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ORIGINAL ARTICLE

Study on finishing characteristics of magnetic abrasive finishing process using low-frequency alternating magnetic field

Jinzhong Wu[1] · Yanhua Zou[1] · Hitoshi Sugiyama[1]

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Abstract This paper describes a new ultra-precision magnetic abrasive finishing (MAF) process using alternating magnetic field. The process principle and the finishing characteristics are described. Specifically, the effects of finishing parameters such as cutting fluid, rotational speed of magnetic pole, and current frequency on change in material removal and surface finish are investigated respectively. Experimental results indicate that neat cutting oil is more suitable for this processing, which can obtain higher material removal and smoother finished surface compared with water-soluble cutting fluid and silicone fluid. The finishing force and material removal are gradually increasing with the increase of rotational speed of magnetic pole. It is confirmed that the angle variation of magnetic particles is decreasing with the increase of current frequency, and the few nanometer surface can be acquired in the condition of low frequency.

Keywords Alternating magnetic field · Cutting fluid · Rotation speed · Current frequency · Material removal · Surface roughness

✉ Yanhua Zou
yanhua@cc.utsunomiya-u.ac.jp

Jinzhong Wu
wjz.0926@163.com

Hitoshi Sugiyama
sugiyama@cc.utsunomiya-u.ac.jp

[1] Graduate School of Engineering, Utsunomiya University, 7-1-2Yoto, Utsunomiya, Tochigi 321-8585, Japan

1 Introduction

With the development of semiconductor and optical high technology industry, the design of components in high surface quality and high precision is demanded strictly. Some parts processing production may be achieved by traditional methods such as grinding, lapping, and honing; however, due to extraordinary properties of materials, complex geometry surface polishing need to be completed by advanced abrasive finishing processes in general.

Magnetic abrasive finishing (MAF) is one such advanced finishing process in which material is removed by the relative motion between the workpiece surface and magnetic abrasive under the influence of a magnetic field [1–3]. This process is considered to be a promising precision finishing technique for flat surfaces, complex curve surface, and inner surfaces of tube because polishing tool (magnetic brush) composed of fine magnetic particles is flexible and easy to use when closely following the finished surface [4–7]. A series of researches on MAF have been reported in recent decades. Shinmura et al. introduced the processing principle and abrasive characteristics of MAF and verified that the realization of precision finishing is possible by MAF [8, 9]. Jain et al. have concluded that the working gap and circumferential speed are the parameters which significantly influence the surface roughness value, proving that forces and change in surface roughness (ΔRa) increase with increase in current to the electromagnet and decrease in the working gap [10–12]. Yin et al. developed three modes of vibration-assisted MAF process for polished 3D micro-curved surface [13, 14]. Pandey et al. have studied the mechanism of surface finishing in UAMAF process and verified that the polishing effectiveness of MAF can be improved significantly by adding ultrasonic vibrations

[15–17]. Zou et al. proposed a plane MAF process using a constant-pressure magnetic brush and elevated the surface quality by improved magnetic abrasive trajectory [18, 19].

The previous researchers have concluded the main parameters affecting the performance of MAF process and find out that the methods improve significantly the efficiency of MAF. However, to processing quality, few nanometer finish surface is still considered to be difficult to obtain effectively through the MAF process, especially in finishing on flat and micro complex surface workpiece made of hard materials. The key issues are as follows: In conventional plane MAF process using static magnetic field, the fine magnetic particles are easy to agglomerate during finishing process and magnetic brush is difficult to recover to its original shape after contact with workpiece surface, which hinder the realization of ultra-precision finishing to some extent. On the other hand, in complex micro surface MAF process, magnetic brush itself is still under static magnetic field, resulting to abrasives being not transported adequately over the magnetic brush to polish into all machined surfaces. Moreover, the edge of micro groove surface is easy to be worn in the continuous process, leading to the damage of the workpiece shape.

In order to overcome these problems, we developed a plane MAF process using alternating magnetic field [20]. We use alternating current to energize electromagnetic, thereby making the magnetic field fluctuate. Therefore, the flexible magnetic cluster will generate a fluctuation of up and down under the action of alternating magnetic field. The fluctuating flexible magnetic cluster not only promotes the scatter of micro magnetic particles but also prevents itself deformation after contact with workpiece surface. Moreover, with the fluctuation of magnetic cluster, the abrasive particles can be refreshed and mixed during finishing process without recharging which achieve circulation and update to ensure the stability of grinding tool.

In this paper, we describe the process principle and finishing characteristics of plane MAF process using low-frequency alternating magnetic field and fabricate a set of experimental setup to polish the SUS304 stainless steel plate. The present work is aimed at studying the effects of finishing parameters such as cutting fluid, rotational speed of magnetic pole, current frequency on change in surface finish, and material removal.

