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ORIGINAL ARTICLE

Study on complex micro surface finishing of alumina ceramic by the magnetic abrasive finishing process using alternating magnetic field

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Abstract

In order to achieve the precision machining of the alumina ceramic surface, we propose surface finishing of alumina ceramic by the magnetic abrasive finishing (MAF) process using low-frequency alternating magnetic field. In previous studies, the effects of important process parameters on finishing force and finishing characteristics were investigated when the magnetic particle diameter was 6 and 30 μm. Due to the higher hardness of alumina ceramics, greater finishing force is needed, so we studied the effect of magnetic particle diameter and alternating magnetic field frequency on the finishing force. In order to determine the best experimental conditions, we study the effect of important process parameters on the finishing characteristics. The experimental results prove that the surface finishing of alumina ceramic can be achieved. The surface roughness of the alumina ceramic plate can be improved from 244.6 nm *Ra* to 106.3 nm *Ra*.

Keywords Alternating magnetic field · Magnetic particles · Alumina ceramic · Magnetic field frequency · Surface roughness

1 Introduction

Alumina ceramics have a wide range of structural and functional applications. Because of its high dielectric constant, high strength, and resistance to thermal stresses, alumina ceramics are widely used as substrates for electronic-device applications [1]. With the development of micro-manufacturing and ultraprecision manufacturing, the number of the workpieces with complex micro structure has increased [2]. The workpiece surface polishing with complex micro structure is very difficult, the problem being more acute in low-toughness ceramics, such as alumina and silicon carbide [3]. Conventional processing methods are difficult to achieve, so there is a need for advanced finishing process to complete.

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 [4, 5]. Since the polishing tool (magnetic brush) made of fine magnetic particles is flexible and easy to follow the finished surface [6, 7], the process is considered to be a promising precision finishing technique for flat surfaces [8, 9], complex curve surface [10], and inner surfaces of tube [11, 12]. In addition to the surface finish of the ferromagnetic material, the process can also polish non-ferromagnetic materials such as stainless steel [13, 14], glass [15], ceramics [16], and brass [17]. Shinmura et al. studied the basic processing principle and abrasive characteristics of plane MAF and verified that the MAF have the ability to achieve precision finishing of flat surface [18, 19].

Despite the potential advantages of the MAF process, the traditional MAF process is still difficult to effectively finishing workpiece with complex micro surface. The key issues are as follows. In the conventional plane MAF process using static magnetic field, magnetic brush itself is still under static magnetic field, so that, it cannot transport abrasives into all finished surfaces adequately. Moreover, the edge side of worn in processing leads to the damage of the workpiece shape.

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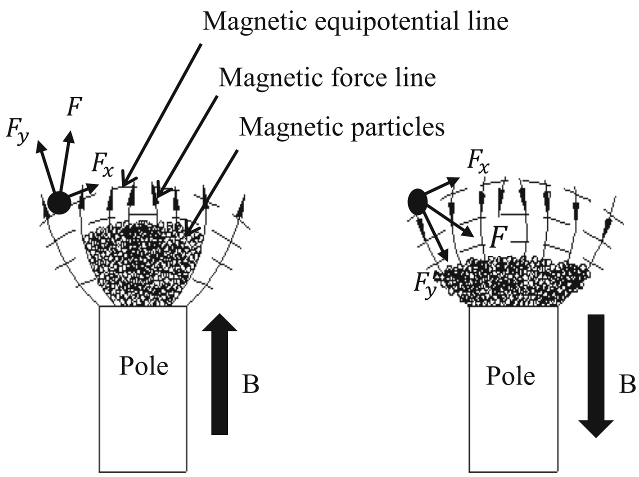

Fig. 1 Schematic diagram of magnetic force acting on a magnetic particle

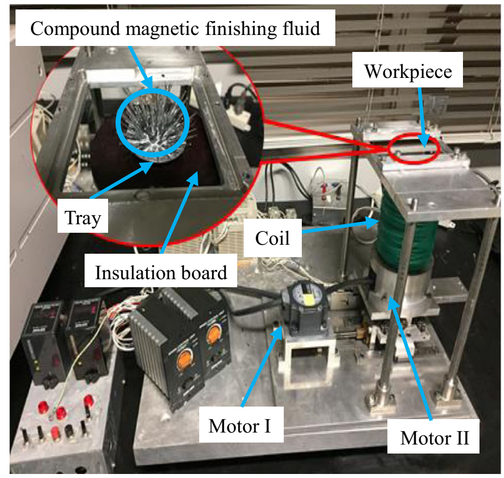

Fig. 3 External view of the experimental setup and processing region expanding photos

In order to overcome these problems, we used the MAF process using alternating magnetic field [20, 21]. In previous studies, the effects of important finishing parameters on surface finish and material removal were investigated when the diameter of the magnetic particles was less than 30 μm and used the MAF process using low-frequency alternating magnetic field in the SUS304 stainless steel plate to complete a few nanometers finishing.

