博士学位論文

Study on elucidation of machining mechanism of ultra-precision magnetic abrasive finishing process using alternating magnetic field

変動磁場を利用した超精密磁気研磨法の加工メカニズム解明に関する研究

謝　恵君

2021 年 3 月

Contents

Chapter I Introduction

1.1 Research background

Surface quality is very important for components because it greatly affects the performance of mechanical parts. The corrosion and fatigue failure of machine elements undoubtedly cause huge financial losses. Excellent surface quality can improve the corrosion resistance [1] and fatigue strength [2] of the material to a certain extent. Moreover, for some precision machinery, surface finish is also an important factor that is indispensable to perform its functions. In addition, the rapid development of semiconductors, optics, electronics, aerospace industry, etc., has increased the demand for ultra-precise surfaces [3]. At the same time, materials with properties such as high hardness, toughness, high strength to weight ratio and brittleness are popular in industries, which poses a principal challenge to the finishing process. The traditional finishing processes like grinding, honing and lapping create micro/nano burrs, subsurface damage and residual stresses, while achieving nanoscale surfaces will increase production costs [4, 5]. Magnetic abrasive finishing (MAF) process can solve some of these problems. MAF process is to fill the magnetic abrasives between the magnetic pole and the workpiece, and the magnetic abrasives form the magnetic brush in the magnetic field. The magnetic brush is pressed against the workpiece due to the magnetic force. 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 [6, 7].

Shinmura et al. [8, 9] introduced the basic principle of plane MAF, developed the plane MAF device using electromagnets, and discussed the effects of process parameters such as finishing fluid and magnetic abrasives supply weight on the machining depth and surface roughness. Shinmura et al. [10] also proposed the use of the MAF process to finish the outer surface of the cylinder and analyzed the effect of the shape of the magnetic pole on the finishing properties. Zou et al. [11, 12] discussed the influence of the magnetic pole movement trajectory on finishing characteristics. Through theoretical analysis and experiments, they proved that the simultaneous rotation and revolution of the magnetic pole can improve the flatness of the finished surface. In addition, they proposed magnetic abrasive finishing combined with the electrolytic process (EMAF) [13, 14]. They discussed the processing principle of EMAF and the stability of finishing. It proves that the EMAF process can significantly improve finishing efficiency. Lee et al. [15, 16] discussed the effect of the combination planetary motion with two-dimensional vibration-assisted magnetic abrasive finishing process on the finishing efficiency and surface quality. They showed that this method helps to improve surface quality and reduce finishing costs. Through experiments, they obtained the best combination of process parameters to improve the surface roughness, and can reduce the surface roughness of SUS304 stainless steel workpiece from 0.14 to 0.032 μm in 12.5 min. Pandey et al. [17-19] studied the ultrasonic-assisted MAF (UAMAF) process. The influence of power supply voltage, abrasive size, magnetic pole rotation speed, and other factors on the finishing characteristics was explored through experiments. And proved that UAMAF process can finish the surface to the nanometer level faster than MAF process. They also proposed model for predicting the material removal rate and surface roughness changes, and compared the predicted value with the experimental value, and proved that the predicted value is in good agreement with the experimental result. Jain et al. [20, 21] 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). They also studied the influence of process parameters such as current, working gap, and rotation speed on the tangential force and normal force in the MAF process. They concluded that the current value and working gap are the most important factors affecting the tangential force and the normal force. Yin et al. improved the deburring efficiency of workpiece edges by using the vibration-assisted MAF process [22]. The polishing of 3D micro-curved surface by vibration-assisted MAF process was proposed, and the effects of workpiece vibration on magnetic field, polishing pressure, in-process abrasive behavior and polishing performances in three vibration modes (horizontal vibration, vertical vibration and compound vibration) [23]. Yamaguchi et al. [24, 25] proposed finishing the inner surface of the tube using the MAF process. The behavioral characteristics of the abrasive were discussed in the process, and the influence of the shape of the magnetic pole on the magnetic flux density distribution was measured.

However, there are some difficulties in the finishing of complex micro surface 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 micro surface. However, when performing complicated micro-curved 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 [26]. 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.

1.2 Research purposes

Due to the static magnetic field, it is difficult for the magnetic cluster to recover its shape after contacting the workpiece. During the finishing process, the distribution of abrasive particles is uneven, and the abrasive particles in contact with the workpiece are gradually passivated, resulting in poor surface accuracy and reduced finishing efficiency. Therefore, the MAF process using alternating magnetic field is proposed. In previous research, it was proved that the MAF process using alternating magnetic field has higher finishing efficiency and surface quality [26, 27]. However, many mechanisms remain unclear. Therefore, this article mainly investigate the mechanism of MAF process using alternating magnetic field. Further improve the finishing efficiency and surface quality, and realize the finishing of complex micro-surfaces.

1.3 Overview of thesis

This thesis discusses the MAF process using alternating magnetic fields. The overview of each chapter of the paper is as follows:

In chapter 1, the research background and some research on MAF process are introduced. In addition, the research purpose of this article is explained and the content of each chapter is summarized.

In chapter 2, first introduced the processing principle of traditional MAF. Secondly, the processing principle and experimental device of the MAF process using an alternating magnetic field are explained. In addition, the changing laws of magnetic force and finishing force in an alternating magnetic field are analyzed. Besides, the influence of the magnetic pole shape on the magnetic field distribution is discussed.

In chapter 3, the application of the MAF process using alternating magnetic field in 5052 aluminum alloy materials is discussed. First, measure the magnetic field distribution in the processing area. Second, the influence of magnetic particle size and current frequency on finishing force is analyzed. Third, the influence of magnetic field frequency and magnetic particle size on the behavior of magnetic clusters is observed and analyzed. Fourth, the influence of process parameters (magnetic particle size, current frequency, abrasive particle size) on finishing characteristics is studied. Finally, ultra-precision finishing experiments were carried out on 5052 aluminum alloy plates.

In chapter 4, the influence of the current change mode on the MAF process using alternating magnetic field is discussed. First, the relationship between current and magnetic flux density in a static magnetic field is discussed. The effect of current change mode on magnetic flux density is studied. Secondly, the relationship between current, magnetic flux density, and finishing force in the static magnetic field is analyzed, and the influence of current change mode on finishing force is discussed. Third, the effects of square wave (AC) and full-wave rectified sinusoidal waveforms on the finishing characteristics and the behavior of magnetic cluster are investigated through experiments. Finally, the optimal current waveform is discussed and verified by experiments.

In chapter 5, the industrial application of MAF process using alternating magnetic field is studied. First, the finishing of alumina ceramic materials is discussed. Secondly, the feasibility of finishing miniature groove is discussed.

In chapter 6, the main conclusions of this thesis are summarized.

References

1. Konefal K, Korzynski M, Byczkowska Z, Korzynska K (2013) Improved corrosion resistance of stainless steel X6CrNiMoTi17-12-2 by slide diamond burnishing, Journal of Materials Processing Technology, 213(11), 1997-2004.
2. Bagehorn S, Wehr J, Maier HJ (2017) Application of mechanical surface finishing processes for roughness reduction and fatigue improvement of additively manufactured Ti-6Al-4V parts, International Journal of Fatigue, 102, 135-142.
3. Wang Y, Hu DJ (2005) Study on the inner surface finishing of tubing by magnetic abrasive finishing. International Journal of Machine Tools and Manufacture 45(1):43-49
4. Jain NK, Jain VK, Jha S (2007) Parametric optimization of advanced fine-finishing processes. Int J Adv Manuf Technol 34:1191–1213
5. Misra A, Pandey PM, Dixit US, Roy A, et al. (2019) Multi-objective optimization of ultrasonic-assisted magnetic abrasive finishing process. Int J Adv Manuf Technol 101:1661–1670
6. Shinmura T, Takazawa K, Hatano E, Matsunaga M, Matsuo T (1990) Study on Magnetic Abrasive Finishing. CIRP Annals 39(1):325-328
7. Sun X, Zou YH (2017) Development of magnetic abrasive finishing combined with electrolytic process for finishing SUS304 stainless steel plane. Int J Adv Manuf Technol 92(9-12):3373-3384
8. Shinmura T, Aizawa T (1989) Study on magnetic abrasive finishing process-development of plane finishing apparatus using a stationary type electromagnet. Bull Jpn Soc Precis Eng 23(3):236-239
9. Shinmura T, Aizawa T (1988) Development of Plane Magnetic Abrasive Finishing Apparatus and its Finishing Performance (2nd Report) Finishing Apparatus using a Stationary Type Electromagnet. J Jpn Soc Prec Eng 54(5):928–933 (in Japanese)

10. Shinmura T, Takazawa K, Hatano E, Aizawa T (1986) Study on Magnetic-abrasive Finishing (2nd Report) Finishing Characteristics. J Jpn Soc Prec Eng 52(10):1761-1767 (in Japanese)
11. Zou YH, Jiao AY, Aizawa T (2010) Study on Plane Magnetic Abrasive Finishing Process - Experimental and Theoretical Analysis on Polishing Trajectory -. Adv Mat Res 126:1023-1028.
12. Jiao AY, Quan HJ, Li ZZ, Zou YH (2015) Study on improving the trajectory to elevate the surface quality of plane magnetic abrasive finishing. Int J Adv Manuf Technol 80(9-12):1613–1623.
13. Sun X, Zou YH (2017) Development of magnetic abrasive finishing combined with electrolytic process for finishing SUS304 stainless steel plane. Int J Adv Manuf Technol 92(9-12):3373-3384.
14. Zou YH, Xing BJ, Sun X (2020) Study on the magnetic abrasive finishing combined with electrolytic process—investigation of machining mechanism, Int J Adv Manuf Technol 108:1675–1689.
15. Lee Y, Wu K, Jhou J et al. (2013) Two-dimensional vibration-assisted magnetic abrasive finishing of stainless steel SUS304. Int J Adv Manuf Technol 69:2723–2733.
16. Lee Y, Wu K, Bai C et al. (2015) Planetary motion combined with two-dimensional vibration-assisted magnetic abrasive finishing. Int J Adv Manuf Technol 76:1865–1877.
17. Mulik RS, Pandey PM (2011) Ultrasonic assisted magnetic abrasive finishing of hardened AISI 52100 steel using unbonded SiC abrasives. Int J Refract Hard Met 29(1):68-77.
18. Misra A, Pandey PM, Dixit US (2017) Modeling of material removal in ultrasonic assisted magnetic abrasive finishing process. Int J Mech Sci 131–132:853-867.

19. Misra A, Pandey PM, Dixit US (2017) Modeling and simulation of surface roughness in ultrasonic assisted magnetic abrasive finishing process. Int J Mech Sci 133:344–356.
20. Jain VK, Kumar P, Behera PK, Jayaswal SC (2001) Effect of working gap and circumferential speed on the performance of magnetic abrasive finishing process. Wear 250(1-12):384-390.
21. Jain VK, Saren KK, Raghuram V, Ravi Sankar M (2019) Force analysis of magnetic abrasive nano-finishing of magnetic and non-magnetic materials. Int J Adv Manuf Technol 100:1137–1147.
22. Yin SH, Shinmura T (2004) Vertical vibration-assisted magnetic abrasive finishing and deburring for magnesium alloy. Int J Mach Tool Manuf 44:1297-1303
23. Yin SH, Shinmura T (2004) A comparative study: polishing characteristics and its mechanisms of three vibration modes in vibration-assisted magnetic abrasive polishing. Int J Mach Tool Manuf 44:383-390
24. Yamaguchi H, Shinmura T, Kaneko T (1996) Development of a New Internal Finishing Process applying Magnetic Abrasive Finishing by use of Pole Rotation System. Int J Jpn Soc Precis Eng 30(4):317-322
25. Yamaguchi H, Shinmura T (2000) Study of an internal magnetic abrasive finishing using a pole rotation system: Discussion of the characteristic abrasive behavior. Precision Engineering 24:237-244
26. Wu JZ, Zou YH, Sugiyama H (2015) Study on ultra-precision magnetic abrasive finishing process using low frequency alternating magnetic field. Journal of Magnetism and Magnetic Materials 386:50-59
27. Wu JZ, Zou YH, Sugiyama H (2016) Study on finishing characteristics of magnetic abrasive finishing process using low-frequency alternating magnetic field. Int J Adv Manuf Technol 85(1-4):585-594

Chapter II Processing principle and experimental device

2.1 Conventional plane MAF process

Figure 2.1 shows the processing principle of the conventional plane MAF process. The basic principle of the conventional plane MAF process is to fill the magnetic abrasive or compound magnetic finishing fluid between the magnetic pole and the workpiece. Magnetic abrasives are made of iron powder and abrasives through sintering or chemical or other techniques [1]. However, sintering requires both high temperature and pressure within an inert gas atmosphere. Subsequently, the sintered material should be crushed mechanically and then sieving is required to sort it into a specific particle size. Obviously, due to the complex production process, additional production costs will increase [2]. Therefore, more and more researches have focused on the use of unbound magnetic abrasives [3-5]. The compound magnetic finishing fluid is obtained by uniformly mixing a certain proportion of magnetic particles, abrasive particles and grinding fluid. In the magnetic field, the magnetic particles are attracted by the magnetic poles and arranged along the lines of magnetic force to form a magnetic brush. The relative movement between the magnetic brush and the workpiece is generated through the feed movement and the rotation movement, thereby realizing the material removal on the surface of the workpiece.

However, there are some problems in the finishing of complex micro-surfaces through the conventional MAF process, that is, when the magnetic brush is subjected to complex micro-curved surface finishing in a static magnetic field, the change in the gap between the magnetic pole and the workpiece causes contact with the workpiece The magnetic brush is 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 magnetic brushes to polish all surfaces. In addition, it is difficult to update the abrasive in contact with the workpiece in a static magnetic field. Therefore, finishing efficiency will gradually decrease. In order to overcome these problems, we proposed MAF process using an alternating magnetic field. In an alternating magnetic field, the magnetic brush will periodically fluctuate up and down due to current changes. This not only continuously mixes and renews the abrasive but also periodically pushes the magnetic brush to the surface of the workpiece.

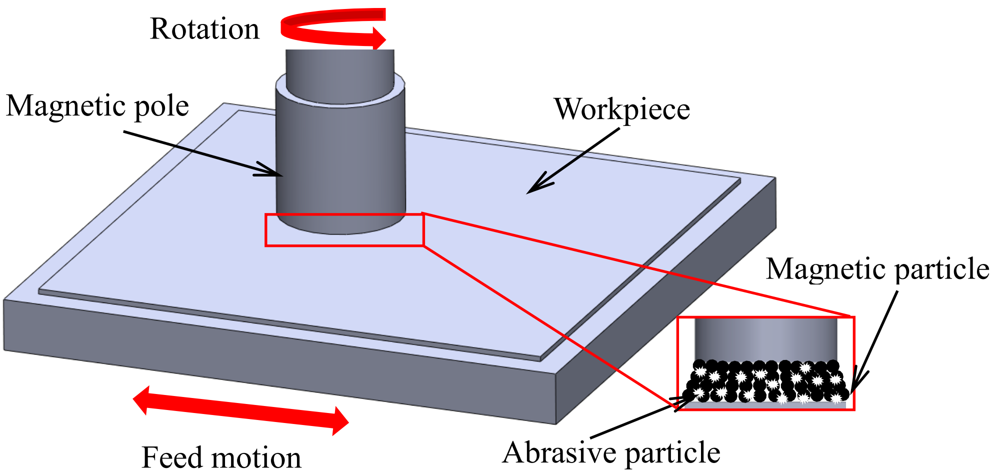


Fig. 2.1 Processing principle of the conventional plane MAF process

2.2 Processing principle

Figure 2.2 shows a schematic of the processing principle. The electrolytic iron powder, the abrasive, and the grinding fluid are uniformly mixed in a certain proportion to form compound magnetic finishing fluid. Place the compound magnetic finishing fluid in the tray. The electrolytic iron powder in the compound magnetic finishing fluid is attracted by the magnetic pole to form the magnetic cluster and carry abrasive particles to press the workpiece. The rotational movement and feed movement of the magnetic pole drive the movement of the magnetic cluster. Through the relative movement of the magnetic cluster and the workpiece, the finishing of the workpiece is realized.

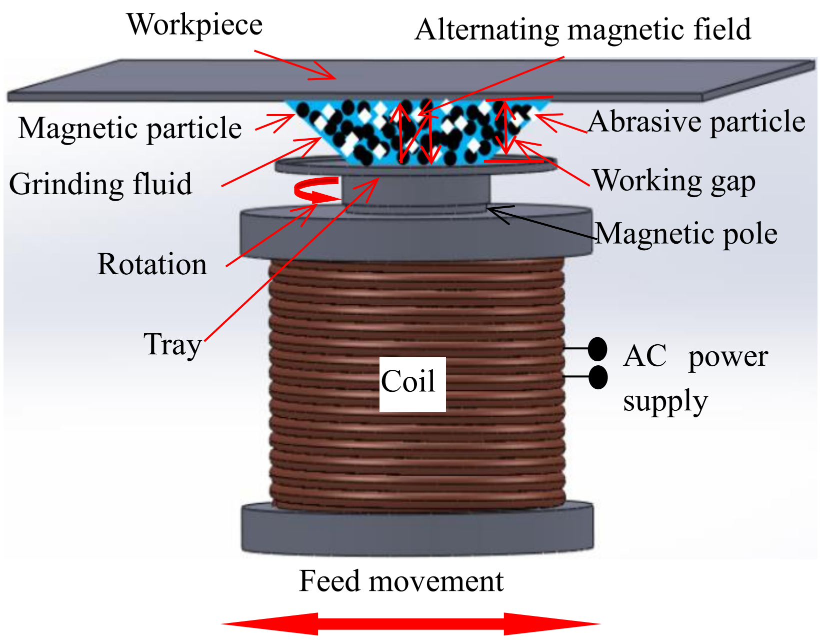


Fig. 2.2 Schematic of processing principle

Due to the static magnetic field, it is difficult for the magnetic cluster to recover its shape after contacting the workpiece. During the finishing process, the distribution of abrasive particles is uneven, and the abrasive particles in contact with the workpiece are gradually passivated, resulting in poor surface accuracy and reduced finishing efficiency. In an alternating magnetic field, the magnetic field changes periodically, and the magnetic clusters fluctuate periodically. When the current becomes zero, the magnetic cluster will fluctuate downward, and when the current becomes the maximum, the magnetic cluster will fluctuate upward. Through the fluctuation of the magnetic cluster, the abrasive particles in contact with the workpiece are replaced, thereby renewing the abrasive particles in contact with the workpiece, ensuring the stability of the grinding tool. Therefore, the finishing efficiency can be improved and a stable finishing process can be realized.

2.3 Experimental setup

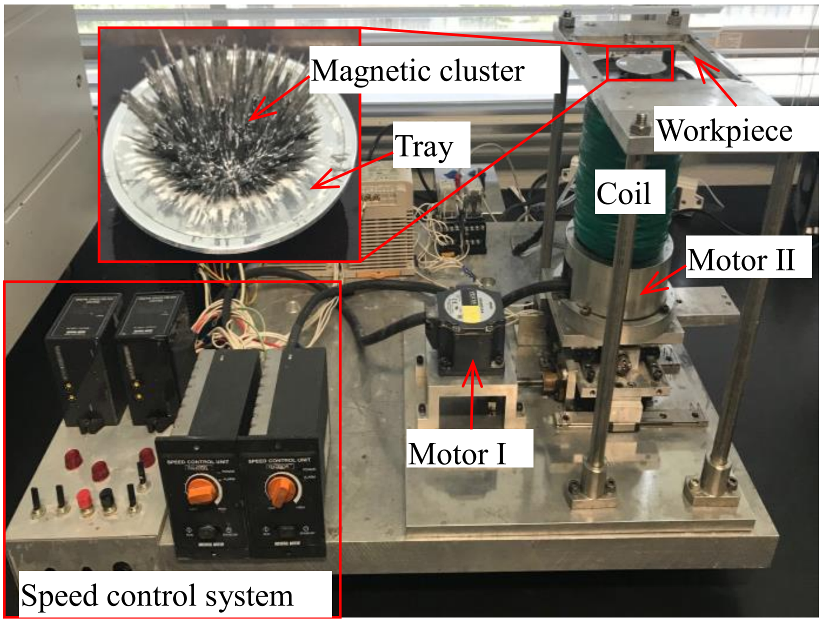


Fig. 2.3 External view of the experimental setup and processing region expanding photos

Figure 2.3 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 rotation direction of the motor I is controlled by two contact switches, and the reciprocating distance is controlled by adjusting the distance between the two contact switches. Place the compound magnetic finishing fluid on the tray with a diameter of 40 mm and a depth of 0.5 mm. 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. Supplying current to the coil generates a magnetic field, and the compound magnetic finishing fluid forms the magnetic cluster in the magnetic field and presses the bottom surface of the workpiece. The relative movement between the magnetic cluster and the workpiece is achieved by rotating and reciprocating movement, thereby realizing material removal.

2.4 Magnetic force analysis of alternating magnetic field

2.4.1 Magnetic force analysis

Figure 2.4 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. (2.1) and (2.2) [6],

$$F_x = \mathrm{V}\chi\mu_0 H\left(\frac{\partial H}{\partial x}\right) \qquad (2.1)$$

$$F_y = \mathrm{V}\chi\mu_0 H\left(\frac{\partial H}{\partial y}\right) \qquad (2.2)$$

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, $\partial H/\partial x$ and $\partial H/\partial y$ are gradients of magnetic field intensity in x and y directions, respectively.

