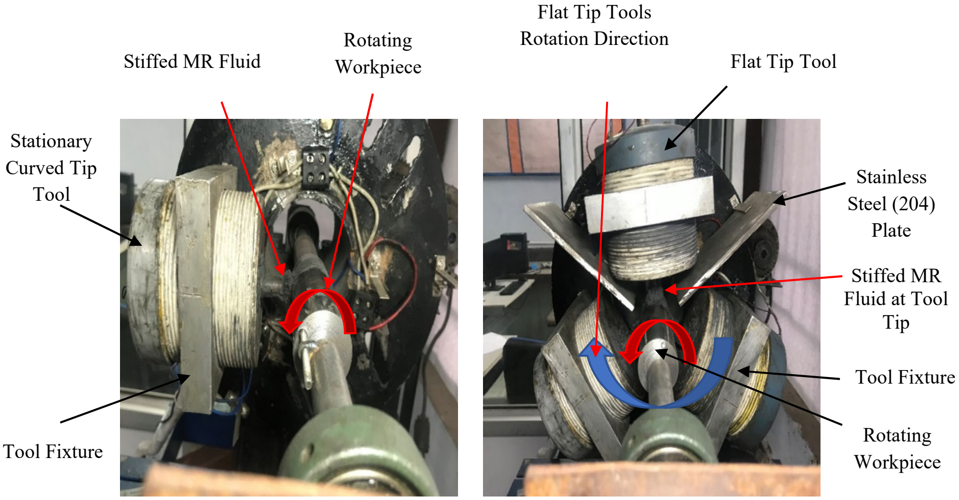
(a) (b)

Figure 3 The magnetic field intensity distribution at flat type tool tip at 0.7 mm working gap (see online version for colours)



A stationary curved tip tool was kept fixed in the existing magnetorheological finishing process (Singh et al., 2016). But, in the present work, three flat tip tools are used instead of a single curved tip tool. Three flat tip tools are arranged on a circular plate at an equal distance to rot the workpiece between them. The flat tip tools also revolve around the workpiece in the opposite direction of the workpiece. More interaction has been achieved because the workpiece and flat tip tools rotate in opposite directions. Secondly, the feed arrangement is also built to give the longitudinal movement to the workpiece in the current experimental setup, which was not present in the existing method. A 6mm thick stainless steel 204-grade plate has been fixed between the single tip tools to redirect the magnetic forces lines and isolate the magnetic coils. The composition of the magnetorheological fluid is presented in Table 2. Before initiating the finishing operation, the magnetorheological polishing fluid is applied to the tool's tip. The magnetic field is generated at the tooltip as the DC current supply is delivered to electromagnet coils. As a result, the CIP's reinforced chains effectively keep the abrasive particles in place, causing the material to be removed from the workpiece surface by relative movement.

Figure 4 Side view of the fabricated setup with (a) a single stationary curved tip tool (b) the three revolving flat tip tools (see online version for colours)



(a) (b)

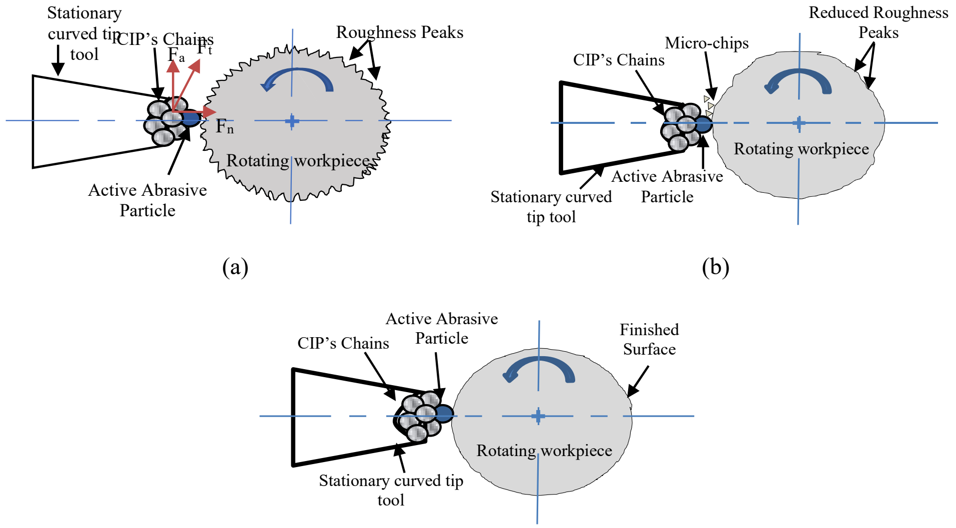
Material removal mechanism of a single fixed curved tip tool and three revolving flat tip tools process have been shown in Figure 5 and Figure 6. Many forces work together to complete the machining operation in the material removal processes. Similarly, the normal force (F_n), tangential force (F_t) and axial forces (F_a) are required to remove the material from the external surface of the workpiece in this process. In both magnetorheological finishing processes, the magnetic flux density is responsible for employing the normal force on the abrasive particle through the CIP's chains. The tangential force (F_a) produces due to the rotation of the workpiece and single tip tools, whereas the axial force (F_a) is generated by the rotating behaviour of the workpiece and tools.