2 Processing principle

2.1 Principle of plane MAF using alternating magnetic field

Figure 1 shows the force analysis of magnetic particles in alternating magnetic field. A magnetic particle along magnetic

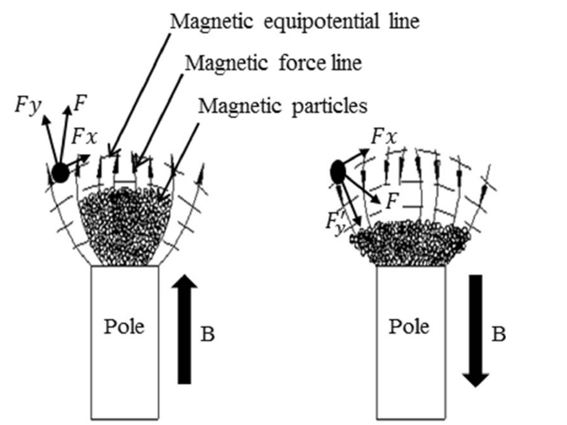


Fig. 1 Force analysis of magnetic particles in alternating magnetic field

equipotential line direction generates a force F_x and along magnetic force line direction generates a force F_y; these are calculated by the following formula (1) [21]:

$$F_x = V\chi\mu_0 H\left(\frac{\partial H}{\partial x}\right)$$

$$F_y = V\chi\mu_0 H\left(\frac{\partial H}{\partial y}\right) \quad (1)$$

where V is the volume of magnetic particle, χ is susceptibility of magnetic particles, μ_0 is permeability of vacuum, H is the magnetic field intensity, and $\partial H/\partial x$ and $\partial H/\partial y$ are gradients of magnetic field intensity in x and y directions, respectively.

Due to the size and direction of alternating current presenting a cyclical variation over time, the direction of magnetic force F_y is changing under alternating magnetic field. Therefore, when the alternating current is supplied to the electromagnet, the magnetic cluster will generate a fluctuation of up and down with the change of magnetic field direction.

Figure 2 shows a schematic of the plane MAF process using alternating magnetic field. The tray contains the compound magnetic finishing fluid (cutting fluid, iron

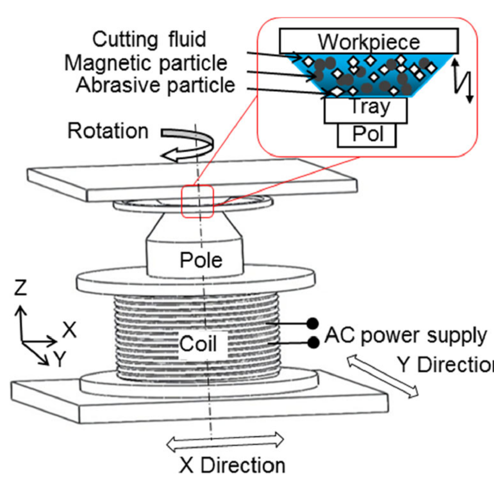


Fig. 2 Schematic of processing principle

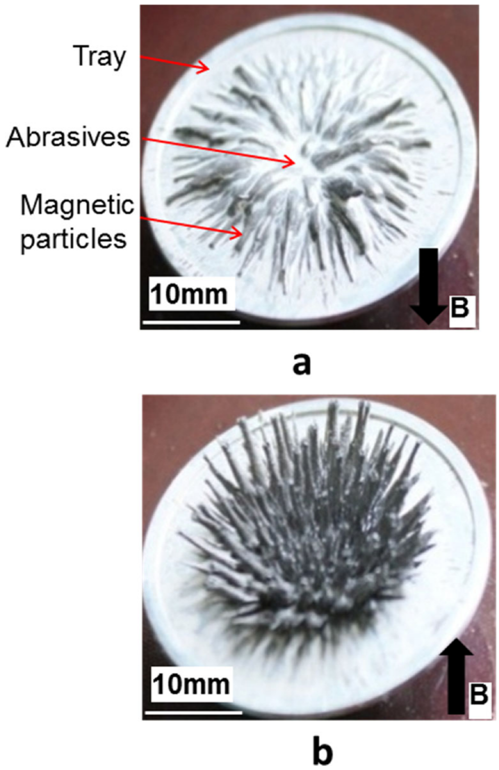


Fig. 3 Movement change of magnetic cluster under alternating magnetic field. **a** Magnetic field direction up. **b** Magnetic field direction down

powders, and abrasives), and the lower is the magnetic pole and the upper is the workpiece. After electromagnetic coil entering alternating current, the iron particles are attracted toward each other along the magnetic force lines and abrasive particles are mixed between the iron particles. The compound magnetic finishing fluid is transformed into magnetic cluster in between the tray and workpiece. With the rotation and movement of magnetic pole, a relative friction is produced between the workpiece surface and magnetic cluster. The friction is combined with fluctuating magnetic force produced by magnetic cluster, thereby realizing effectively the material removal.

