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Performance Evaluation of Improved Ball End Magnetorheological Finishing Process

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Abstract**—**A novel nanofinishing process using improved ball end magnetorheological (MR) finishing tool was developed for finishing of flat as well as 3D surfaces of ferromagnetic and non ferromagnetic workpieces. In this process a magnetically controlled ball end of smart MR polishing fluid is generated at the tip surface of the tool which is used as a finishing medium and it is guided to follow the surface to be finished through computer controlled 3-axes motion controller. The experiments were performed on ferromagnetic workpiece surface in the developed MR finishing setup to study the effect of finishing time on final surface roughness. The performance of present finishing process on final finished surface roughness was studied. The surface morphology was observed under scanning electron microscopy and atomic force microscope. The final surface finish was obtained as low as 19.7 nm from the initial surface roughness of 142.9 nm. The outcome of newly developed finishing process can be found useful in its applications in aerospace, automotive, dies and molds manufacturing industries, semiconductor and optics machining etc.

Keywords**—**Ball end MR finishing tool, Magnetorheological finishing, Nanofinishing

I. Introduction

THE surface roughness plays an important role in product quality, precision fits and high-strength applications and polishing of brittle materials is highly demanded [1, 2].The conventional polishing process can lead to the formation of damage sites on workpiece surfaces. Such damage sites result from both surface and subsurface mechanical damage that is inherent to the high normal loads associated with conventional lap polishing [3]. Magnetorheological finishing (MRF) was invented and developed by an international group of collaborators at the Center for Optics Manufacturing (COM) in the mid-1990s [4], and commercialized by QED Technologies, Inc. in 1997 [5]. MRF has been described as an advanced polishing technique that can finish optics without propagating the subsurface damage layer [6, 7]. The removal of subsurface damage using MRF can be attributed to the small normal stress applied to the glass surface compared to large shear stress which is created by the interaction of the tool's magnetic field and the magnetorheological polishing (MRP) fluid through the converging gap [8]. MR fluids are the key element of MRF technology. In general, MR polishing fluids consist of magnetic carbonyl iron powder (CIP), polishing abrasives, carrier fluid, and stabilizers. Properties such as plasticity, elasticity, and apparent viscosity change with the application of magnetic field. MRF is used to precision finishing of concave, convex, flat and aspherical optical components [9]. Recently, authors have designed and developed a nanofinishing process using ball end MR finishing tool which was already reported [10].This is used for finishing of flat as well as 3D surfaces of ferromagnetic and non ferromagnetic materials. The MR finishing tool was comprised of concentrically placed inner core, electromagnet coil and outer core and it rotates as a whole during the finishing operation. In this design there were no any cooling coils applied over the outer surface of electromagnet coil due to its rotational motion.

The improved ball end magnetorheological finishing tool has been used for the present MR finishing process (Fig.1). It comprises of a central rotating core, stationary electromagnet coil and further copper cooling coils integrated over the outer surface of the stationary electromagnet coil to cool it continuously. The cooling medium is supplied by low temperature bath. The two ball bearings, timing pulley and rotary valve are mounted on the MR finishing tool. A magnetically generated stiffened ball end of MRP-fluid at the tip surface of tool was used as a finishing medium. The main advantage of the tool design is in flow of intermittent pressurized MRP-fluid through centre of the tool core and gets stiffened controlled ball end shape of MRP-fluid at the tip of the tool. The flow of MRP- fluid at the tip of tool is intermittent during the finish operation. Whenever MRP- fluid is required to be conditioned after certain period of finishing operation then only it flows at the tip surface of the tool. Otherwise the already formed stiffen ball end of MRP-fluid is used continuously for finishing operation. The conditioning of MRP-fluid at the tip surface of the tool can be done by replenishing fresh MRP-fluid.