Table 2 Composition of the magnetorheological polishing fluid

Constituents	*Size*	*% Volume concentration*
Carbonyl iron particles (CIP)	400 mesh size	20%
Silicon carbide abrasives (Sic)	800 mesh size	20%
Carrier fluid	(80% paraffin oil and 20% AP3 grease)	60%

In the first phase, details of the material removal process of the stationary curved tip tool method have been shown in Figure 5. As the stiffened magnetorheological polishing fluid at the curved tip tool approaches the rotating external surface of the cylindrical workpiece. Normal force exerted by the CIP's chains helps to indent the active abrasive particle into the roughness peaks of the rotating cylindrical workpiece surface, as shown in Figure 5(a). Tangential force and axial force combinedly help to shear off the roughness peaks in the form of microchips from the cylindrical workpiece, as shown in Figure 5(b). Figure 5(c) shows that the roughness peaks were reduced after completing the finishing cycle, and the cylindrical workpiece surface was well finished.

Figure 5 Schematic representation of a stationary curved tip tool for material removal mechanism (a) the external cylindrical surface initial roughness peaks facing the active abrasive grasped by the CIPs chains, (b) peaks being chopped off in the form of microchips, and (c) external cylindrical surface that has been finished by removing its roughness peaks (see online version for colours)



(a) (b)

(c)

The second phase, utilising three revolving flat tip tools, begins with active abrasive indentation, as shown in Figure 6(a). More relative movement and high tangential force create between the tools and workpiece because the workpiece and flat tip tools rotate in opposite directions, resulting in easy removal of the additional material from the workpiece during the finishing process, as observed in Figure 6(b). Finally, the roughness peaks are reduced, and the mild steel shaft's external surface has finely polished [Figure 6(c)]. The tangential cutting force generated by the rotating flat tip tools on the active abrasives, as well as the interaction between the tools and the workpiece, are both important in shearing the roughness peaks from the cylindrical workpiece and increasing the material removal rate, which helps to speed up the finishing process.