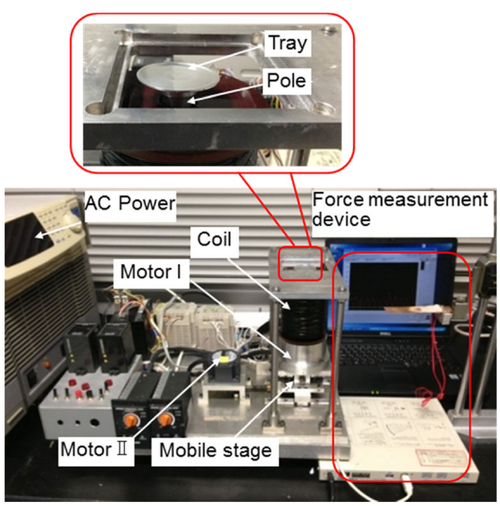


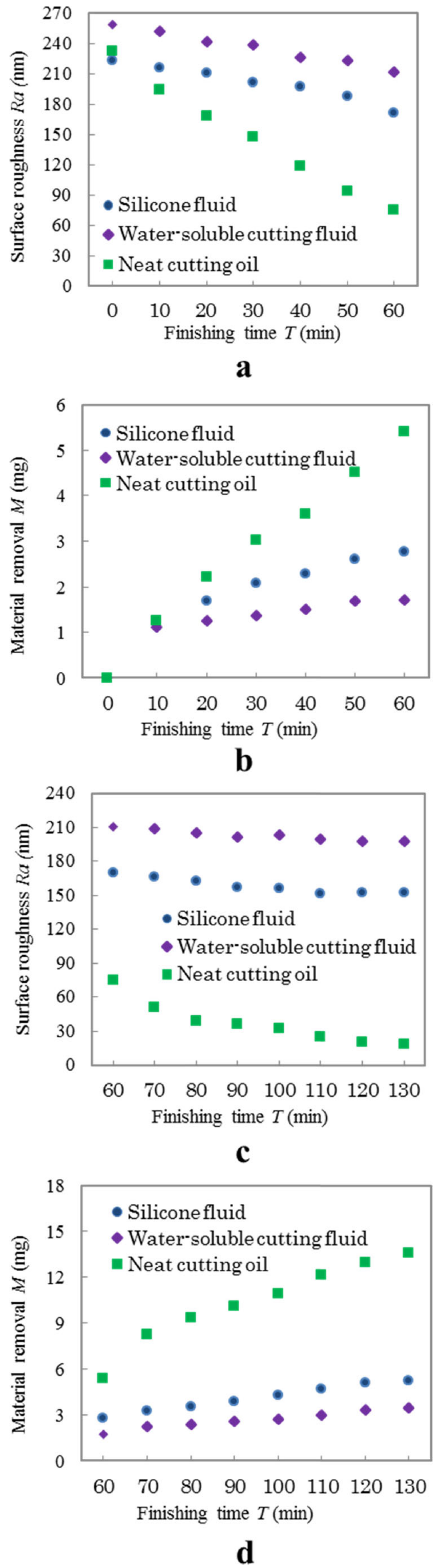
Fig. 4 External view of experimental setup

Table 1 Experimental conditions

Parameters	First stage	Second stage
Finishing time (min)	60	70
Magnetic particles	Electrolytic iron powder, 30 μm in mean dia 1.2 g	Carbonyl iron powder, 6 μm in mean dia 1.2 g
Abrasive	Al_2O_3, 0–1 μm in mean dia 0.3 g	Diamond powder, 0–1 μm in mean dia 0.3 g
Workpiece	SUS304 stainless steel plate with the size of 80 mm×90 mm×1 mm	
Alternating current	1.9 A (average)	
Magnetic flux density	0.14 T	
Feed speed of mobile stage	260 mm/min	
Cutting fluid	Type 1: water-soluble cutting fluid (SCP-23): 0.8 ml Type 2: silicone fluid (KF-96-50CS):0.8 ml Type 3: neat cutting oil (Honilo 988): 0.8 ml	
Rotational speed of magnetic pole (r/min)	200, 250, 300 350, 400, 450	
Current frequency (Hz)	1, 3, 5, 7, 9	

2.2 Characteristic abrasive behavior in process

Characteristic abrasive behavior of the MAF using low-frequency alternating magnetic field is the cyclic up and down fluctuation of magnetic cluster, which not only promotes to the scatter of micro magnetic particles but also prevents itself deformation after contact with workpiece surface. Under the action of low-frequency alternating magnetic field, the flexible magnetic cluster which consisted of micro iron powders can generate a higher finishing force against finished surface and may closely follow the finished surface. Utilizing this characteristic, we may conduct ultra-precision finishing on flat surface and micro complex surface. The continued fluctuation of flexible magnetic cluster promotes the abrasives into all-finished surface, combining effectively corner and groove surface. Moreover, with the fluctuation of magnetic cluster, the abrasive particles can be refreshed and mixed during finishing process without recharging, which improve homogeneousness of finish surface and enhance finishing efficiency. Figure 3 shows the characteristic behavior of magnetic cluster in process. When the direction of magnetic field is forced down, the abrasives may adequately



◀ **Fig. 5** Effect of cutting fluid on the surface roughness and material removal (current frequency=3 Hz, rotation speed=200 r/min). **a** Surface roughness (first stage). **b** Material removal (first stage). **c** Surface roughness (second stage). **d** Material removal (second stage)

mix together with magnetic particles. When the direction of magnetic field is forced up, magnetic particles may drive the abrasives to float to the magnetic cluster surface to polish the workpiece. The continued up and down movement change of the magnetic clusters achieves circulation and update to ensure the stability of grinding tool.