In this paper, we study the feasibility of finishing alumina ceramic by the MAF process using alternating magnetic field. Because the alumina ceramic hardness is higher than that in stainless steel, so this experiment selected larger diameter magnetic particles. In this paper, firstly, the effects of magnetic particle diameter and alternating magnetic field frequency on finishing force are studied. Secondly, the effect of magnetic particle diameter and alternating magnetic field frequency on finishing characteristics was studied by stainless steel plate experiment. Finally, the experiments have been conducted on alumina ceramic workpieces, and the influence of experimental parameters was analyzed.

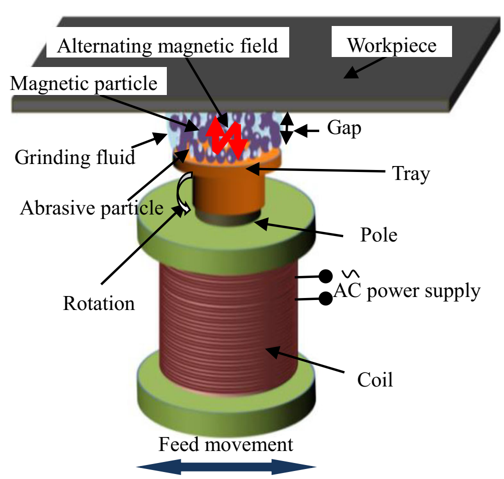

Fig. 2 Schematic of the processing principle

2 Processing principle and experimental setup

2.1 Force analysis of magnetic particles

Figure 1 shows the schematic diagram of magnetic force acting on a magnetic particle in alternating magnetic field. A magnetic particle along magnetic equipotential line direction generates a force F_x and along magnetic force line direction generates a force F_y. It is calculated by the following Eqs. (1) and (2) [22]:

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

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

where V is the volume of magnetic particle, χ is the susceptibility of abrasive particles, μ_0 is the permeability of vacuum,

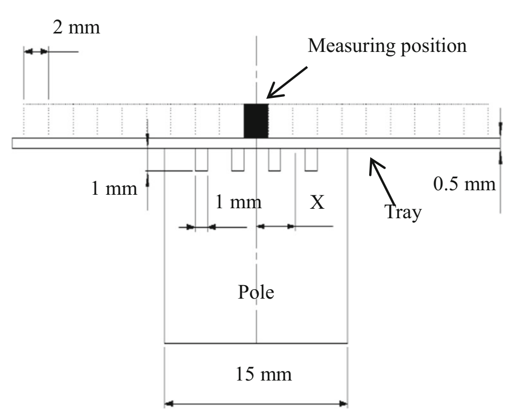

Fig. 4 Measurement method of magnetic flux density effective value in the processing region

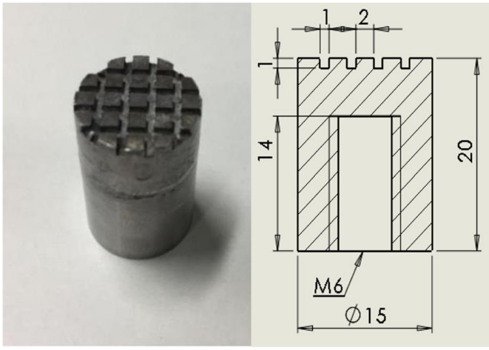

Fig. 5 Magnetic pole shape

H is the magnetic field intensity, and $\partial H/\partial x$ and $\partial H/\partial y$ are the gradients of magnetic field intensity in x and y directions, respectively. Owing to that the direction of alternating current presents a cyclical variation over time, the force direction of F_y is changing with magnetic field frequency. This is not only to be able to transport abrasive to the surface, used to polish the workpiece, but also to achieve the surface abrasive cycle and update, to ensure the stability of grinding tools.

2.2 Processing principle

Figure 2 shows a schematic of the magnetic abrasive finishing (MAF) process using alternating magnetic field. The composite magnetic finishing fluid (grinding fluid, iron powders, abrasives) is placed on the tray. The tray is connected to the pole and below the workpiece. After electromagnetic coil entering alternating current, the iron particles are attracted towards 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. In addition, motors