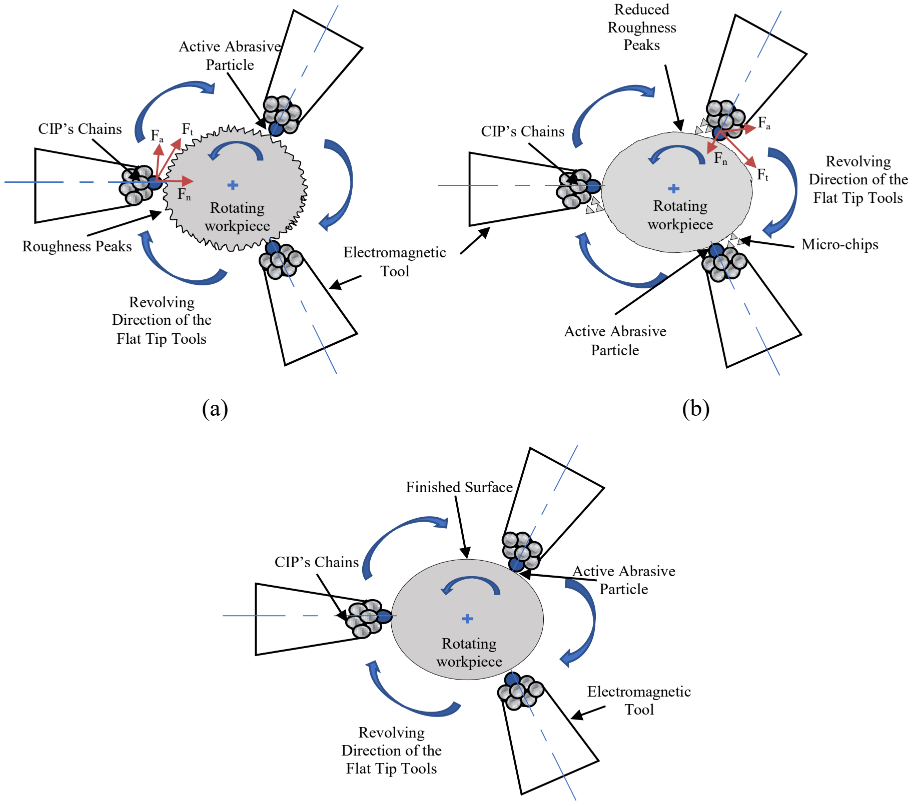
Because of a novel method, limited literature data is available to help determine the values of the parameters. A number of different combinations of rotating speed of workpiece and revolving speed of tools were tried on the newly fabricated setup to determine the effect on surface roughness value. The active abrasives are helped in shearing out roughness peaks from the cylindrical workpiece by the tangential cutting force provided by the tool's revolving speed. But as the revolving speed of the tools increases, a significant centrifugal force is produced due to the high revolving speed of the tools, which causes to disperse of magnetorheological polishing fluid from the tooltip. During the trial experiments, it was observed that a lower rotation speed of the flat tip tools combined with a higher rotating speed of the workpiece yielded statistically significant results for surface roughness value. The primary purpose of the rotating speed of the workpiece is to smooth the workpiece's outer surface. The MR polishing fluid's shear-thinning effect causes the process' performance to fall after the particular limit of workpiece rotation speed (Sidpara and Jain 2014). The high rotation speed of the workpiece weakens the magnetorheological polishing fluid, causing the CIP chains to lose their grip on the active abrasives. Additionally, if the speed is too slow, the active abrasives finish on the same place as the cylindrical workpiece's external surface for an extended period. Various combinations of the rotating speed of the cylindrical workpiece and the tools revolving speed were explored throughout the trials to see how they affected the material removal rate in terms of surface roughness value. The higher rotating speed of the cylindrical workpiece and the lower revolving speed of the tools results in the active abrasives travelling more over the external cylindrical surface. Magnetic flux intensity is directly proportional to the amount of current supplied to the electromagnet coil. At the lower current value (e.g., 1 A or 2 A) less magnetic flux density is produced at the tooltip, resulting in weakened CIP's chains having a loose grip on the abrasive particles. A rigid chain structure is formed at a higher value of the current (e.g., 4 A and 5 A). In that case, the abrasive particles also remove the uproots material along with the roughness peaks; hence pit formation starts on the surface of the workpiece. The reciprocation speed of the workpiece (feed) provides the axial force that plays a significant role in shearing the roughness peaks. The improvement in the external surface of the workpiece has been seen up to the reciprocation speed of the workpiece, 30 cm/min. Beyond the reciprocation of the workpiece, 30 cm/min higher axial force acts on the active abrasive particles. The CI particle chains begin to break because of the strong axial force imposed on them and cannot fully hold on to the abrasives. As a result, the abrasives cannot complete the cylindrical workpiece effectively and begin rolling across the workpiece surface. After the preliminary experimentation, the value of parameters has been selected to compare the results of both processes as follows, rotating speed of the workpiece 500 rpm, revolving speed of flat tip tools 30 rpm, magnetising current 3 A, reciprocation speed of workpiece 30 cm/min and working gap 0.7 mm.

Table 3 Conditions and parameters for the experimentation

Parameters	*Conditions*	
	For a stationary curved tip tool	*For three revolving flat tip tool*
Finishing cycle time (min)	90	90
Feed rate (cm/min)	30	30
Magnetising current (A)	3A	3A (each coil)
Rotational speed of tool (RPM)	---	30
Rotation speed of workpiece (RPM)	500	500
Working gap (mm)	0.7	0.7

To compare both processes' finishing performance, experimentation has been performed on the stationary curved tip magnetorheological finishing process and three revolving flat tip tools magnetorheological finishing processes at the same experimental parameters and conditions as mentioned in Table 3.

