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ORIGINAL ARTICLE

Study on the magnetic abrasive finishing process using alternating magnetic field: investigation of mechanism and applied to aluminum alloy plate

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Abstract
In order to achieve the finishing of complex microsurface, the magnetic abrasive finishing process using alternating magnetic field was proposed. In this paper, the mechanism of the magnetic abrasive finishing process using alternating magnetic field was investigated. At the same time, the influence of magnetic particle size and magnetic field frequency on magnetic cluster changes was observed and the relationship between finishing force and alternating magnetic field was analyzed. In addition, the feasibility of ultraprecision finishing of 5052 aluminum alloy plate through this process was studied, and the influence of relevant process parameters on the finishing characteristics was analyzed. The experimental results show that the surface roughness of 5052 aluminum alloy plate improved from 318 to 3 nm *Ra* in 15 min.

Keywords Magnetic abrasive finishing · Alternating magnetic field · Precision finishing · Mechanism · Aluminum alloy

1 Introduction

Smoother surfaces are needed in high-tech industries, such as aerospace, die polishing, semiconductors, and medical devices. There are some difficulties in the finishing of complex microsurface by traditional processes. Since the grinding tool of the magnetic abrasive finishing (MAF) process is a flexible magnetic brush formed by fine particles, the process is considered to be possible to achieve finishing of complex microsurface. However, when performing complicated microcurved surface finishing in a static magnetic field, a change in the gap between the magnetic pole and the workpiece causes the magnetic brush contacting the workpiece to be pressed toward the magnetic pole. Since the magnetic field near the magnetic pole is stronger, the magnetic brush will be difficult to recover. This makes it difficult for the magnetic brush to polish all surfaces. In addition, it is difficult to renew the abrasive in contact with the workpiece in a static magnetic field [1, 2]. Therefore, the finishing efficiency will gradually decrease. In order to overcome these problems, we proposed a MAF process using alternating magnetic field. In an alternating magnetic field, the magnetic brush periodically fluctuates up and down due to changes in current. This not only continuously mixes and updates the abrasive, but also periodically pushes the magnetic brush toward the workpiece surface [3, 4].

The basic principle of the conventional plane MAF process is to fill the magnetic abrasive between the magnetic pole and the workpiece, and the magnetic abrasives form the magnetic brush in the magnetic field. Through the relative movement between the magnetic brush and the workpiece, the material on the surface of the workpiece is removed, thereby achieving finishing of the surface [5, 6]. The process has low processing power, adaptability to complex workpiece profiles, easy control of cutting edge, low temperature rise, and high processing quality [7]. Therefore, there are many studies on MAF. Shinmura et al. [8, 9] reported the effect of diamond-coated magnetic abrasives on the finishing performances of Si3N4 fine ceramic bars, and also proved that the MAF process can effectively remove burrs. Yamaguchi et al. [10, 11] proposed the use of the MAF process to finish the inner surface of the tube and to investigate the characteristics of the abrasive behavior in view of the magnetic field distribution. Jain et al.

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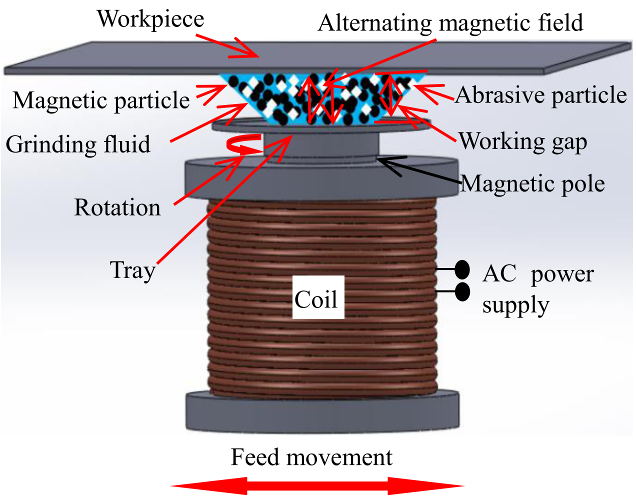


Fig. 1 Schematic of processing principle

[12] studied the effect of working gap and circumferential speed on material removal and surface roughness, and concluded that the working gap and circumferential speed are the parameters which significantly influence the surface roughness value (*Ra*). Jain et al. [13] studied the influence of current, working gap, etc. on the force of the MAF process. They concluded that the force can be increased by increasing the current and reducing the working gap. Abrasive particle mesh size is a significant factor for influencing tangential force. Yin et al. [14] considerably increased deburring efficiency by using the vibration-assisted MAF process. Zou et al. [15–17] studied the influence of polishing trajectory of magnetic brush on the surface precision and homogeneity, and verified through experimental and theoretical analysis that the improved polishing trajectory of magnetic brush can improve the precision of plane magnetic abrasive finishing. In addition, the processing principle and finishing characteristics of the electrolytic magnetic abrasive finishing process have been reported.

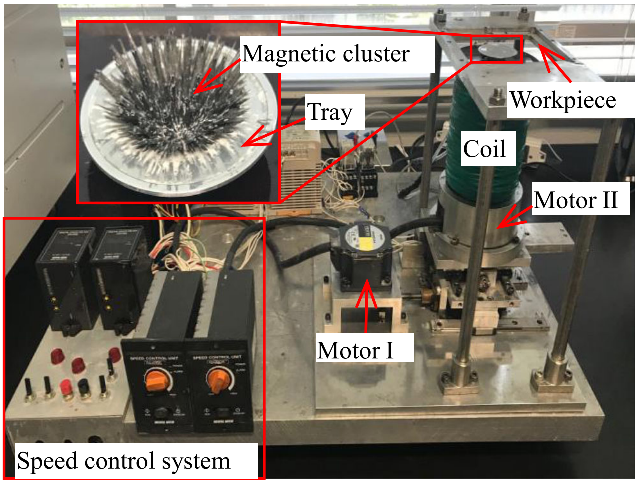


Fig. 2 External view of the experimental setup and processing region expanding photos

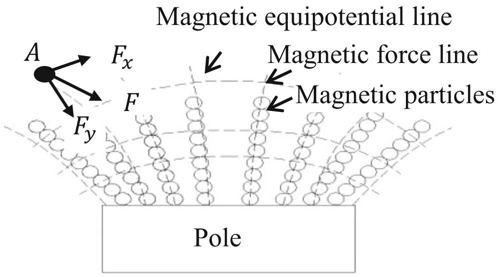


Fig. 3 The magnetic force acting on a magnetic particle in magnetic field

In the previous research, the basic characteristics of the process were studied, and it was verified that the process has higher processing efficiency than the MAF process using static magnetic field, and the process is used to achieve several nanometers of finishing of SUS304 stainless steel plate [1, 3]. Some process parameters were measured and analyzed, and the feasibility of using this process to finishing the alumina ceramic workpiece was verified [4]. However, there are still some mechanisms that have not been clarified. In addition, aluminum alloy is widely used in aerospace, aviation, shipbuilding, and other important fields due to its light weight, corrosion resistance, high specific strength, and good processing adaptability [18–22]. With the development of related fields, higher demands are made on the surface quality of aluminum alloys. The traditional mechanical polishing process tends to leave traces on the surface. Therefore, this paper proposes the ultraprecision finishing of aluminum alloy surface by magnetic abrasive finishing process using alternating magnetic field.

