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Effect of abrasive size and glue mass ratio on material removal and surface finish in magnetically driven internal finishing process

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Abstract

Magnetically driven internal finishing (MDIF) technique could effectively improve the inner surface finish of non-ferromagnetic parts. To further maximize the material removal rate of MDIF, magnetic polishing tools with various abrasive sizes and glue mass ratio were fabricated to polish AISI 316 stainless steel straight tubes in this study. Material removal rate and surface generation were evaluated in single point polishing experiments. Experimental results suggest that increasing abrasive size results in larger material removal rate and surface roughness. In addition, magnetic polishing tools with higher epoxy resin mass percentage could achieve higher material removal rate. A maximum material removal rate of 20.2 µm/min was achieved by employing a magnetic polishing tool with 75 µm SiC abrasive and 70:30 epoxy resin. The resultant surface roughness is 0.575 µm Ra and 3.278 µm Rz.This study provides a promising polishing tool for finishing the internal surfaces of metallic tubes with high efficiency.

Keywords: Internal finishing; magnetically driven finishing; material removal; surface finish

1. Introduction

Functional components with internal surfaces are widely used in aerospace, medical as well as mould and die industries, such as fuel injectors [1], biopsy needles [2] and cooling channels [3]. The surface finish of these internal surfaces plays an important role in the friction, fatigue, corrosion and fluid flow properties of those components [4–8]. Thus, surface finishing methods need to be conducted to reduce their surface roughness [9–11].

To improve the surface finish of internal surfaces, a number of techniques have been developed, including abrasive flow-based, fluidized bed based and magnetic-based methods [12]. Though these methods have been proven to readily finish internal surfaces or cavities with various geometries and materials, they may still encounter limitations such as uneven material removal rate, abrasive embedding, workpiece material dependency or low efficiency. Hence, Zhang et al. [13–15] proposed magnetically driven internal finishing (MDIF) and the corresponding magnetic polishing tool which has a strongly-bonded abrasive coating by epoxy resin glue adhesion. The fabrication process of this magnetic polishing tool was simple and did not require expensive magnetic abrasive particles (MAPs). The fixed-abrasive polishing tool increased the engagement of the abrasive abrasion process thus further increased material removal rate. Single point polishing experiments showed that an 82 % improvement of surface roughness was achieved within only 2 min polishing time. However, Zhang et al. [14] only validated the feasibility of the developed magnetic polishing tool in internal surface finishing in terms of surface finish and material removal rate by identical tools. The effect of tool fabrication parameters, such as abrasive size and glue mass ratio, on material removal rate and final surface finish has not been reported yet.

Hence, this paper aims to further investigate the polishing performance of magnetic polishing tools with different abrasive sizes and glue mass ratio so that a guidance of developing polishing tool with high material removal rate could be proposed.

2. Experiment

2.1. Principle of magnetically driven internal finishing

The working mechanism of the magnetically driven internal finishing technique is schematically illustrated in Figure 1(a). A magnetic polishing tool covered by bonded abrasive is placed inside a stainless steel tube workpiece which is clamped on Kistler 9256C dynamometer through a purposely designed aluminum fixture. The fixture keeps a distance between the workpiece and the steel dynamometer so that the magnetic field of the polishing tool will not be affected by the ferromagnetic dynamometer. A set of external magnets is rotated by a spindle and the spinning external magnets will drive the internal polishing tool to rotate as well. Abrasive on the tool surface will abrade the workpiece and remove asperities. The picture of the actual polishing setup is shown in Figure 1(b). It is noteworthy that half of the workpiece is cut by EDM for convenient observation and measurement, as seen in Figure 1(c).

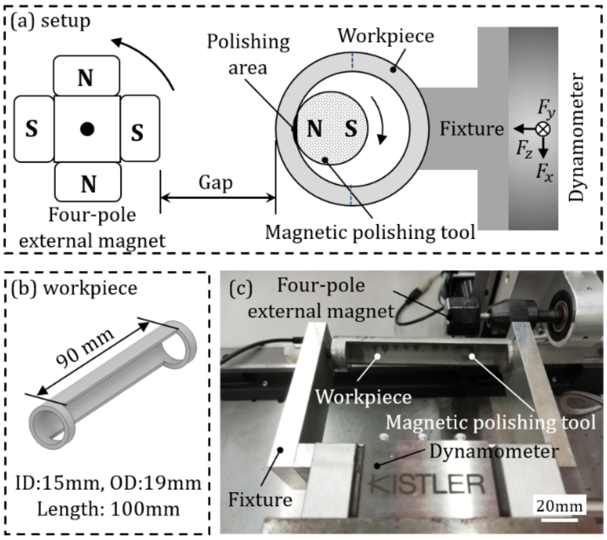

Figure 1 Polishing setup (a) schematic diagram, (b) actual setup and (c) AISI 316 stainless steel workpiece