The MR finishing tool tip with stiffened ball end of MRP-fluid can be easily made reachable for the different 3D surface profiles. The vertical tapered tool tip with stiffened ball end of MRP-fluid has flexibility to move over different kinds of 3D surfaces in a workpiece such as grooves, in-depth pocket or projections at different angles with help of computer controlled program. This is the key benefits of the present finishing process. These surfaces in workpiece are inaccessible for finishing by regular MRF process where finishing tool is a rotating wheel of bigger size. The developed process can finish the work piece surfaces similar to the machining of 3D surfaces by CNC ball end milling process. The newly developed finishing process has found its potential

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applications in aerospace, automotive, dies and molds manufacturing industries, semiconductor and optics machining etc.

A photograph of improved ball end magnetorheological finishing setup as per the developed design is shown in Fig.1. The MR finishing tool is a main part of the newly developed ball end magnetorheological finishing process. This is attached on the XYZ movement table. Its orientation was kept vertically on Z-slide such that the tip side of the tool can approach the surface of a work piece and driven by a servo motor. A computer integrated motion controller is developed to precisely control the rotational speed of central rotating core. The workpiece holder includes a rectangular platform mounted on X-Y linear slides. Three stepper motors were used for controlling the linear motion in X-Y-Z directions, where as the X - Y direction motion controllers are used for controlling the horizontal linear motion of workpiece and Z motion controller is used for controlling the vertical linear motion of MR finishing tool. The MR polishing fluid delivery system comprises of a storage tank (funnel shape) along with speed controlled stirrer and a delivery peristaltic pump for supplying MRP-fluid from the storage tank to the MR finishing tool. An AC Variable Frequency Drive (VFD) is used to vary the speed of peristaltic pump.

Fig. 2 describes schematically the mechanism of ball end magnetorheological finishing process. The pressurized MRP-fluid enters axially from the top end of MR finishing tool. As soon as it reaches at tip surface of tool, the electromagnet become switched ON. The ferromagnetic carbonyl iron particles of MRP-fluid aligned along the direction of magnetic lines of forces and forms a stiffened structure whose physical texture was found like a wet clay ball end shape with very high apparent viscosity at tip surface of tool (Fig.3b). The magnetic field strength can be controlled by controlling the magnetizing current in real time and hence controls the stiffness of ball end of MRP-fluid at the tip surface of tool during finishing. The finishing action and feed direction on work surface is shown in Fig.3a. The amount of material sheared from the peaks of the work surface by abrasive grains depends on the bonding strength of stiffened ball end of MRP- fluid provided by magnetic field-induced structure of MR fluid. The non magnetic abrasive particles having cutting edges are tightly held between magnetic iron particles over the surface of stiffened ball end finishing spot of MRP-fluid. The polishing spot formed by MR particle chains with abrasive particles shears the peaks from the workpiece surface and hence appropriate finishing of work surfaces has been performed.