This paper first studies the mechanism of the MAF process using alternating magnetic field, including the law of the change of magnetic force and finishing force in the alternating magnetic field and the influence of magnetic field frequency and magnetic particle size on the magnetic cluster change. Secondly, the effects of magnetic particle size, magnetic field frequency, and abrasive size on the finishing characteristics were studied when the workpiece was the 5052 aluminum alloy plate. Finally, the highly efficient ultraprecision finishing experiments of the 5052 aluminum alloy plate were designed and implemented.

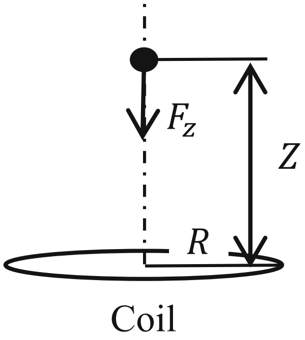


Fig. 4 The simplified model of the magnetic force acting on a magnetic particle in an alternating magnetic field

2 Processing principle and experimental setup

2.1 Processing principle

The experimental principle is shown in Fig. 1. The coil is supplied with alternating current to generate an alternating magnetic field. The composite magnetic finishing fluid (grinding fluid, magnetic particles, abrasive particles) is placed on the tray. The tray is connected to the pole and below the workpiece. In the magnetic field, the magnetic particles form the magnetic cluster along the direction of the magnetic force line. When the magnetic field is weakened, the magnetic particles will fall due to gravity, so the magnetic cluster will fluctuate up and down with the change of the current in the alternating magnetic field. The fluctuate enables the abrasive particles in contact with the workpiece surface to be circulated and updated, ensuring the stability of the grinding tool. In addition, the magnetic pole can achieve rotational motion and reciprocating motion. This causes relative friction between the workpiece surface and the magnetic cluster, thereby realizing effectively the material removal.

2.2 Experimental setup

Figure 2 shows an external view of the experimental setup and the photograph of the processing area. The electromagnetic coil is connected to the mobile station and they can be driven by the motor I to realize reciprocating motion. The tray is fixed to the magnetic pole and they can realize a rotary motion driven by the motor II. The speed of motor I and motor II can be controlled by the speed control system. Electromagnetic coil can be supplied with voltages and frequencies in the range of 1–300 V and 1–999 Hz supplied by the alternating current power device.

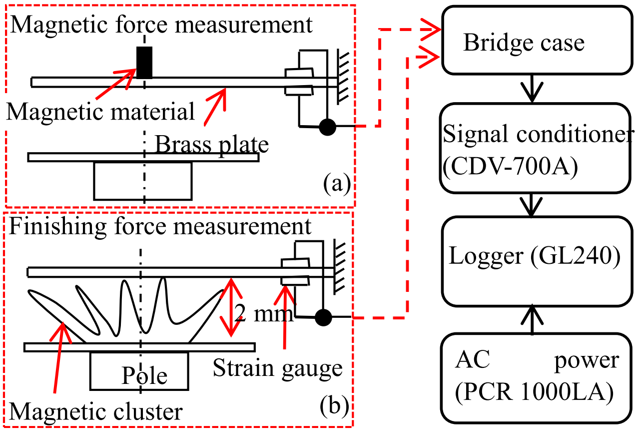
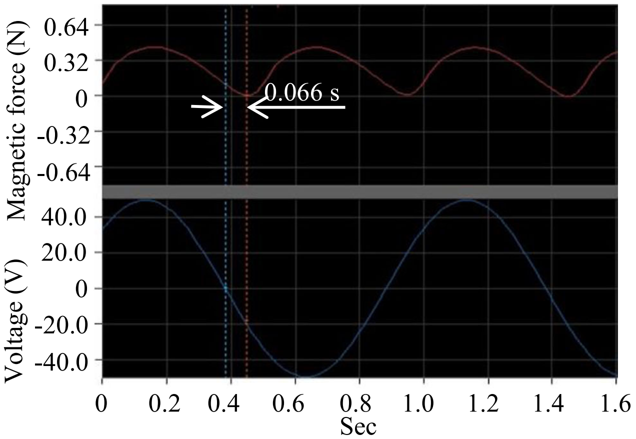
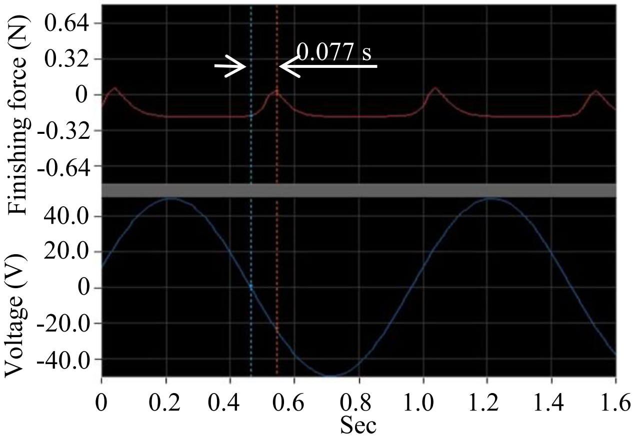


Fig. 5 Schematic diagram of waveform generation system



(a) The waveform of the magnetic force and voltage



(b) The waveform of the finishing force and voltage

Fig. 6 The waveform of the magnetic force and finishing force

3 Investigation of mechanism

3.1 Magnetic force analysis of alternating magnetic field

Figure 3 shows the schematic diagram of magnetic force acting on a magnetic particle in magnetic field. F_x and F_y can be calculated by Eqs. (1) and (2) [23],

$$F_x = V\chi\mu_0 H\left(\frac{\partial H}{\partial x}\right) \tag{1}$$

$$F_y = V\chi\mu_0 H\left(\frac{\partial H}{\partial y}\right) \tag{2}$$

where x is the direction of the line of magnetic force, y is the direction of the magnetic equipotential line, V is the volume of magnetic particle, χ is susceptibility of particles, $\mu_0$is permeability of vacuum, H is the magnetic field intensity at point A, and $\partial H/\partial x$ and $\partial H/\partial y$ are gradients of magnetic field intensity in x- and y-directions, respectively.