2.2. Preparation of magnetic polishing tools

To fabricate magnetic polishing tools with evenly distributed abrasive coating, an in-lab fabrication process is developed. Firstly, a thin layer of epoxy resin glue is spread evenly to the surface of a sphere magnet. The glue contains two parts, i.e. epoxy resin A and curing agent B. Only by properly mixing A and B can the glue be cured and work. The mass ratio of A and B may affect the curing time and mechanical properties of solidified glue, such as impact strength, tensile energies-to-break and fracture toughness [16–18]. Secondly, the sphere magnet is put into a container with abrasive particles so that the abrasive will adhere to the magnet. To make the polishing tool round and ensure abrasive particles distributed uniformly, the polishing tool is constantly rolled between two flat plates. After rolling, the polishing tool is cured at room temperature until the epoxy resin glue solidifies thoroughly. The above process could be repeated to make multilayer polishing tools. The sphere magnet used in the experiments is NdB permanent magnet with an 8 mm diameter and N35 grade (Lifton Pte Ltd).

Two types of magnetic polishing tools are fabricated in this study, as presented in Table 1. Type I polishing tool is fabricated by changing abrasive size while keeping the mass ratio of epoxy resin A and curing agent B constant as 50:50. Mass of epoxy resin A and curing agent B is measured by an A&D GR-200 analytical balance with 0.1 mg resolution. Since silicon carbide (SiC) abrasive is usually used to polish stainless steels due to its moderate hardness and low cost [19–21], it is also employed in this study. The average diameters of SiC abrasive are 3, 36.5 and 75 µm, namely Group 1–3, respectively. Four identical polishing tools were fabricated for each abrasive size. The diameter of polishing tools is measured by a Vernier caliper at six different positions. The diameter deviations of fabricated tools are all within 0.06 mm and the abrasives are found to distribute uniformly on the tool surface. Type II polishing tool is made by changing epoxy resin and curing agent mass ratio while keeping the abrasive size constant as 36.5 µm. The mass ratios of epoxy resin A and curing agent B used in the experiment are 30:70, 40:60, 60:40 and 70:30, namely Group 4–7. Similarly, four polishing tools were made for each glue mass ratio and the average diameter of all Type II polishing tools is 8.24 mm ± 0.05 mm. Abrasive particle density on the fabricated Type II tools was measured and calculated by Keyence VHX-6000 digital microscope. The measurement results showed that no significant difference of abrasive particle density was found and the average abrasive particle density was $4.21 \pm 0.19 \times 10^8$ per m^2.

Table 1 Glue mass ratio and abrasive size of fabricated polishing tools

Tool type	Tool group	Glue mass ratio A:B	Abrasive size/µm
Type I	Group 1	50:50	3
	Group 2	50:50	36.5
	Group 3	50:50	75
Type II	Group 4	30:70	36.5
	Group 5	40:60	36.5
	Group 6	60:40	36.5
	Group 7	70:30	36.5

2.3. Experiment procedure

Two types of fabricated polishing tools were employed to finish AISI 316 stainless steel tubes with a 19-mm outer diameter (OD), 15-mm inner diameter (ID), and 100 mm length. The workpiece tube was made by extrusion and the average initial surface roughness Ra of the inner surface is 2.226 µm. The polishing conditions are shown in Table 2. During polishing, the polishing tools stayed at a single point on the workpiece surface without linear feeding, which is named single point polishing experiments. When the polishing experiments were finished, the workpiece tubes were cleaned with ethanol. The polished area was observed under Keyence digital microscope and measured crossing the centerline by a Tylor Hobson Talysurf Model 120 profilometer. A cutoff length of 0.25 mm was used for surface roughness measurement and three measurements were conducted for each polishing condition.