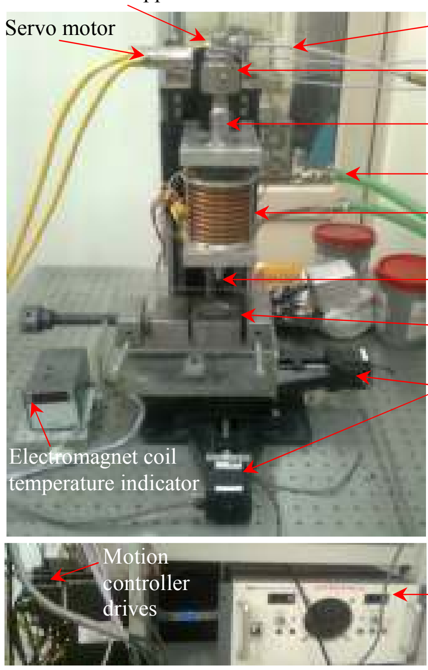

Fig.1 Photograph of the new MR finishing setup

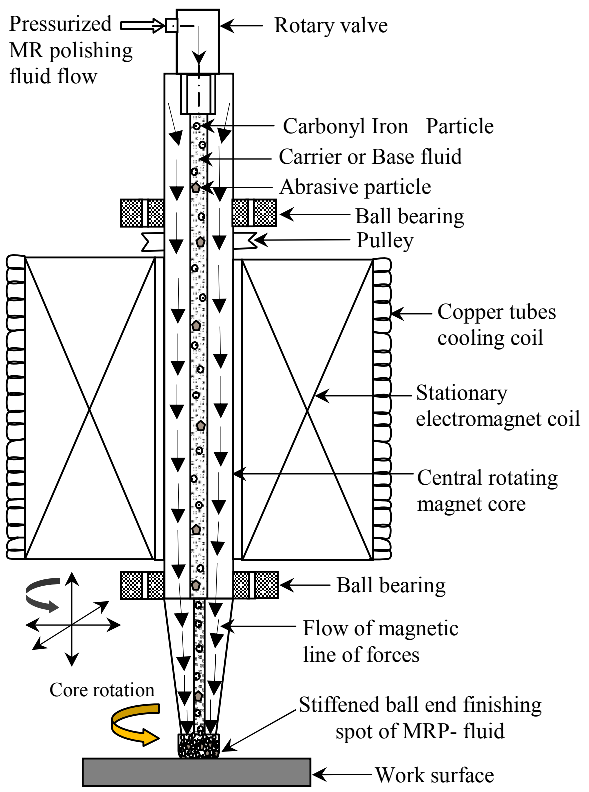

Fig. 2 Schematic of mechanism of ball end MR finishing process

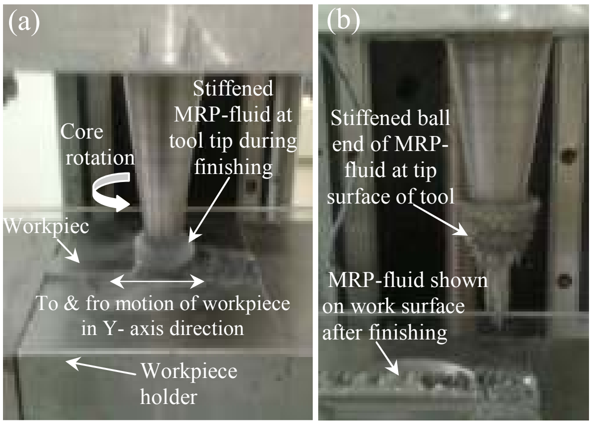

Fig. 3 Stiffened MRP- fluid at the tip surface of MR finishing tool is shown (a) during finishing on workpiece surface and (b)after finishing where electromagnet still kept ON

II. Experimentation

Experiments were performed on newly developed magnetorheological finishing experimental set-up as shown in Fig.1. In the present work, experiments were conducted on ferromagnetic workpiece and effect of finishing time on final surface finish was studied. The flat surface facilitates easy measurement and observations under SEM, AFM and Talysurf etc, therefore to examine the performance of present finishing process the experiments were conducted on ferromagnetic workpiece of size 70 x 10 x 4 mm. A suitable workpiece holder of die steel was made by milling a rectangular slot of the workpiece dimension. The workpiece was kept in a rectangular slot of workpiece holder and precision vice holds the workpiece holder tightly along with workpiece. The reciprocating motion to workpiece was given by Y movement of linear slide which is driven by computer controlled stepper motor (Fig. 3a). The top workpiece surface area of 50 x10 mm was finished. This was achieved by to & fro motion of workpiece in Y- axis direction at feed rate of 50 mm/min. The variation of surface roughness of workpiece was measured at every 30 min of finishing time. MR polishing (MRP) fluid was prepared indigenously by mixing the compositions as per the % volume concentration given in Table 1. The experimental parameters and conditions are reported in Table.2. The initial centre line average (CLA) surface roughness Ra of approximately 142.9 nm was obtained after grinding the workpiece on surface grinder. The surface roughness profiles were obtained by Taylor Hobson Talysurf and to understand the finished surface characteristics and texture, the Scanning Electron Microscope (SEM) and atomic force microscope (AFM) were used.

