Effect of Polishing Fluid Composition on Forces in Ball End Magnetorheological Finishing Process

Z. Alam, D.A. Khan, F. Iqbal and S. Jha[*]

Department of Mechanical Engineering
Indian Institute of Technology, Delhi - 110016, INDIA

Abstract

Ball end magnetorheological finishing (BEMRF) is a nanofinishing process used for fine finishing of flat as well as complex 3D surfaces of a variety of materials. In magnetically energized state, magnetorheological polishing (MRP) fluid containing carbonyl iron particles (CIPs) and polishing grade abrasives is used to remove materials from the workpiece surface. The composition of the MRP fluid greatly influences the forces during the finishing process. Using a dynamometer both normal and shear forces applied by the MRP are recorded on-line. A central composite design of experiments is used to plan the experiments and ANOVA to correlate these forces and process parameters. The process parameters selected here are vol.% of CIPs and vol.% of abrasives which are varied from 5% to 25% and 5% to 20% respectively to measure the forces during experimentation. Both normal and shear forces increase with increase in the CIPs content in the fluid. This is because higher concentration of CIPs increases the magnetic permeability of the MRP fluid making it stiffer when exposed to magnetic field. In case of abrasive concentration it is observed that the forces initially increase with increase in abrasive content but begins to decline after a certain point. The hypothesis behind this is that initially the increased abrasives fill the void between the CIPs chains and strengthens the chain structure of the fluid. However beyond a certain point increased number of abrasives hinders the chain formation leading to the increase in number of broken chains. This decreases the forces during finishing.

Keywords: Magnetorheological, Polishing Fluid, Smart Fluid, Nanofinishing, Finishing Forces, Ball End.

1. INTRODUCTION

Surfaces with nanometer level of finish are prime requirement for today’s precision based industries. Owing to their excellent properties these highly-finished products caters to a variety of industries like aerospace, automobile, biomedical, electronics, etc. However realization of these products by traditional finishing process is extremely difficult. The traditional finishing process does not provide any control of the finishing forces acting on the working surface. The excessive forces lead to surface damages and residual stresses. To overcome this problem of uncontrolled normal force acting on the workpiece surface during finishing process, researchers have come up with various advanced finishing process in the last two decades. One among them is the ball end magnetorheological finishing (BEMRF) process [1] which relies on the smart behaviour of magnetorheological fluids to precisely control the finishing force.

BEMRF process has been successfully used for nanofinishing of a wide variety of materials that include both ferromagnetic [2] and nonmagnetic substances [3-6]. The finishing medium used in this process consists of a mixture carbonyl iron particles (CIPs) and abrasives in carrier fluid and is known as magnetorheological polishing (MRP) fluid. The working principle and material removal mechanism associated with the BEMRF process is shown in Fig. 1. A magnetic pole is formed at the tool tip when the electromagnet around it is energized. This magnetic pole induces the ferromagnetic workpiece below it and an opposite pole is formed at the top surface of the workpiece [7]. It leads to the development of a strong magnetic field in the working gap between the tool tip and the workpiece surface. Due to this the MRP fluid present in the working gap changes its rheology from Newtonian fluid to viscoplastic fluid and becomes stiff [8]. The CIPs cluster along field lines and grip the abrasives between them. Also as compared to the workpiece surface, the tool tip is nearer to the electromagnet and hence the flux density near the tool tip is higher than that near the workpiece surface. This gradient in flux density causes the CIPs to move towards the tool tip and in the process of doing so push the abrasives towards the workpiece surface [9]. Gripped by the CIPs chains the active abrasives in contact with the workpiece surface perform the micro-cutting of the roughness peaks. Two types of forces are associated with the material removal mechanism of the BEMRF process. While the normal force acting on the abrasive particle comes from the magnetic CIPs, the shear force is due to the yield strength of the MRP fluid.