3 Experimentation

3.1 Experimental setup

External view of the experimental setup is shown in Fig. 4. The selected workpiece is SUS304 stainless steel plate with the size of 80 mm×90 mm×1 mm. Under the workpiece is the tray filled with compound magnetic finishing fluid. The tray is fixed on the magnetic pole so that it can achieve self-rotation by connecting the

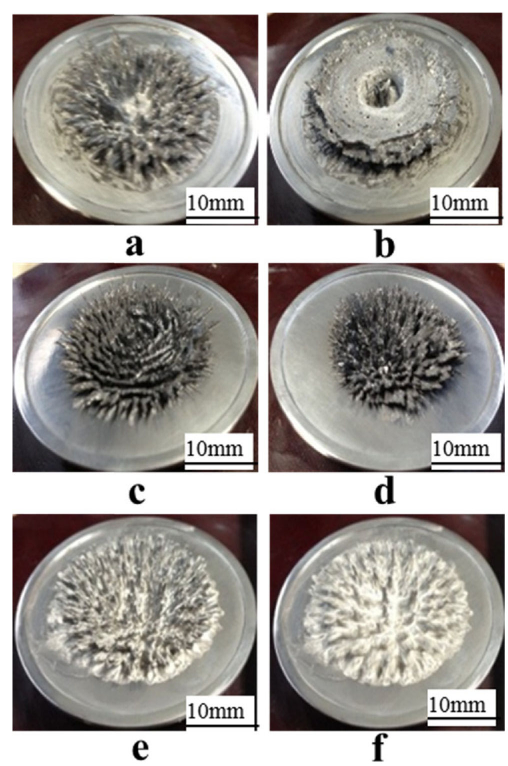


Fig. 6 Effect of cutting fluid on magnetic cluster. **a** Before finishing (water-soluble cutting fluid). **b** After finishing (water-soluble cutting fluid). **c** Before finishing (silicone fluid). **d** After finishing (silicone fluid). **e** Before finishing (neat cutting oil). **f** After finishing (neat cutting oil)

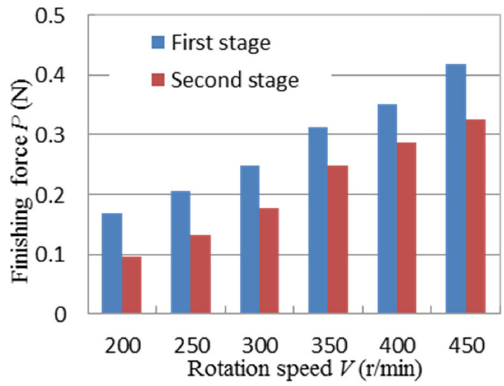


Fig. 7 Effect of rotational speed of magnetic pole on the finishing force (current frequency=3 Hz, neat cutting oil)

magnetic pole to motor. An electromagnetic coil with the wire diameter of 1 mm and 2000 turns has been selected to be installed on the mobile stage to achieve movement in all directions. Alternating current power device can supply the voltage and frequency in the range of 1—300 V and 1—999 Hz according to experimental needs. A finishing force measuring system has been designed in this study. The force is measured by using two diamagnetism strain gauges (KFN-2-350-C9-11) and a data record processor (PCD-300A) (Kyowa Electronic Instrument Co. Ltd), and the measurement result is analyzed by the control software (PCD-30A).

3.2 Experimental method and conditions

The experimental conditions are shown in Table 1. In this study, the experiment was divided into two stages to investigate the effect of cutting fluid, rotational speed of magnetic pole, and current frequency on finishing characteristics. The finishing time of the first stage was 60 min and the second finishing stage was 70 min. In order to improve the finishing efficiency, electrolytic iron powder with the mean diameter of 30 μm and aluminum oxide (Al_2O_3) were selected in the first stage. To realize the nano-level finishing, the diameter of magnetic particle is within several microns in general. Therefore, in the second stage, carbonyl iron powder with the diameter of 6 μm and diamond powder with the mean diameter of 1 μm were selected. Electrolytic iron powder and carbonyl iron powder have superior magnetic properties as soft magnetic material. The most outstanding characteristic is that they have low coercive force, and the coercive force is decreasing gradually with the smaller iron particle size.