III. Result and discussion

Fig. 4 shows the effect of finishing time on surface roughness value of a workpiece measured at every 30 min during the present MR finishing. The first experiment was

TABLE I
COMPOSITION OF SYNTHESIZED MR POLISHING FLUID

Sl. No.	Constituent	% Volume concentration
1	carbonyl iron powder of CS grade	20
2	abrasives silicon carbide (SiC) of mesh size 800	20
3	base fluid paraffin oil plus AP3 grease	60

TABLE II
EXPERIMENTAL PARAMETERS AND CONDITIONS

Sl. No.	Parameters	Conditions
1	each finishing cycle time	30 min
2	abrasives silicon carbide (SiC) powder mesh number	800
3	constant feed rate to workpiece for reciprocating motion	50 mm/min
4	rotational speed of central core	500 rpm
5	magnetizing current	4A
6	working gap	0.66 mm
7	workpiece material	ferromagnetic

conducted for the finishing time of 30 min on ferromagnetic workpiece as per the experimental conditions given in Table 2. It has been found that surface roughness of workpiece was decreased significantly from initial values R_a= 142.9 nm to R_a= 27.6 nm as shown in the Fig.4. This significant change in surface roughness value demonstrates the finishing capability of newly developed finishing device on ferromagnetic workpiece.

The same workpiece was used for all experiments and successive polishing was done. The final surface roughness obtained after previous experiment was taken as initial roughness value for next experiment. The second experiment was performed for the further finishing time of 30 min. The surface roughness of the workpiece was found little increased to R_a= 28.9 nm from previous measured value R_a= 27.6 nm as shown in the Fig.4.It was observed that the measured value of surface roughness decreases for first 30 min of finishing and then little increases for the next 30 min of finishing. This may be due to some ploughed material left in craters of workpiece during surface grinding were not completely removed in first 30 min of finishing. When these ploughed material has been completely removed the actual craters and grinding marks are exposed for measurement resulting in little increased Ra after 30 min of finishing. The details about the effect of the ploughed material left during surface grinding have been already reported by Jha and Jain [11].

The further third experiment was performed for the further finishing of 30 min as per the conditions given in Table 2 The surface roughness of the workpiece was found decreased to R_a= 23.3 nm from previous measured value R_a= 28.9 nm as shown in Fig.4. In this finishing cycle the actual exposes peaks and grinding marks have been removed. Hence results in reduction in R_a value.Again next experiment was carried out for further finishing of 30 min. The surface roughness of the workpiece was found further decreased to R_a= 19.7 nm from previous measured value R_a= 23.3 nm as shown in Fig.4. The most of the peaks got sheared resulting in reduction of Ra value significantly. The surface gets flattened with small sharp peaks and few valleys left out are clearly visible in Fig.5. The surface obtained for this finishing cycle with low Ra is the actual finished surface with reduced peaks and grinding marks.

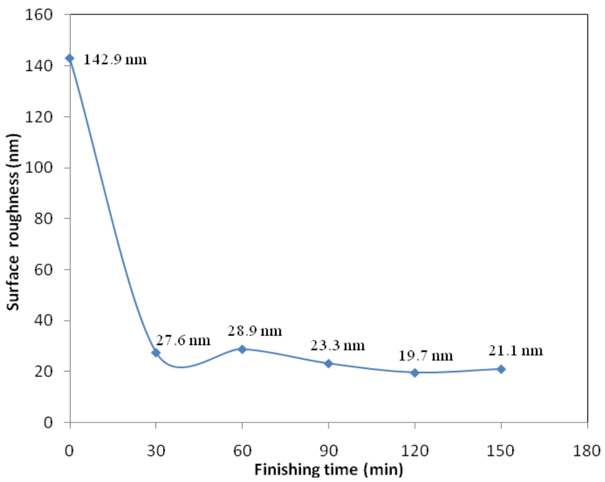

Fig. 4 Effect of finishing time on surface roughness value of ferromagnetic work piece