Table 1 Measurement conditions

Magnetic particles	Carbonyl iron powder, 6 μm in mean dia: 1.2 g Electrolytic iron powder, 30 μm in mean dia: 1.2 g Electrolytic iron powder, 75 μm in mean dia: 1.2 g Electrolytic iron powder, 149 μm in mean dia: 1.2 g
Abrasive particles	WA#10000: 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	0 rpm
Feed speed of mobile stage	0 mm/min
Working gap	1 mm
Alternating current	1.9 A (average)
Magnetic field frequency	1 Hz, 3 Hz, 5 Hz, 7 Hz

In order to study the relationship between magnetic force and the alternating magnetic field, the model is simplified as shown in Fig. 4. A magnetic particle is on the axis of the coil. The coil radius is R, and the magnetic field at a distance of Z along the axis of the coil can be calculated by Eq. (3) [24],

$$H = \frac{\mathrm{IR}^2}{2\left(R^2 + Z^2\right)^{3/2}} \tag{3}$$

In an alternating magnetic field, the current can be calculated by Eq. (4),

$$I = I_m sin\omega t \tag{4}$$

where I is the instantaneous current value, I_m is the current maximum, ω is the angular frequency, and t is the time.

Therefore, when a magnetic particle is on the axis of the coil, the magnetic force acting on it can be calculated by the Eq. (5),

$$F_z = \frac{3\mathrm{V}\chi\mu_0 Z I_m^2 R^4}{8\left(R^2 + Z^2\right)^4}(\cos 2\omega t{-}1) \tag{5}$$

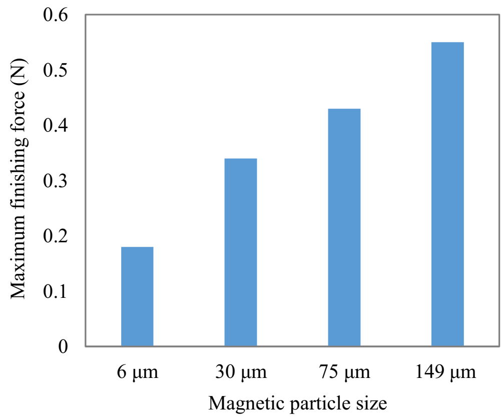
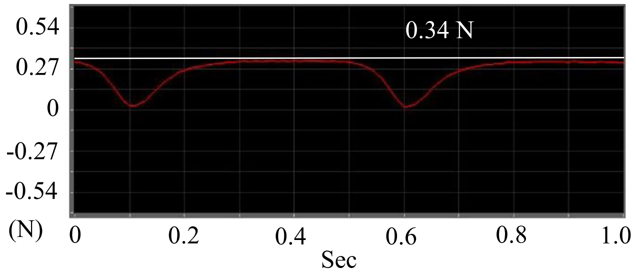
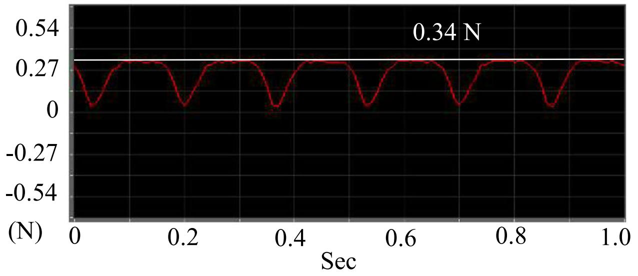


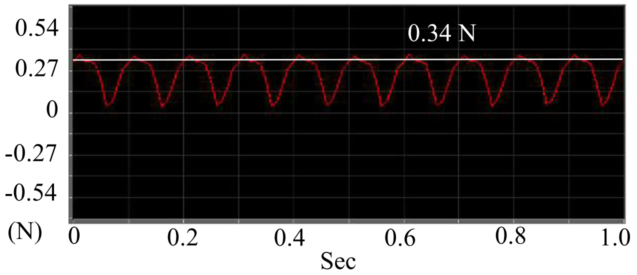
Fig. 7 Effect of magnetic particle size on finishing force (magnetic field frequency = 1 Hz)



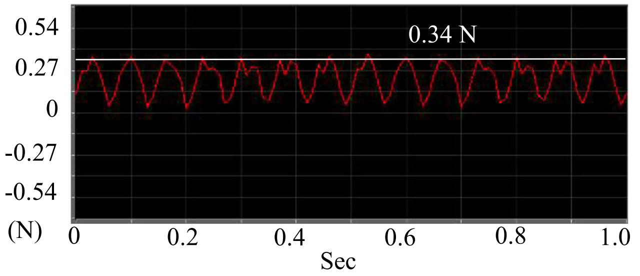
(a) 1 Hz



(b) 3 Hz



(c) 5 Hz



(d) 7 Hz

Fig. 8 Effect of magnetic field frequency on finishing force (magnetic particle size = 30 μm)

Table 2 Measurement conditions

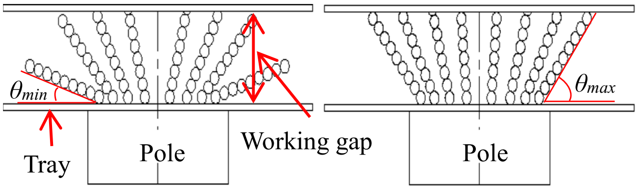
Magnetic particles	Carbonyl iron powder, 6 μm in mean dia: 1.2 g Electrolytic iron powder, 30 μm in mean dia: 1.2 g Electrolytic iron powder, 75 μm in mean dia: 1.2 g Electrolytic iron powder, 149 μm in mean dia: 1.2 g
Abrasive particles	WA#10000: 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	350 rpm
Feed speed of mobile stage	0 mm/min
Working gap	6 mm
Alternating current	1.9 A (average)
Magnetic field frequency	1 Hz, 3 Hz, 5 Hz, 7 Hz

From the above analysis, it can be concluded that a magnetic particle on the coil axis in the alternating magnetic field have a magnetic force period of twice the current period. In addition, it can be seen from the Eq. (5) that the increase in the volume of the magnetic particles increases the magnetic force which increases the attractive force between the two magnetic particles. At the same time, the increase in the volume of the magnetic particles increases the contact area between adjacent magnetic particles. Therefore, the force required for the relative displacement of two adjacent magnetic particles is greater. This means that the magnetic cluster formed by the larger magnetic particles is more difficult to deform under the same conditions. This leads to an increase in finishing force.