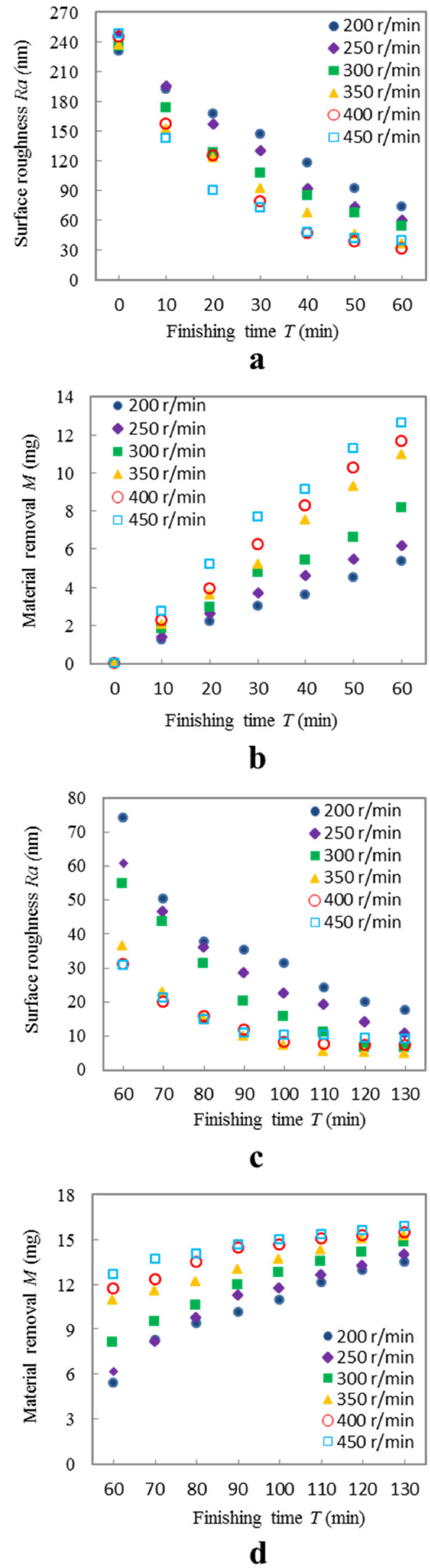


Fig. 8 Effect of rotational speed of magnetic pole on the surface roughness and material removal (current frequency=3 Hz, neat cutting oil). **a** Surface roughness (first stage). **b** Material removal (first stage). **c** Surface roughness (second stage). **d** Material removal (second stage)

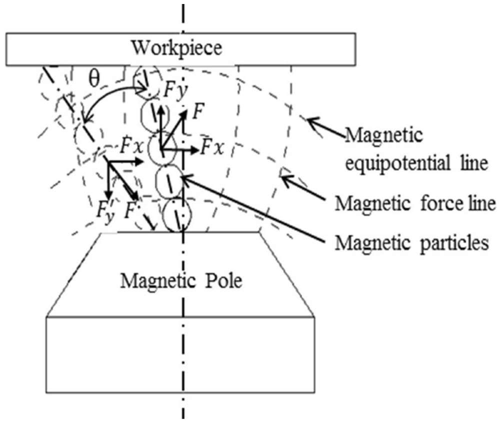


Fig. 9 Movement change of magnetic particles under alternating magnetic field

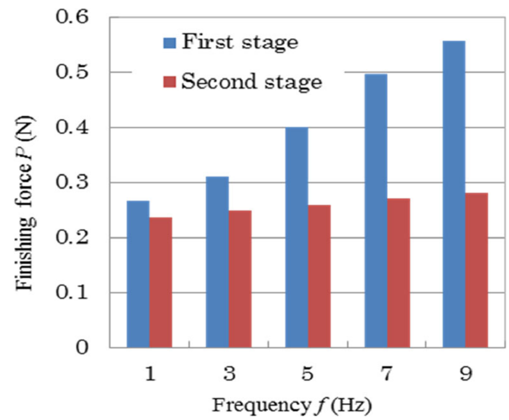


Fig. 10 Effect of rotational speed of magnetic pole on the finishing force (current frequency=3 Hz, neat cutting oil)

Therefore, they can show the excellent responsiveness to improve the fluctuation of magnetic cluster under alternating magnetic field.

In order to understand the variation of material removal and finish surface over the time, we measured the workpiece every 10 min. In any experiments, the surface roughness (*Ra*) and surface morphology were acquired with WYKO NT1100M Veeco non-contact white light interferometer. We used the ×20 objective with a multiple magnification detector of ×1; the field of view was 0.3 mm.

4 Experimental results and discussion

Effects of cutting fluid, current frequency, and rotational speed of magnetic pole on finishing characteristics have been discussed in the following sub-sections.

4.1 Cutting fluid

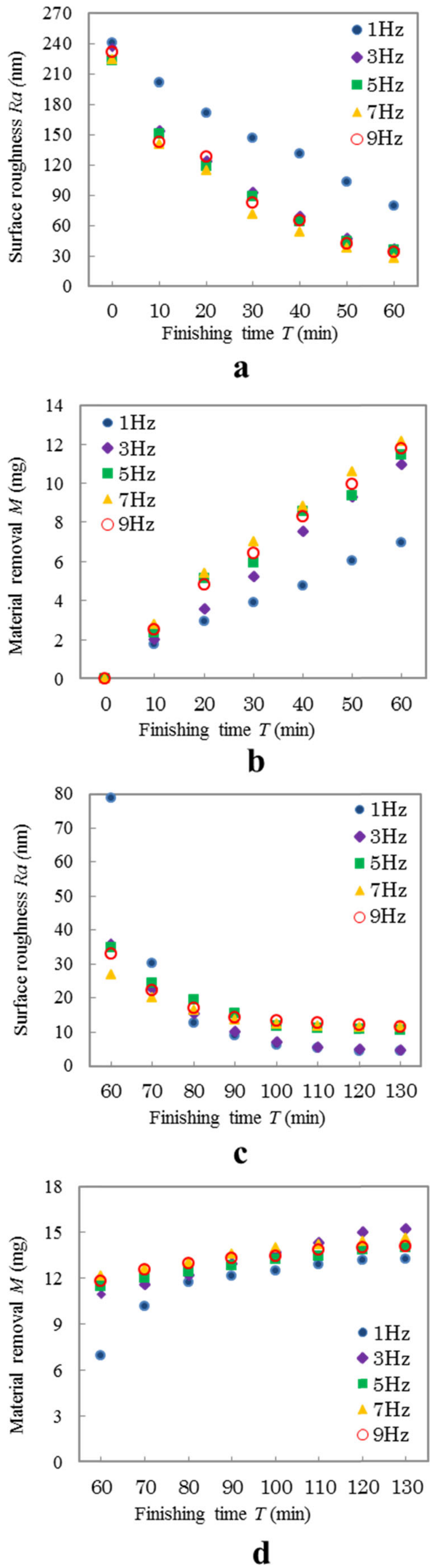
Cutting fluid is an important component of compound magnetic finishing fluid, which is the carrier of magnetic particles, affecting the distribution of abrasives and playing a role in lubrication and cooling in process. Therefore, cutting fluid properties is the basis of ensuring the finishing quality and efficiency. We selected water-soluble cutting fluid, silicone fluid, and neat cutting oil based on the composition of cutting fluid for experiments.