Again further trial experiment was performed for the next 30 min of finishing. In this trial, the surface roughness of the workpiece was found little increased to R_a= 21.1 nm from previous measured value R_a= 19.7 nm as shown in the Fig.4 This may due to the sharp cutting edges of SiC abrasive may start deteriorating the finished surface of workpiece resulting little increase in Ra value. It means that surface finish with SiC800 abrasive is saturated for 120 min of finishing for a given conditions (Table 2). Therefore, the performance of present finishing process on final surface roughness was found to reduce up to 19.7 nm for 120 min of finishing of a given conditions. After that, the performance start decreasing in terms of deteriorate finished surface with increased in R_a for a given conditions. But further improvement in performance may be possible to reduce R_a value without deteriorating the finished surface. For this, it may require fine SiC abrasives whose particles size less than the present SiC. Also it may require some gentle experimental conditions to perform further finishing. Hence, the left over finishing abrasive marks can be removed even after finishing of 120 min without deteriorating the finished surface of workpiece.

The surface roughness profile of a workpiece before, and after final finishing by improved ball end MR finishing process is shown in Figs.5 (a) and (b) respectively. It can be seen that the surface roughness of the workpiece is reduced from 142.9 nm to 19.7 nm after 120 min of finishing with continuous cooling of electromagnet. The surface morphology of workpiece was observed by using scanning electron microscopy (SEM) at 1000x was measured for initial and final surface of a workpiece as shown in Fig.6 (a) and (b) respectively and it can be seen that there is better improvement in surface characteristic of finished surface as compared to initial surface of a workpiece. It was also observed that some left over fine finishing abrasives marks was seen on the finished surface.

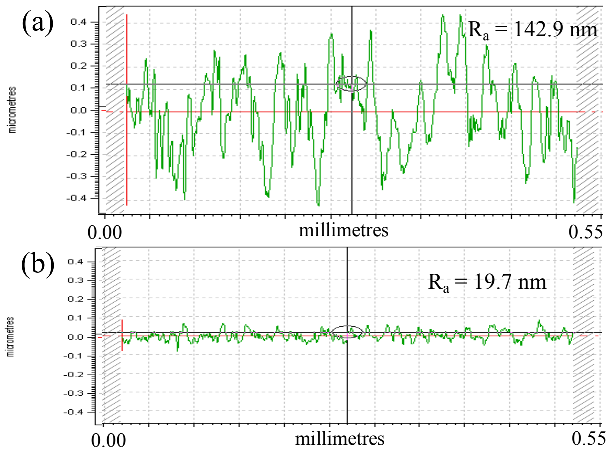

Fig. 5 Surface roughness profile of (a) initial workpiece surface and (b) finished surface after 120 min of ball end MR finishing process

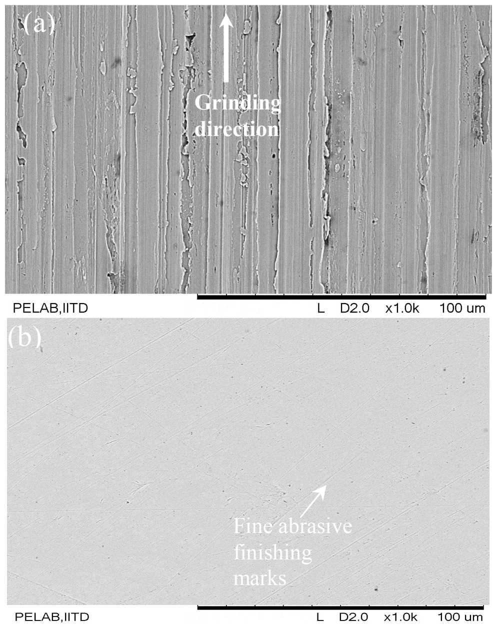

Fig. 6 SEM micrograph at 1000 x (a) initial surface and (b) finished surface after ball end MR finishing process with 120 min of finishing time

