Experimental Investigations on the Effect of Relative Particle Sizes of Abrasive and Iron Powder in Polishing Fluid Composition for Ball End MR Finishing of Copper

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Abstract

Demand for ultra-finished copper mirrors is very high in defense and laser optics industries due to their high heat conductivity and high durability. These copper mirrors are made in simple as well as complex shapes to meet the optical needs of the applications. In ultra-finishing, soft materials require gentle finishing forces to achieve scratch free highest degree of surface quality. Ball end magnetorheological finishing (BEMRF) is an advanced finishing process that confirms both the requirements of today's optical industries i.e. finishing of complex surfaces and up to nanometer level of surface finish. The magnetorheological (MR) polishing fluid which is utilized in this process is a composition of abrasive and ferromagnetic particles in a carrier medium. In the magnetorheological effect the ferromagnetic particles magnetically polarize and arrange themselves in the form of chains in which the abrasive particles are gripped. In the present study it has been explored that the relative particle sizes of the abrasive (alumina) and the ferromagnetic substance (iron particles) affect the chain structure in the energized MR polishing fluid and in turn the quality of the surface finish achieved. The study has carried out over different MR polishing fluids composed of three different sizes of iron particles and five different sizes of polishing grade abrasives. The results of normal finishing force and surface roughness show that MR polishing fluid having iron powder of 300 mesh size and alumina powder of 1000 mesh size is a most suitable combination for best surface finishing on copper samples.

Keywords: Ball End, Magnetorheological, Surface, Roughness, Force, Iron Powder, Polishing Fluid.

1. INTRODUCTION

The finishing operation of a manufactured part is often considered as the most critical operation as it not only imparts visual appeal to the product but also determines the product's performance, quality and life span. In electronics and metal optics industries, highly finished copper is used as interconnect material and metallic mirrors respectively [1]. This is due to the natural quality that copper possess like good thermal conductivity, high reflectivity, high heat capacity and light weight etc. However finishing of copper up to nanometer level is an extremely challenging task [2, 3]. The traditional finishing processes, characterized by uncontrolled finishing force, are not suitable for nanofinishing of soft material like copper as they damage the finished surface. In loose abrasive finishing processes this high normal force causes the loose abrasives to embed and damage the finished surface [4-6].

Researchers have also come up several advanced finishing processes to finish soft materials like copper and aluminum but even these processes have some limitations or the other. Chemo-mechanical polishing (CMP) is often suitable for flat and less complex surfaces only. Moreover the chemical slurry used in the process not only reacts with the finished surface but also poses environmental concern related to its disposal [7]. Copper is also finished by single-point diamond turning (SPDT) process. Being essentially a turning process, it has two major limitations: one only axi-symmetric parts can be finished and the other is that the single point tool leaves concentric marks on the finished surface [8, 9]. In the past one decade magnetic-assisted finishing processes like magnetorheological finishing (MRF) [10], magnetic abrasive finishing (MAF) [11], and magnetorheological abrasive flow finishing (MRAFF) [12] have been used for nanofinishing of soft materials like copper. These processes have the advantage of very precise control of normal force through magnetic field strength. Again these processes are also limited by the fact that they also can be used to finish either flat or less complex surfaces only. Ball end magnetorheological (MR) finishing [13, 14] is a variant of MRF process which is used for nanofinishing of a variety of materials and is capable of finishing both flat and complex three-dimensional surfaces. In addition to it, precise control of finishing forces by altering the strength of magnetic field is also possible here [15].

In this process the finishing medium, known as magnetorheological polishing fluid (MRP), consists of a mixture of abrasives and ferromagnetic particles dispersed in carrier fluid. The pressurized MRP fluid is pumped through a hollow spindle and when it reaches the tool tip, the electromagnet is energized [16]. This leads to the formation of a stiff ball of MRP fluid at the tool tip. The stiffness of this fluid ball can be controlled through the magnetizing current supplied to the electromagnet. Schematically the ball end MR finishing process is shown in Fig. 1.