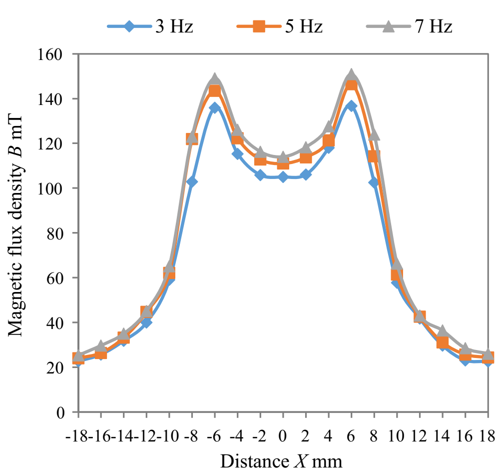

Fig. 6 Magnetic field distribution in the processing region

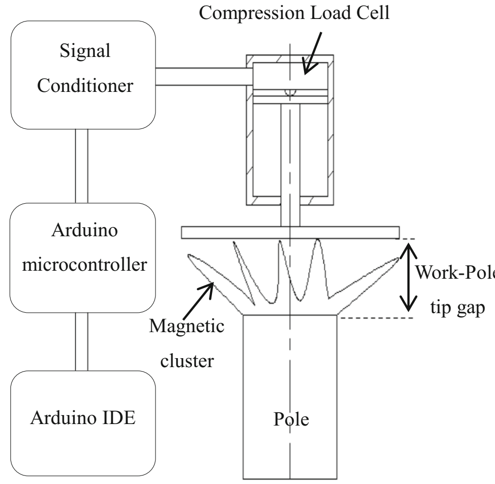

Fig. 7 Schematic view of the force measuring system

are used to achieve the magnetic pole rotation and feed movement. This causes relative friction between the workpiece surface and the magnetic cluster, thereby realizing effectively the material removal.

2.3 Experimental setup

Figure 3 shows the external view of the experimental setup and processing region expanding photos. The electromagnetic coil is connected to the mobile station, which is controlled by the motor I and can reciprocate in one direction. The rotary motion is controlled by the motor. The compound magnetic finishing liquid is placed on the tray with a diameter of 40 mm and a depth of 0.5 mm at the top of the magnetic pole. There is an insulation board between the coil and the tray. Alternating current power device can supply the voltage and frequency in the range of 1–300 V and 1–999 Hz.

Table 1 Measuring conditions

Measuring instrument	LMA-A-5N small-sized compression load cell
Work-pole tip gap	1.5 mm
Finishing fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Magnetic particles	Electrolytic iron powder, 30 μm in mean diameter: 1.2 g; Electrolytic iron powder, 75 μm in mean diameter: 1.2 g; Electrolytic iron powder, 149 μm in mean diameter: 1.2 g; Electrolytic iron powder, 330 μm in mean diameter: 1.2 g;
Abrasives	WA no. 10000, 0.3 g
Magnetic field frequency	1, 3, 5, 7 Hz