From the BEMRF process mechanism it is clear that the forces are directly linked to the constituents of the MRP fluid. However the exact nature of the influence of these constituents on the finishing forces involved in BEMRF process are not known. In the past researchers have tried to study and investigate forces on other magnetorheological (MR) fluid based finishing processes but experimental investigations into effect of MRP fluid composition on forces associated with BEMRF process is scarce. Finishing with nano diamond abrasive particles by magnetorheological finishing (MRF) process DeGroote et al. [10] found the drag forces to increase linearly with abrasive concentration level. However Shorey et al. [11] reported a contrary trend showing decrease in the value of drag forces with increase in abrasive concentration. Jung et al. [12] studied the effect centrifugal forces on surface roughness due to the rotation of the wheel in MRF process. An experimental based study conducted by Sidpara and Jain [13] on magnetorheological fluid based finishing (MRFF) process revealed that the normal and tangential forces depended primarily on the working gap followed by concentration of CIP and wheel speed. Theoretical models for normal and tangential forces were also predicted by Sidpara and Jain [14] and Alam and Jha [7] for MRFF and BEMRF processes respectively. Singh et al. [15] also proposed material removal mechanism and normal force associated with the working gap in BEMRF

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[*] Email: suniljha@mech.iitd.ac.in

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process. The above literature survey reveals limited study on the effect of fluid composition parameters on forces in BEMRF process. In the present work an attempt has been made to see the effect of MRP fluid constituents (CIPs and abrasives) on both normal and shear forces.

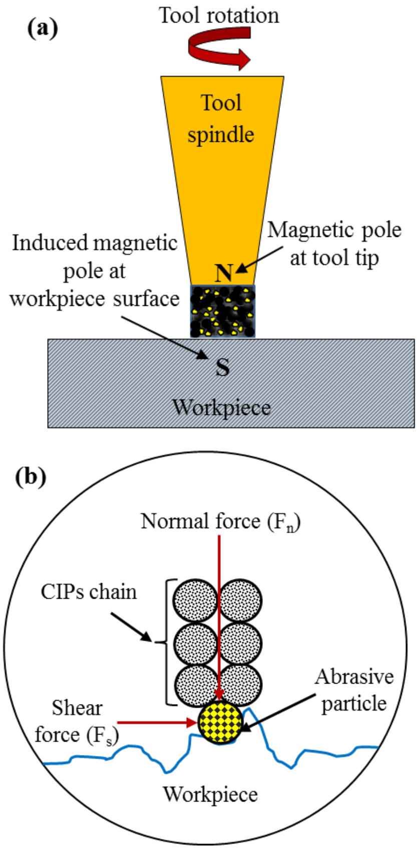

Fig. 1. Schematic diagram of (a) BEMRF process and (b) material removal mechanism

2. EXPERIMENTATION

Although BEMRF process is used for a variety of materials, in this study mild steel is selected as workpiece material. A disc shaped workpiece with 35 mm diameter and 5 mm thiskness is prepared on a lathe machine and hand grinded to prepare the initial surface for experimentation. The constituents of the MRP fluid are silicon carbide (SiC) of #800 mesh size, CIPs of CS grade and carrier medium consisting of grease and heavy paraffin oil. A constant machining parameters was employed for all the experiments. The selected machining parameters for this study are: 5 amperes direct current (DC) supplied to the electromagnet tool, working gap of 0.9 mm, spindle rotational speed of 200 rpm and feed rate of 10 mm/min.

All the experiments are performed on a 3-axis CNC BEMRF machine where the electromagnet tool assembly is mounted on the vertical Z axis and the workpiece is placed on the horizontal X-Y table [16]. A 'Schunk' made dynamometer is mounted below the workpiece fixture and is used to record the forces acting on the workpiece surface as shown in Fig. 2. Both normal and shear forces are simultaneously measured. The measurement of forces was started before the energized fluid makes contact with the workpiece surface and continued till it pressed against the surface at a certain working gap and started rotating thereafter. Initially when the MRP fluid is pressed against the workpiece surface a higher value of normal force is recorded which gets stabilized when the tool spindle stars rotating and the excess fluid is squeezed out of the working gap. For analysis, the value of stabilized forces after the start of tool spindle rotation is considered. Figure 3 shows a sample graph of the force measurement data for both the forces.