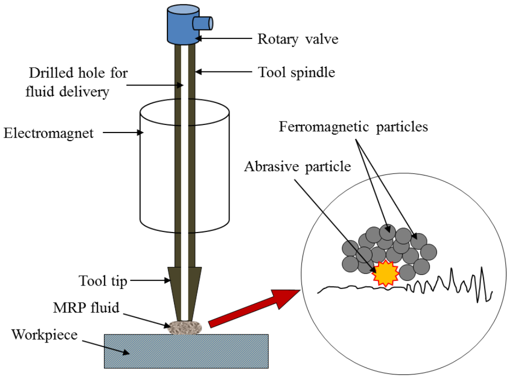

Fig. 1. Schematic representation of ball end MR finishing process

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In non-energized state the constituents of MRP fluid are randomly dispersed in the carrier medium but when magnetically energized, the ferromagnetic particles form chains and grip the abrasive between them [17]. This provides yield strength to the MRP fluid which in turn results in the required shear force for finishing operation. Normal force exerted by the abrasive on the workpiece surface is caused by magnetic levitation effect due to the difference in magnetic flux density between the tool tip and the workpiece surface [18]. In the present work copper is finished by the ball end MR finishing process and experimental investigations is carried out to study the variation in forces and surface roughness value on copper with relative sizes of abrasives and ferromagnetic particles used in MRP fluid.

2. EXPERIMENTATION

A three axis CNC ball end MR finishing machine, where the electromagnet tool assembly is mounted on the vertical Z axis and workpiece is kept on the linear X-Y slide, is used for performing the experiments. Oxygen free high conducting (OFHC) copper in the form of discs of 35 mm diameter and 6 mm thickness is used as the workpiece material. A permanent magnet of 0.5 Tesla is placed below the copper samples to enhance the magnetic flux in the working gap [2]. The constant machining parameters used for experimentation are: 6A direct current (DC) supplied to the electromagnet, 1.2 mm working gap, 300 rpm of tool spindle speed, 10 mm/min of table feed rate, 20 mm of finishing length and 32 minutes of finishing time (8 finishing cycles). The MRP fluids used in this study have a fixed 20:20:60 composition in which 20 vol.% of alumina and 20 vol.% of electrolytic iron powder (EIP) is mixed in 60 vol.% of carrier fluid (a mixure of heavy paraffin oil and grease). Also, to protect the copper samples from corrosion, 0.5 grams of benzotriazole (BTA) is added to per 100 ml of MRP fluid.

The relative size of the abrasives and EIP in the MRP fluid affect the finishing performance of the ball end MR finishing process. To analyze this effect of relative size, MRP fluids with combinations of different sizes of abrasives and EIP is prepared. The EIP of mesh size 200, 300, 400 and abrasive of mesh size 1000, 2000, 3000, 4000 and 5000 are chosen for the study. A total of 15 experiments were performed and the value of forces and surface roughness were recorded. The responses in the form of normal force and percent change in roughness at different relative sizes of EIP and abrasive particles is shown in table 1.

Table 1 Summary of responses

Sl. No.	EIP (mesh size)	Abrasive (mesh size)	Normal force (N)	Initial R_a, nm	Final R_a, nm	% ΔR_a
1.	200	1000	14.88	65.90	29.40	55.38
2.	200	2000	15.15	61.70	38.50	37.60
3.	200	3000	15.78	68.50	49.40	27.88
4.	200	4000	14.83	53.20	43.40	18.42
5.	200	5000	14.57	50.30	43.80	12.92
6.	300	1000	13.97	56.80	21.40	62.32
7.	300	2000	14.13	56.80	29.40	48.23
8.	300	3000	14.22	50.50	34.50	31.68
9.	300	4000	12.99	64.10	47.40	26.05
10.	300	5000	12.83	53.20	40.90	23.12
11.	400	1000	11.45	76.00	44.00	42.10
12.	400	2000	11.87	49.90	34.40	31.06
13.	400	3000	12.33	53.20	42.40	20.30
14.	400	4000	11.31	65.20	43.40	33.43
15.	400	5000	11.10	50.30	30.70	38.96

3. RESULTS AND DISCUSSION

The effect of relative sizes of constituents of MRP fluid i.e. abrasives and EIP on normal force and percent change in surface roughness during finishing of copper is discussed in the following sub-sections.