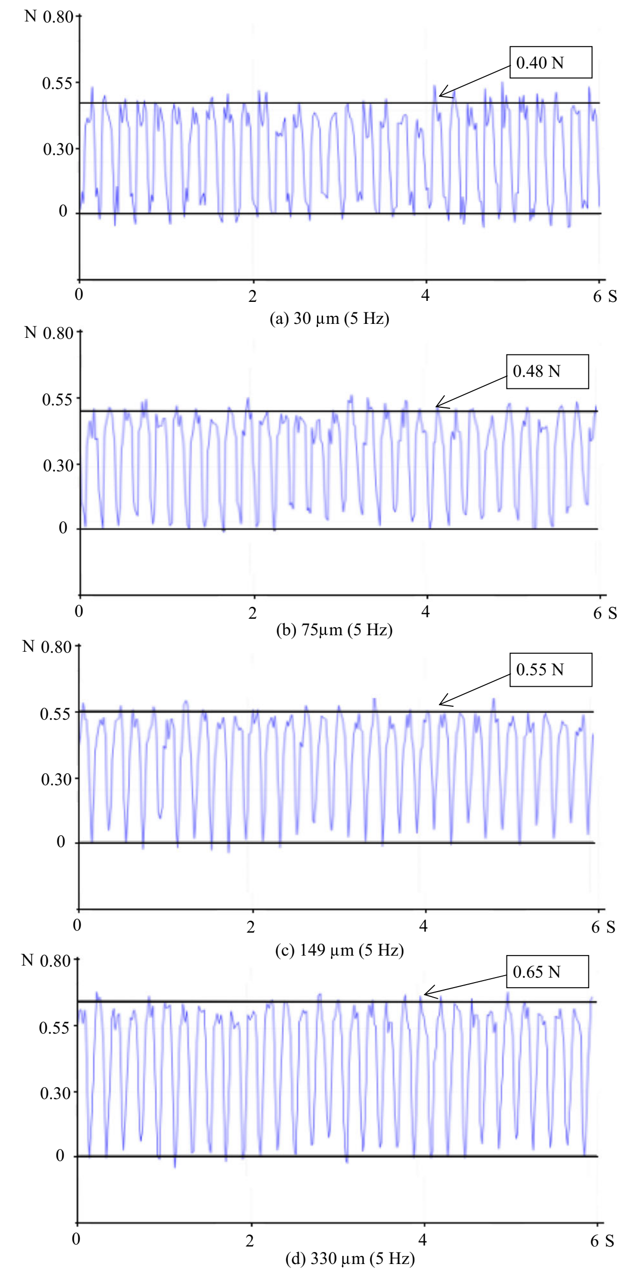

Fig. 8 Effect of magnetic particles on the finishing force

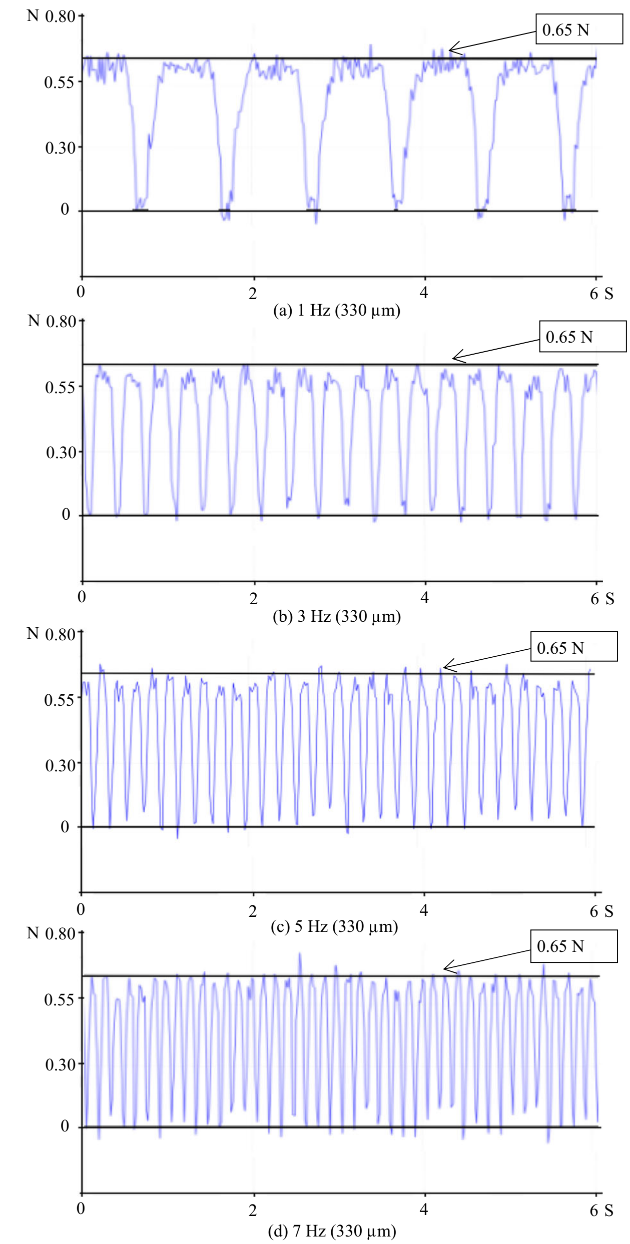

Fig. 9 Effect of magnetic field frequency on the finishing force

3 Measurement of magnetic flux density and finishing force

3.1 Magnetic flux density measurement

The magnetic field distribution in the processing region controls the finishing force distribution of the magnetic particles, which has an important effect on finishing characteristics. Therefore, we measure the magnetic flux density distribution in the processing region. In this study, we use AC power, current peak value is 3 A, and average value is 1.9 A. We measured the magnetic flux density effective value at current frequencies of 3, 5, and 7 Hz, respectively. The measurement method of magnetic flux density effective value in the processing region is shown in Fig. 4. The measurement instrument is made in EMIC with the type of Probe T-401. The diameter of the magnetic pole is 15 mm with the material of the SS400 (JIS), and there are four crossing grooves, width is 1 mm, and depth is 1 mm. The shape of the magnetic pole is shown in Fig. 5. The tray has the thickness of 0.5 mm and the diameter of 40 mm. We divided the tray into 19 sections, i.e., every 2 mm from the center to both sides to conduct magnetic flux density measurement.

The magnetic field distribution in the processing region at different current frequencies is shown in Fig. 6. It can be seen that the magnetic field distribution in the

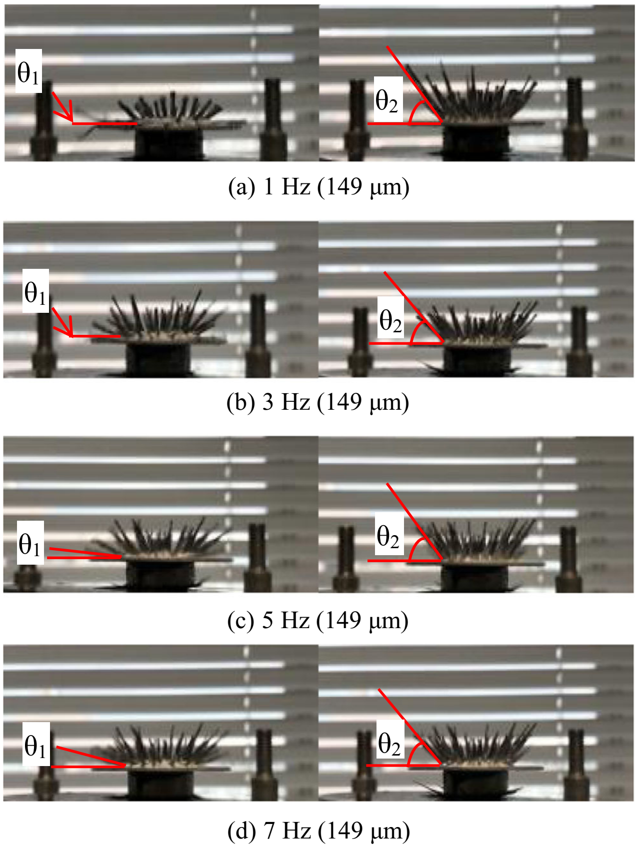

Fig. 10 Image of magnetic cluster angle changes

processing area is similar at different current frequencies, and as the current frequency increases, the effective value of the magnetic flux density increases slightly. At the edge of magnetic pole ($X = \pm 7.5$ mm), the maximum value of the effective value of the magnetic flux density is obtained. So, the magnetic particles on the tray are most intensively distributed at the edge of the magnetic pole ($X = \pm 7.5$ mm).