Figure 6 Schematic diagram of material removal mechanism with three revolving flat tip tools (a) the external cylindrical surface initial roughness peaks facing the active abrasive grasped by the CIPs chains (b) peaks being chopped off in the form of microchips (c) external cylindrical surface that has been finished by removing its roughness peaks (see online version for colours)



(a) (b)

(c)

3 Results and discussion

A new technique has been proposed to finish the external cylindrical surfaces. Table 4 shows the impact of employing a stationary curved tip tool and three revolving flat tip tools to change the average surface roughness value R_a of the external surface of a cylindrical workpiece.

In experimentation, with a stationary curved tip tool, the magnetorheological finishing process noted that the average surface roughness value R_a reduces from 684 nm to 430 nm in the first half an hour of the finishing cycle, reduces from 430 nm to 280 nm in the next half an hour, and further reduces from 280 nm to 210 nm in the next half an hour of the finishing cycle. Similarly, experimentation has been done with the magnetorheological finishing process based on three revolving flat tip tools at the same parameters and conditions. The average roughness value Ra has been seen to have reduced from 684 nm to 270 nm in the first half an hour, 270 nm to 165 nm in the next half an hour, and 165 nm to 110 nm in the next half an hour of the finishing cycle. As shown in Table 4, the three rotating flat tip tools method has been reduced more R_a value than a stationary curved tip tool process within 30 minutes of finishing. It demonstrates the newly established process's efficiency in terms of completion time. Additionally, within the first half an hour of the experiment, there has a statistically significant decrease in the percentage change of the R_a value by both the processes. Because roughness peaks have a lower base area at their apex, fewer forces are required to shear material from the external cylindrical workpiece. As the finishing duration increases, the base area of the roughness peaks increases, which demands more power to remove the material. That is why, after 30 minutes of experimentation, the percentage variation in R_a values decreases.

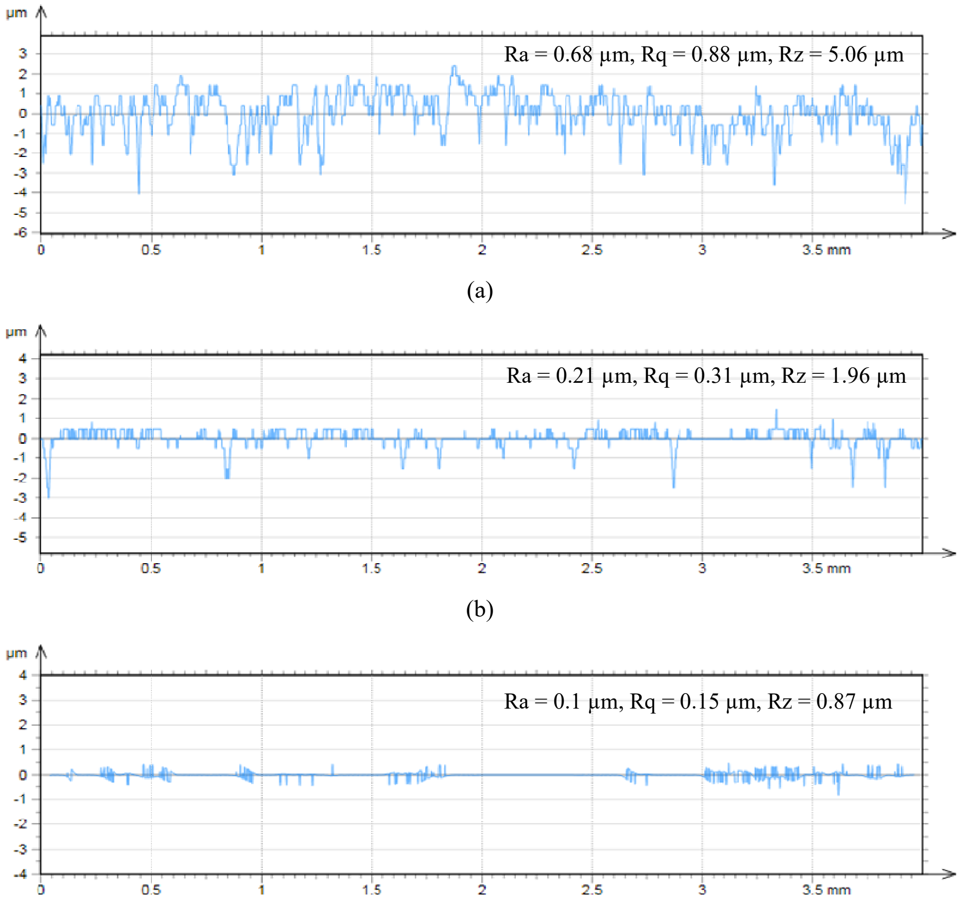
Table 4 Effect on roughness value with the finishing time