In order to study the relationship between magnetic force and the alternating magnetic field, the model is simplified as shown in Fig. 2.5. 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. (2.3) [7],

$$\mathrm{H} = \frac{IR^2}{2(R^2 + Z^2)^{3/2}} \qquad (2.3)$$

In an alternating magnetic field, the current can be calculated by Eq. (2.4),

$$I = I_m \sin \omega t \qquad (2.4)$$

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

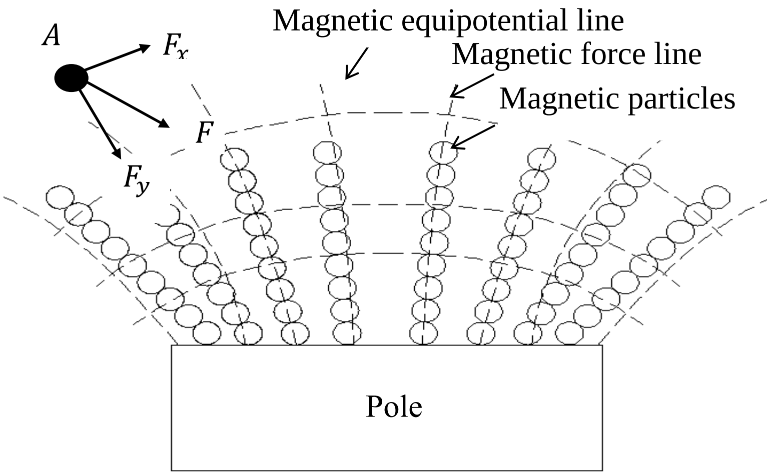


Fig. 2.4 The magnetic force acting on a magnetic particle in magnetic field

Therefore, when a magnetic particle is on the axis of the coil, the magnetic force acting on it can be calculated by the Eq. (2.5),

$$F_z = \frac{3V\chi\mu_0 Z I_m^2 R^4}{8(R^2+Z^2)^4}(\cos 2\omega t - 1) \qquad (2.5)$$

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. (2.5) 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.

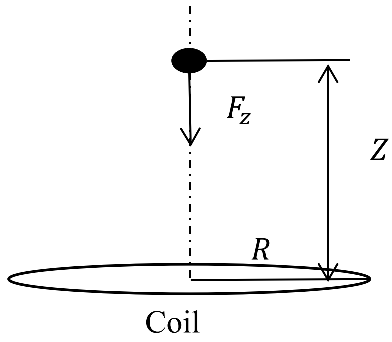


Fig. 2.5 The simplified model of the magnetic force acting on a magnetic particle in an alternating magnetic field

2.4.2 Magnetic force measurement

2.4.2.1 Measurement methods and conditions

In order to verify the changing law of the magnetic force acting on the magnetic particles in the alternating magnetic field, we measured the magnetic force and voltage waveforms. The magnetic force measurement system is shown in Fig. 2.6. 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. 2.6. The brass plate is 1 mm thick. The magnetic material has a height of 10 mm and a diameter of 4 mm.

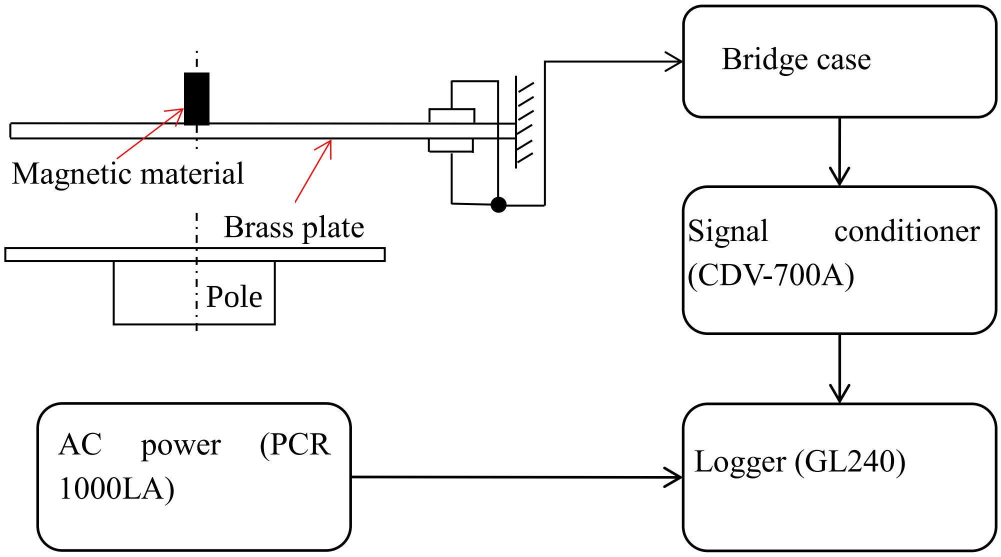


Fig. 2.6 Schematic diagram of magnetic force measurement system

2.4.2.2 Measurement results and discussion

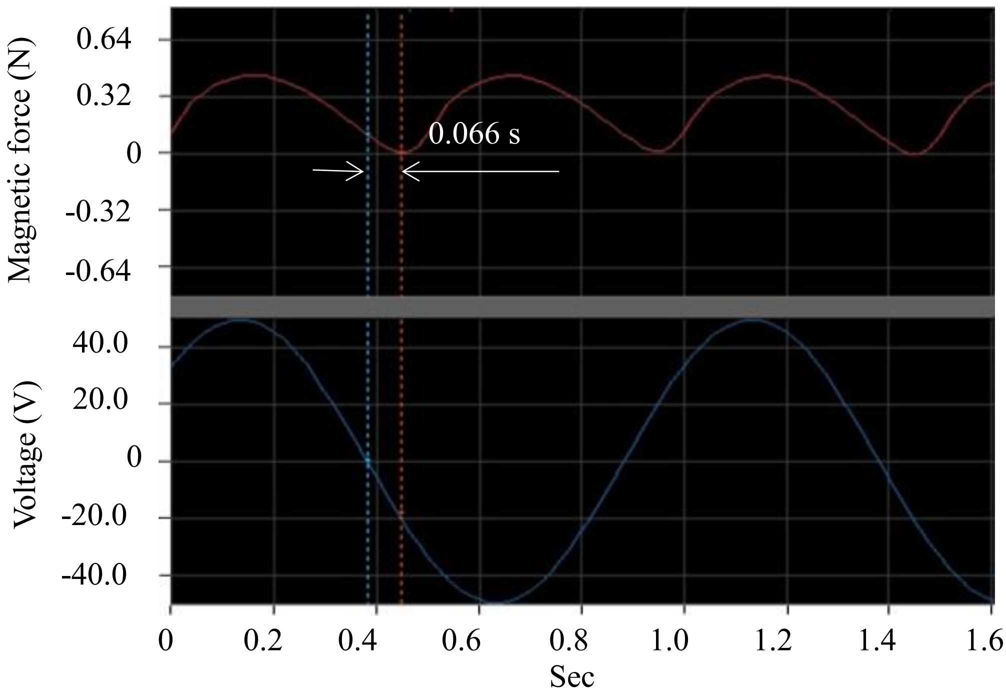


Fig. 2.7 The waveform of the magnetic force and voltage

The waveform of the magnetic force is shown in Fig. 2.7. As can be seen from the figure, the magnetic force varies 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. This is consistent with the results of the previous discussion, that is, the direction of the magnetic force does not change, but it changes with the absolute value of the current. In addition, it can be seen from the figure that the change curve of magnetic force lags behind the change curve of voltage. And this mainly depends on the magnetization characteristics of the material.

2.4.3 Finishing force measurement

2.4.3.1 Measurement methods and conditions

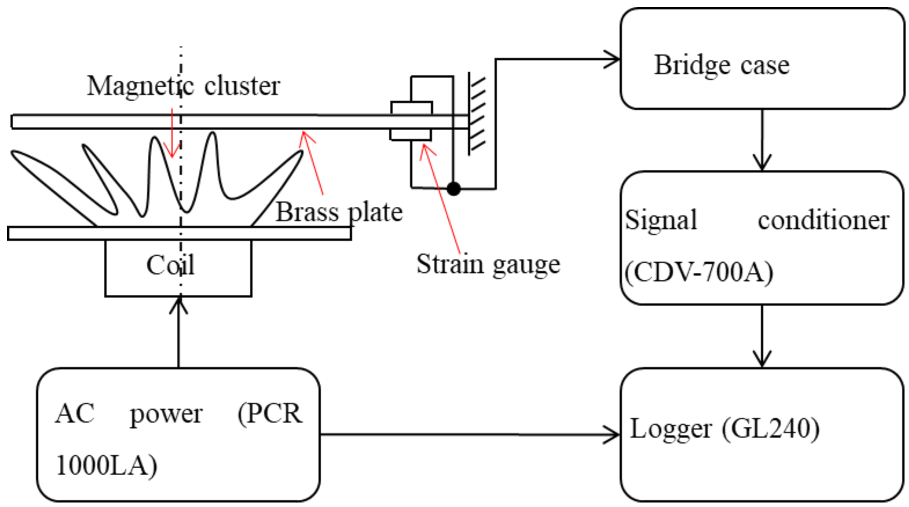


Fig. 2.8 Schematic diagram of finishing force measurement system

In the MAF process using alternating magnetic fields, the finishing force is provided by magnetism. Therefore, the finishing force should have a similar changing law with the magnetic force. In order to verify the changing law of finishing force, the finishing force was measured. The measuring system of finishing force is similar to the magnetic measuring system, as shown in Figure 2.8. Fill between the brass plate and the magnetic poles with magnetic particles (1.5 g) with an average diameter of 149 μm, and record the power supply voltage and the signal conditioner voltage with the logger.

2.4.3.2 Measurement results and discussion

The measurement result of the finishing force is shown in Figure 2.9. It can be seen that the finishing force and the magnetic force have the same changing law, that is, the changing frequency of the finishing force is twice the frequency of the power supply. In addition, the change in the finishing force also lags behind the voltage change.

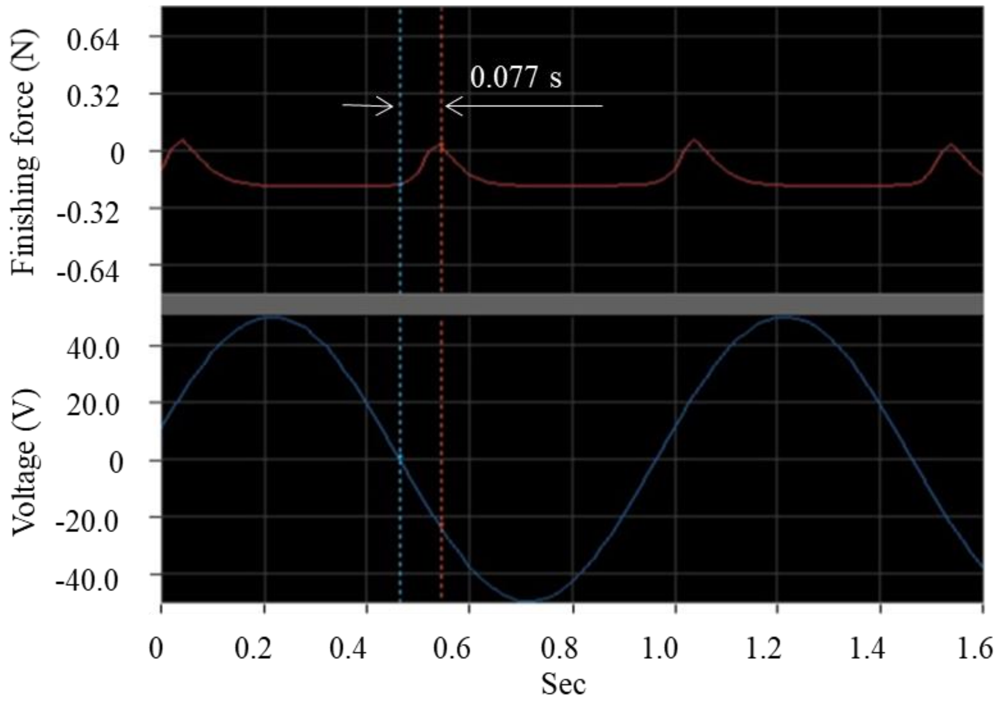


Fig. 2.9 The waveform of the finishing force and voltage

2.5 Magnetic pole shape

In this study, the magnetic pole with a diameter of 15 mm, the material of the SS400 (JIS), and there are four crossing grooves, width is 1mm, depth is 1 mm. The shape of the magnetic pole is shown in Fig. 2.10. In order to study the influence of the change of the magnetic pole shape on the magnetic field distribution, the "Magnet7" software is used to simulate the magnetic field distribution of the magnetic pole. Based on the above dimensions, simulation models were established, as shown in Fig. 2.11. There are two types, one is non-groove, and the other is four cross grooves at the bottom, with a width of 1mm and a depth of 1mm. The mesh size of the magnetic pole is 1 mm.

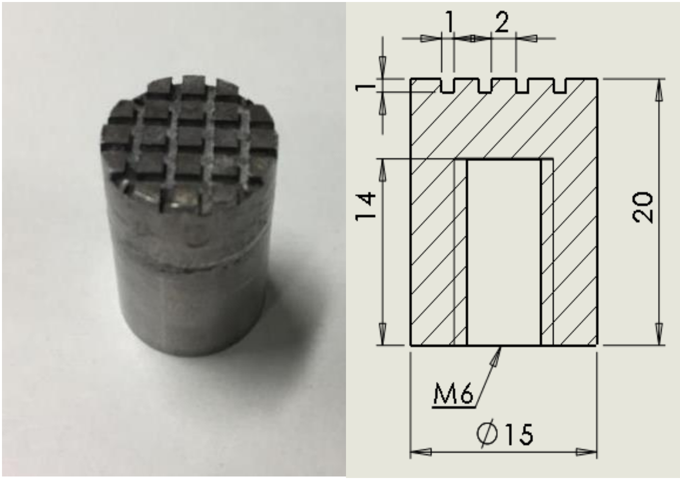
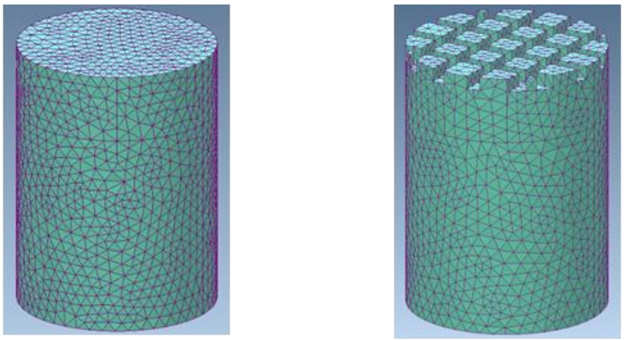


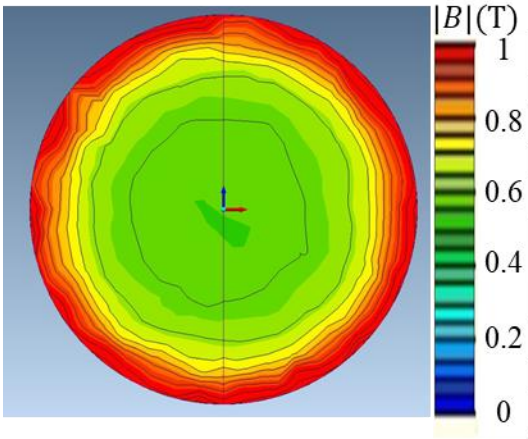
Fig. 2.10 Magnetic pole shape



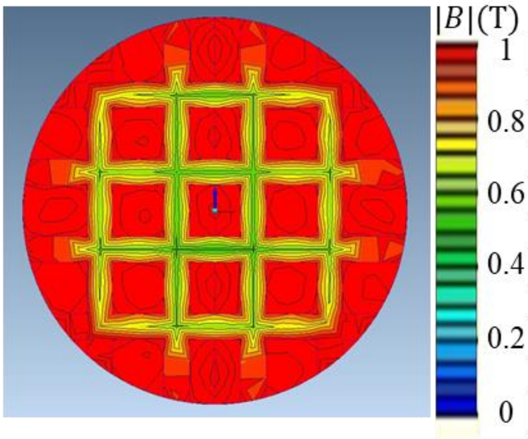
(a) No groove　　(b) With groove

Fig. 2.11 Simulation models of magnetic poles

The simulation results are shown in Figure 2.12. It can be seen that the magnetic pole with no grooves has the strongest of the magnetic field at the edge of the bottom surface, which is due to the edge effect. When the pole has grooves, the strongest position of the magnetic field is offset toward the center of the bottom. This reduces the effect of edge effects to some extent.



(a) No groove

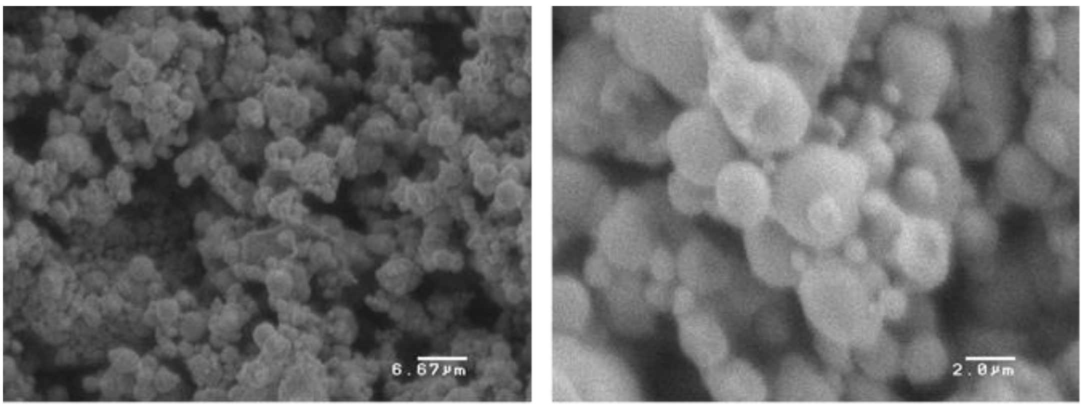


(b) With groove

Fig. 2.12 Magnetic field simulation

2.6 Composition of MAF finishing tools

In this study, compound magnetic finishing fluid formed by mixing magnetic particles, abrasive particles and grinding fluid was used as a finishing tool. In previous studies, it has been proved that the use of oil-based slurry can better maintain the state of magnetic clusters, obtain better surface quality and improve finishing efficiency. Therefore, oily polishing fluid was used in this study.



(a) 6 μm

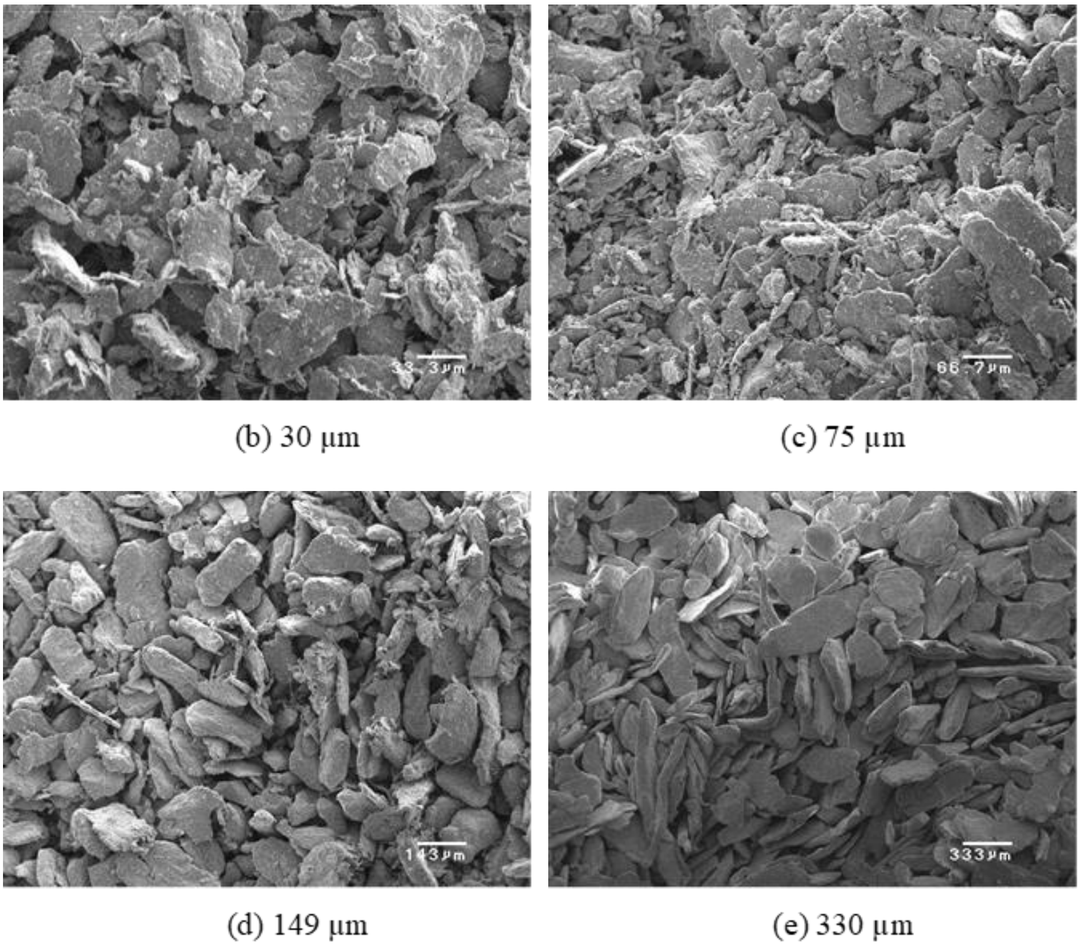
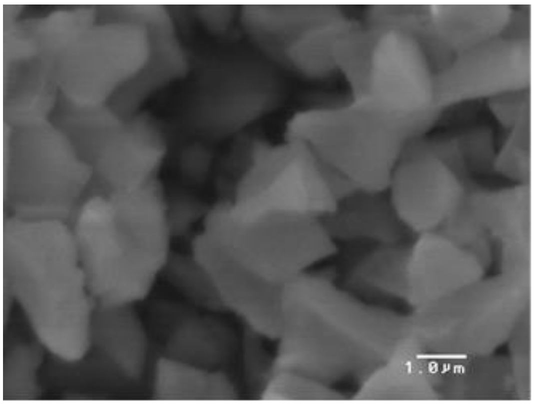


Fig. 2.13 SEM image of magnetic particles

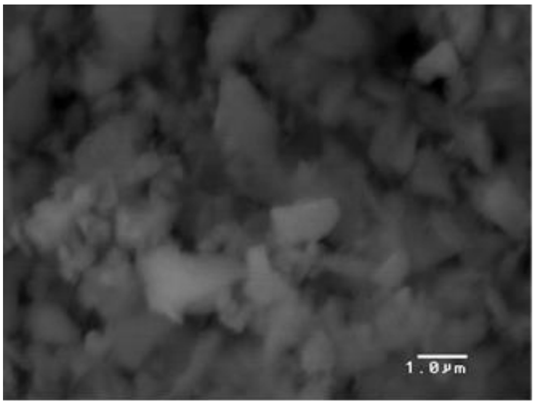
According to the initial roughness of the workpiece surface and the hardness of the workpiece, the appropriate size of magnetic particles is selected, which helps to improve the finishing efficiency and reduce the finishing time. In this study, the magnetic particles used are shown in Figure 2.13. The average diameter of magnetic particles from 2.13 (a) to 2.13 (e) is 6 μm, 30 μm, 75 μm, 149 μm, 330 μm, respectively. It can be seen that the magnetic particles with an average diameter of 6 μm are carbonyl iron powders, which are approximately spherical particles. The magnetic particles with an average diameter of 30 μm, 75 μm, 149 μm, and 330 μm are electrolytic iron powder, and most of their shapes are similar to flakes.