3.2 Research on magnetic force and finishing force

3.2.1 The relationship between magnetic force and finishing force and magnetic field

To study the relationship between force (magnetic force and finishing force) and magnetic field, we measured the force and voltage waveforms. The waveform generation system is shown in Fig. 5. The basic principle of the system is that the resistance value of the diamagnetism strain gauge (KFN-2-350-C9-11) changes according to the deformation of the brass plate. When the brass plate is deformed after being stressed, the output voltage value of the strain bridge circuit changes due to the change in the resistance of the strain gauge. In addition, the output voltage is amplified by the signal conditioner (CDV-700A) and then connected to the logger (midi LOGGER GL240). At the same time, AC power is also connected to the logger. The logger has a sampling period of 20 ms. Magnetic force and finishing force were measured under the condition that the magnetic field frequency was 1 Hz. When measuring the magnetic force waveform, a cylindrical magnetic material (SCM435) is placed above the brass plate (on the pole axis) as shown in Fig. 5a. The brass plate is 1-mm thick. The magnetic material has a height of 10 mm and a diameter of 4 mm. The finishing force waveform was measured by filling magnetic particles (1.5 g) having an average diameter of 149 μm between the brass plate and the magnetic pole as shown in Fig. 5b.



(a) The lowest position (b) The highest position

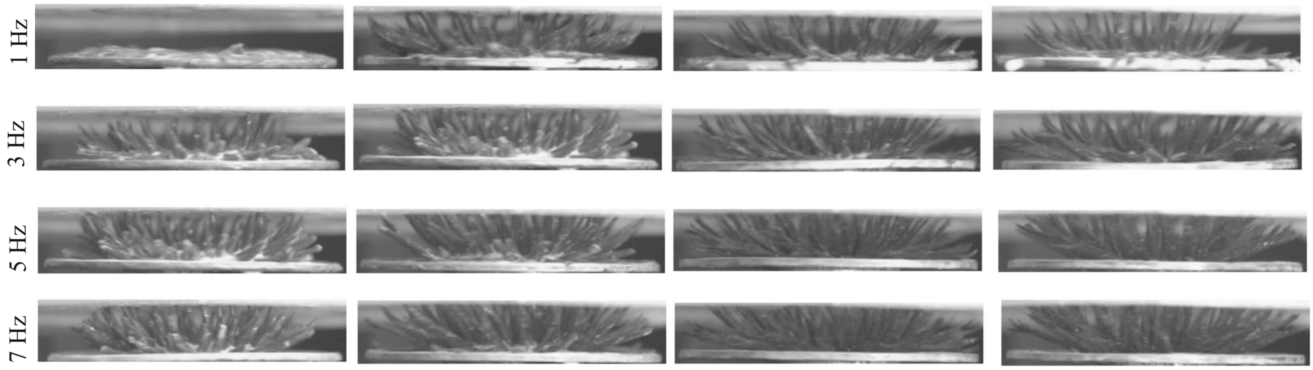
Fig. 9 Schematic diagram of angle measurement method

The waveform of the magnetic force and finishing force is shown in Fig. 6. As can be seen from the figure, the magnetic force and the finishing force vary with the absolute value of the voltage, so the period of the magnetic force and the finishing force is twice the period of the magnetic field. In addition, due to the hysteresis effect, the waveform of the magnetic force and finishing force lags behind the voltage waveform.

3.2.2 Finishing force measurement

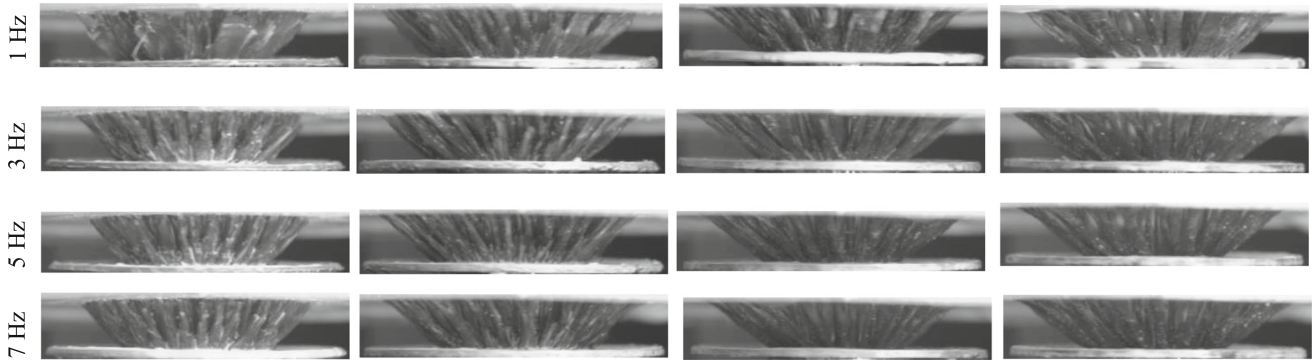
Due to the low hardness of the aluminum alloy material, it does not require too much finishing force to achieve finishing. Therefore, the finishing force is first measured. The measurement conditions are shown in Table 1. The composite magnetic finishing fluid used in the measurement consisted of 1.2 g of magnetic particles, 0.3 g of abrasive particles (WA#10000), and 0.8 ml of oily grinding fluid (Honilo 988). The effect of the magnetic field frequency and magnetic particle size on the finishing force is measured.

When the magnetic field frequency is 1 Hz, the effect of magnetic particle size on finishing force is shown in Fig. 7. As the size of the magnetic particles increases, the finishing force increases. This is because as the size of the magnetic particles increases, the attraction between the magnetic particles increases, which makes the magnetic clusters harder and thus has a greater finishing force. When the magnetic particle size



(1) 6 μm (2) 30 μm (3) 75 μm (4) 149 μm

(a) The lowest position



(1) 6 μm (2) 30 μm (3) 75 μm (4) 149 μm

(b) The highest position

Fig. 10 Photos of the magnetic cluster at the lowest and highest positions

is 30 μm, the effect of the magnetic field frequency on the finishing force is as shown in Fig. 8. It can be seen from the measurement results that the magnetic field frequency has little effect on the maximum value of the finishing force.