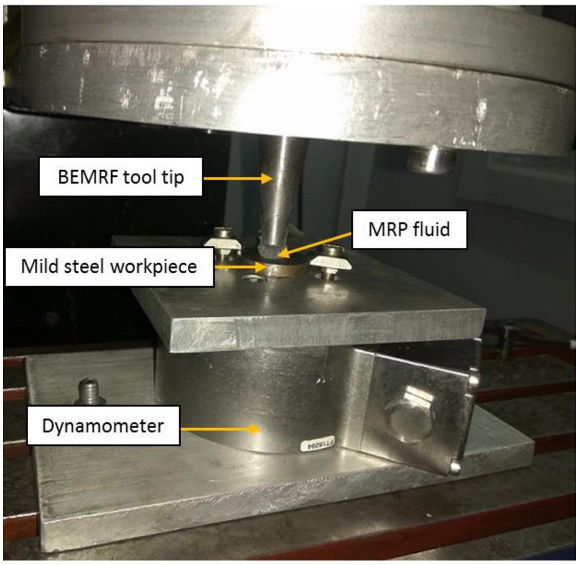

Fig. 2. BEMRF setup with dynamometer

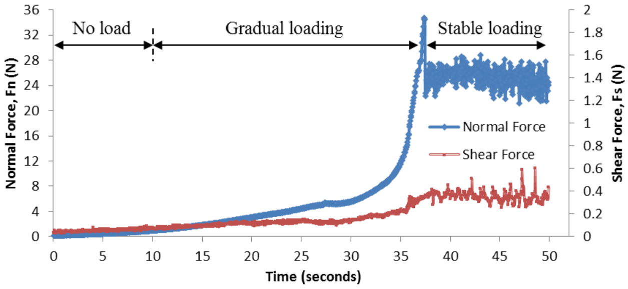

Fig. 3. Force measurement for normal and shear force

2.1 Design of Experiments

The process parameters selected here are vol.% of CIPs (C) and vol.% of SiC abrasives (A) which are varied from 5% to 25% and 5% to 20% respectively to measure the forces during experimentation. The upper limit of the constituents (25 vol.% CIPs and 20 vol.% abrasives) are chosen so that the fluidity of the MRP fluid is maintained. The actual values of the process parameters distributed in five levels are shown in table 1. A central composite design technique was used for experimentation and a total of 13 readings for both the forces were recorded and compiled in table 2.

Table 1 Levels of process parameters and their absolute values

Parameters	Levels				
	-1.414	-1	0	1	1.414
CIPs *C* (vol.%)	5	8	15	22	25
Abrasive *A* (vol.%)	5	7.2	12.5	17.8	20

The response (F_n and F_s) as a function of the input variables (vol.% of CIPs and vol.% of abrasives (SiC)) are given by quadratic equations (Eqs. (1) and (2)) having very good coefficient of correlation ($R^2 = 0.98$ for normal force, F_n and $R^2 = 0.96$ for shear force, F_s). Within the selected range of the above process parameters, these equations can be used to obtain forces against any absolute values of the process parameters.

$$F_n = -14.88 + 1.758C + 3A - 0.02891C^2 - 0.1251A^2 \quad (1)$$

$$F_s = -0.273 + 0.0467C + 0.0557A - 0.000719C^2 - 0.002323A^2 \quad (2)$$

Table 2 Summary of responses

S. No.	CIPs (vol.%)	Abrasive (vol.%)	Normal force (F_n)	Shear force (F_s)
1.	8.0	7.2	11.84	0.30
2.	22.0	7.2	24.67	0.67
3.	8.0	17.8	10.67	0.27
4.	22.0	17.8	23.52	0.64
5.	5.0	12.5	11.86	0.32
6.	25.0	12.5	28.96	0.79
7.	15.0	5.0	17.31	0.51
8.	15.0	20.0	15.12	0.48
9.	15.0	12.5	22.84	0.59
10.	15.0	12.5	22.14	0.61
11.	15.0	12.5	23.90	0.58
12.	15.0	12.5	21.94	0.57
13.	15.0	12.5	23.80	0.64

3. RESULTS AND DISCUSSION

The effect of various compositions of MRP fluid i.e. vol.% of CIPs and abrasives on normal and shear force during finishing of mild steel workpiece is discussed in the following sub-sections.

3.1 Effect of CIPs concentration

The effect of CIPs concentration on normal and shear forces is shown in Fig. 4. In the figure it is seen that both the forces increase with the increase in the CIPs concentration. CIPs play a crucial role in BEMRF process. They are responsible for providing the magnetorheological effect to the MRP fluid used in this process. The magnetic permeability of the ferromagnetic CIPs causes the formation of small dipole when energized by the BEMRF tool's electromagnet. The micron sized dipoles cluster along field lines to provide the stiffness to the MRP fluid. Greater the number of CIPs, higher is the width and strength of the chain-like-structure providing better stiffness to the MRP fluid. This leads to increased amount of normal and shear force being exerted on the workpiece surface.