Table 2.1 Standard specifications of particle size

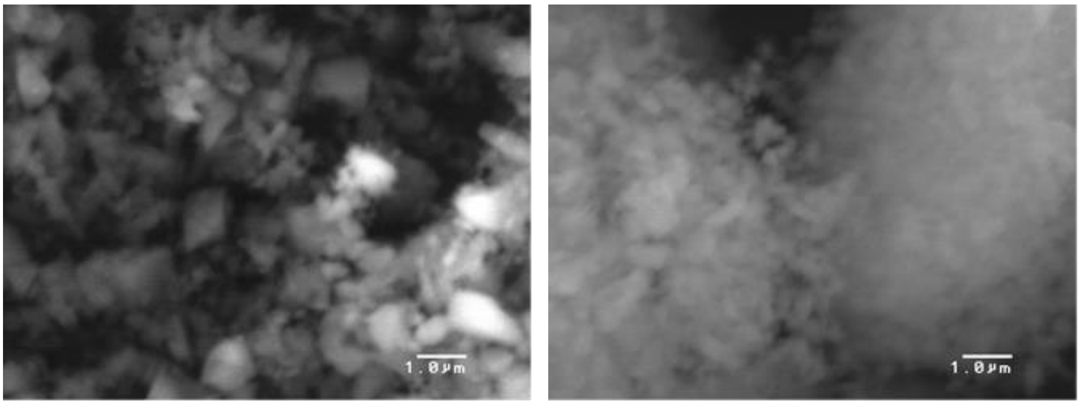
Particle size	Particle distribution (μm)			
	Maximum particle size	Particle size at 3% point	Particle size at 50% point	Particle size at 94% point
# 1000	≦32.00	≦27.00	11.9 ± 1.00	≧7.00
# 1200	≦27.00	≦23.00	9.90 ± 0.80	≧5.50
# 1500	≦23.00	≦20.00	8.40 ± 0.60	≧4.50
# 2000	≦19.00	≦17.00	6.90 ± 0.60	≧4.00
# 2500	≦16.00	≦14.00	5.60 ± 0.50	≧3.00
# 3000	≦13.00	≦11.00	4.00 ± 0.40	≧2.00
# 4000	≦11.00	≦8.00	3.00 ± 0.40	≧1.30
# 6000	≦8.00	≦5.00	2.00 ± 0.40	≧0.80
# 8000	≦6.00	≦3.50	1.20 ± 0.30	≧0.60
# 10000	---	---	0.50 ~ 0.70	---
# 20000	---	---	0.40 ~ 0.50	---



(a) WA#6000



(b) WA#8000



(c) WA#10000 (d) WA#20000

Fig. 2.14 The SEM image of abrasive particles

The abrasive particles used in this study are WA particles. WA is a fused White Alumina abrasive powder. It is produced by crushing fused alumina into a powder and then sorting the particles into a uniform size. It is high purity alumina, with at least a 96.0% pure Al_2O_3 composition. It has a hardness next to that of silicon carbide. Further, WA is chemically inert and able to bear high temperatures, and it has extremely high insulation characteristics. Table 2.1 shows the standard specifications of particle size. Among them, the abrasive particles used in this article were observed by SEM. Figure 2.14 is the SEM image of abrasive particles.

2.7 Conclusions

In this chapter, the processing principle and experimental device of MAF process using alternating magnetic field are introduced, and the experimental details are described. The main content can be summarized as follows.

1. The processing principle of conventional plane MAF technology is introduced.
2. The processing principle and experimental device of the MAF process using an alternating magnetic field are introduced.

3. The change law of magnetic force and finishing force in alternating magnetic field is analyzed by mathematical model and verified by measurement. In an alternating magnetic field, the period of magnetic force and finishing force is twice the current period.
4. The magnetic pole shape used in the experiment is introduced. The simulation of the magnetic field proves that the magnetic field can be distributed more uniformly by using the grooved magnetic pole, which can improve the edge effect to a certain extent.

References

1. Shinmura T, Takazawa K, Hatano E (1987) Study on magnetic abrasive finishing, Bull. Japan Soc. Precis. Eng. 21 (2) 139–141.
2. Chang GW, Yan BH, Hsu RT (2002) Study on cylindrical magnetic abrasive finishing using unbonded magnetic abrasives. International Journal of Machine Tools and Manufacture, 42(5), 575-583.
3. Singh AK, Jha S, Pandey PM (2011). Design and development of nanofinishing process for 3D surfaces using ball end MR finishing tool. International Journal of Machine Tools and Manufacture, 51(2), 142-151.
4. Kansal H, Singh AK, Grover V (2018). Magnetorheological nano-finishing of diamagnetic material using permanent magnets tool. Precision Engineering, 51, 30-39.
5. Yamaguchi H, Srivastava AK, Tan MA, Riveros RE, Hashimoto F (2012). Magnetic abrasive finishing of cutting tools for machining of titanium alloys. CIRP annals, 61(1), 311-314.
6. Shinmura T, Aizawa T (1989) Study on internal finishing of non-ferromagnetic tubing by magnetic abrasive machining process. Bull Jpn Soc Precis Eng 23(1):37–41
7. Jiles D (2015) Introduction to magnetism and magnetic materials. CRC press

Chapter III Investigation on application of aluminum alloy plate

3.1 Introduction

Aluminum alloys have the characteristics of light weight, corrosion resistance, high specific strength, good processing adaptability features, and so on [1, 2]. They are widely utilized in aerospace, aviation, shipbuilding, and other important fields [3-5]. 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, and electrochemical polishing can cause pollution. The grinding tool of the MAF process is composed of micron/nano-level particles, so the finishing force is low, the cutting depth is shallow, and it is more suitable for ultra-precision finishing of the surface. El-Taweel proposed a combined process of electrochemical turning (ECT) and magnetic abrasive finishing (MAF) for the machining of 6061 Al/Al2O3 (10%wt) composite materials. They demonstrated that assisting ECT with MAF leads to an increase machining efficiency and resultant surface quality significantly, as compared to that achieved with the traditional ECT of some 147.6% and 33%, respectively [6]. Vahdati et al. [7] applied the MAF process to finishing aluminum pipes. They discussed the influence of the magnetic flux density, machining time, the amount of magnetic abrasive powder and the rotation speed of the workpiece on the surface roughness. According to the experimental results, using permanent magnets of 1 T, the amount of 8g of ilmenite powder of mesh 150, rotating speed of 750 rpm, and 30–40 min of process time, will result into a surface roughness of 0.45 μm *Ra* from the original value of 2 μm *Ra*. Gheisari et al. [8] proposed a new machining process to use MR fluid to finish the cylindrical surface. They showed that the application of fast rectilinear alternating motion in the process can effectively improve the surface of the workpiece, and the surface roughness of the aluminum cylinder can be improved from about 200 nm *Ra* to 50 nm *Ra*. Xing et al. [9] discussed the magnetic abrasive finishing combined with electrolytic (EMAF) process on A5052 aluminum alloy plate. They report that compared with the traditional MAF process, the EMAF process can achieve higher finishing efficiency. In addition, when using the EMAF process to finish the surface of aluminum alloy A5052, the processing voltage should not be too high. When the working gap is 1 mm and the concentration of the NaNO3 aqueous solution is 15%, the recommended processing voltage is about 3.4V. Wang et al. [10] discussed the use of MAF process for finishing pipes of three materials, such as Ly12 aluminum alloy, 316L stainless steel and H62 brass. They reported that using transformer oil or stearic acid liquid can significantly improve *MRR*, because transformer oil helps to form a physisorption film, and stearic acid helps to form a chemisorption film. Jiao et al. [11] applied the MAF process to improve the surface quality of the hole wall and eliminate burrs on the edge of the hole. They used 7075 aluminum alloy as a workpiece, and analyzed the influence of magnet spinning speed, abrasive mesh, and abrasive filling amount on the diameter deviation of the hole and surface roughness of the inner wall. They reported that the burrs were significantly removed and the burr removal efficiency was improved by 33.3% compared with the conventional magnetic abrasive finishing process.

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 [12, 13]. However, there are still some mechanisms that have not been clarified. In addition, the finishing effect of MAF process using an alternating magnetic field on aluminum alloy materials has not been investigated. This chapter discusses the ultra-precision finishing of aluminum alloy surface by magnetic abrasive finishing (MAF) process using alternating magnetic field. This chapter 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 ultra-precision finishing experiments of the 5052 aluminum alloy plate were designed and implemented.

3.2 Magnetic flux density distribution

3.2.1 Measurement methods and conditions

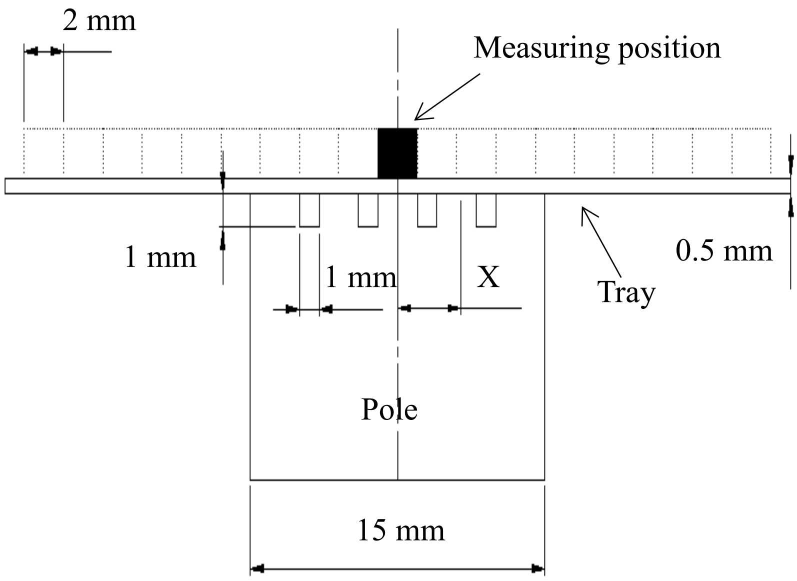


Fig. 3.1 Measurement method of magnetic flux density effective value in processing region

The magnetic field distribution in 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 processing region. In this study, we use AC power, current peak value is 3 A, average value is 1.9 A. We measured the magnetic flux density effective value at current frequencies of 7 Hz. The measurement method of magnetic flux density effective value in processing region is shown in Fig. 3.1.

The measurement instrument is made in EMIC with the type of Probe T-401. The magnetic pole with the diameter of 15 mm, the material of the SS400, and there are four crossing grooves, width is 1mm, depth is 1 mm. The tray has the thickness of 0.5 mm and the diameter of 40 mm. We divided the tray into nineteen sections, namely every 2 mm from the center to both sides to conduct magnetic flux density measurement.

3.2.2 Measurement results and discussion

The magnetic field distribution in processing region is shown in Fig. 3.2. It can be seen that the magnetic flux density at the same distance from the magnetic pole axis is basically the same. The magnetic flux density gradually increases from the magnetic pole axis to the edge of the magnetic pole (X=±7.5 mm), and then rapidly decreases. At the edge of magnetic pole (X=±7.5 mm), the maximum value of the effective value of the magnetic flux density is obtained. This largely affects the distribution of magnetic particles. Since the magnetic flux density at the edge of the magnetic pole is the strongest, the magnetic particles on the tray are most intensively distributed at the edge of the magnetic pole (X=±7.5 mm).

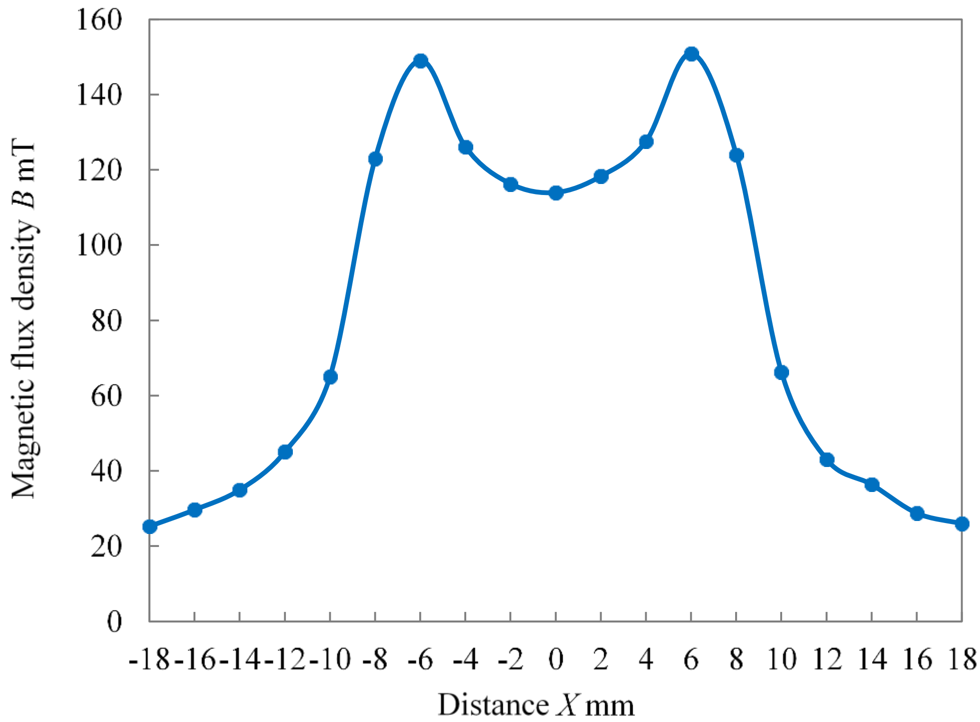


Fig. 3.2. Magnetic field distribution in processing region

3.3 The influence of process parameters on finishing force

3.3.1 Measurement methods and conditions

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 3.1. 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.

Table 3.1 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

3.3.2 Measurement results and discussion

3.3.2.1 Magnetic particle size

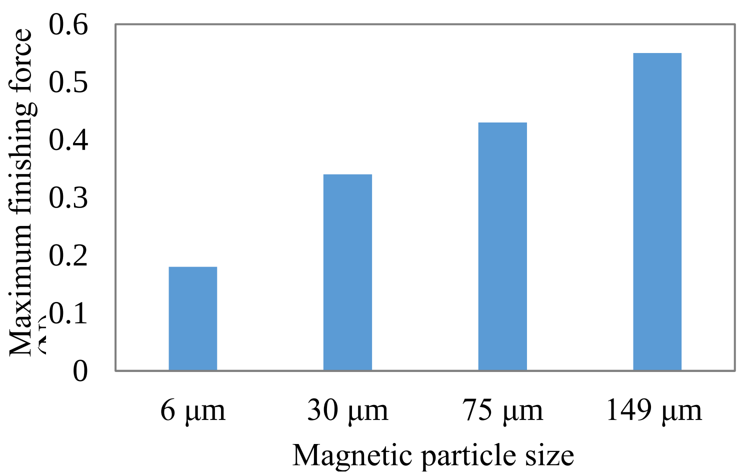
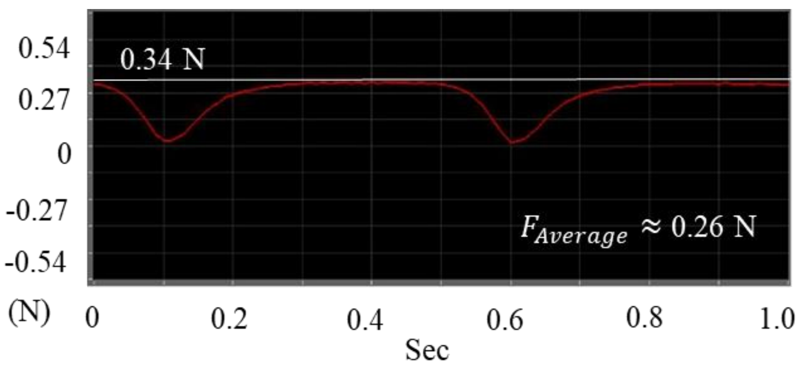


Fig. 3.3 Effect of magnetic particle size on finishing force (Magnetic field frequency = 1 Hz)

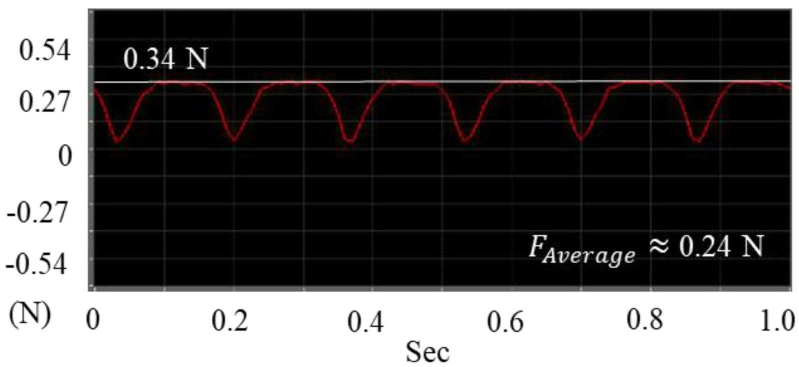
When the magnetic field frequency is 1 Hz, the effect of magnetic particle size on finishing force is shown in Fig. 3.3. As the size of the magnetic particles increases, the finishing force increases. This is because as the size of the magnetic particles increases, the attraction between the magnetic particles increases, which makes the magnetic clusters harder and thus has a greater finishing force.

3.3.2.2 Magnetic field frequency

When the magnetic particle size is 30 μm, the effect of the magnetic field frequency on the finishing force is as shown in Fig. 3.4. It can be seen from the measurement results that the magnetic field frequency has little effect on the maximum value of the finishing force.