Table 2 Effect of current frequency on angle variation

Angle variation θ (°)	Current frequency (Hz)
30~45	1
15~30	3
5~15	5
5~10	7
0~5	9

Figure 5 shows the effect of three different kinds of cutting fluid on the finish surface and material removal. It can be seen that the higher surface roughness improvement and material removal can be obtained using neat cutting oil. In contrast, when we use water-soluble cutting fluid or silicone fluid, it is difficult to obtain the few nanometers finished surface.

Why is the finish performance so different using different grinding fluids? This is because grinding fluid has a great impact on the state of magnetic cluster. Figure 6 shows the changes of magnetic cluster shape before and after finishing in the conditions of using three different kinds of cutting fluids. As shown in Fig. 6a, we can see that magnetic cluster produced serious distortion using water-soluble cutting fluid. The magnetic particles (black grains) generate fault after contacted with workpiece, and abrasives (white powder) cannot disperse uniformly under the alternating magnetic force. Silicone fluid can exhibit an excellent dispersion stability to prevent the agglomeration of magnetic particles. However, magnetic particles themselves cannot produce movement changes to promote the roll of abrasive particles under the influence of alternating magnetic field. Therefore, it is difficult to improve finishing efficiency and precision. Figure 6c shows that the neat cutting oil mixes with magnetic particles and abrasives adequately and the magnetic cluster suffered little deformation after finishing. This is because magnetic cluster itself can produce the up and down movement in alternating magnetic field, which not only promotes the dispersion of magnetic particles but also drives the abrasive to float to the magnetic cluster surface for the polishing of workpiece.



◀ **Fig. 11** Effect of current frequency on the surface roughness and material removal (current frequency=3 Hz, neat cutting oil). **a** Surface roughness (first stage). **b** Material removal (first stage). **c** Surface roughness (second stage). **d** Material removal (second stage)

4.2 Rotation speed

In this experiment, we investigated the effect of rotational speed of magnetic pole on finishing force, finish surface, and material removal. Some magnetic particles and abrasive grains will be thrown out of tray when the rotational speed of magnetic pole is higher than 450 r/min. Therefore, rotational speed of magnetic pole is controlled within 450 r/min.

Increase of finishing force will increase the cutting depth and material removal rate, but excessive finishing force can cause scratch and hinder the realization of nano-level finishing. Therefore, the finishing force has an important influence on finishing characteristics. In finishing process, magnetic particles produce a fluctuating magnetic force in a vertical aspect under the influence of alternating magnetic field. Moreover, with the rotation of magnetic pole, a frictional force in the horizontal direction will be produced. Therefore, finishing force is considered as a resultant force of fluctuating magnetic force and frictional force. Figure 7 shows the effect of rotational speed of magnetic pole on finishing force. It can be seen that finishing force is increasing gradually with the increase of rotational speed of magnetic pole. This is because the centrifugal force acting on magnetic particles is increasing as the rotation speed increases. It intensifies the collision of magnetic cluster against the workpiece, increasing frictional force. Moreover, we can observe that finishing force of the first stage is higher than that of the second stage in the same rotation speed. The fluctuating magnetic force is increasing gradually with the increase of magnetic particle diameter. In the two stages, the magnetic particle diameters we used are 30 and 6 μm, respectively. Therefore, the first stage produced a higher finishing force.

Figure 8 shows the effect of rotational speed of magnetic pole on the surface roughness and material removal. It can be seen that the material removal is increasing gradually with the increase of rotation speed. The friction is increasing with the increase of relative speed between workpiece and magnetic cluster, which is combined with fluctuating finishing force produced by the up and down movement of magnetic particles, causing stock removal to increase rapidly.

On the other hand, it is observed that the effect of rotation speed of magnetic pole on surface roughness improvement is different in different stages. Figure 8a