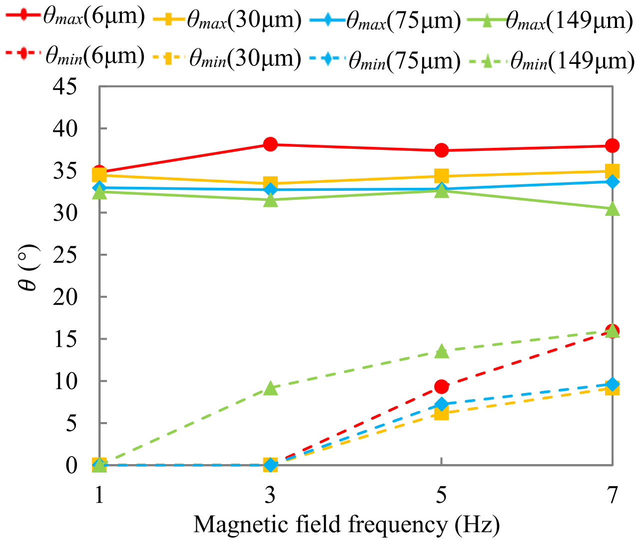


Fig. 11 The angle between the periphery of the magnetic cluster and the tray

3.3 Observation and measurement of magnetic cluster

The magnetic cluster is the grinding tool of the MAF process, and the change in the shape of the magnetic cluster has a great influence on the finishing process. The magnetic particle size and magnetic field frequency have a great influence on the shape of the magnetic cluster, so the changes in the magnetic cluster are observed and measured at different magnetic particle sizes and magnetic field frequencies.

3.3.1 Measurement method and conditions

The measurement conditions are shown in Table 2. In the measurement, the composite magnetic finishing fluid by mixing 1.2 g of magnetic abrasives, 0.3 g of abrasive particles (WA#10000), and 0.8 ml of oily grinding fluid (Honilo 988) was used. The magnetic pole rotation speed was set to 350 rpm during shooting. Use a high-speed camera (MEMRECAM HX-7) to shoot the magnetic cluster in motion. The shooting speed of the high-speed camera is 1000 FPS. The maximum and minimum angles between the tray and the periphery of the magnetic cluster are measured by the

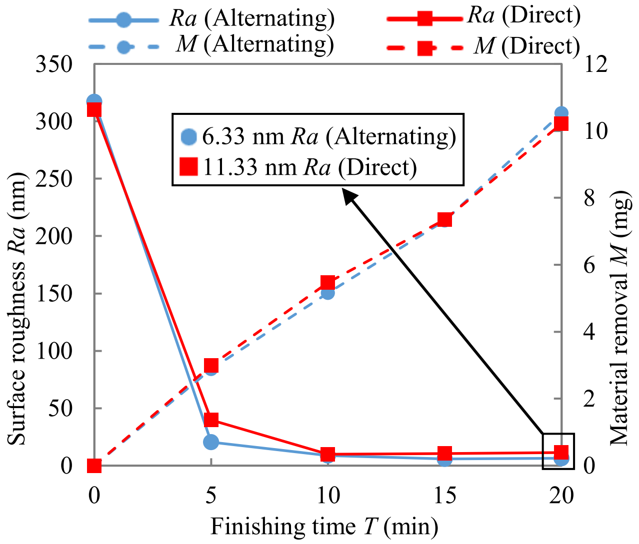
Table 3 Experimental conditions

Workpiece	5052 aluminum alloy plate with the size of 100 mm × 100 mm × 1 mm
Magnetic particles	Electrolytic iron powder, 30 μm in mean dia:1.2 g
Abrasive particles	WA#20000: 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	350 rpm
Feed speed of mobile stage	260 mm/min
Working gap	1 mm
Magnetic field	Type 1: direct magnetic field: direct current: 1.9 A Type 2: alternating magnetic field: alternating current: 1.9 A (average); frequency: 1 Hz
Finishing time	Single 5 min, single 10 min (20 min)

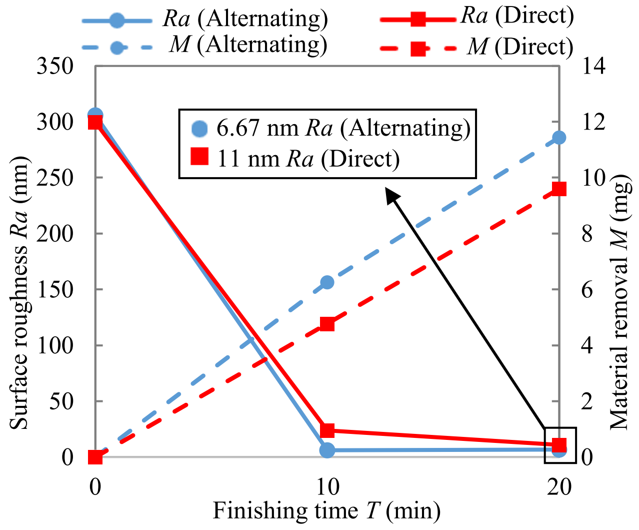
software HXLink. The angle measurement method is shown in Fig. 9. $\theta_{\min}$ and $\theta_{\max}$ are the angles between the tray and the magnetic cluster periphery when the magnetic cluster fluctuates to the lowest and highest positions, respectively. The lowest position is the position of the magnetic cluster before the rising phenomenon occurs. The middle moment of the two lowest position moments is selected as the highest position. The fluctuation range of the magnetic cluster periphery is $\theta_{\min}$ to $\theta_{\max}$. The result of the measurement is the average of the eight measurements after the maximum and minimum values are removed. When the magnetic cluster fluctuates to the lowest position, if there are very few positions where the angle is 0, the measurement result is the average value after removing the maximum and minimum values of eight measurements while ignoring the position of the angle of 0.