(a) 1 Hz



(b) 3 Hz

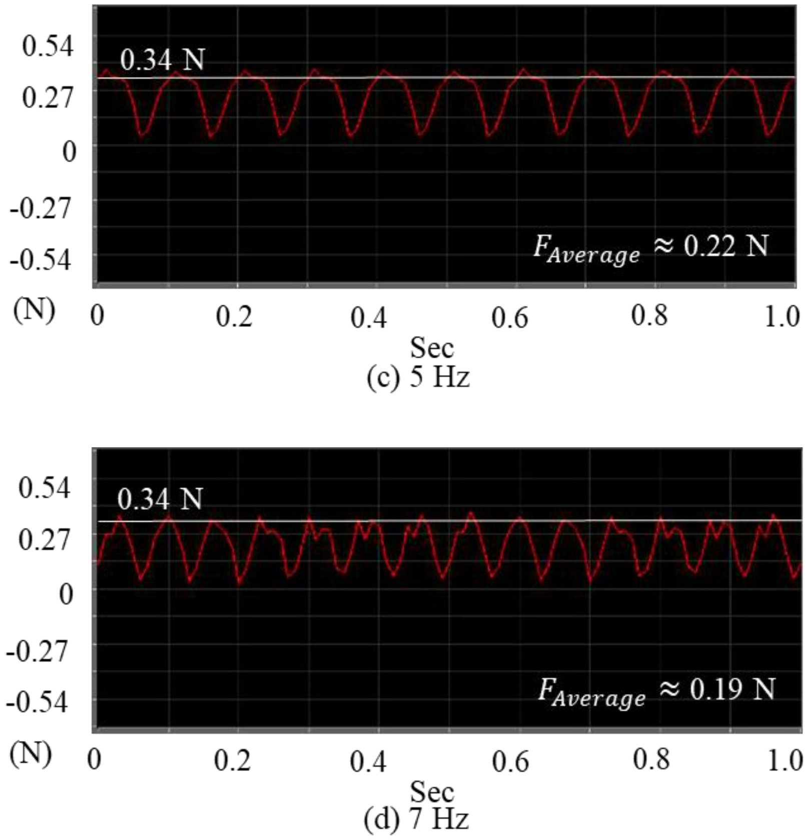


Fig. 3.4 Effect of Magnetic field frequency on finishing force (Magnetic particle size = 30 μm)

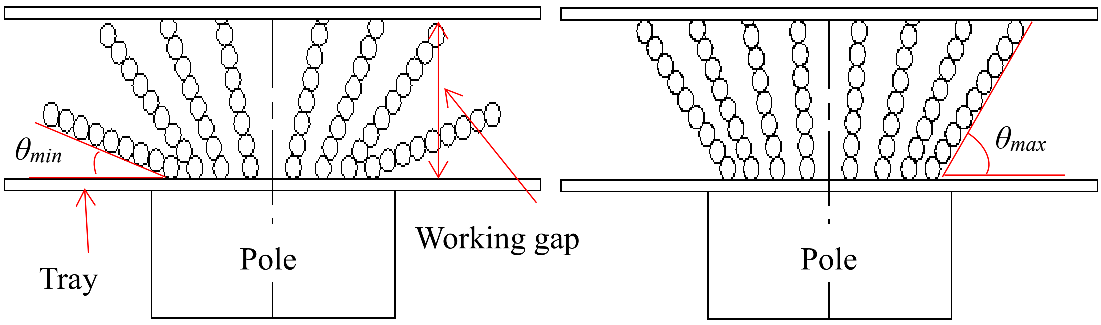
3.4 Observation of magnetic cluster behavior

3.4.1 Observation methods and conditions

In order to clarify the behavior characteristics of the magnetic cluster under different conditions, we observed the movement of the magnetic cluster. The observation conditions are shown in Table 3.2. 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 software HXLink.

Table 3.2 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



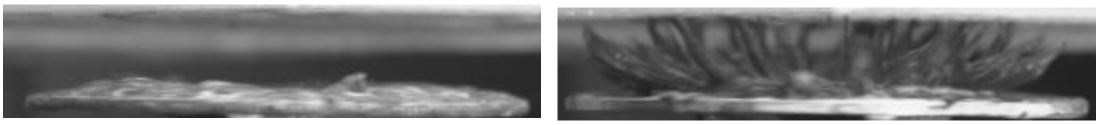
(a) The lowest position (b) The highest position

Fig. 3.5 Schematic diagram of angle measurement method

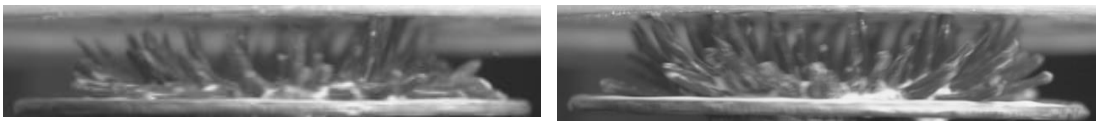
The angle measurement method is shown in Fig. 3.5. θ_{min} and θ_{max} are the angles between the tray and the magnetic cluster periphery when the magnetic cluster fluctuates to the lowest and highest positions, respectively. The lowest position is the position of the magnetic cluster before the rising 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 θ_{min} to θ_{max}. The result of the measurement is the average of the 8 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 8 measurements while ignoring the position of the angle of 0.

3.4.2 Observation results and discussion

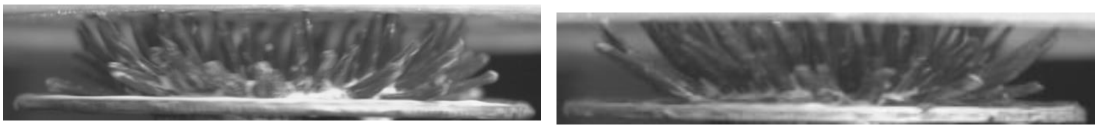
According to the observation, the fluctuation frequency of the magnetic cluster is twice the frequency of the magnetic field. Photographs of the magnetic cluster at the lowest and highest positions are shown in Fig. 3.6. It can be seen that as the magnetic particle size increases, the ability of the 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.



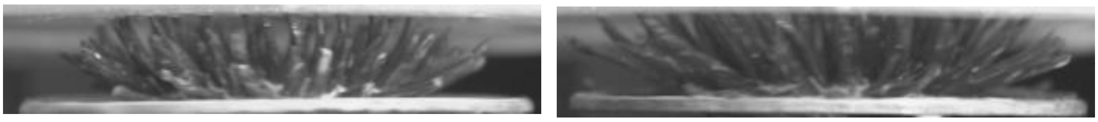
1 Hz



3 Hz

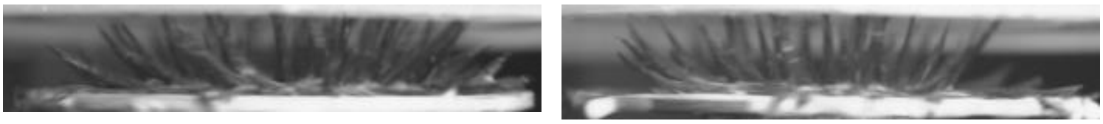


5 Hz

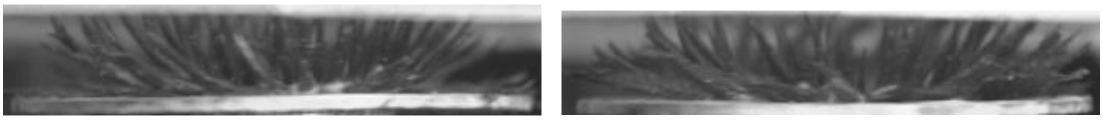


7 Hz

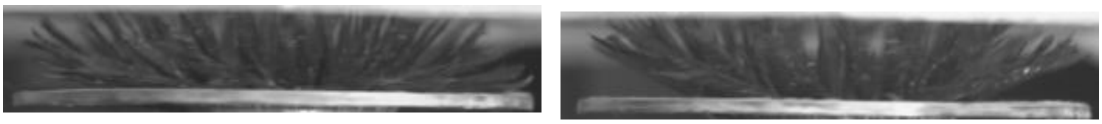
(1) 6 μm (2) 30 μm



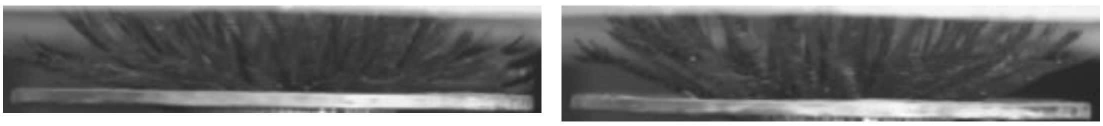
1 Hz



3 Hz



5 Hz

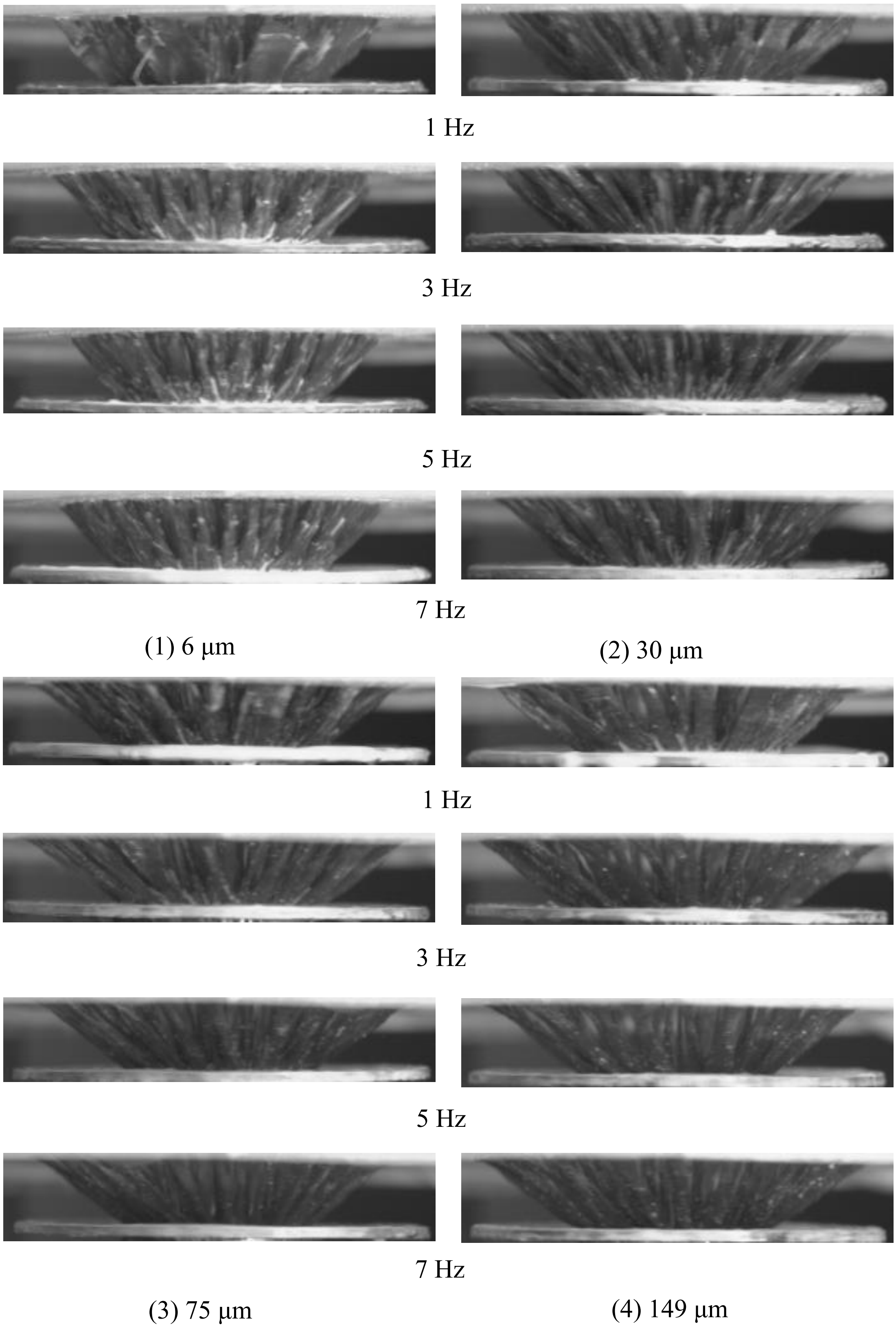


7 Hz

(3) 75 μm (4) 149 μm

(a) The lowest position

Fig. 3.6 Cont.



(b) The highest position

Fig. 3.6 Photographs of the magnetic cluster at the lowest and highest positions

The measurement results are shown in Fig. 3.7. It can be seen that as the magnetic field frequency increases, θ_{min} increases and θ_{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 θ_{min} to decrease, thereby increasing the fluctuation range of the magnetic cluster. As the size of the magnetic particles increases, θ_{min} increases and θ_{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 θ_{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 θ_{max} decreases.

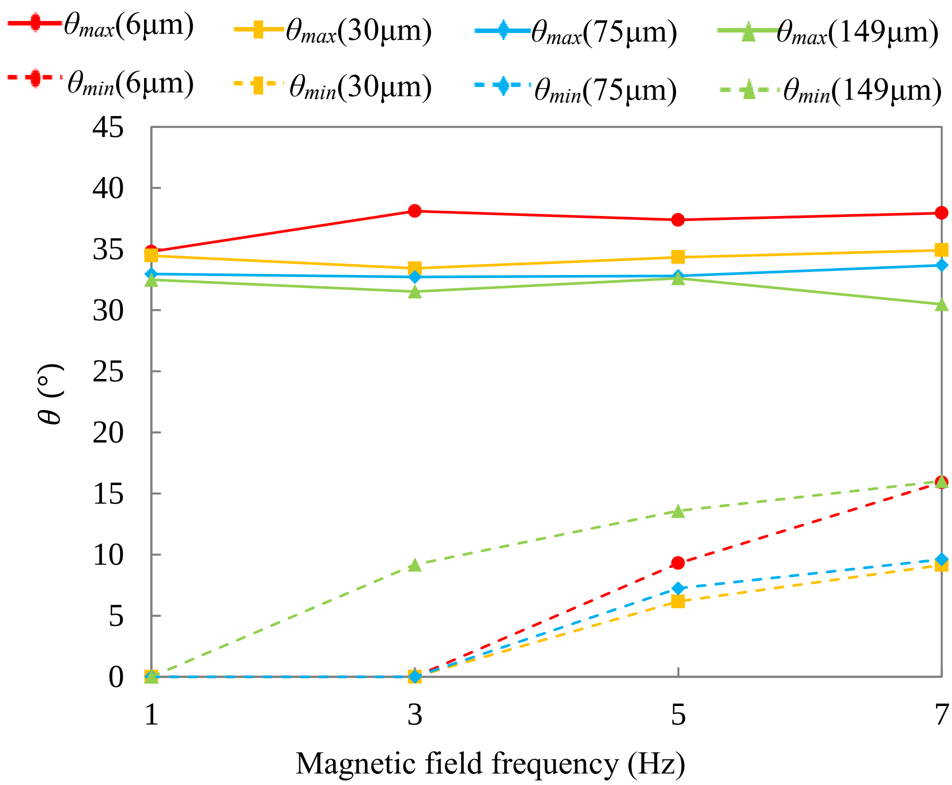


Fig. 3.7 The angle between the periphery of the magnetic cluster and the tray

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 θ_{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.

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.

3.5 Finishing characteristics analysis

3.5.1 Comparison between direct and alternating magnetic field

3.5.1.1 Experimental conditions and method

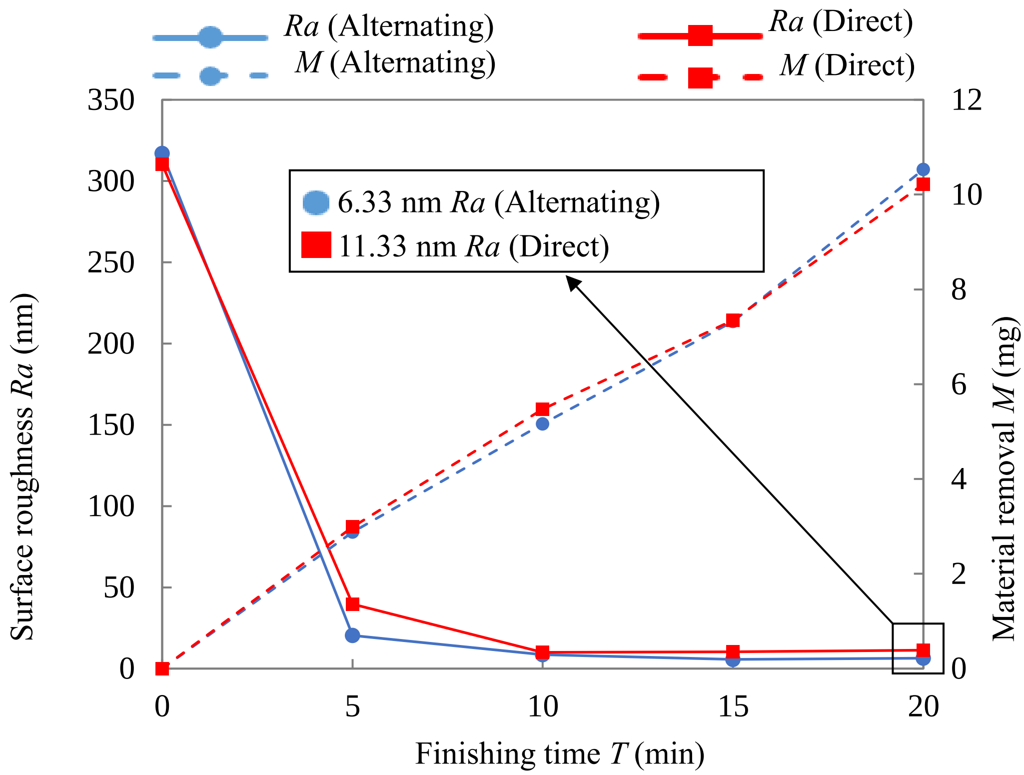
The experimental conditions are shown in Table 3.3. The 5052 aluminum alloy plate was selected as the workpiece. The coil is supplied with a direct current and an alternating current having a current frequency of 1 Hz. The total finishing time is 20 min. To investigate the difference between a direct magnetic field and an alternating magnetic field, we set the single finishing time to 5 min and 10 min. Use an ultrasonic cleaner to clean the workpiece before measurement. The cleaning fluid is alcohol.

Table 3.3 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)

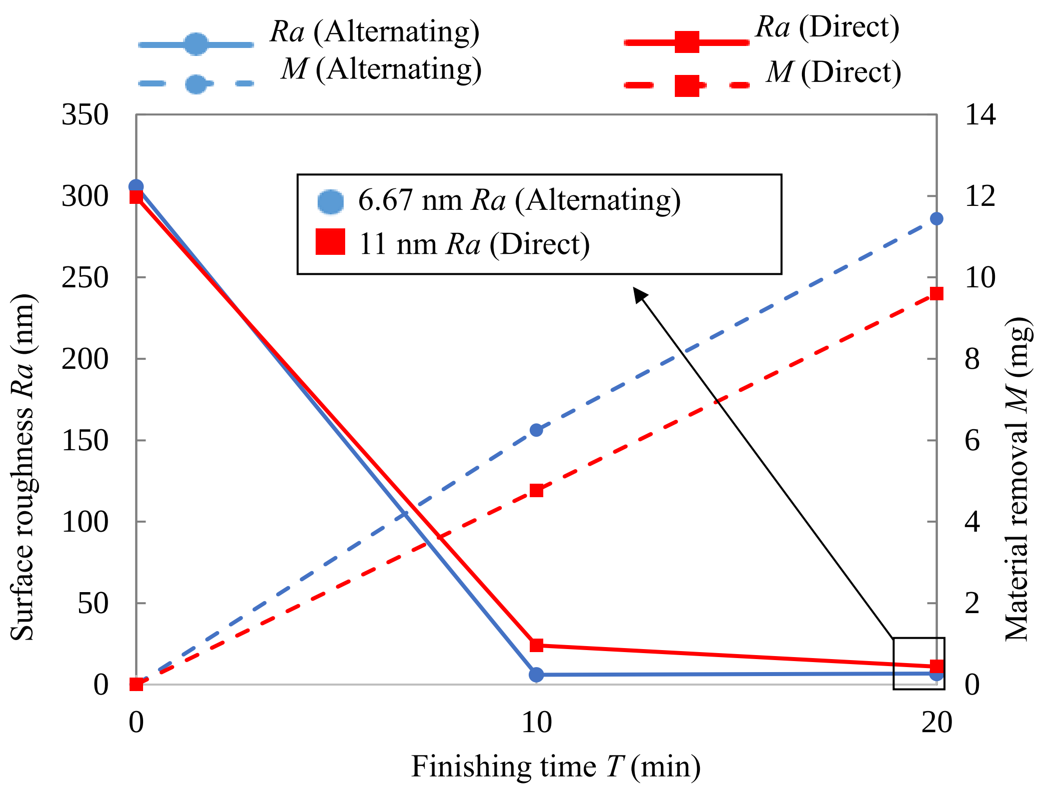
3.5.1.2 Experimental results and discussion

Figure 3.8(a) 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.



(a) Single finishing time 5 min

Fig. 3.8 Cont.



(b) Single finishing time 10 min

Fig. 3.8 Effect of magnetic field type on surface roughness and material removal

3.5.2 Process parameters optimization

3.5.2.1 Experimental conditions and method

The experimental conditions are shown in Table 3.4. The 5052 aluminum alloy plate was selected as the workpiece. In this experiment, we first explored the effect of magnetic particle size on finishing characteristics. Secondly, the influence of magnetic field frequency and abrasive size on material removal and surface roughness was investigated. The current waveform used in the experiment is sinusoidal alternating current. 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 minutes. Use an ultrasonic cleaner to clean the workpiece before measurement. The cleaning fluid is alcohol.

Table 3.4 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)

3.5.2.2 Effect of magnetic particles

Figure 3.9 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 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 μm and 75 μm, the final surface roughness is very close. However, it can be seen from Fig. 3.10 that when the average diameter of magnetic particles is 75 μm, there are finishing marks on the workpiece surface.