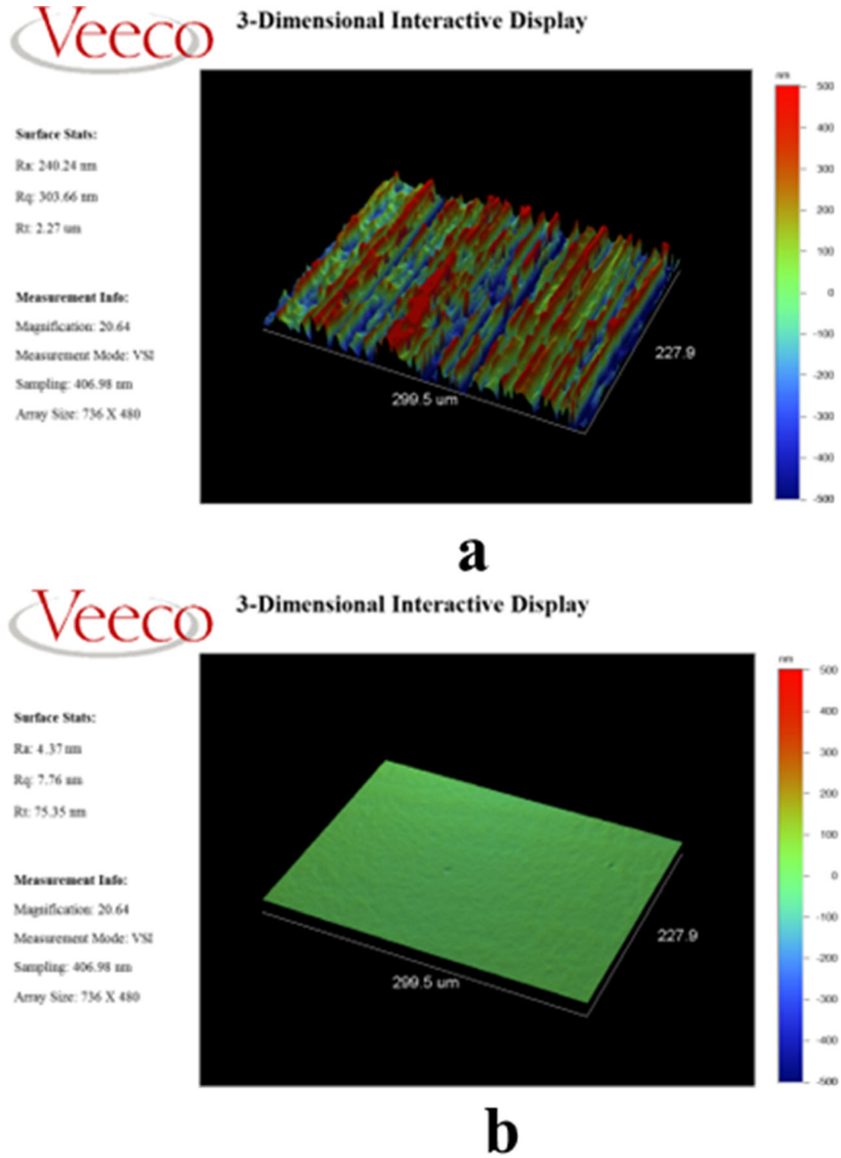


Fig. 12 3D profile images of finishing surface. **a** Before finishing, **b** after finishing

shows that in the first stage, the improvement of surface roughness is the best in the condition that rotation speed is 400 r/min. Figure 8c shows that in the second stage, the improvement of surface roughness is the best when rotation speed is 350 r/min. From the experimental results, we may infer that when the surface roughness of SUS304 stainless steel plate is greater than 90 nm, the highest finishing efficiency will be obtained in the case that the rotational speed of magnetic pole is 450 r/min. When surface roughness is between 40 and 90 nm, 400 r/min is considered to be the best experimental condition. When surface roughness is lower than 40 nm, the best finish surface will be obtained in the condition of 350 r/min, and the surface roughness of SUS304 stainless steel plate is improved from *Ra* 236.37 nm to *Ra* 4.66 nm in final.

4.3 Current frequency

In this experiment, we investigated the effect of current frequency on the movement of magnetic particles, finishing force, finish surface, and material removal.

Figure 9 shows the movement change of magnetic particles under alternating magnetic field. Owing to the force direction of F_y which is changing with the magnetic field direction, magnetic particles can produce the up and down movement change. The change speed and angle θ are closely related to current frequency. Table 2 shows angle variation of magnetic particles in different frequencies. It can be seen that the angle variation θ is decreasing with the increase of current frequency. The greater the change in the angle of magnetic particles, magnetic cluster is more flexible. Therefore, we can obtain the most flexible magnetic cluster in the condition of 1 Hz.

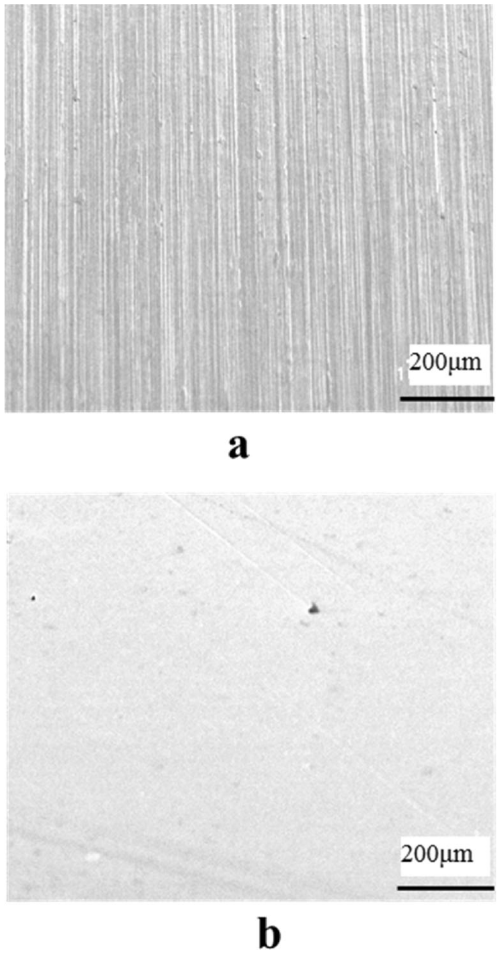


Fig. 13 SEM images of finishing surface. **a** Before finishing, **b** after finishing