3.3.2 Measurement results and discussion

According to the observation, the fluctuation frequency of the magnetic cluster is twice the frequency of the magnetic field. Photographs of the magnetic cluster at the lowest and highest positions are shown in Fig. 10. It can be seen that as the magnetic particle size increases, the ability of the magnetic cluster to carry the abrasive is reduced. At the same time, the magnetic cluster length increases, but when the average diameter is 149 μm, since the volume of the magnetic particles increases, the number of particles decreases, so the length change is not significant. In addition, according to observations, increasing the magnetic particle size will increase the retention time at the highest position. In order to investigate the fluctuation range of the magnetic cluster, the angle between the periphery of the magnetic cluster and the tray is measured. The measurement results are shown in Fig. 11. It can be seen that as the magnetic field frequency increases, $\theta_{\min}$ increases and $\theta_{\max}$ does not change significantly (except for magnetic particles having an average diameter of 6 μm). This is because a decrease in the magnetic field frequency increases the fall time of the magnetic cluster in one cycle, and thus causes $\theta_{\min}$ to decrease, thereby increasing the fluctuation



(a) Single finishing time 5 min



(b) Single finishing time 10 min

Fig. 12 Effect of magnetic field type on surface roughness and material removal. **a** Single finishing time 5 min. **b** Single finishing time 10 min

Table 4 Experimental conditions

Workpiece	5052 aluminum alloy plate with the size of 100 mm × 100 mm × 1 mm
Magnetic particles	Carbonyl iron powder, 6 μm in mean dia: 1.2 g Electrolytic iron powder, 30 μm in mean dia: 1.2 g Electrolytic iron powder, 75 μm in mean dia: 1.2 g Electrolytic iron powder, 149 μm in mean dia: 1.2 g
Abrasive particles	WA#8000: 0.3 g, WA#10000: 0.3 g, WA#20000: 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	350 rpm
Feed speed of mobile stage	260 mm/min
Working gap	1 mm
Alternating current	1.9 A (average)
Magnetic field frequency	1 Hz, 3 Hz, 5 Hz, 7 Hz
Finishing time	20 min (single 5 min)

range of the magnetic cluster. As the size of the magnetic particles increases, $\theta_{\min}$ increases and $\theta_{\max}$ decreases (except for magnetic particles having an average diameter of 6 μm). This is because an increase in the size of the magnetic particles causes the magnetic force acting on the magnetic particles to increase at the same magnetic field intensity, which allows a smaller current to drive the magnetic cluster to move upwards, so $\theta_{\min}$ increases. The increase of the magnetic force enhances the attractive force between the magnetic particles, resulting in a greater force being required to change the shape of the magnetic cluster, so $\theta_{\max}$ decreases.

In particular, when the average diameter of the magnetic particles is 6 μm, the particle size is too small to make the magnetic cluster more similar to the slurry, which increases the magnetic cluster viscosity, so the magnetic cluster change is more similar to the liquid and solid state conversion. In addition, when the magnetic particle size is 6 μm, the magnetic cluster formed is short and the working gap is wide, which makes it less affected by the upper plate, so the $\theta_{\max}$ angle is larger. Further, when the magnetic field frequency is 1 Hz and the average diameter of the magnetic particles is 6 μm, the magnetic cluster return to the state of the slurry when the magnetic cluster is at the lowest position. Because the magnetic force acting on the magnetic particles is small, and the duration of the weak magnetic field strength is long.

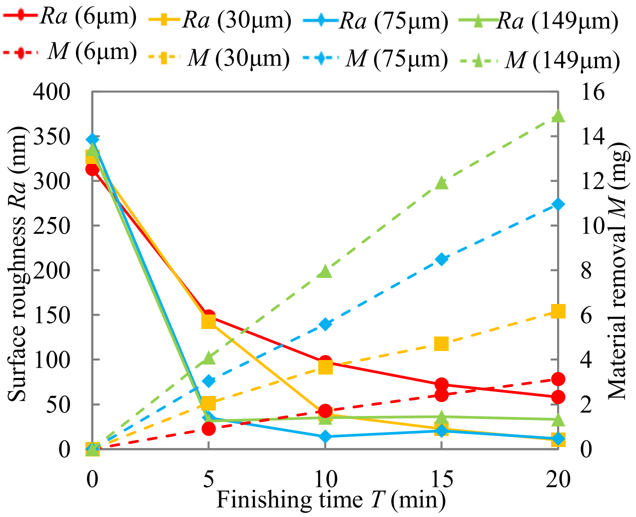


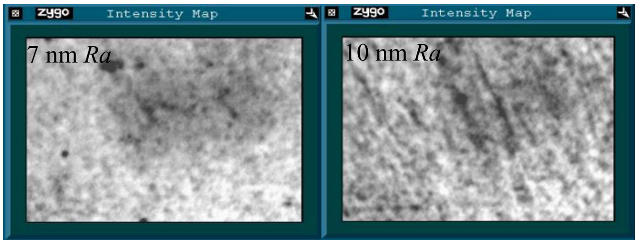
Fig. 13 Effect of magnetic particle size on surface roughness and material removal (magnetic field frequency = 3 Hz, abrasive = WA#10000)

Therefore, an increase in the size of the magnetic particles will increase the finishing efficiency, but the reduction in the ability to carry the abrasive and the increase in the depth of the cut will result in a decrease in the processing accuracy. Reducing the frequency of the magnetic field will make the mixing of the abrasive particles and the magnetic particles more uniform due to the increase in the fluctuation range of the magnetic cluster and the decrease of the fluctuation frequency, which will be more advantageous for ultra-precision finishing.

4 Discussion on the experiment of aluminum alloy plate

4.1 Comparison between direct and alternating magnetic field

In this study, the effects of direct and alternating magnetic fields on the finishing characteristics were compared when the workpiece was the 5052 aluminum alloy plate.