3.2 Finishing force measurement

The finishing force is important to understand the mechanism of material removal and it has a profound impact on finishing characteristics in finishing process. Therefore, we measured the effect of the relevant parameters on the finishing force.

3.2.1 Measurement method and conditions

The schematic view of the force measuring system is shown in Fig. 7. The finishing force was measured by using a small-sized compression load cell (LMA-A-5N) and a signal conditioner (CDV-700A). The measurement value and wave shape were analyzed by the Arduino microcontroll and the control software (Arduino IDE). The experimental conditions are shown in Table 1. In this measurement, we investigated the effects of magnetic field frequency and magnetic particle diameter on finishing force.

3.2.2 Measurement results and discussion

Figure 8 shows the effect of the magnetic particle diameter on the finishing force in the case if the magnetic field frequency is 5 Hz. As shown in Fig. 8, as the diameter of the magnetic particles increases, the finishing force increases. This is because the finishing force is mainly composed of magnetic force, and the increase in the diameter of the magnetic particles leads to an increase in the magnetic force. Therefore, the finishing force will increase with the increase of magnetic particle diameter.

Figure 9 shows the effect of the magnetic field frequency on the finishing force when the diameter of the magnetic particles is 330 μm. It can be seen from Fig. 9 that the maximum value of the finishing force is approximately the same at different magnetic field frequencies. Figure 10 is a series of images taken in a slow motion video, which shows the change in

Table. 2 Experimental conditions

Workpiece	SUS304 stainless steel plate with the size of 100 mm × 100 mm × 1 mm		
Magnetic particles	Electrolytic iron powder, 30 μm in mean diameter: 1.2 g	Electrolytic iron powder, 149 μm in mean diameter: 1.2 g	Electrolytic iron powder, 330 μm in mean diameter: 1.2 g
Abrasive	WA no. 10000, 0.3 g		
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml		
Rotational speed of magnetic pole	350 rad/min		
Feed speed of mobile stage	260 mm/min		
Alternating current	1.9 A (Average)		
Magnetic field frequency	3, 5, 7 Hz		
Finishing time	20 × 4 min (80 min)		

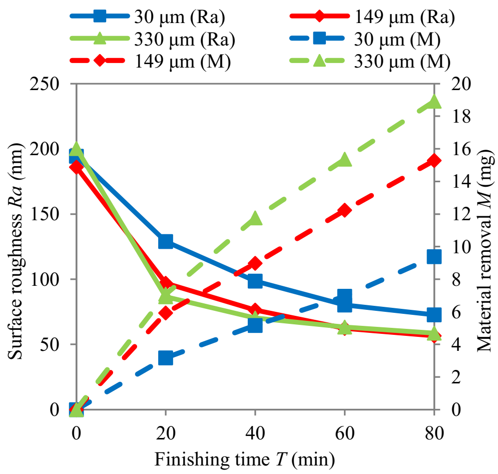

Fig. 11 Effect of magnetic particles on the surface roughness and material removal (magnetic field frequency = 7 Hz)

magnetic cluster angle at different magnetic field frequencies. In the alternating current cycle, θ_1 is the minimum angle between the peripheral magnetic cluster and the tray, and θ_2 is the maximum angle between the peripheral magnetic cluster and the tray. As can be seen from Fig. 10, θ_2 is approximately the same and θ_1 increases as the magnetic field frequency increases. Therefore, with the magnetic field frequency increase, the vibration angle $(\theta_2 - \theta_1)$ of the magnetic cluster decreases and the vibration frequency of the magnetic cluster increases, which makes the magnetic cluster harder.

4 SUS304 stainless steel plate experiments

4.1 Experimental method and conditions

The experimental conditions are shown in Table 2. In this study, the selected workpiece was SUS304 stainless steel plate with the size of 100 mm × 100 mm × 1 mm. The completion time of the experiment is 80 min, and every 20 min, we measure the workpiece weight and surface roughness, in order to understand the surface finish and material removal changes. Before testing, we use an ultrasonic cleaner to clean the workpiece. The cleaning fluid is alcohol.

4.2 Experimental results and discussion

4.2.1 Effects of magnetic particles on finishing characteristics

The magnetic particle size is one of the main parameters to determine the magnetic force acting on the magnetic particles. Figure 11 shows the influence exerted by the finishing time and by the magnetic particle diameter on the surface roughness and the quantity of material removed from workpiece.