3.1 Effect of abrasive mesh size

The effect of abrasive mesh size on normal finishing force is shown in Fig. 2. Increasing the abrasive mesh size (from #1000 to #3000) increases the normal finishing force but after certain limit of abrasive mesh size (here #3000) the normal finishing force start decreasing on further increasing the abrasive mesh size. Abrasive mesh size has inverse relation with the abrasive grit size. So as the abrasive mesh size increases, the abrasive particle size decrease and abrasive become finer. The fine abrasive particles occupy the space between EIP chains when fluid is magnetized and results in dense columnar structure of MRP fluid. This energized fluid exerted higher normal force during the finishing operation. This is the reason that higher normal finishing forces are observed when abrasive mesh size is increased from 1000 to 3000 mesh size. At 3000 mesh size the normal finishing force was measured highest for all EIP mesh sizes. For abrasive mesh sizes from 3000 to 5000 the abrasive become so finer that during the process of chain formation the finer abrasive particles occupy the position in between EIP chains and obstruct the chains to become complete. These incomplete EIP chains results in weakening of the MRP fluid column. Due to this, with higher values of the abrasive mesh sizes, the normal finishing forces decreases.

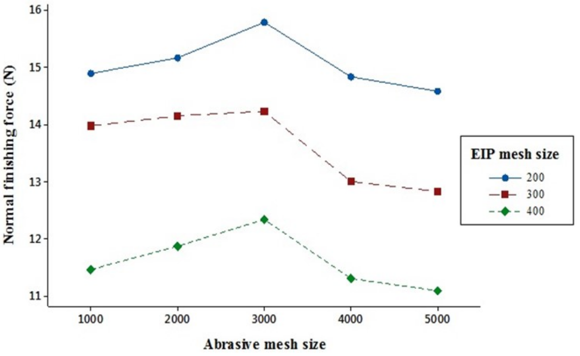

Fig. 2. Effect of abrasive mesh size on normal force

Figure 3 shows the effect of mesh size of abrasive on percent change in surface roughness (% $\Delta R_{a)}$ of copper surface. From the figure it is seen that for EIP of 200 and 300 mesh sizes the % ΔR_a decreases on increasing the abrasive mesh size. This is because the finer abrasive particles cut less material during finishing due to which % ΔR_a decreases. For EIP of 400 mesh size it was observed that for abrasive particles from 1000 to 3000 mesh size % ΔR_a decreases and from 3000 to 5000 mesh size % ΔR_a increases. The decreasing trend of % ΔR_a was observed due to less material removal because of low abrasive particle size. But as the abrasive particle size become more fine for 3000 to 5000 mesh size, the combination of finer abrasive sizes become so perfect with finer EIP that it increases the % ΔR_a. Again from Fig. 3 it is seen that the results of % ΔR_a for 300 mesh size EIP are better than 200 mesh size EIP for all values of abrasive mesh sizes. This could also be because of the combination of relative sizes of abrasive and EIP particles. The highest % ΔR_a was reported for the MRP fluid containing abrasive of 1000 mesh size and the EIP of 300 mesh size and the maximum change in surface roughness (% ΔR_a) was recorded as 62.32%.