(a) 30 μm × 50 (b) 75 μm × 50

Fig. 14 Intensity map of surface after finishing

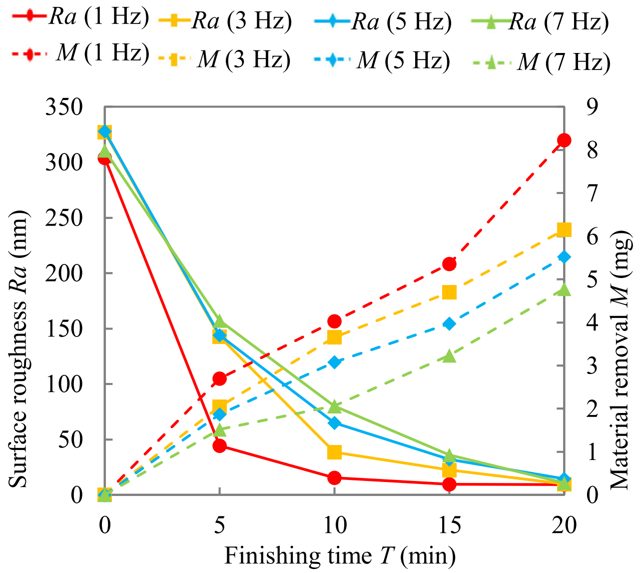


Fig. 15 Effect of magnetic field frequency on surface roughness and material removal (magnetic particles size = 30 μm, abrasive = WA#10000)

4.1.1 Experimental conditions and method

The experimental conditions are shown in Table 3. The 5052 aluminum alloy plate was selected as the workpiece. The coil is supplied with a direct current and an alternating current having a current frequency of 1 Hz. The total finishing time is 20 min. To investigate the difference between a direct magnetic field and an alternating magnetic field, we set the single finishing time to 5–10 min. Use an ultrasonic cleaner to clean the workpiece before measurement. The cleaning fluid is alcohol.

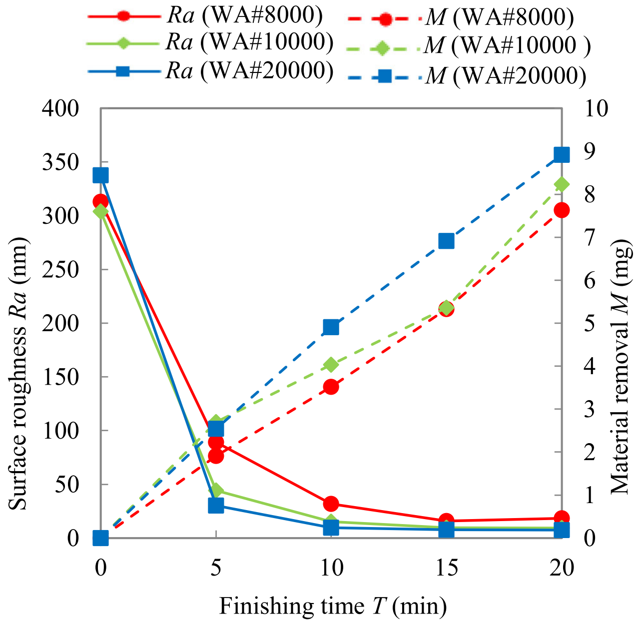


Fig. 16 Effect of abrasive particles on surface roughness and material removal (magnetic particles size = 30 μm, magnetic field frequency = 1 Hz)

4.1.2 Experimental results and discussion

Figure 12a and b are the experimental results for a single finishing time of 5 min and 10 min, respectively. It can be seen that under the condition of a single finishing time of 5 min, although a smoother surface is obtained under an alternating magnetic field, the difference in the quality of material removal is not obvious. In the case of a single finishing time of 10 min, not only a smoother surface is obtained under the alternating magnetic field, but also the quality of material removal is higher than in the direct magnetic field. This is because the magnetic clusters fluctuate with changes in current in the alternating magnetic field, which allows the abrasive particles in contact with the workpiece to be renewed during the finishing process while allowing the abrasive particles to be continuously mixed to provide a more uniform distribution. Moreover, this phenomenon is evident as the single finishing time increases. Therefore, a smoother surface can be obtained under an alternating magnetic field, and as the single finishing time increases, higher finishing efficiency will be obtained.

4.2 Finishing characteristics analysis

In order to achieve high-efficiency and high-precision finishing, we first studied the influence of the main processing parameters on finishing characteristics.

4.2.1 Experimental conditions and method

The experimental conditions are shown in Table 4. The 5052 aluminum alloy plate was selected as the workpiece. We studied the effects of magnetic particle diameter, magnetic field frequency, and abrasive size on finishing efficiency and surface quality, respectively. The total finishing time is 20 min. To understand the changes in surface roughness and material removal, we measured the workpiece weight and surface roughness every 5 min. Use an ultrasonic cleaner to clean the workpiece before measurement. The cleaning fluid is alcohol.

4.2.2 Effect of magnetic particles

Figure 13 shows the effect of magnetic particle size on surface roughness and material removal when the magnetic field frequency is 3 Hz and the abrasive is WA#10000. As the size of the magnetic particles increases, the finishing efficiency increases, but the surface smoothness decreases. This is because an increase in the size of the magnetic particles increases the finishing force, so the depth of cut increases, resulting in new

Table 5 Experimental conditions

Workpiece		5052 aluminum alloy plate with the size of 100 mm × 100 mm × 1 mm
Abrasive particles		WA#20000: 0.3 g
Grinding fluid		Oily grinding fluid (Honilo 988): 0.8 ml
Feed speed of mobile stage		260 mm/min
Working gap		1 mm
Alternating current		1.9 A (average)
Magnetic field frequency		1 Hz
Finishing time		15 min (single 5 min)
Step 1	Magnetic particles	Electrolytic iron powder, 75 μm in mean dia: 1.2 g
	Rotational speed of magnetic pole	380 rpm
Step 2	Magnetic particles	Electrolytic iron powder, 30 μm in mean dia: 1.2 g
	Rotational speed of magnetic pole	350 rpm
Step 3	Magnetic particles	Carbonyl iron powder, 6 μm in mean dia: 1.2 g
	Rotational speed of magnetic pole	350 rpm

scratches on the surface. Simultaneously, the abrasive carrying capacity is reduced, resulting in a decrease in the amount of abrasive on the surface of the workpiece, which also reduces the surface precision to some extent. In addition, when the average diameter of the magnetic particles is 30 and 75 μm, the final surface roughness is very close. However, it can be seen from Fig. 14 that when the average diameter of magnetic particles is 75 μm, there are finishing marks on the workpiece surface.

4.2.3 Effect of magnetic field frequency

Figure 15 shows the effect of magnetic field frequency on surface roughness and material removal when the average diameter of magnetic particles is 30 μm and the abrasive is WA#10000. It can be seen that as the frequency of the magnetic field decreases, the finishing efficiency increases. This is because as the frequency of the magnetic field decreases, the magnetic clusters have a greater ability to mix and renew the abrasive particles while driving more abrasive particles to the workpiece surface. According to the measurement, the frequency has little effect on the maximum finishing force of the magnetic cluster. The increase in the number of abrasive particles participating in the finishing process reduces the force acting on the individual abrasive particles. However, since the hardness of the aluminum alloy is low, the force required to effectively cut the material is small, so reducing the frequency of the magnetic field will increase the number of abrasive particles that effectively cut the material. In addition, the increase in frequency slightly increases the time that the magnetic cluster is in contact with the workpiece. However, due to the short finishing time, the impact on the finishing efficiency is small. Therefore, a higher finishing efficiency is obtained when the magnetic field frequency is 1 Hz.