It can be seen that the material removal increases with the increase of the magnetic particle diameter. This is because the finishing force increases as the diameter of magnetic particles increases. Moreover, the finishing area increases as the diameter of the magnetic particles increases. This is because the magnetic force increases with the increase of the magnetic particle diameter, which makes the magnetic cluster to become longer in the finishing process, resulting in an increase in the finishing area. Figure 12 is the surface picture after the processing when using three kinds of magnetic particles difference in grain size. As can be seen from Fig. 12, the processing area increases as the diameter of the magnetic particle increases. The increase in the finishing area also leads to the increase in material removal.

4.2.2 Effects of frequency on finishing characteristics

Figure 13 shows the influence exerted by the finishing time and by the magnetic field frequency on the surface roughness and the quantity of material removed from workpiece in the case of magnetic particles diameter of 330 μm. As shown in Fig. 13, when the magnetic field frequency is 7 Hz, the most material is removed. This is because there is a gap of 1.5 mm between the tray and the workpiece. At the same time, as the magnetic field frequency increases, the vibration angle of the magnetic cluster decreases and the vibration frequency of the magnetic cluster increases. When the magnetic cluster and the tray angle are smaller, the magnetic cluster does not contact

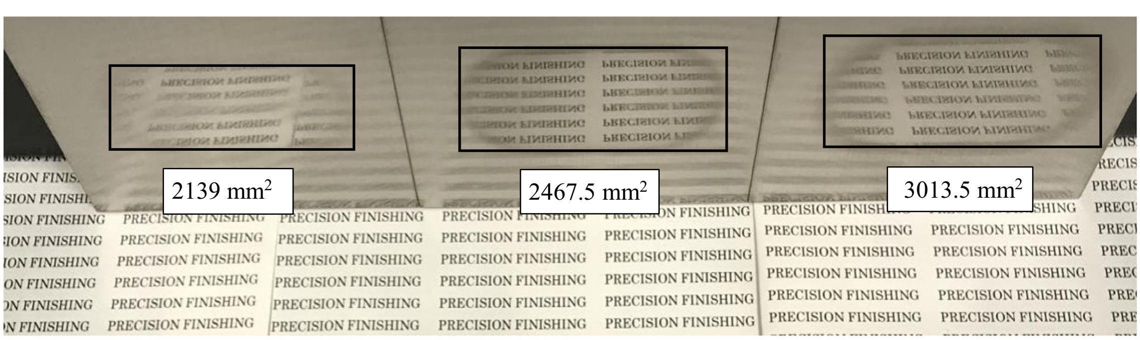

Fig. 12 Finishing area (magnetic field frequency = 7 Hz)

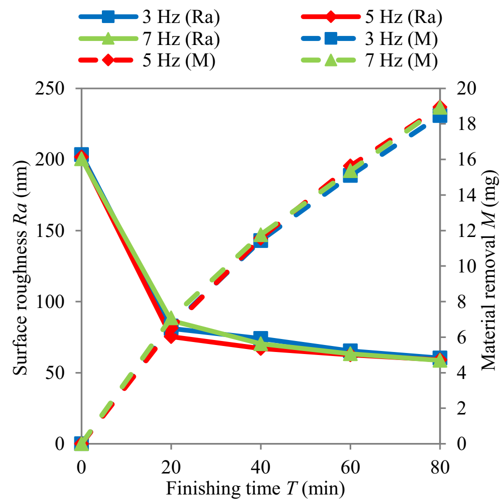

Fig. 13 Effect of magnetic field frequency on the surface roughness and material removal (330 μm)

with the workpiece surface. Therefore, in the same processing time, when the magnetic field frequency is 7 Hz, the contact time between the magnetic cluster at the edge of the processing area and the workpiece is the longest. When the magnetic field frequency is 5 Hz in the first 20 min, the working surface is better than 3 and 7 Hz. This is because the frequency of the magnetic field affects the vibration angle and vibration velocity of the magnetic cluster, which changes the hardness of the magnetic cluster, affects the finishing effect. When the magnetic particle diameter is 330 μm, the magnetic field frequency is 5 Hz; the finishing effect is the best.

5 Alumina ceramic plate experiments

5.1 Experimental method and conditions

The experimental conditions are shown in Table 3. In this study, the selected workpiece was alumina ceramic plate with the size of 100 mm × 100 mm × 2.5 mm. As the alumina ceramic hardness is higher than that in stainless steel, the diamond powder is selected as the abrasive, and the magnetic particle diameter is chosen to be 330 μm, in order to obtain a larger magnetic force. The completion time of the experiment is 80 min; every 20 min, we measure the workpiece weight and surface roughness, in order to understand the surface finish and material removal changes. Before testing, we use an ultrasonic cleaner to clean the workpiece. The cleaning fluid is alcohol. After finishing process (80 min), the surface of the workpiece is observed using an optical profilometer (NewView 7300).