When the concentration of CIPs is low in the MRP fluid, a thin chain of CIPs get aligned along the magnetic field lines. Therefore the bonding of the cross-linked chains of CIPs around the abrasive particle is not very strong [17]. This leads to decrease in both normal and shear forces. Furthermore, during finishing operations with low concentration of CIPs, the thin CIPs chains easily break and the loose abrasive does not provide the cutting action. Hence for effective nanofinishing operation a minimum value of CIPs concentration in MRP fluid is essential.

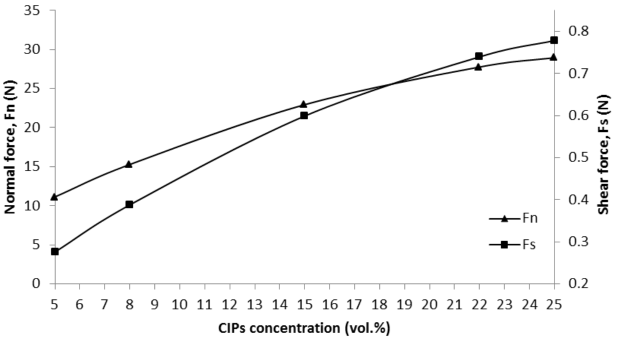

Fig. 4. Effect of CIPs concentration on normal force (Fn) and shear force (Fs) (at 12.5 vol.% abrasive concentration)

3.2 Effect of abrasive concentration

While the role of abrasives in material removal process is clearly established, its effect on forces in various magnetorheological processes is vaguely understood. Some researchers [10] have found the forces to increase with the increase in abrasive concentration while others [11] have reported a decreasing trend for the forces. In BEMRF process, the variation of the normal and shear force at different abrasive concentration in MRP fluid is shown in Fig. 5. In the present study, the concentration of abrasives is varied from 5% to 20%. It is observed that initially both the forces increase with increase in the abrasive concentration. However beyond a certain abrasive concentration (12.5 vol.%) the forces show a decreasing trend with further increase in the abrasive concentration value. The reason behind this is that initially for low abrasive concentration value when the amount of abrasives is increased, the abrasives fill the voids between the CIPs chains and increases the strength of the MRP fluid. This leads to increase in both the forces. However when the amount of abrasives are further increased the extra abrasives that get trapped between the CIPs chains increase the distance between two CIPs (R'). This reduces the magnetic interaction force between two CIPs as given by Eq. (3). Consequently the strength of the MRP fluid decreases leading to the drop in normal and shear force. The interaction magnetic force (F_{int}) between two CIPs is given as [18]

$$F_{int} = \frac{\mu_0 \pi}{9}\left(\frac{r^2 CM}{R'}\right)^2 \quad (3)$$

where r is the radius of a carbonyl iron particle, R' is the distance between the centers of two CIPs, M is the intensity of magnetization, μ_o is the permeability of free space and C is the collect coefficient (function of magnetic field strength H).

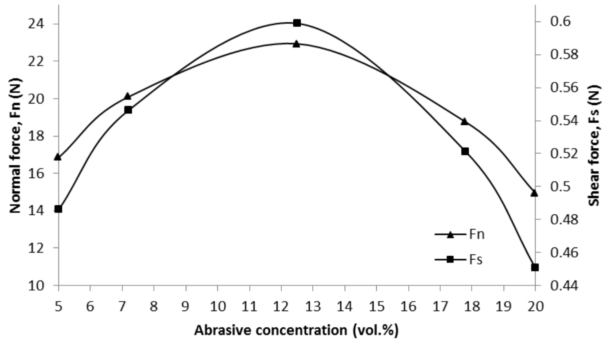

Fig. 5. Effect of abrasive concentration on normal force (Fn) and shear force (Fs) (at 15 vol.% abrasive concentration)

4. CONCLUSION

From the present study on the effect of MRP fluid composition on the forces in BEMRF process the following can be concluded.

- Experimentally it is found that both the parameters of MRP fluid composition (CIPs and abrasive) contribute significantly towards normal and shear force.
- To analyze the effect of input parameters on the response (normal and shear force) a total of 13 experiments are performed using the full factorial design scheme. The obtained quadratic models have a good correlation with the experimental values.
- Increase in the concentration of CIPs increases the magnetic permeability of the MRP fluid. Consequently the strength of the MRP fluid increases leading to greater forces being experienced by the workpiece surface.
- In case of abrasive concentration both forces increase up to a certain concentration value and then decreases. While the increase in forces are attributed to the strengthening of MRP fluid through filling of voids by abrasives, the decrease of forces beyond a certain limit is due to reduction of magnetic interaction force between two CIPs.

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