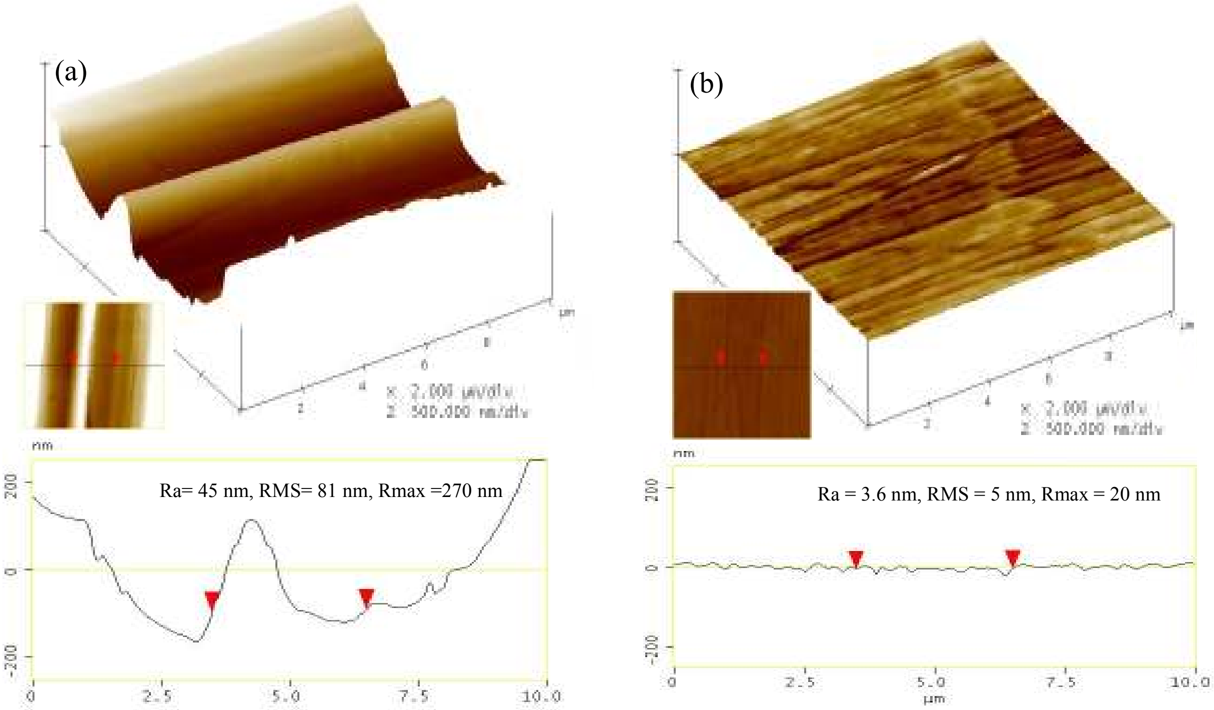

Fig.7 AFM images for workpiece surface: (a) initial, (b) after 120 min of finishing for current 4A, gap 0.66mm, and rotational speed 500 rpm

Fig.7 shows the atomic force microscopy (AFM) images before and after final finishing by improved ball end magnetorheological finishing process. It can be seen that the surface quality improved significantly and the workpiece surface got flattened with some small sharp peaks and few valleys left out which were clearly visible in AFM images. Therefore, the improved ball end MR finishing process demonstrates ability to finish the work surface with continuous cooling of electromagnet and stable rotation of central tool core inside the stationary electromagnet coil.

IV. Conclusion

The performance of improved ball end MR finishing process is successfully demonstrated on ferromagnetic workpiece with continuous cooling of electromagnet and smooth rotation of tool tip. The surface roughness of ferromagnetic workpiece was reduced to 19.7 nm from 142.9 nm with 120 min of finishing. The ability of newly developed ball end MR finishing tool to reduce surface roughness and improve the surface characteristics of a workpiece is demonstrated. This confirms that the present finishing process is capable to perform nanofinishing on ferromagnetic workpiece.

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