Working cycle	*Surface roughness of workpiece after finishing with a stationary curved tool (μm)*		*Surface roughness of workpiece after finishing with three revolving flat tools (μm)*	
	Initial surface roughness	*After completion of a cycle*	*Initial surface roughness*	*After completion of a cycle*
30	0.68	0.43	0.68	0.27
60	0.43	0.28	0.27	0.165
90	0.28	0.21	0.165	0.10

The initial surface roughness profile of the external cylindrical surface is shown in Figure 7(a), and the final surface roughness profile of the external cylindrical surface after finishing 1 hour 30 minutes with both magnetorheological processes is shown in Figures 7(b), and 7(c). After completing the 90-minute finishing cycle with a stationary curved tip tools process, found that the R_a, R_q, and R_z values reduced to 0.21 μm, 0.31 μm, and 1.96 μm, respectively, from their beginning values of 0.68 μm, 0.88 μm, and 5.06 μm. Similarly, after completing 1 hour 30 minutes finishing cycle with the three revolving flat tip tools based magnetorheological process R_a, R_q, and R_z values decreased to 0.1 μm, 0.15 μm, and 0.87 μm from their initial values of 0.68 μm, 0.88 μm, and 5.06 μm.

Both processes have been run at the same experimental parameters and conditions. It has been noted that the surface roughness values of R_a, R_q, R_z reduces by 69.29%, 64.41%, 61.26%, respectively, with the stationary curved tip tool and the three rotating flat tip tools procedure decreasing the roughness values to 85.38%, 84.51%, and 82.7%, respectively. The reason behind that is the newly developed process's finishing performance is that the more relative movement occurs between the workpiece and the grasped active abrasives by the CIP particle chains because of the rotating nature of both workpiece and tools.

Figure 7 Surface roughness profile of (a) primary surface of the cylindrical workpiece after the grinding operation (b) after 1 hour 30 minutes finishing with a single stationary curved tip tool process (c) after 1 hour 30 minutes finishing with the three revolving flat tip tools process (see online version for colours)



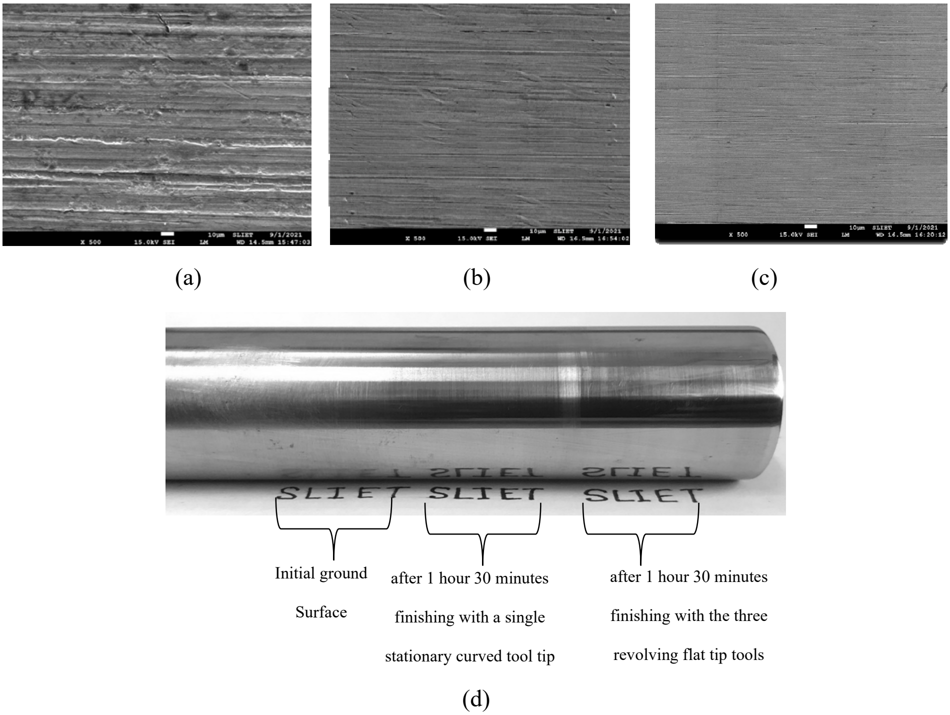
(a)