Table 2 Single point polishing conditions

Parameters	Values
Spindle speed/rpm	1600
External bar magnets	NdB bar magnet, 20 mm × 10 mm × 6 mm, Grade G50
Workpiece tube	OD 19 mm, ID 15 mm, L 100 mm
Initial surface roughness, Ra/µm	2.226
Initial surface roughness, Rz/µm	11.097
Gap distance/mm	11.5
Polishing time/minute	10

3. Results and discussion

3.1. Effect of abrasive size on material removal rate and surface finish

The three-dimensional profile of the polished area for different abrasive sizes is presented in Figure 2. It is seen that the polished area is a bent leaf-shape with good axisymmetry, which is confirmed by the centerline profile shown by the blue line in Figure 2. It is found that as abrasive size increases, the region of the polished area increases as well. Furthermore, the depth of the polished area also increases. However, abrasive size increase leads to high asperities on a polished surface, as seen in the surface roughness profile in the red line. The maximum depth of the centerline profile is used to characterize the material removal rate. The dependence of material removal rate and surface roughness Ra on abrasive size is quantitively plotted in Figure 3. It is found that both material removal rate and surface roughness increase proportional with abrasive size, which is consistent with conventional abrasive finishing theory. In addition, the maximum material removal rate of 18.1 µm/min is obtained with the 75-µm abrasive polishing tool and the minimum surface roughness Ra of 0.117 µm is obtained by the 3-µm abrasive polishing tool.

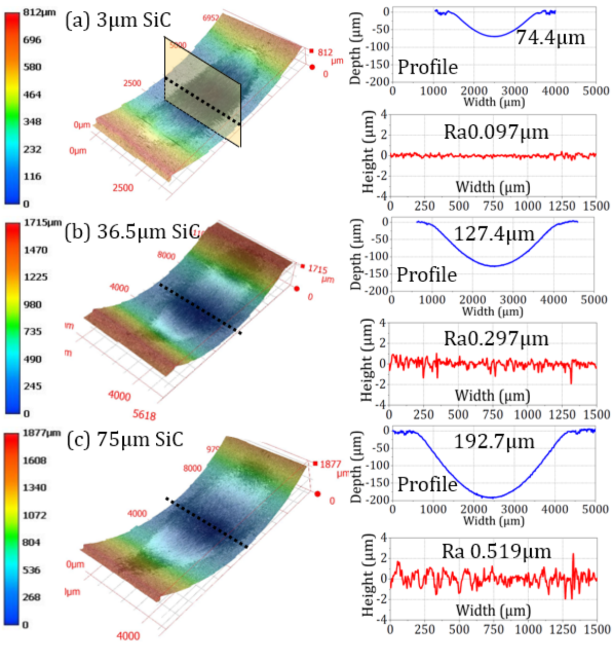

Figure 2 Surface roughness profile, three-dimensional and two-dimensional profile of polished footprint by magnetic polishing tool with (a) 3 µm SiC (b) 36.5 µm SiC and (c) 75 µm SiC abrasive coating

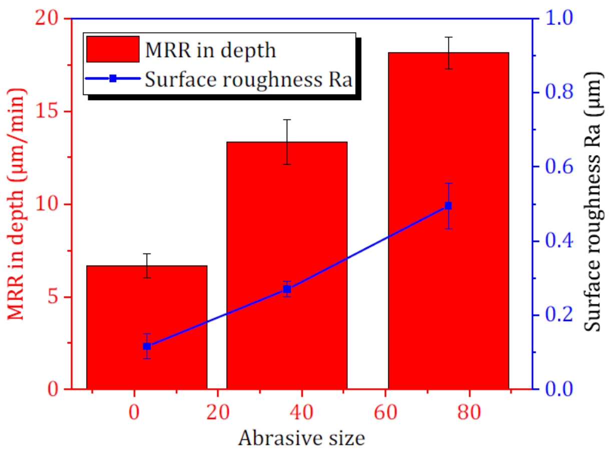

Figure 3 Dependence of material removal rate in depth and surface roughness Ra on the abrasive size

3.2. Effect of glue mass ratio on material removal rate and surface roughness

Figure 4 shows the dependence of material removal rate in depth and surface roughness Ra on glue mass ratio. It should be noted that the results of Group 3 (glue mass ratio: 50:50 and abrasive size: 36.5 µm) from abrasive size experiments were also incorporated so that the incremental of glue mass ratio was smooth. Results show that as the mass percentage of epoxy resin A increases, the material removal rate shows an increasing trend as well. Whereas, the surface roughness Ra first decreased and then increased slightly and reached a plateau when the mass percentage of epoxy resin was larger than 60 %. The dependence of material removal rate on glue mass ratio might be explained by analyzing the material removal mechanism of this polishing process, which could be regarded as an abrasive wear process. According to abrasive wear theory [22,23], the material removal volume V is expressed as:

$$V = \alpha\beta\frac{WL}{H_v} \tag{1}$$

where W is the normal load, L is sliding distance, H_v is the hardness of workpiece, α is the shape factor of an abrasive asperity and β is the degree of wear at one abrasive asperity. Generally, α is taken as 0.1 and β ranges from 0 to 1.0. In the polishing experiments, the polishing conditions were kept consistent for different glue mass ratio tools. Hence, the load W, sliding distance L, and workpiece hardness H_v should be the same. In light of the fact that the average abrasive size and abrasive particle density were identical for these polishing tools, the larger mass percentage of epoxy resin A may increase the bonding strength [16] between abrasive particles and the sphere magnet, thus enlarge the wear of single abrasive β. Experiments and analysis will be further conducted in the future to verify this hypothesis that increasing the bonding strength of abrasive particles on the polishing tool will enhance the material removal ability of the tool.

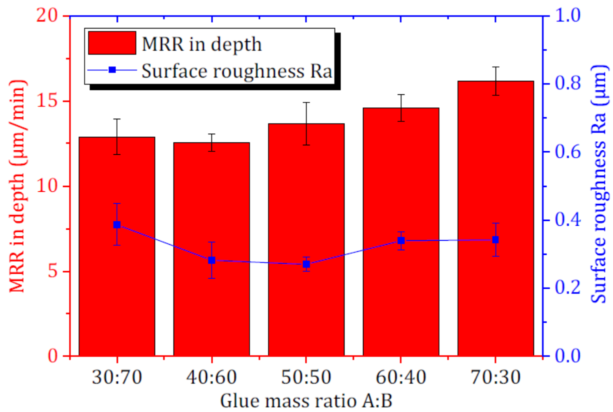

Figure 4 Material removal rate in depth and surface roughness Ra against glue mass ratio

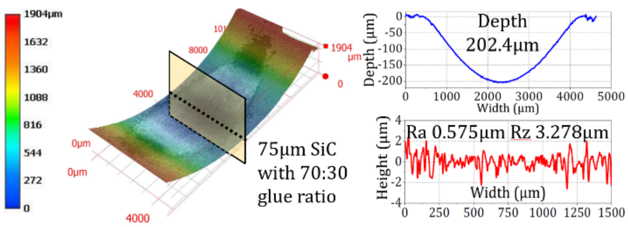

Figure 5 Surface roughness profile, three-dimensional and two-dimensional profile of polished footprint by a magnetic polishing tool with 75 µm SiC abrasive coating and 70:30 glue mass ratio

Based on the abrasive size experiments and glue mass ratio experiments, it is envisaged that the polishing tool with larger abrasive size and larger epoxy resin mass percentage will contribute to a higher material removal rate. Hence, another group of polishing tools was fabricated with 75 µm SiC abrasive and glue mass ratio 70:30. Polishing experiments with the same parameters listed in Table 2 were carried out on the AISI 316 stainless steel workpiece tube by using these newly fabricated polishing tools. The polishing results are presented in Figure 5. As expected, the new polishing tools achieved the highest material removal in depth of 202.4 µm, equivalent to a material removal rate of 20.2 µm/min, and the surface roughness is 0.575 µm Ra and 3.278 µm Rz. The tool shows slight wear, i.e. abrasive shelding, after 10-min polishing time but the tool life can be extended to more than 30 min by making the second layer of the abrasive coating. In sum, this proposed polishing method with the novel tools is a highly efficient candidate for finishing industrial internal surfaces.

4. Conclusions

To develop a magnetic abrasive polishing tool with better performance, the effect of abrasive size and glue mass ratio on material removal rate and surface finish are experimentally investigated. The major findings of this study are listed below:

- The polished area is a leaf-shape with a smooth axial symmetrical centerline profile;
- As abrasive size increases, both material removal rate and surface roughness increase linearly as expected;
- As the mass ratio of A glue increases, material removal rate also increases while surface roughness may reach a plateau when epoxy resin mass percentage is larger than 60 %;
- The maximum material removal rate as high as 20.2 µm/min is achieved by using the magnetic polishing tool with 75 µm SiC abrasive and 70:30 glue mass ratio. The material removal rate is around seventy-five times higher than that in loosely-bonded abrasive finishing [13].

In the future, experiments and analysis will be carried out to investigate the bonding strength between the abrasive and the polishing tool. In addition, the performance of polishing additively manufactured internal surfaces will be explored by this novel polishing tool.

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