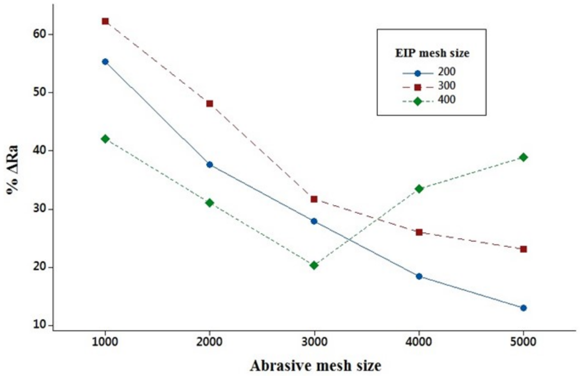

Fig. 3. Effect of abrasive mesh size on % ΔR_a

3.2 Effect of EIP mesh size

The effect of mesh size of EIP on normal finishing force is shown in Fig. 4. As the mesh value of EIP increase the particles become finer as explained earlier too. EIP is ferromagnetic in nature whose magnetization depends on the size of the particles. For the same intensity of magnetic field, the magnetization of bigger ferromagnetic particles is more as compared to smaller sized particles. Due to higher magnetization of the bigger EIP particles, the chains of EIP become dense as well as grow in length and width. This makes the MRP fluid stiff which results in higher normal force being exerted on the copper surface. Hence the normal finishing forces are more for decreasing values of EIP mesh size.

Figure 5 shows that % ΔR_a both increase and decrease (for some abrasive mesh size it increases and for others it increases and then decrease) on increasing the EIP mesh size even though the magnetization of EIP particles decreases on increasing the EIP mesh size. The hypothesis behind this is that the relative size of the abrasive particles and EIP play a crucial role in the strength of EIP chains in the magnetically energized state. The inter-particle distance between two EIP is totally dependent upon the size of the abrasive particle trapped in between. Hence the strength of the MRP fluid, responsible for micro-cutting of roughness peaks, depend upon the relative particle sizes of both abrasive and EIP.

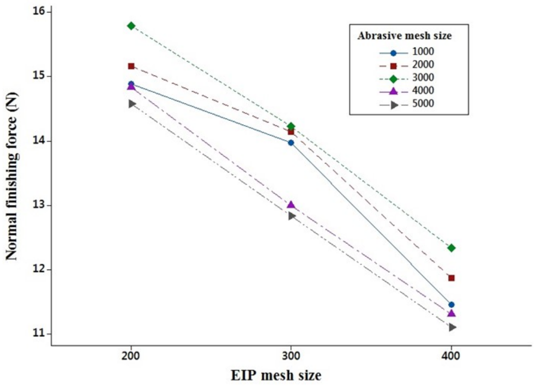

Fig. 4. Effect of EIP mesh size on normal force

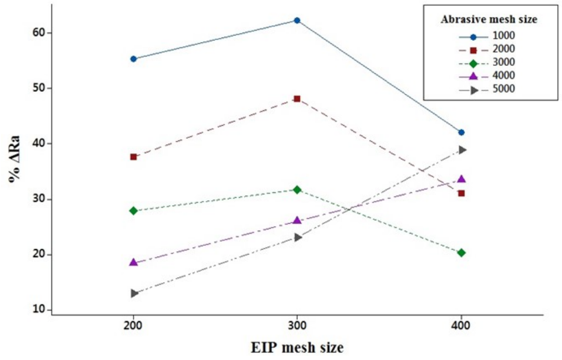

Fig. 5. Effect of EIP mesh size on % ΔR_a

4. CONCLUSION

From the experimental investigations carried out for effect of relative particle sizes of MRP fluid's constituents on finishing of copper by ball end MR finishing process, the following can be concluded.

- Two important parameters: normal finishing force and % ΔR_a are used as responses for this study. Both these factors are essential for finishing of soft material like copper.
- Normal force decreases with increase in EIP mesh size due to the decrease in magnetization of EIP particles. In case of abrasive mesh size, normal force increases and then decreases.
- While % ΔR_a decreases with increase in abrasive mesh size no fixed pattern is observed for EIP mesh size. This is because here the relative size of both abrasive and EIP contribute towards the strength of MRP fluid and effect cannot be studied in isolation.
- The best combination of abrasive and EIP particles is observed at 1000 and 300 mesh sizes respectively at which the maximum % ΔR_a of 62.32% was recorded.

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