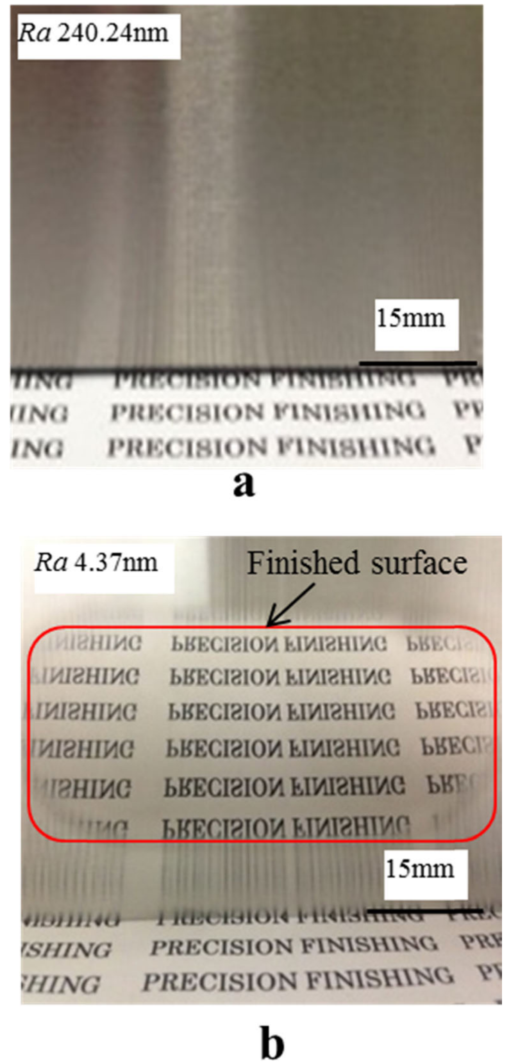


Fig. 14 Photographs of finishing surface. **a** Before finishing, **b** after finishing

Figure 10 shows the effect of current frequency on finishing force. It can be seen that the finishing force is increasing with the increase of current frequency in the first stage. This is because the vibration angle of magnetic particles is smaller and vibration speed faster as frequency increases, which makes the magnetic cluster to become harder, improving finishing force. However, in the second finishing stage, the magnetic cluster becomes extra-soft when the diameter of magnetic particles is 6 µm so that the increase of current frequency has few effects on finishing force.

Figure 11 shows the effects of current frequency on the surface roughness and material removal. In the first stage, when frequency is smaller than 7 Hz, the surface roughness improvement and material removal rate are increasing gradually with the increase of frequency. This is because the finishing force is increasing with the increase of frequency. However, in the second stage, the highest surface roughness improvement is obtained in the case of 1 Hz; in contrast, the finish surface is difficult to be improved to 10 nm when current frequency is greater than 5 Hz. This is because the increase of frequency has few effects on finishing force in the second stage, but the increase of magnetic cluster angle variation may effectively promote the roll of abrasive particles and improve the cross-cutting effects of abrasives. Figures 12 and 13 show the 3D profile and SEM image of the finished surface in the following conditions: neat cutting oil, rotational speed of magnetic pole is 350 r/min, and current frequency is 1 Hz. The surface roughness of SUS304 stainless steel plate is improved from 240.24 to 4.37 nm. Moreover, photographs of before and after finishing surface are shown in Fig. 14. It can be seen that a smooth surface with less scratches is obtained. From these results, it has been understood that the nano-level finishing of SUS304 stainless steel plate can be realized by MAF process using low-frequency alternating magnetic field.

5 Conclusions

This paper studied the finishing characteristics of MAF process using alternating magnetic field. The main conclusions are summarized as follows:

1. Neat cutting oil is more applicable to MAF process using alternating magnetic field. It can combine with magnetic particles and abrasives adequately and promote the magnetic cluster to produce feasible fluctuating magnetic force. In MAF process using alternating magnetic field, neat cutting oil can obtain higher material removal and smoother finish surface compared with water-soluble cutting fluid and silicone fluid.
2. The finishing force and material removal are increasing gradually with the increase of rotational speed of magnetic pole. The effect of rotational speed of magnetic pole on surface roughness improvement rate is different in different finishing stages. When surface roughness of the SUS304 stainless steel plate is greater than 90 nm, the highest finishing efficiency is obtained in the case of 450 r/min. When surface roughness is between 40 and 90 nm, 400 r/min is considered to be the best experimental condition. When surface roughness is lower than 40 nm, the best finish surface is obtained in the condition of 350 r/min.
3. Finishing force is increasing and the angle variation of magnetic particles is decreasing with the increase of current frequency. The increase of angle variation can promote the roll of abrasive particles and improve the utilization rate of the abrasive.
4. In the first stage, when current frequency is smaller than 7 Hz, the surface roughness improvement and material removal rate is increasing gradually with the increase of frequency. In the several nano-level finishing stage, the best finish surface is obtained in the case of 1 Hz. The experimental results show that in the case of finish surface which is lower than 30 nm, MAF process using low-frequency alternating magnetic field can realize the few nanometer finishing more effectively.
5. In the present research, the surface roughness of SUS304 stainless steel plate can be improved from *Ra* 240.24 nm to *Ra* 4.37 nm in the following conditions: neat cutting oil, rotational speed of magnetic pole is 350 r/min, and current frequency is 1 Hz.

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