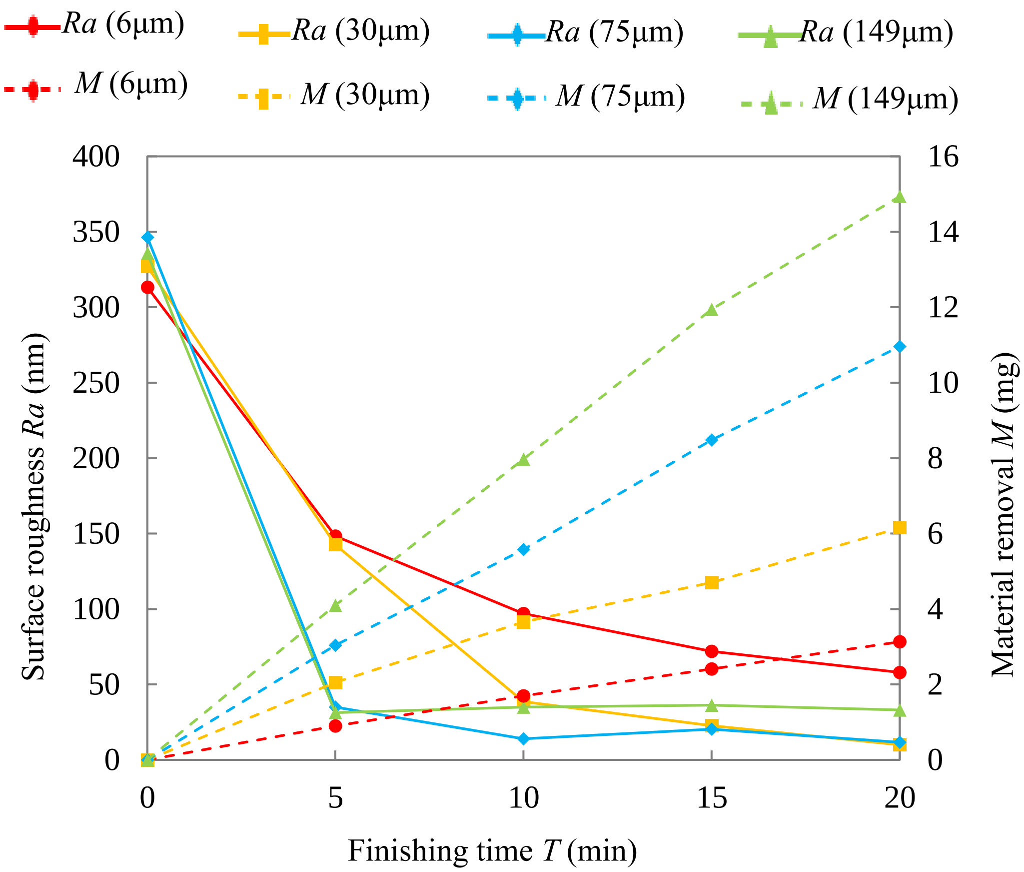
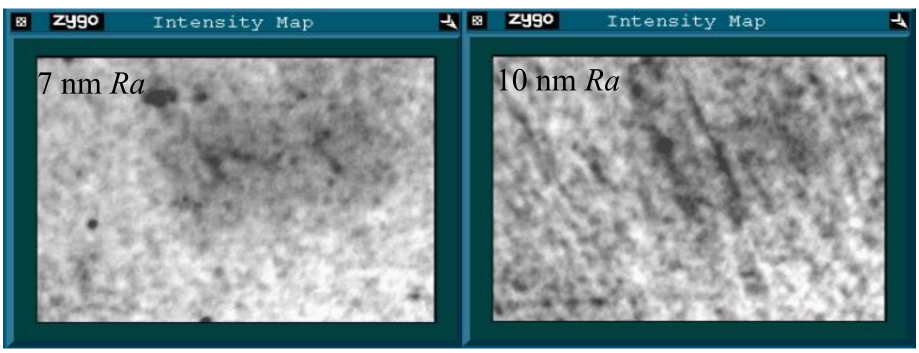


Fig. 3.9 Effect of magnetic particle size on surface roughness and material removal

(magnetic field frequency = 3 Hz, abrasive = WA#10000)



(a) 30 μm (b) 75 μm

Fig. 3.10 Intensity map of surface after finishing

3.5.2.3 Effect of magnetic field frequency

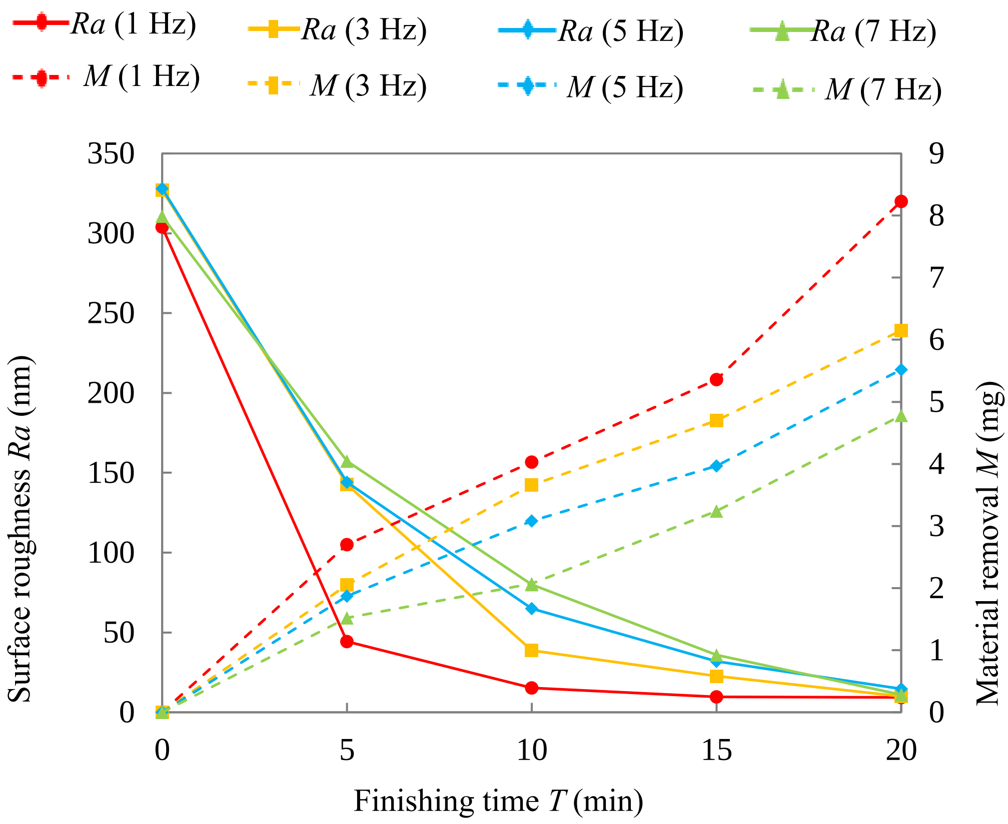


Fig. 3.11 Effect of magnetic field frequency on surface roughness and material removal (magnetic particles size = 30 μm, abrasive = WA#10000)

Figure 3.11 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.

3.5.2.4 Effect of abrasive particles

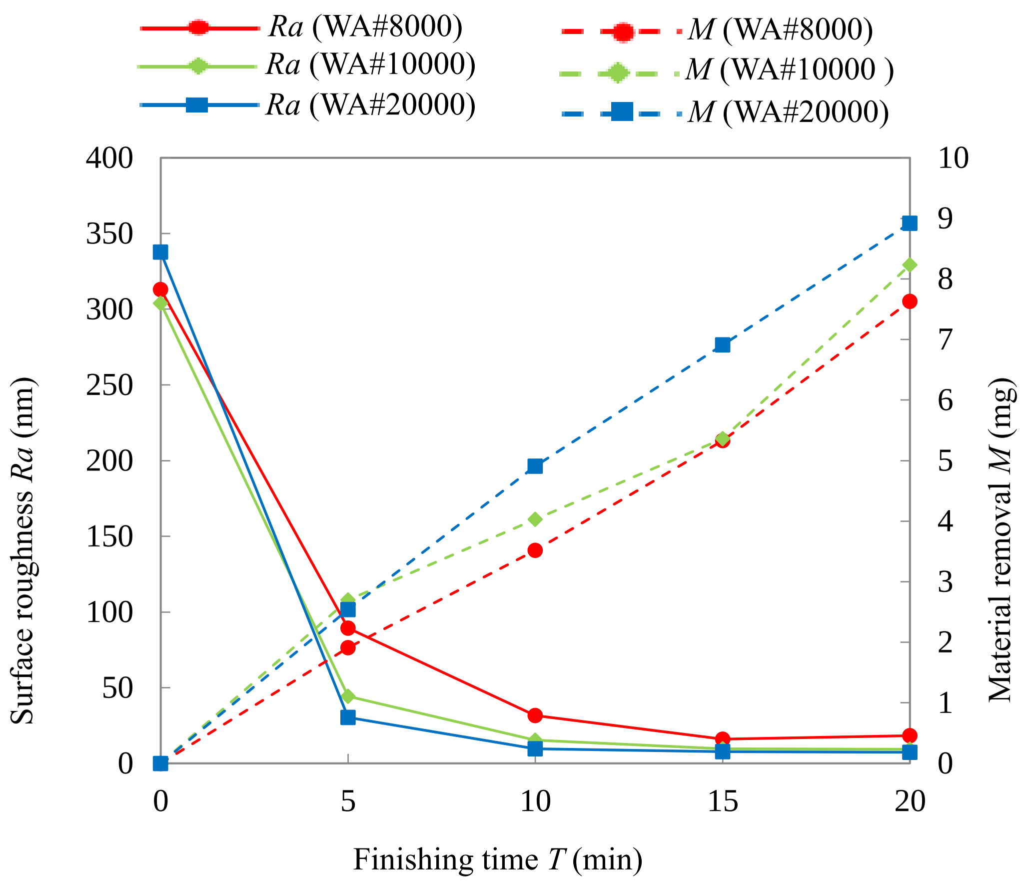


Fig. 3.12 Effect of abrasive particles on surface roughness and material removal

(magnetic particles size = 30 μm, magnetic field frequency = 1 Hz)

Figure 3.12 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.

3.6 Ultra-precision finishing 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 ultra-precision finishing of the 5052 aluminum alloy plate, the following experiment were designed and performed.

3.6.1 Experimental conditions and method

The experimental conditions are shown in Table 3.5. The experiment was carried out in three steps. The processing time for each step was 5 minutes, for a total of 15 minutes. According to previous studies [13], 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.

Table 3.5 Experimental conditions

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

3.6.2 Experimental results and discussion

The experimental results are shown in Fig. 3.13. 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 3.14 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 ultra-precision finishing of 5052 aluminum alloy plate can be realized by MAF process using alternating magnetic field.

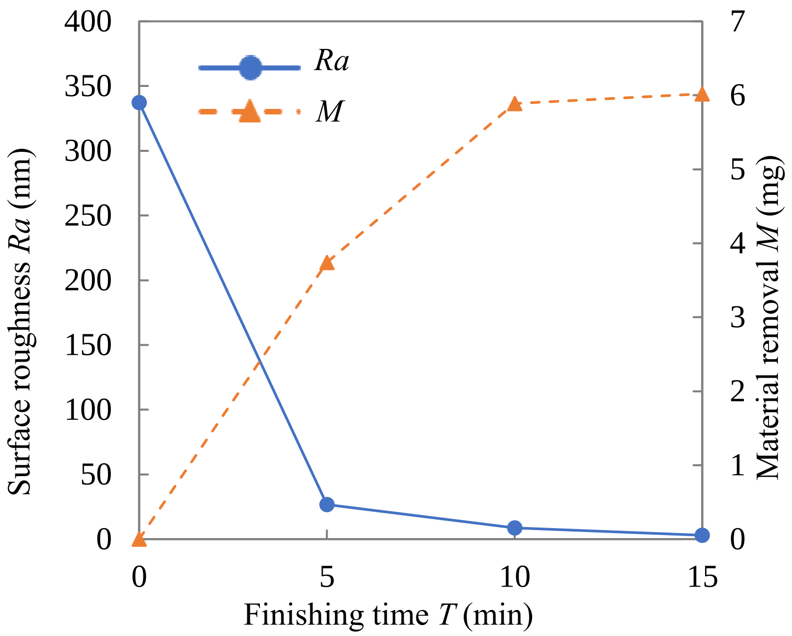
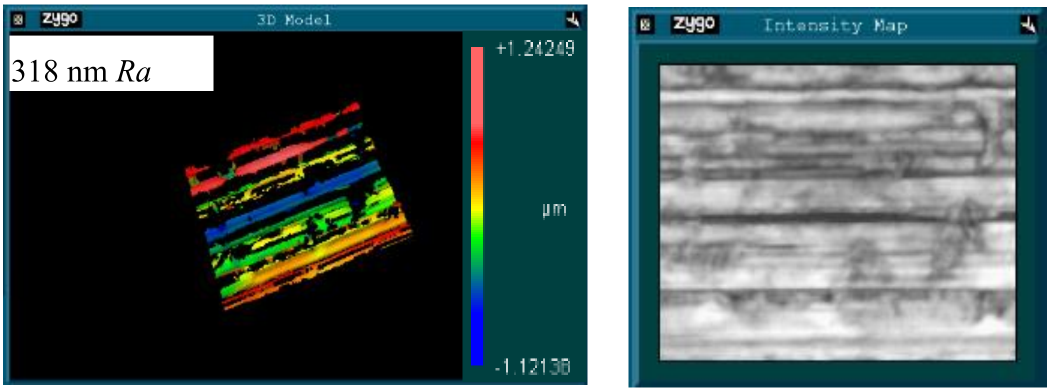
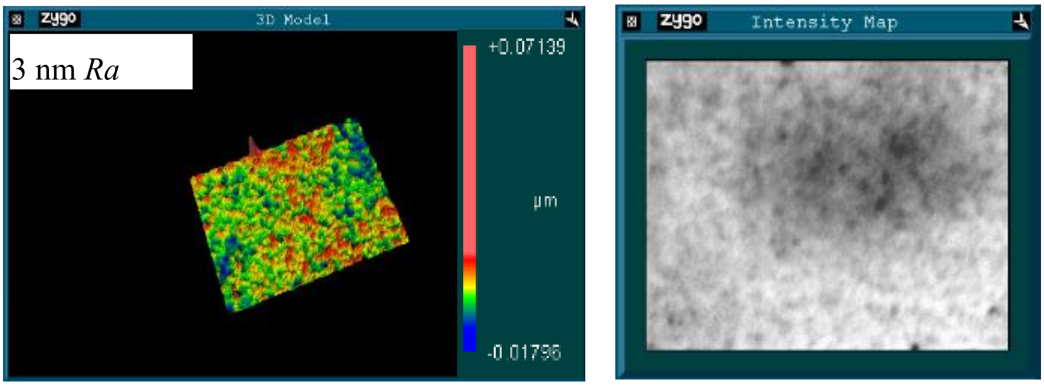


Fig. 3.13 Changes in material removal and surface roughness with finishing time



(a) Before finishing



(b) After finishing

Fig. 3.14 3D model and intensity map of the surface before and after finishing

3.7 Conclusions

In this chapter, the influence of the process parameters on the finishing characteristics of 5052 aluminum alloy workpieces when the MAF process using an alternating magnetic field is used is discussed. Through research, high-efficiency nano-level ultra-precision finishing of 5052 aluminum alloy plates has been realized. The main conclusions are as follows.

1. The magnetic flux density is unevenly distributed in the finishing area, and the strongest magnetic flux density is at the edge of the magnetic pole.

2. As the average diameter of the magnetic particles increases, the finishing force increases. The current frequency has almost no effect on the maximum finishing force, but the average finishing force decreases as the current frequency increases.
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 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.
5. 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.
6. The experimental results show that the MAF process using alternating magnetic field can realize ultra-precision finishing of 5052 aluminum alloy plate. The surface roughness of the workpiece improved from 318 nm Ra to 3 nm Ra within 15min.

References

1. Perez OR, Valdez S, Molina A, Mejia-Sintillo S, Garcia-Perez C, Salinas-Bravo VM, Gonzalez-Rodriguez JG (2017) Corrosion Behavior of Al–Mg–Zn-Si Alloy Matrix Composites Reinforced with Y2O3 in 3.5% NaCl Solution. Int J Electrochem Sci 12:7300-7311
2. Wang FB, Liu JK, Li LL, Shu QL (2017) Green machining of aluminum honeycomb treated using ice fixation in cryogenic. Int J Adv Manuf Technol 92(1-4):943-952
3. Barekar NS, Dhindaw BK (2014) Twin-Roll Casting of Aluminum Alloys – An Overview. Mater Manuf Process 29(6):651-662
4. Ding M, Zhang PL, Zhang ZY, Yao S (2010) A novel assembly technology of aluminum alloy honeycomb structure. Int J Adv Manuf Technol 46(9-12):1253-1258
5. Tolga Dursun, Costas Soutis (2014) Recent developments in advanced aircraft aluminium alloys. Materials and Design 56: 862-871
6. El-Taweel, TA (2008) Modelling and analysis of hybrid electrochemical turning-magnetic abrasive finishing of 6061 Al/Al2O3 composite. Int J Adv Manuf Technol 37, 705–714.
7. Vahdati M, Vahdati N (2009) Micromachining of aluminum pipes using magnetic abrasive finishing. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, 27(3), 1503-1505.
8. Gheisari R, Ghasemi AA, Jafarkarimi M, Mohtaram S (2014) Experimental studies on the ultra-precision finishing of cylindrical surfaces using magnetorheological finishing process. Production & Manufacturing Research, 2(1), 550-557.

9. Xing BJ, Zou YH (2020) Investigation of Finishing Aluminum Alloy A5052 Using the Magnetic Abrasive Finishing Combined with Electrolytic Process. Machines, 8(4): 78.
10. Wang Y, Hu D (2005) Study on the inner surface finishing of tubing by magnetic abrasive finishing. Int J Mach Tools Manuf 45(1): 43-49.
11. Jiao AY, Zhang GF, Liu BH, Liu WJ (2020) Study on improving hole quality of 7075 aluminum alloy based on magnetic abrasive finishing. Adv Mech Eng 12(6), 1687814020932006.
12. Wu JZ, Zou YH, Sugiyama H (2015) Study on ultra-precision magnetic abrasive finishing process using low frequency alternating magnetic field. J Magn Magn Mater 386:50-59
13. Wu JZ, Zou YH, Sugiyama H (2016) Study on finishing characteristics of magnetic abrasive finishing process using low-frequency alternating magnetic field. Int J Adv Manuf Technol 85(1-4):585-594

Chapter IV Investigation on the influence of current change mode

4.1 Discussion on magnetic field changes

4.1.1 The relationship between magnetic flux density and current in a static magnetic field

4.1.1.1 Measurement methods and conditions

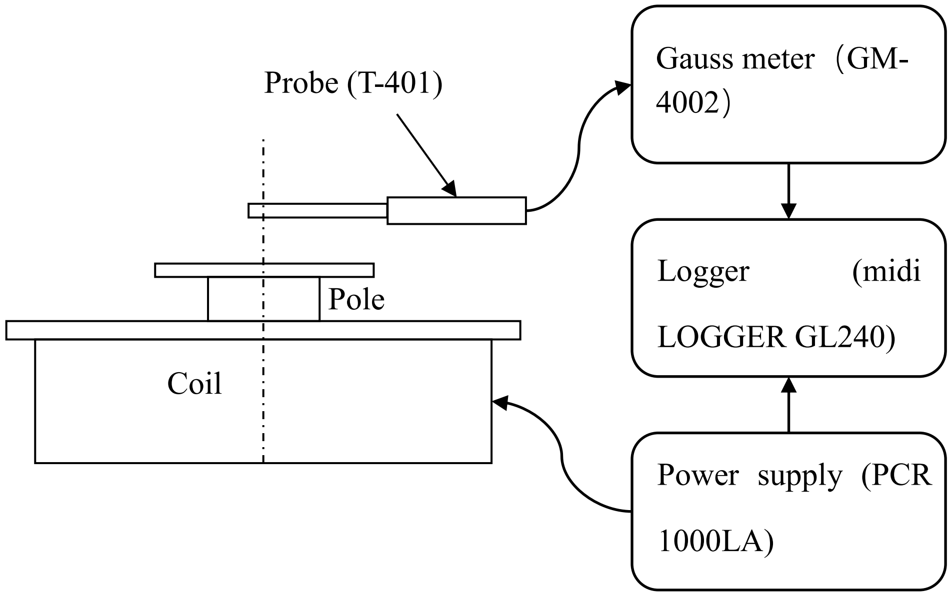


Fig. 4.1 Schematic diagram of magnetic flux density measurement system

In order to analyze the influence of the current waveform on the magnetic field and the finishing force, when the current gradually increases and reaches a stable state, the changes in the magnetic flux density and finishing force are measured respectively. The schematic diagram of the magnetic flux density measurement system is shown in Fig. 4.1. Fix the probe above the magnetic pole and adjust the position of the measuring area of the probe so that the center is located on the axis of the magnetic pole and 1.5 mm away from the magnetic pole. The probe (T-401) is connected to the gauss meter (GM-4002), and the output signal of the gauss meter is connected to the logger (GL240). At the same time, the power supply outputs direct current and connects the output signal to the logger and the coil. The current supplied to the coil is from -4 A to 4 A, and the magnetic flux density value is recorded every 0.1 A.