5.2 Experimental results and discussion

Figure 14 shows the changes in surface roughness with finishing time. The cases of 0–1.5-μm and 2–3-μm diamond powder show nearly similar improvement rates of surface roughness, and the case of the 4–8-μm diamond powder shows slightly less improvement rate of surface roughness compared to the 0–1.5-μm or 2–3-μm diamond abrasive. The three sizes of abrasive produced finished surface roughness of 106.3-, 88.3-, and 168.6-nm *Ra* for 0–1.5-, 2–3-, and 4–8-μm diamond powder, respectively. Figure 15 shows the finished workpiece surface. The clarity of text reflection reflects the smoothness of the workpiece. As the smoothness of the workpiece surface increases, the text is reflected more clearly. It can be seen that, in the case of diamond abrasive, the size is 0–1.5 μm, the text reflects the most clear, and the workpiece surface should be the smoothest, but according to the surface roughness measurement results, in the case of diamond abrasive, size is 2–3 μm to get the most smooth surface. To further study this mechanism, the surface was examined using optical surface profiler (NewView 7300).

We randomly take three points on the initial workpiece surface for measurement and compare the measurement results, taking the median point as the initial surface measurement point. Figure 16 shows the observation points after the finishing process. The left-right direction in Fig. 16 is the direction of the magnetic pole reciprocate. In the processing area, the surface quality at the position about 12 mm from

Table 3 Experimental conditions

Workpiece	Alumina ceramic plate 100 mm × 100 mm × 2.5 mm
Magnetic particles	Electrolytic iron powder, 330 μm in mean diameter 1.2 g
Abrasive	Diamond powder,0–1.5 μm in mean diameter 0.3 g
	Diamond powder,2–3 μm in mean diameter 0.3 g
	Diamond powder,4–8 μm in mean diameter 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	350 rad/min
Feed speed of mobile stage	260 mm/min
Alternating current	1.9 A (Average)
Magnetic field frequency	5 Hz
Finishing time	20 × 4 min (80 min)

the center line of the reciprocating direction is better than that in the center line position at the reciprocating direction. This is because the peak value of magnetic flux density decreases gradually from the edge of the magnetic pole to the center of the magnetic pole and produced a maximum value at the magnetic pole edge. Therefore, the magnetic cluster on the edge of the magnetic pole has the largest force on the workpiece, and the distribution of magnetic particles is the most dense. Dense magnetic particles are more conducive to the improvement of surface quality [23]. Thus, point A is selected as the observation point of the center line of the reciprocating direction, and point B is selected as the observation point of 12 mm from the center line of the reciprocating direction.

Figure 17 shows the surface image of before and after finishing with the different sizes of diamond abrasives. The pores were observed in all surfaces images; this must disturb the measure of surface roughness. According to the photo of NewView 7300, the surface smoothness of point A and point *B* is improved the greatest when the diamond abrasive size is 1–1.5 μm compared with that of the other two cases. In the case of diamond abrasive size of 2–4 μm, the point A surface smoothness is only slightly improved. In the case of diamond abrasive size of 0–1.5 μm, the surface roughness of point A and point *B* is 134- and 84-nm *Ra* respectively, and in the case of diamond abrasive size of 2–3 μm, the surface roughness of point A and point B is 173 and 127-nm *Ra*. So, when the diamond abrasive diameter is 1–1.5 μm, we get the best finishing effect.

Therefore, alumina ceramic workpiece surface finishing by the MAF process using alternating magnetic field is feasible. In this paper, in the case of diamond abrasive size of 0–1.5 μm, the workpiece surface roughness improved the highest.

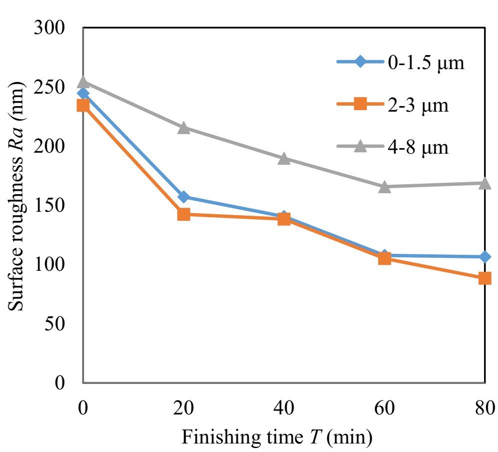

Fig. 14 Effects of size of diamond powder on surface roughness

(a) Diamond powder of 0-1.5 μm

(b) Diamond powder of 2-3 μm

(c) Diamond powder of 4-8 μm

Fig. 15 Photographs of finishing surface

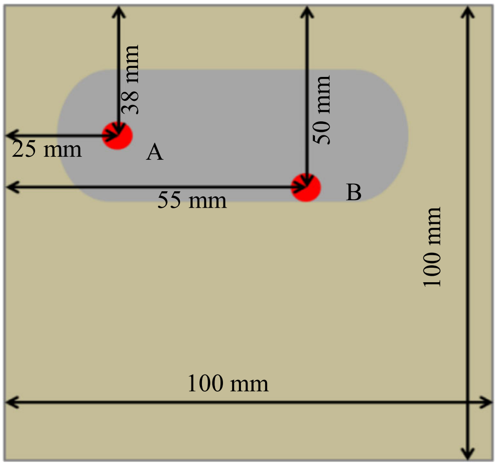

Fig. 16 Examine points

6 Conclusions

This paper studies alumina ceramic workpiece surface finishing by the MAF process using alternating magnetic field. The main conclusions are summarized as follows:

1. Through the study of finishing force, as a result, as the magnetic particle diameter increases, the finishing force increases. In this measurement condition, different frequencies have little effect on the finishing force.
2. In order to determine the effect of magnetic particle diameter and magnetic field frequency on the finishing characteristics, we made a series of experiments in the case of the SUS304 stainless steel plate as the workpiece. The results showed that the material removal and finishing efficiency increase as the diameter of magnetic particles increases, and in the first 20 min of processing, when current frequency is smaller than 7 Hz, the material removal is increasing gradually with the increase of frequency. When the magnetic particle diameter is 330 μm, the best finish surface is obtained in the condition of 5 Hz.
3. We made a set of experiments on alumina ceramic plate, and the results proved to be able to achieve the alumina ceramic finishing. In the case when the completion time is 80 min, the surface roughness of alumina ceramic plate can be improved from 244.6 to 106.3-nm *Ra*.

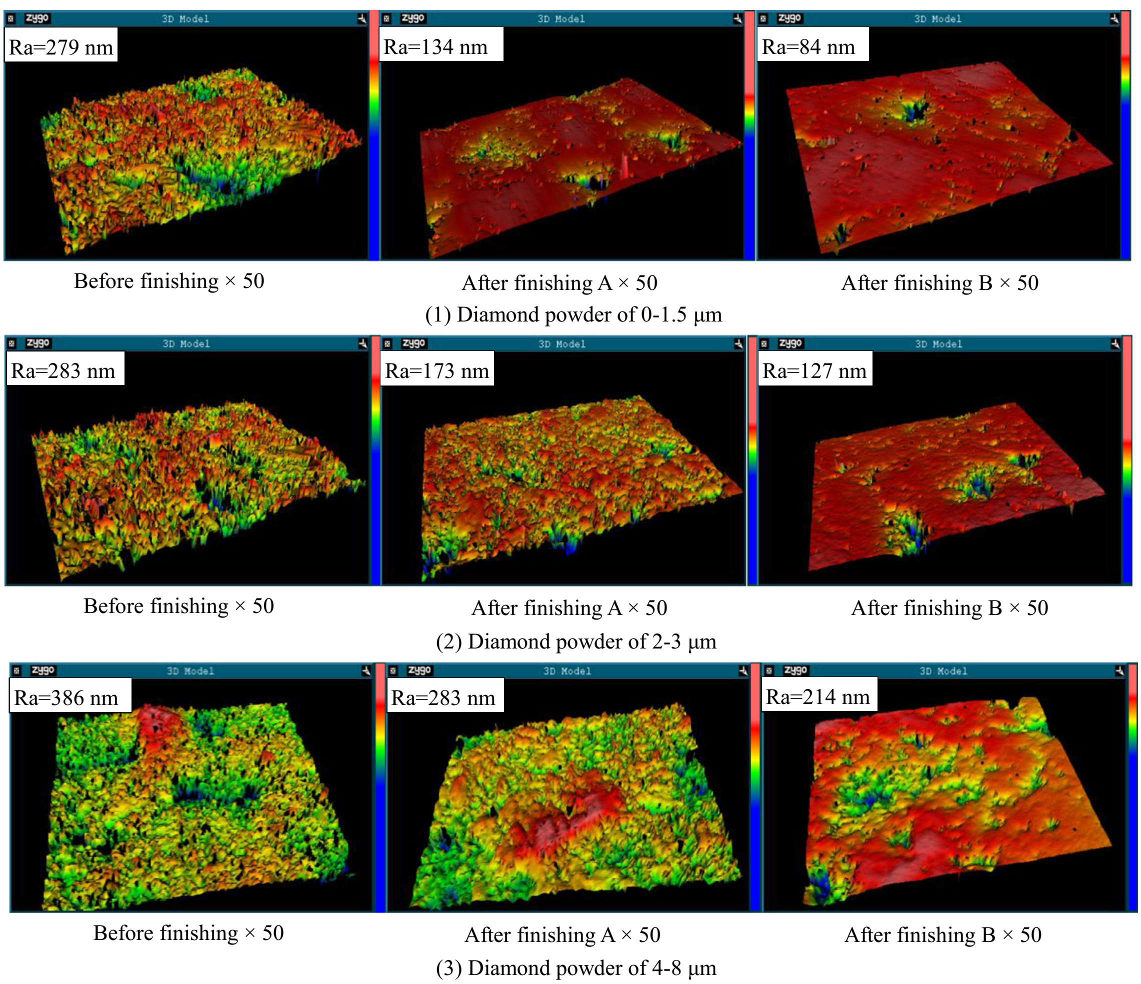

Fig. 17 Surface image of before and after finishing with the different sizes of diamond abrasives

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