(b)

(c)

SEM images have been captured with the JEOL’s JSM-7610FPlus model at 500× magnification. Figure 8(a) shows the SEM image of the primary external surface of the cylindrical workpiece, and Figures 8(b) and 8(c) show the image of the external surface of the mild steel workpiece after 1 hour 30 minutes of magnetorheological finishing with a fixed curved tip tool process and three revolving flat tip tools process. As seen in Figure 8(a), grinding marks and scratches have been seen on the initial surface of the mild steel workpiece. Figures 8(b) and 8(c) show the improved surface quality of the external surface of the cylindrical workpiece after applying the magnetorheological finishing process with a stationary curved tip tool and the three revolving flat tip tools for 1 hour 30 minutes. Additionally, a mirror reflection test has also been done, as shown in Figure 8(d). The reflection test evaluates the mild steel shaft surface appearance. This test shows the changes in the appearance of the mild steel shaft’s surface before and after the MR finishing. Figure 8(d) illustrate reflection test images of the mild steel shaft’s primary ground surface and after magnetorheological finishing surface, respectively. A white sheet with the word ‘SLIET’ is placed in front of the mild steel shaft for the reflection test. Figure 8(d) displays the inscription ‘SLIET’ reflected on the mild steel shaft’s original ground surface. Due to the grinding marks and scratches, the word ‘SLIET’ is unreadable. After MR finishing, the grinding layers are reduced, resulting in a smooth surface. Figure 8(d) shows that the word ‘SLIET’ is clearly visible on the nicely polished mild steel shaft after finishing both processes for 1 hour and 30 minutes. The word ‘SLIET’ reflects more clearly on the shaft’s area where the finishing has been done with the three flat tip tools process. After finishing with a stationary curved tip tool and three revolving flat tip tools for 1 hour and 30 minutes, the reflection image test shows that the three revolving flat tip tools process produces better surface characteristics with the same experimental parameters and conditions. Surface roughness profiles, SEM and mirror-image studies demonstrate a considerable improvement in finishing the cylindrical mild steel workpiece external surface with the three revolving flat tip tools than a stationary curved tip tool under identical experimental circumstances. Thus, it confirmed that the new magnetorheological finishing method using revolving flat tip tools is more effective than the stationary curved tip tool for completing exterior cylindrical surfaces. Aside from that, the newly developed method is suited for the nano finishing of machines and equipment parts, hydraulic and pneumatics industry parts, pump and motors shafts industry, automobile transmission components, and marine industry.

Figure 8 SEM images of (a) primary surface of the cylindrical workpiece after the grinding operation (b) after 1 hour 30 minutes finishing with a single stationary curved tip tool process (c) after 1 hour 30 minutes finishing with the three revolving flat tip tools process (d) image of the workpiece which has been showing the mirror image of the text ‘SLIET’ before and after the finishing both methods at different places



4 Conclusions

Magnetorheological process based on the three revolving flat tip tools has been successfully developed to provide superfinishing operation to the external cylindrical surfaces. The following conclusions are observed during the experimentation analysis.

- The rotation of flat tip tools around the mild steel workpiece generates a more tangential force. The reciprocating speed of the workpiece produces the axial force on the active abrasive particles, which considerably influences the rate of material removal and finish quality.
- After finishing the operation, the average roughness of the mild steel external cylindrical workpiece reduced from 0.684 μm to 0.21 μm for 1 hour 30 minutes cycle with a stationary curved tip tool process.
- After finishing the operation, the average roughness of the mild steel external cylindrical workpiece reduced from 0.684 μm to 0.10 μm for 1 hour 30 minutes with the three revolving flat tip tools process.
- Surface roughness profiles, SEM photographs, and reflection images show significant improvements in the surface characteristics for the revolving flat tip tools magnetorheological process compared to the stationary curved tip tool magnetorheological process.
- Investigation of magnetorheological finishing should be on materials such as ceramics, polymers, and composites used in a wide range of industrial applications. The MR finishing method should also be used to finish industrial applications with multi-grooves or complicated shapes.

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