4.1.1.2 Measurement results and discussion

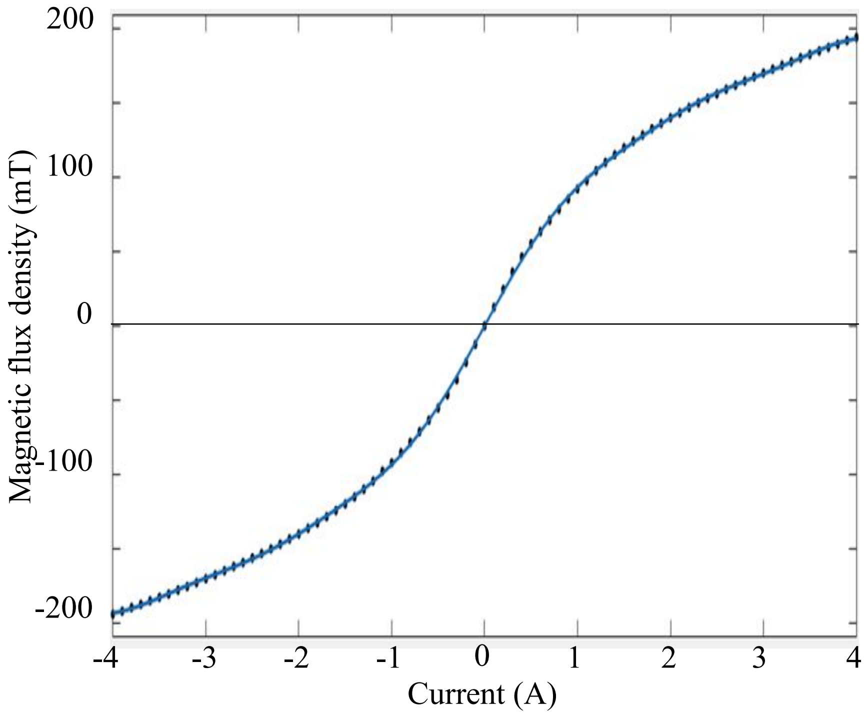


Fig. 4.2 The relationship between magnetic flux density and current

The measurement result is shown in Figure 4.2. According to the measurement result, the direction of the magnetic flux density changes when the direction of the current changes. But when the absolute value of the current is the same, the absolute value of the magnetic flux density is basically the same. Therefore, the relationship between the absolute value of the current and the absolute value of the magnetic flux density can be obtained by polynomial fitting, as shown in the following equation,

$$|B| = -0.7123|I|^4 + 8.872|I|^3 - 43.97|I|^2 + 127.9|I| + 0.6382 \quad (R^2 = 1) \quad (4.1)$$

In addition, as the absolute value of the current increases, the rate of increase of the magnetic flux density gradually decreases.

4.1.2 The influence of current change mode on magnetic flux density

4.1.2.1 Measurement methods and conditions

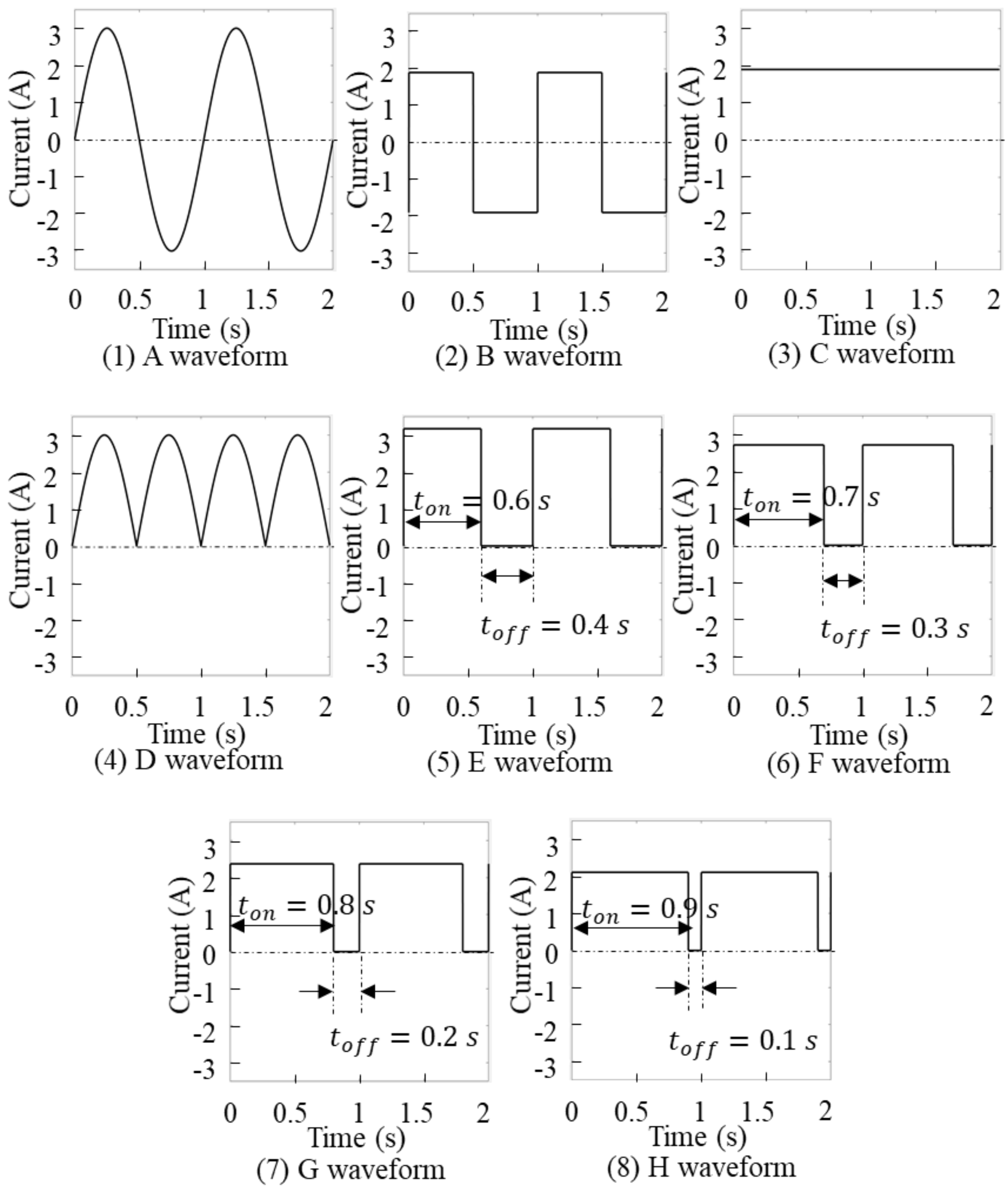


Fig. 4.3 Current waveform

This study explored the effects of the eight current waveforms shown in Fig. 4.3 on the magnetic field, finishing force, and finishing characteristics. Among them, A waveform, B waveform, and C waveform are sine waveform, square waveform, and smooth DC waveform respectively. The D waveform is a sine waveform after full-wave rectification. E waveform, F waveform, G waveform, and H waveform are pulse waves with duty cycle of 60%, 70%, 80%, and 90% respectively. When measuring the magnetic flux density, the current frequency of the AC power supply is set to 1 Hz. Since the D waveform is obtained after full-wave rectification of the A waveform, the frequency is 2 Hz. Set the average current of all waveforms to 1.9 A.

The measurement method is shown in Fig. 4.1. According to the relationship between the magnetic flux density and the current obtained in the steady-state, draw the change curve of the magnetic flux density (steady-state value curve). In order to analyze the influence of the magnetization and demagnetization process on the magnetic flux density, the average value of the absolute value of the measured magnetic flux density (B_{avg}) and the average value of the absolute value of the magnetic flux density in the steady-state (B_{savg}) were calculated respectively. B_{savg} is calculated based on the relationship between current and magnetic flux density in steady-state (Eq. 4.1). As the following equation,

$$B_{savg} = \sum_{i=1}^{n} |B(I_i)| \Big/ n \tag{4.2}$$

where I_i is the current value taken every 20 ms. Calculate the B_{savg} value of one cycle for each waveform. Calculate the magnetic flux density loss/gain coefficient (τ) relative to the steady-state under different current change modes through Eq. (4.3),

$$\tau = B_{avg} \Big/ B_{savg} \tag{4.3}$$

First, in order to determine the influence of the waveform shape on the magnetic flux density, compare the A waveform and the B waveform. Secondly, it compares the influence of current direction change (A waveform and D waveform) on the magnetic flux density. Finally, the influence of pulse current on magnetic flux density is discussed.

4.1.2.2 Effect of current waveform shape

To determine the influence of the current waveform shape on the magnetic flux density, the change curves of the magnetic flux density and voltage in the A and B waveforms were measured. The measurement results are shown in Fig. 4.4. Comparing the change curve of magnetic flux density and voltage, it can be seen that the change of magnetic flux density is different from the change of voltage due to the demagnetization or magnetization process. This is mainly reflected in the change of the magnetic flux density in the process of magnetization and demagnetization lags behind the change of the power supply.

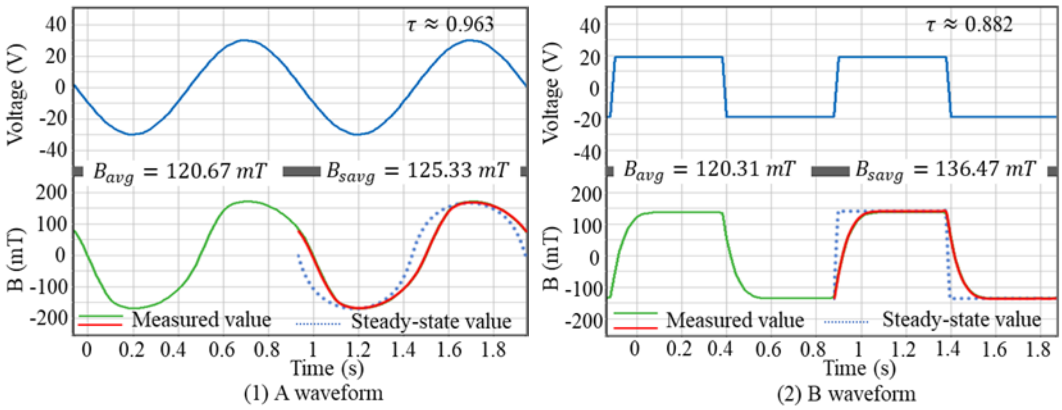


Fig. 4.4 The influence of current waveform shape on magnetic flux density.

By comparing the steady-state value curve with the measured value curve, it can be seen that when the current increases, the magnetic flux density will be less than the steady-state magnetic flux density. Correspondingly, in the process of current reduction, the magnetic flux density is greater than the magnetic flux density in the steady-state.

It can be seen from τ that the magnetic flux density is weakened relative to the static magnetic field in both the A waveform and the B waveform. In the B waveform, the loss is greater than the A waveform. By comparing the B_{avg}, it can be found that the B_{avg} is basically the same under the two waveforms. This is because although the loss in the B waveform is greater than that in the A waveform, the increase rate of the magnetic flux density decreases as the current increases.

4.1.2.3 Effect of current direction change

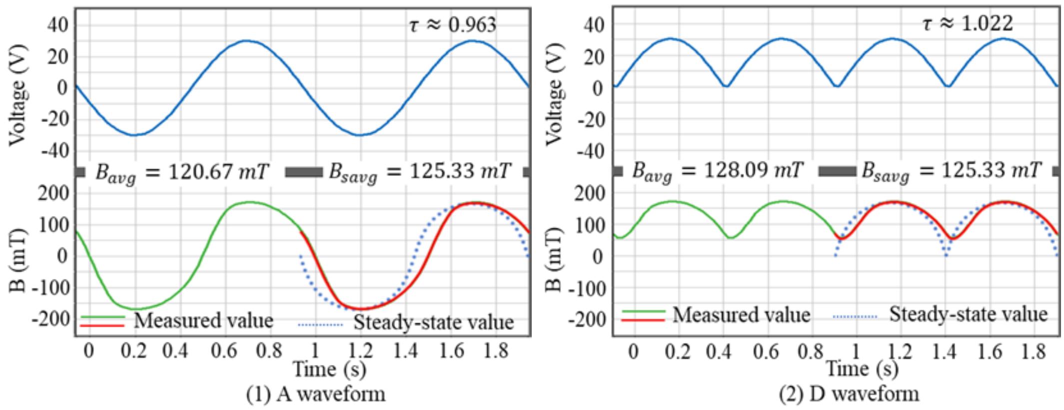


Fig. 4.5 The effect of current direction change on magnetic flux density.

In order to determine the influence of the current direction change on the magnetic flux density, the magnetic flux density and voltage change curves of the A and D waveforms are compared. The measurement results are shown in Figure 4.5. Same as before, the change of the magnetic flux density in the process of magnetization and demagnetization lags behind the change of the power supply. Comparing the steady-state value curve and the measured value curve of the D waveform, the magnetic flux density has not been reduced to 0 due to the presence of residual magnetism. At the same time, according to the τ value, it can be found that the magnetic flux density of the D waveform is enhanced compared to the static magnetic field. Therefore, the D waveform B_{avg} is slightly larger than the A waveform.

4.1.2.4 Effect of pulse current

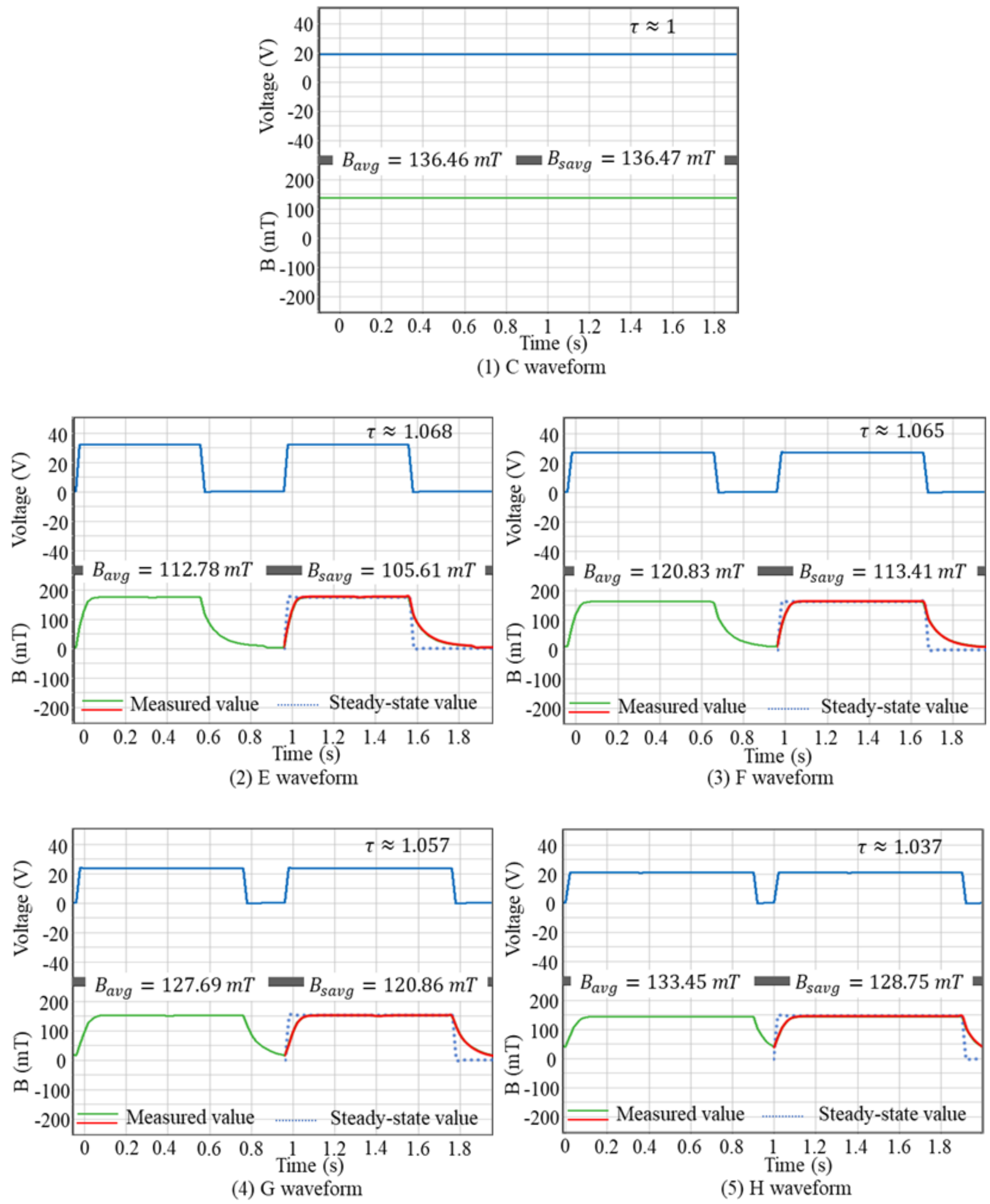


Fig. 4.6 The effect of pulse current on magnetic flux density.

According to the previous discussion, the magnetic flux density will increase to a certain extent when the current direction is unchanged. Therefore, the change in magnetic flux density during pulse current was measured. The measurement results are shown in Figure 4.6. By comparing the measured value curve and the steady-state value curve, it can be clearly seen that the increase in magnetic flux density in the magnetization process lags behind the increase in current. During the T_{off} time, the magnetic flux density gradually decreases. When the average current is the same, B_{avg} gradually increases with the increase of the duty cycle. This is mainly because the increased rate of the magnetic flux density gradually decreases with the increase of the current. By comparing the value of τ, it can be found that as the duty cycle increases, the gain relative to the static magnetic field gradually decreases. This mainly depends on the interval time between two T_{on}, namely T_{off}. It can be seen from the measurement results that the complete elimination of residual magnetism occurs when the T_{off} time is between 300 ms and 400 ms, that is, the duty cycle is between 60% and 70%.

4.2 Discussion on finishing force changes

4.2.1 The relationship between finishing force and magnetic flux density in static magnetic field

4.2.1.1 Measurement methods and conditions

The measuring system of the finishing force is shown in Fig. 4.7. Fix the load cell above the magnetic pole and connect it with the signal conditioner. The output signal of the signal conditioner and the power supply are simultaneously connected to the logger. The measurement conditions of the finishing force are shown in Table 4.1. Mix 1.2 g of electrolytic iron powder, 0.3 g of abrasive particles, and 0.8 ml of grinding fluid uniformly and place them on the tray. Adjust the position of the load cell so that the gap between the bottom plate and the tray is 1.5 mm. During the measurement, the magnetic pole performs a rotating movement at a speed of 350 rpm. Due to the rotating movement of the magnetic pole, the magnetic abrasive slurry will occasionally be thrown out when the magnetic force is small, which will affect the measurement results. In addition, according to previous studies, the magnitude of the finishing force is not affected by the direction of the current but is related to the absolute value of the current. Therefore, the finishing force is measured when the current is in one direction, and the minimum current value is set to 0.9 A. Measure the finishing force every 0.1 A, and calculate the average value of the measured value of 6 seconds as the value of the finishing force at the corresponding current value.

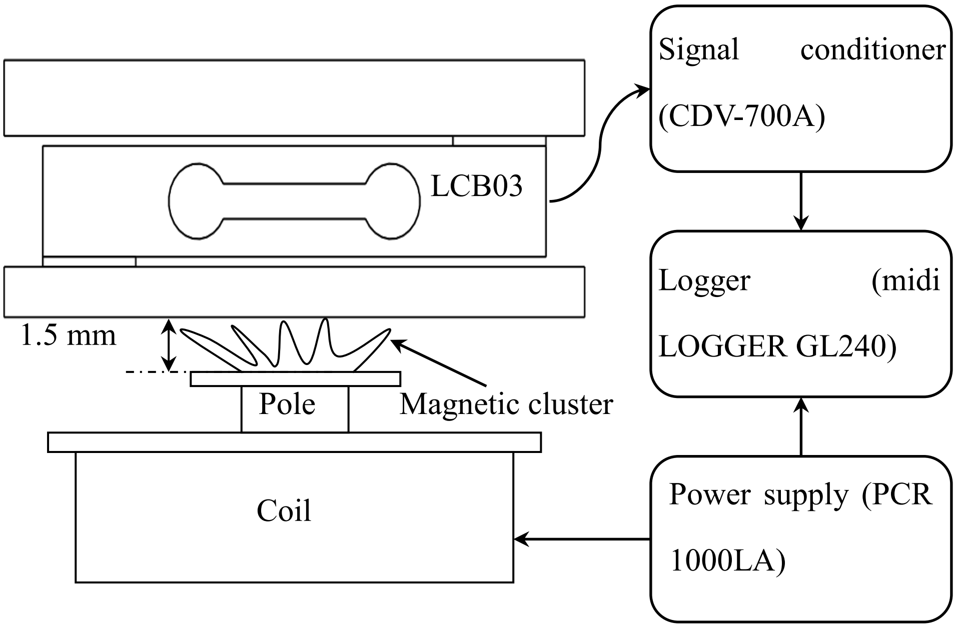


Fig. 4.7 Schematic diagram of finishing force measurement system

Table 4.1 Measurement conditions

Magnetic particles	Electrolytic iron powder, 75 μm in mean dia:1.2 g
Abrasive particles	WA#8000: 0.3 g,
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed	350 rpm
Feed speed of mobile stage	0 mm/min
Working gap	1.5 mm
Current	0.9 A to 4 A(Step 0.1 A)