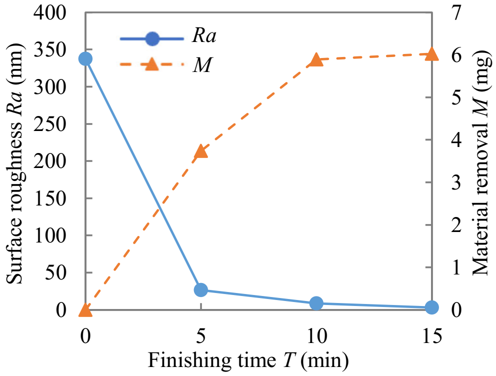
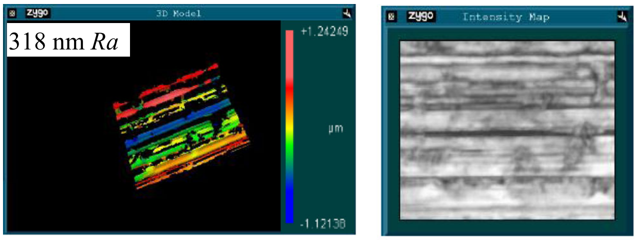
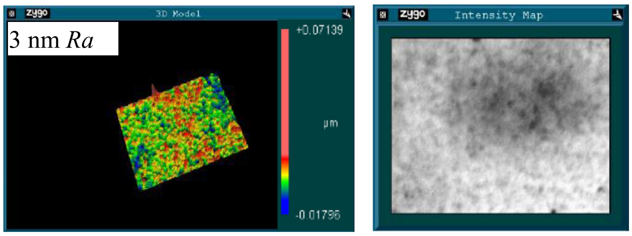


Fig. 17 Changes in material removal and surface roughness with finishing time



(a) Before finishing × 50



(b) After finishing × 50

Fig. 18 3D model and intensity map of the surface before and after finishing

4.2.4 Effect of abrasive particles

Figure 16 shows the effect of abrasive particles on surface roughness and material removal when the average diameter of magnetic particles is 30 μm and the magnetic field frequency is 1 Hz. As can be seen from the figure, the finishing efficiency and surface quality increase with the decrease of the abrasive size, and the highest finishing efficiency and the smoothest surface are obtained when the abrasive is WA#20000. This is because when the weight is the same, the reduction in the size of the abrasive particles increases the number of abrasive particles, which increases the number of abrasive particles in the magnetic cluster. Due to the reduction in the size of the abrasive increases, the number of abrasive particles that contact a single magnetic particle, so that the force on a single magnetic particle is dispersed into more parts, which reduces the force acting on a single abrasive particle. However, the hardness of the aluminum alloy is low, so the force required to effectively cut the material is smaller. Moreover, smaller abrasive particles can more easily enter the groove on the surface of the workpiece. Therefore, an increase in the number of abrasive particles that effectively cut the material increases the finishing efficiency, and a reduction in the depth of the cut makes the finished surface smoother.

4.3 Ultraprecision finishing experiment of 5052 aluminum alloy plate

Through experiments, the effects of main experimental parameters on finishing efficiency and surface quality were investigated. In order to achieve the highly efficient ultraprecision finishing of the 5052 aluminum alloy plate, the following experiment were designed and performed.

4.3.1 Experimental conditions and method

The experimental conditions are shown in Table 5. The experiment was carried out in three steps. The processing time for each step was 5 min, for a total of 15 min. According to previous studies [3], during the roughing phase, increasing the pole rotation speed will increase the finishing efficiency. Therefore, the magnetic pole rotation speed is set to 380 rpm in the first step. In the third step, magnetic particles having an average diameter of 6 μm were used in order to further improve the surface quality. The other experimental methods are the same as the above experiment.

4.3.2 Experimental results and discussion

The experimental results are shown in Fig. 17. The surface roughness of the workpiece was improved to 8.67 nm *Ra* after completion of the second step and improved to 3 nm *Ra* after completion of the third step. The surface quality of the workpiece is further improved by reducing the magnetic particle size. Figure 18 shows the 3D model and intensity map of the surface before and after finishing. It can be seen that there is only a few scratches on the finished surface. Therefore, the ultraprecision finishing of 5052 aluminum alloy plate can be realized by MAF process using alternating magnetic field.

5 Conclusions

This paper investigates the mechanism of the MAF process using alternating magnetic field and uses this process to perform ultraprecision finishing of 5052 aluminum alloy plate. The main conclusions are summarized as follows:

1. In this paper, the mechanism of MAF process using alternating magnetic field is investigated. Through theoretical analysis, in the alternating magnetic field, the period of the magnetic force acting on a magnetic particle is twice the period of the magnetic field.
2. According to the measurement results, in the alternating magnetic field, the period of the finishing force and the magnetic force is twice the period of the magnetic field, and the change of the finishing force and the magnetic force lags behind the change of the magnetic field. In addition, according to the measurement, the finishing force increases as the size of the magnetic particles increases, and the magnetic field frequency has little effect on the maximum value of the finishing force.
3. Through the observation and measurement results of the magnetic cluster, increasing the magnetic particle size will increase the length of the magnetic cluster, the duration of the highest position, but will reduce the ability of the magnetic cluster to carry the abrasive and the fluctuations of the magnetic cluster. Reducing the frequency of the magnetic field will result in a more uniform mixing of the magnetic particles with the abrasive particles.
4. It is proved by experiments that a smoother surface can be obtained under the alternating magnetic field, and the advantage of the MAF process using alternating magnetic field is more obvious with the increase of the single finishing time. When the magnetic field frequency is 1 Hz, higher finishing efficiency can be obtained. In the roughing stage, the increase in the size of the magnetic particles will increase the finishing efficiency, but in the finishing stage, the decrease in the size of the magnetic particles will increase the surface quality. Decreasing the size of the abrasive will increase the finishing efficiency and surface quality.
5. The experimental results show that the MAF process using alternating magnetic field can realize ultraprecision finishing of 5052 aluminum alloy plate. The surface

roughness of the workpiece improved from 318 to 3 nm *Ra* within 15 min.

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