4.2.1.2 Measurement results and discussion

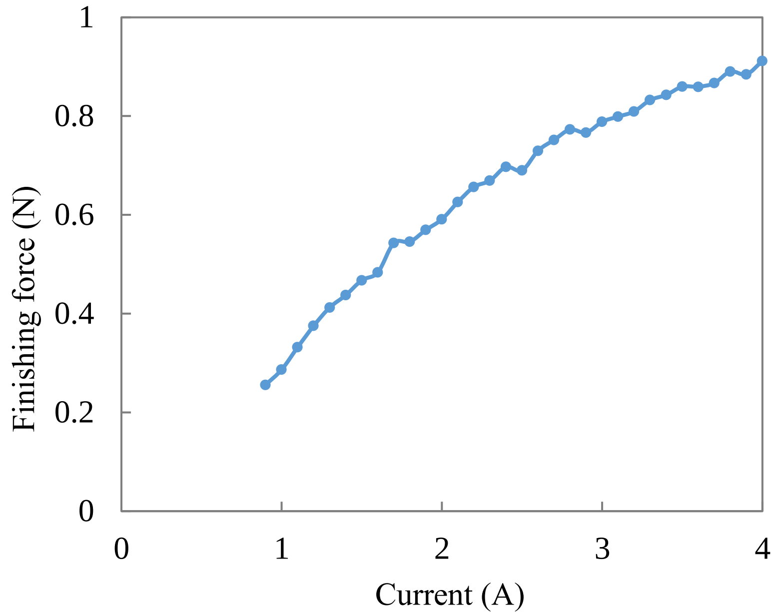


Fig. 4.8 The relationship between finishing force and current

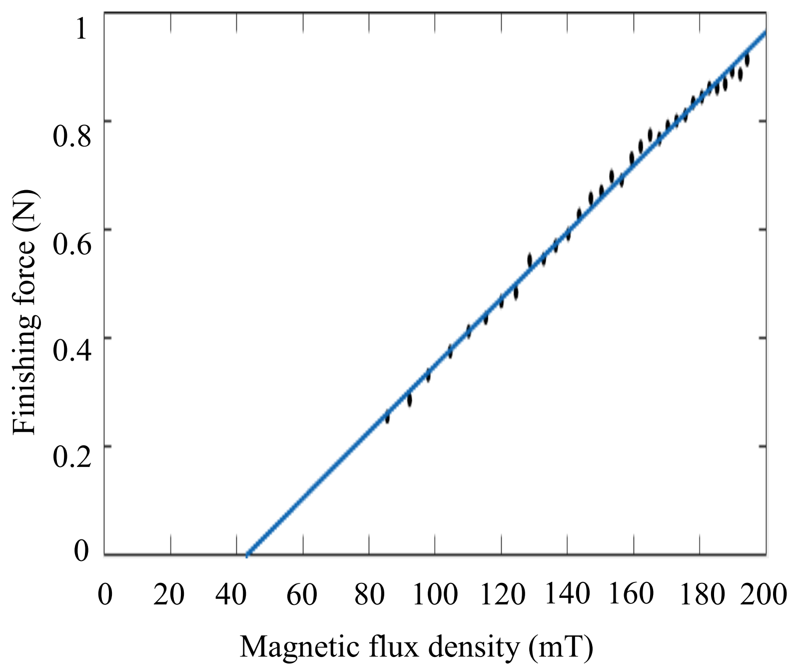


Fig. 4.9 The relationship between finishing force and magnetic flux density

The measurement results are shown in Fig. 4.8. It can be seen that as the current increases, the finishing force increases, but the increasing rate of finishing force gradually slows down. According to the measurement results of Fig. 4.8 and Fig. 4.2, the relationship between the finishing force and the magnetic flux density can be obtained, as shown in Fig. 4.9. It can be seen that the magnetic flux density and finishing force are approximately linear when the current value is between 0.9 A and 4 A. Perform polynomial fitting through MATLAB to obtain Eq. (4.4)

$$F = 0.0061123 \times B - 0.26106 \qquad (R^2 = 0.9954) \qquad (4.4)$$

4.2.2 The influence of current change mode on finishing force

4.2.2.1 Measurement methods and conditions

The measuring method of finishing force is shown in Fig. 4.7. For different waveforms, set the average current value to 1.9 A. Except for the current value, the measurement conditions are the same as those shown in Table 4.2. The change of finishing force in the above 8 current waveforms was measured. In addition, in order to clarify the influence of the current change mode on the finishing force, the change curve of the finishing force is calculated based on the measured value of the magnetic flux density and the relationship between the magnetic flux density and the finishing force. Compare the difference between the calculated value and the measured value to analyze the influence of the current change mode on the finishing force. The calculation method of finishing force is shown in Eq. 4.5. Since the finishing force is independent of the direction of the magnetic flux density, the absolute value of the magnetic flux density is used for calculation. When the magnetic flux density is less than 80 mT (I=0.9 A), approximate the predicted value to the calculated value of Eq. 4.4. Since the finishing force does not change in direction, when calculating the finishing force, if the calculated value is less than 0, it will be equal to 0.

$$\begin{cases} F = 0.0061123 \times |B| - 0.26106 & 80mT \le |B| < 190mT \\ F \approx 0.0061123 \times |B| - 0.26106 & 42.72mT \le |B| < 80mT \\ F \approx 0 & |B| \le 42.72mT \end{cases} \quad (4.5)$$

Table 4.2 Measurement conditions

Magnetic particles	Electrolytic iron powder, 75 μm in mean dia:1.2 g
Abrasive particles	WA#8000: 0.3 g,
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed	350 rpm
Feed speed of mobile stage	0 mm/min
Working gap	1.5 mm
Current	0.9 A to 4 A(Step 0.1 A)

4.2.2.2 Effect of current waveform shape

Figure 4.10 shows the measurement results of the finishing force in the A and B waveforms. The red curve in the figure is the finishing force calculated according to Equation 4.5, and the blue curve is the measured value of the finishing force. It can be seen that the calculated values of A and B waveforms are both greater than the measured values. According to the results, it is speculated that since the magnetic particles are magnetized and demagnetized periodically in the alternating magnetic field, some energy will also be lost in the process. Therefore, when the current direction changes periodically, the measured value of the finishing force is smaller than the calculated value. In addition, the average value of the finishing force is roughly the same in the two waveforms, which corresponds to the measurement result of the magnetic flux density.

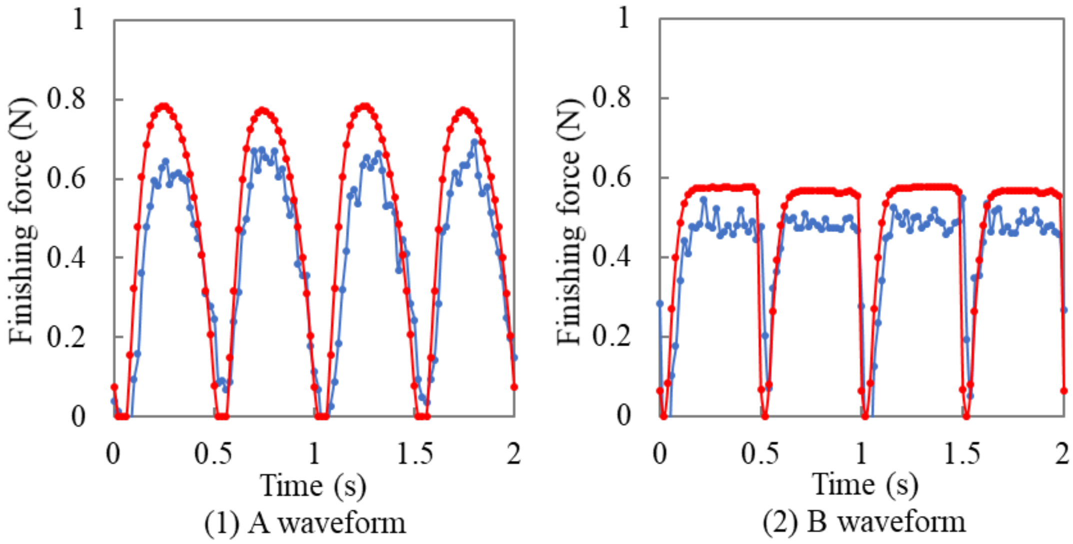


Fig. 4.10 Variation curve of finishing force (A waveform and B waveform).

4.2.2.3 Effect of current direction change

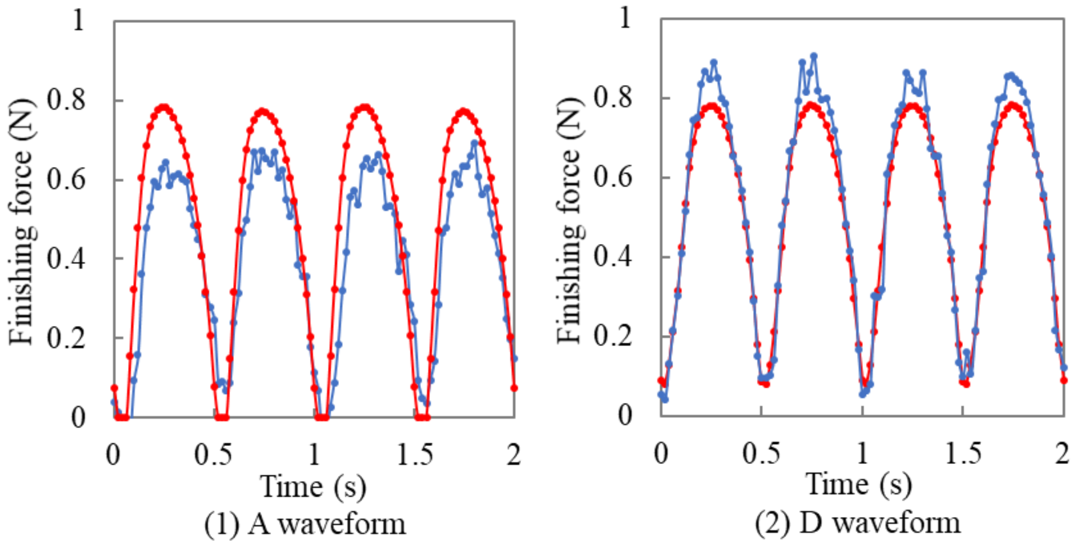


Fig. 4.11 Variation curve of finishing force (A waveform and D waveform).

Figure 4.11 shows the finishing force change curve of A waveform and D waveform. It can be seen that the measured value of finishing force in D waveform is greater than that of A waveform. At the same time, it can be seen that most of the measured value curve of the D waveform finishing force is consistent with the calculated value curve, but the maximum value is slightly higher than the calculated value. According to the measurement result of the magnetic flux density, it can be inferred that the magnetic particles also have residual magnetism when the current direction is unchanged. Furthermore, the vibration of the measuring device will also have a certain degree of influence on the measurement result. However, based on the above results, it can be concluded that under the same other conditions, the average value of the finishing force is higher than the alternating current when the current direction is unchanged.

4.2.2.4 Effect of pulse current

Figure 4.12 shows the change curve of the finishing force. In the pulse current, as the duty cycle increases, the average finishing force increases. Although the average current is the same, the increased rate of finishing force gradually decreases as the current increases. In the case of the C waveform, the average finishing force value is only slightly smaller than the H waveform. This is because there is no periodic magnetization and demagnetization process in the C waveform, and the increase rate of the finishing force will decrease as the current increases. In addition, the comparison of the measured value curve and the calculated value curve shows that in the above waveform, the difference between the measured value and the calculated value is small. Therefore, when the current direction does not change, energy loss can be reduced. At the same time, the average finishing force higher than the static magnetic field can be obtained by adjusting the duty cycle.

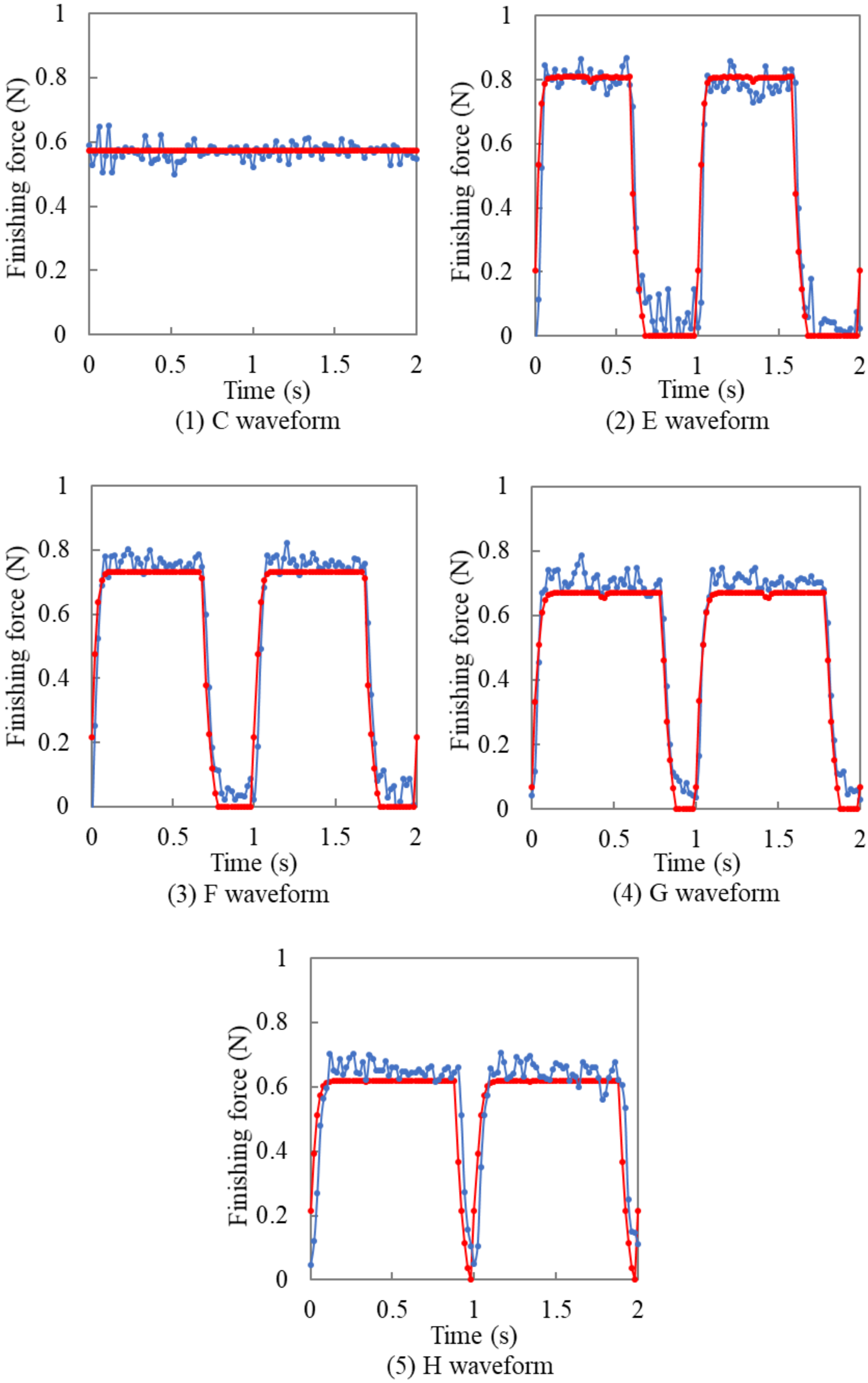


Fig. 4.12 The change curve of finishing force (Pulse waveform).

4.3 Effect on finishing characteristics when using AC square wave

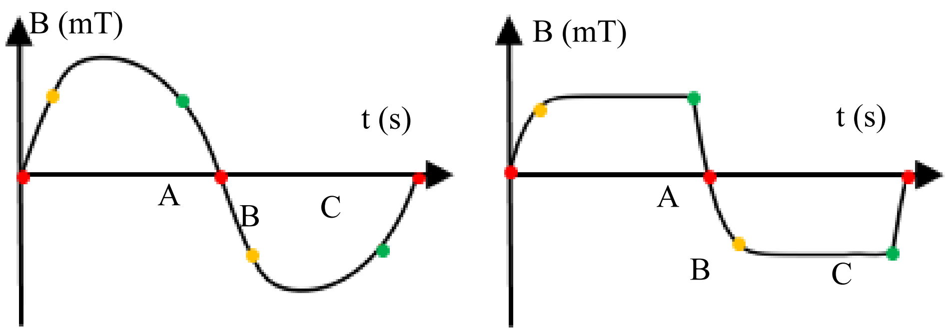
4.3.1 Observation of magnetic cluster behavior

4.3.1.1 Observation methods and conditions

The measurement conditions are shown in Table 4.3. 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) were used. The rotation speed of the magnetic pole during shooting is 0. The rotation speed of the magnetic pole during shooting is 0. Use a high-speed camera to capture the fluctuating behavior of magnetic clusters. The shooting speed of the high speed camera is 1000 FPS. In the observation, the current frequency is set to 1 Hz. Since the fluctuation amplitude of the magnetic clusters under the two waveforms is not much different at 1 Hz, the difference in the fluctuation process of the magnetic clusters is mainly observed. The difference in the fluctuation speed of magnetic clusters is obtained by the difference in the number of frames. As shown in Fig. 4.13, t_A is when the magnetic cluster just fluctuates down to the lowest position, t_B is when the magnetic cluster just fluctuates up to the highest position, and t_C is before the magnetic cluster starts to fall significantly. Therefore, in a fluctuation cycle, the magnetic cluster will fluctuate from the lowest position (t_A) up to the highest position (t_B), stay for a period of time (t_B to t_C), and then fluctuate down to the lowest position (t_A) to complete the fluctuation cycle. The magnetic cluster completes the cycle and renewal of abrasive particles during the up and down fluctuations, and at the same time has a higher finishing efficiency near the highest position (t_B to t_C). Denote the time from t_C to t_A as T1, t_B to t_C as T2, and t_A to t_B as T3.

Table 4.3 Measurement conditions

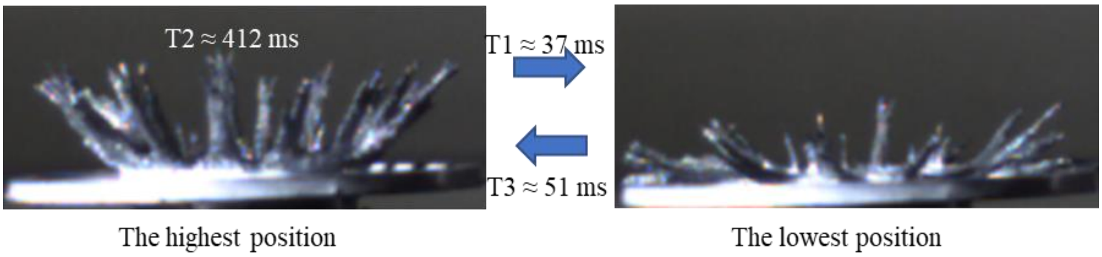
Magnetic particles	Electrolytic iron powder, 30 μm in mean dia:1.2 g Electrolytic iron powder, 75 μm in mean dia:1.2 g Electrolytic iron powder, 149 μm in mean dia:1.2 g Electrolytic iron powder, 330 μm in mean dia:1.2 g
Abrasive particles	WA#10000: 0.3 g
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Rotational speed of magnetic pole	0 rpm
Feed speed of mobile stage	0 mm/min
Current waveform	A waveform, B waveform
Alternating current	1.9 A (Average)
Magnetic field frequency	1 Hz



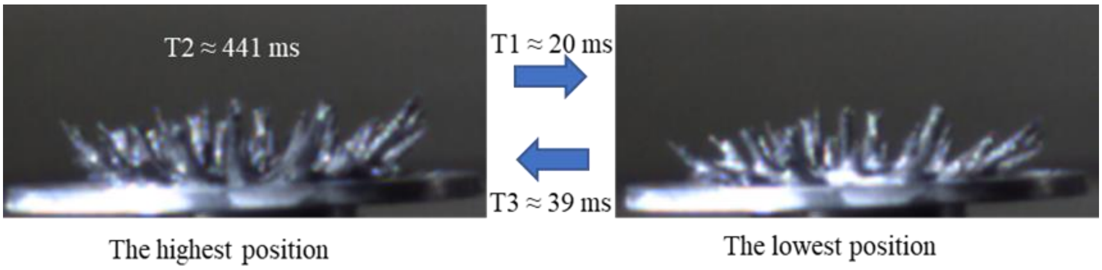
(a) A waveform (b) B waveform

Fig. 4.13 Magnetic cluster fluctuations in square wave and sine wave

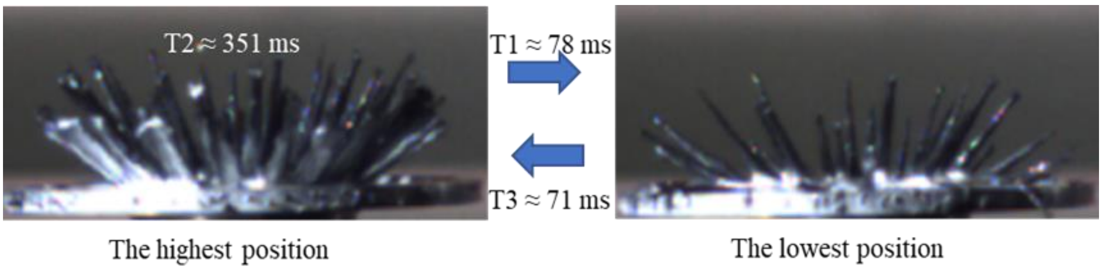
4.3.1.2 Observation results and discussion



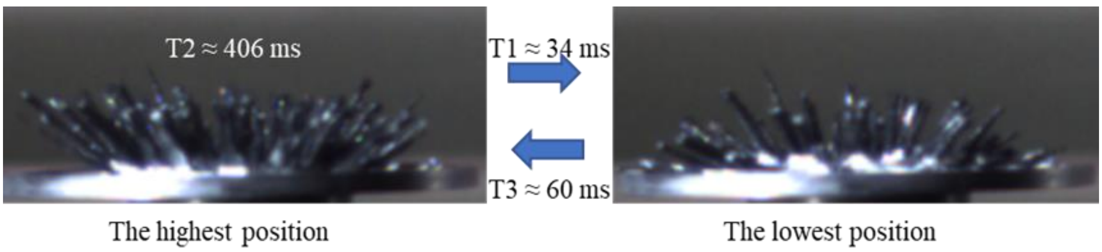
(a) A waveform, 330 µm



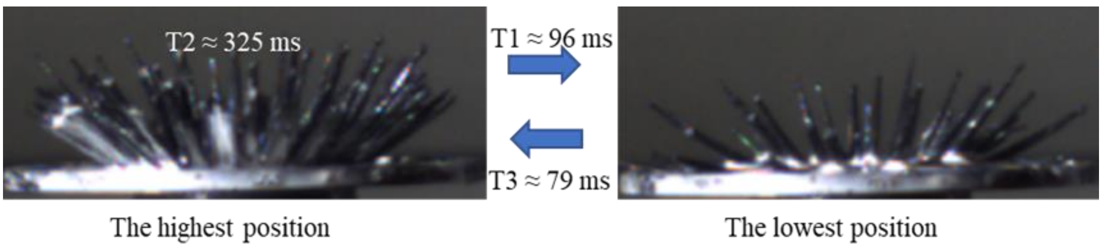
(b) B waveform, 330 µm



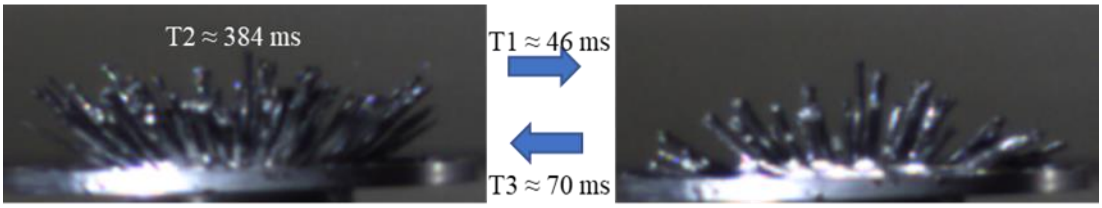
(c) A waveform, 149 µm



(d) B waveform, 149 µm



(e) A waveform, 75 µm



(f) B waveform, 75 μm

Fig. 4.14 The lowest position and the highest position in the fluctuation period of the magnetic cluster.

Through observation, it is found that in the B waveform, the magnetic clusters fluctuate up or down faster. For example, when the average diameter of magnetic particles is 75um, the duration of the magnetic cluster at the highest position of the A waveform is about 325 ms, and the duration of the magnetic cluster at the highest position of the B waveform is about 384 ms. This rule also exists for magnetic particles of other sizes. which is, when the size of the MPs is the same, T2 is longer than A waveform in the case of B waveform. As the size of the MPs increases, T2 increases when the current waveform is the same. At the same time, the difference in T2 of the two waveforms gradually decreases, increasing with the size of the MPs. When the magnetic cluster is in the highest position, it means that it will have a higher finishing efficiency than other positions.

4.3.2 Experimental conditions and method

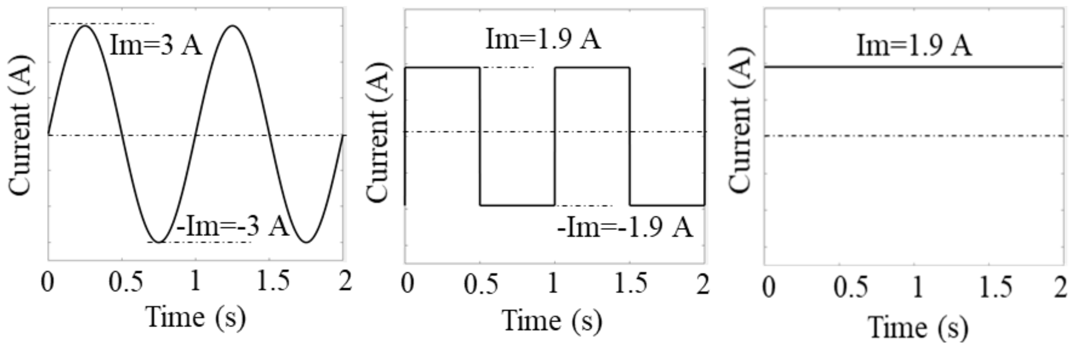
The experimental conditions are shown in Table 4.4. SUS304 austenitic stainless-steel plates of size 100 × 100 × 1 mm are prepared as workpieces. The composite magnetic finishing fluid used in the experiment was obtained by uniformly mixing 1.2 g electrolytic iron powder, 0.3 g APs, and 0.8 mL oily grinding fluid. Because this experiment mainly investigates the influence of finishing parameters, and at the same time under optimized experimental conditions, the surface roughness is basically stable after 40 min. Therefore, the total finishing time is set to 40 min, and the workpiece is cleaned and measured every 10 min.

Table 4.4 Experimental conditions.

Workpiece	SUS304 stainless steel plate with the size of 100 mm×100 mm×1 mm
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 ml
Working gap	1.5 mm
Feed speed	260 mm/min
Current	1.9 A (Average)
Finishing time	Single 10 min (40 min)
Magnetic particles	Electrolytic iron powder, 75 μm in mean dia:1.2 g Electrolytic iron powder, 149 μm in mean dia:1.2 g Electrolytic iron powder, 330 μm in mean dia:1.2 g
Current waveform	A waveform, B waveform, C waveform
Current frequency	1 Hz, 4 Hz, 7 Hz
Abrasive particles	WA#6000: 0.3 g, WA#8000: 0.3 g, WA#20000: 0.3 g
Rotational speed	350 rpm, 450 rpm, 550 rpm

The surface roughness of the workpiece is measured by the surface roughness meter (SURFPAK-SV produced by Mitutoyo Corporation, Kawasaki, Japan). The weight of the workpiece is measured using a semi-micro balance AEG-80SM (Shimadzu Corporation, Kyoto, Japan, minimum weighing unit: 0.01 mg). The amount of material removal is obtained by calculating the difference between the weight of the workpiece before and after finishing. In this experiment, three types of currents are used, which are A waveform, B waveform, and direct current (C waveform) as shown in Figure 4.15. The average value of the absolute value of the current under different waveforms is 1.9

A. The maximum and minimum current of B waveform is 1.9 A. The effects of three currents on finishing characteristics are compared. In addition, discuss the effects of MPs size, magnetic field frequency, APs size, and magnetic pole rotation speed on finishing characteristics when using B waveform.



(a) A waveform (b) B waveform (c) C waveform

Fig. 4.15 Current waveform

4.3.3 Experimental results and discussion

4.3.3.1 Current waveform shape

The effect of the current waveform on surface roughness and MR is shown in Figure 4.16. It can be seen that the amount of MR is the least and the surface quality is the worst at C waveform. This is mainly because, in the case of A waveform and B waveform, the magnetic cluster constantly fluctuate with changes in current. This fluctuating motion can continuously update the APs in contact with the workpiece, thereby ensuring the stability of the finishing tool. Therefore, the finishing efficiency is higher than in C waveform. In the case of B waveform, the amount of MR is slightly higher than that of A waveform, and the surface roughness changes faster than A waveform. In order to analyze the reason, the change of magnetic flux density was measured.

Figure 4.4 shows the change curve of the magnetic flux density above the magnetic pole axis with time. It can be seen that the maximum magnetic flux density is greater than B waveform in the case of A waveform. But calculating the average value of the absolute value of the magnetic flux density (*Ba*) in one cycle, it is found that the *Ba* values of A waveform and B waveform are only slightly different, which are 120.67 mT and 120.31 mT, respectively. The finishing force is mainly affected by the size of MPs and the strength of the magnetic field. Therefore, in the case of the two waveforms, the average finishing force should be close. According to previous observations of the magnetic cluster, it can be found that the hold time (T2) of the magnetic cluster at the highest position is longer in the case of B waveform. Therefore, higher finishing efficiency is obtained in the case of B waveform.

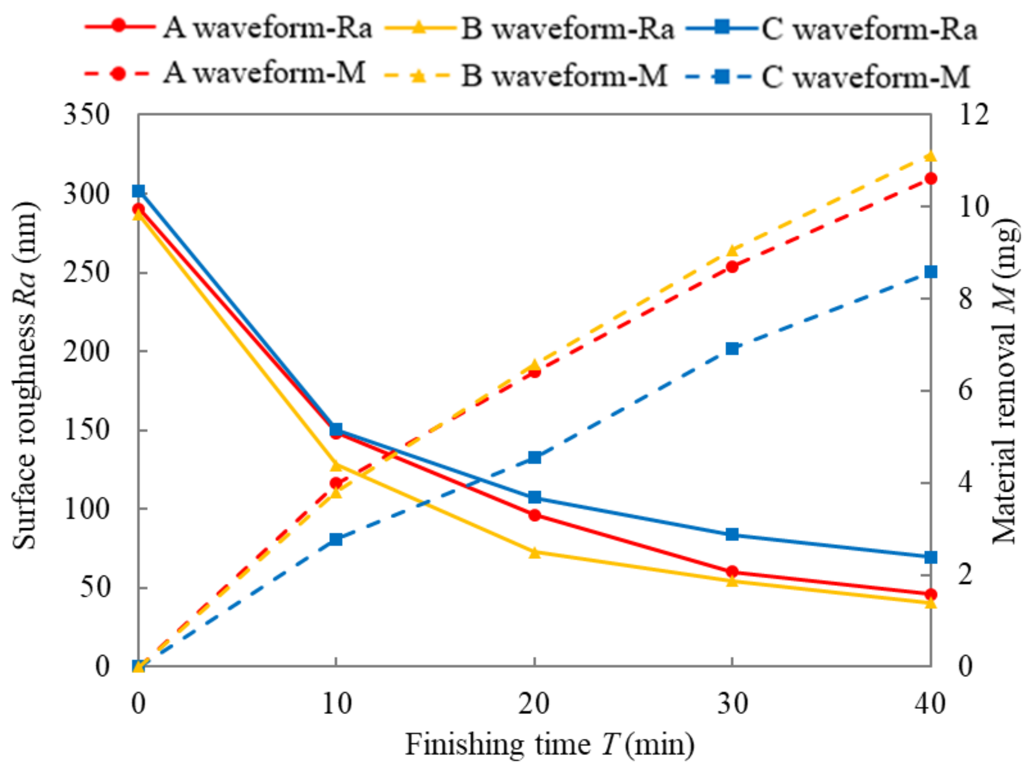


Fig. 4.16 The effect of current waveform on surface roughness and material removal. (Magnetic particles: 149 μm, frequency: 1 Hz, abrasive particles: WA#8000, rotational speed: 350 rpm)

4.3.3.2 Magnetic particle size

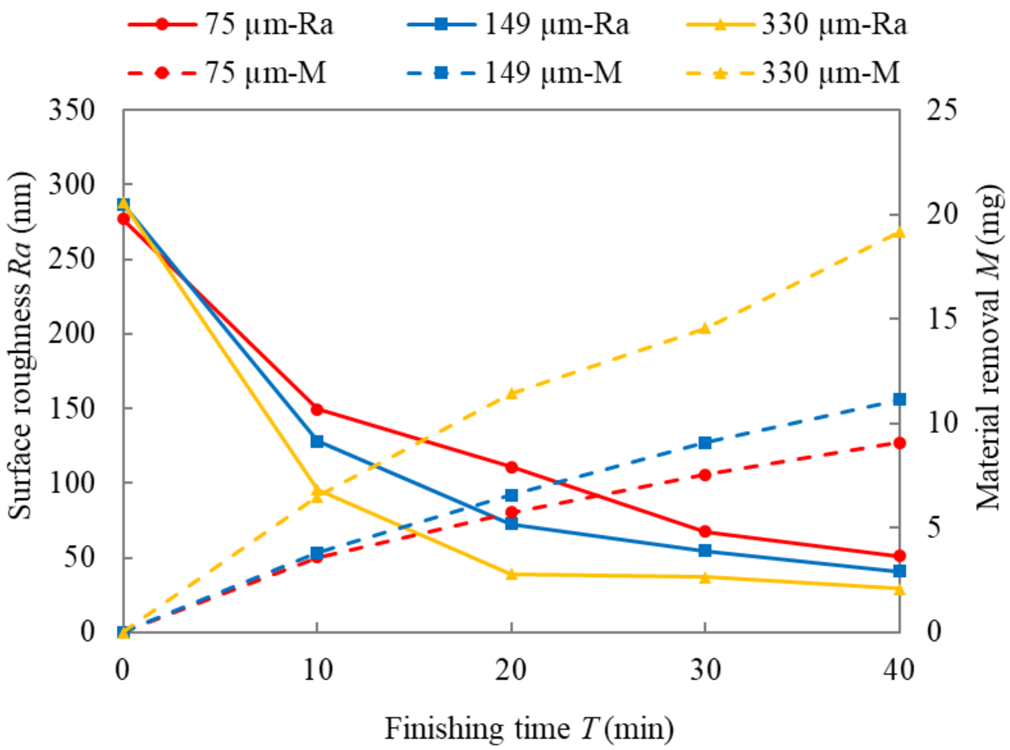


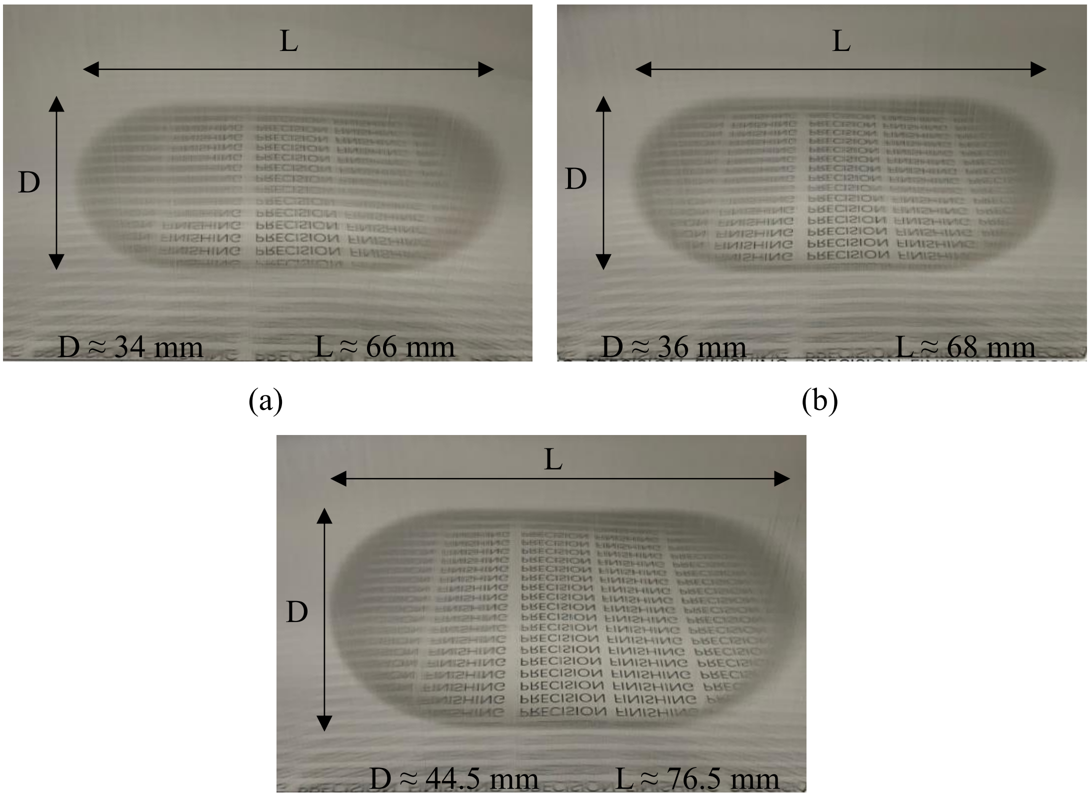
Fig. 4.17 The effect of magnetic particles size on surface roughness and material removal. (Current waveform: B waveform, frequency: 1 Hz, abrasive particles: WA#8000, rotational speed: 350 rpm).

Figure 4.17 shows the effect of the MPs size on surface roughness and MR. According to the observation of the workpiece surface, the finishing area increases as the size of MPs increases, as shown in Figure 4.18. In the figure, L is the length of the finishing area, and D is the rotating diameter of the magnetic cluster. It can be seen that as the size of APs increases, D gradually increases. This is because the magnetic force between MPs increases as the particle size increases [1]. Therefore, the magnetic cluster that can be formed is longer, and the finishing area increases. In order to accurately evaluate the MR, the MR per unit area (Q, mg/mm2) is calculated.

$$Q = MR/S \tag{4.6}$$

where MR (mg) is the total amount of MR, and S (mm^2) is the area of the finishing area. The finishing area S is calculated by the following equation,

$$S = (L - D) \times D + \pi(D/2)^2 \qquad (4.7)$$



(c)

Fig. 4.18 Photos of the workpieces. (a) Magnetic particles: 75 μm; (b) Magnetic particles: 149 μm; (c) Magnetic particles: 330 μm.

The Q at different particle sizes is shown in Figure 4.19. According to Figure 4.17 and Figure 4.19, it can be seen that as the size of MPs increases, Q increases and the surface roughness changes faster. This is mainly because the increase in the size of the MPs will increase the finishing force, thereby increasing the finishing efficiency [2, 3].

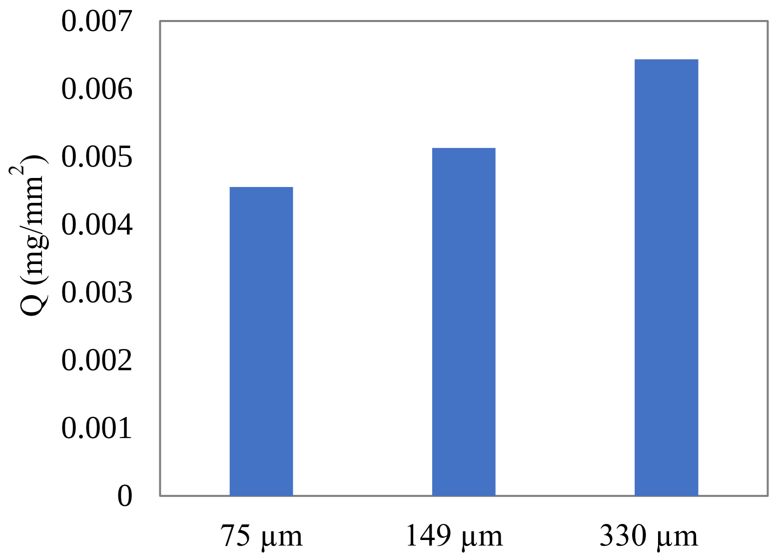


Fig. 4.19 The amount of material removal per unit area (Q).

4.3.3.3 Current frequency

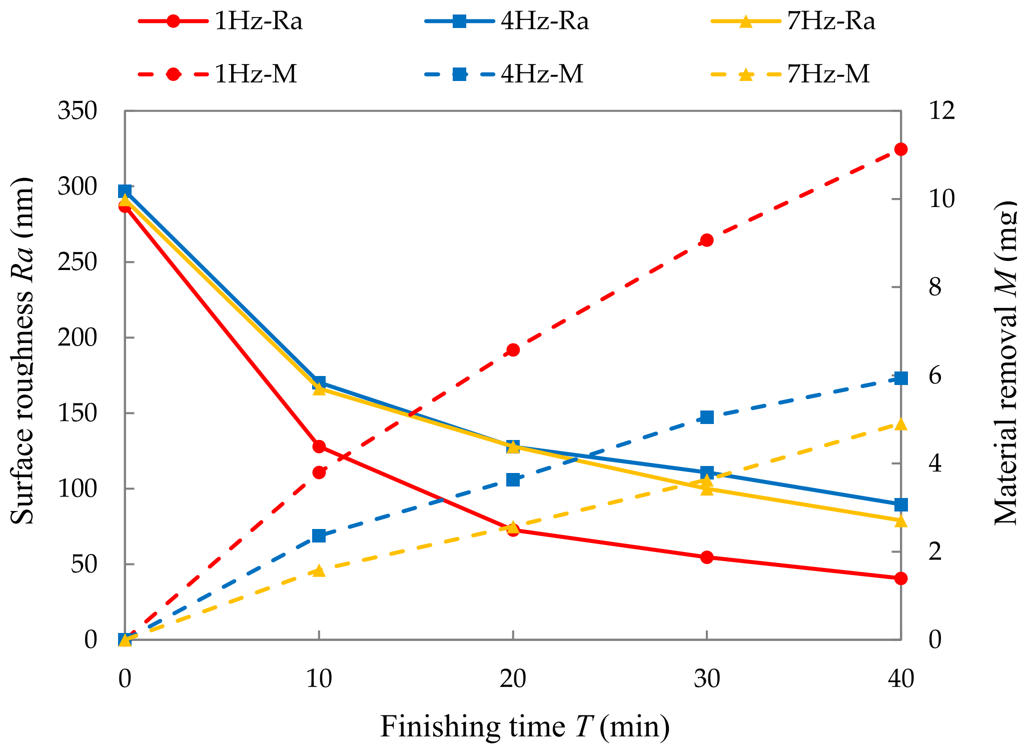


Fig. 4.20 The effect of current frequency on surface roughness and material removal.

(Magnetic particles: 149 μm, current waveform: B waveform, abrasive particles: WA#8000, rotational speed: 350 rpm)

Figure 4.20 shows the effect of current frequency on surface roughness and MR. It can be seen that as the frequency of the current increases, the amount of MR decreases significantly. The surface quality is best obtained at 1 Hz. According to the comparison between the measured value and the reference curve in Figure 4.4, it can be seen that the magnetic flux density is relatively weakened during the magnetization process and relatively enhanced during the demagnetization process. But in the case of B waveform, the degree of weakening is significantly greater than the degree of enhancement. Therefore, as the frequency of the current increases, the degree to which the magnetic flux density is weakened increases. In turn, the finishing efficiency is reduced.

4.3.3.4 Abrasive particles size

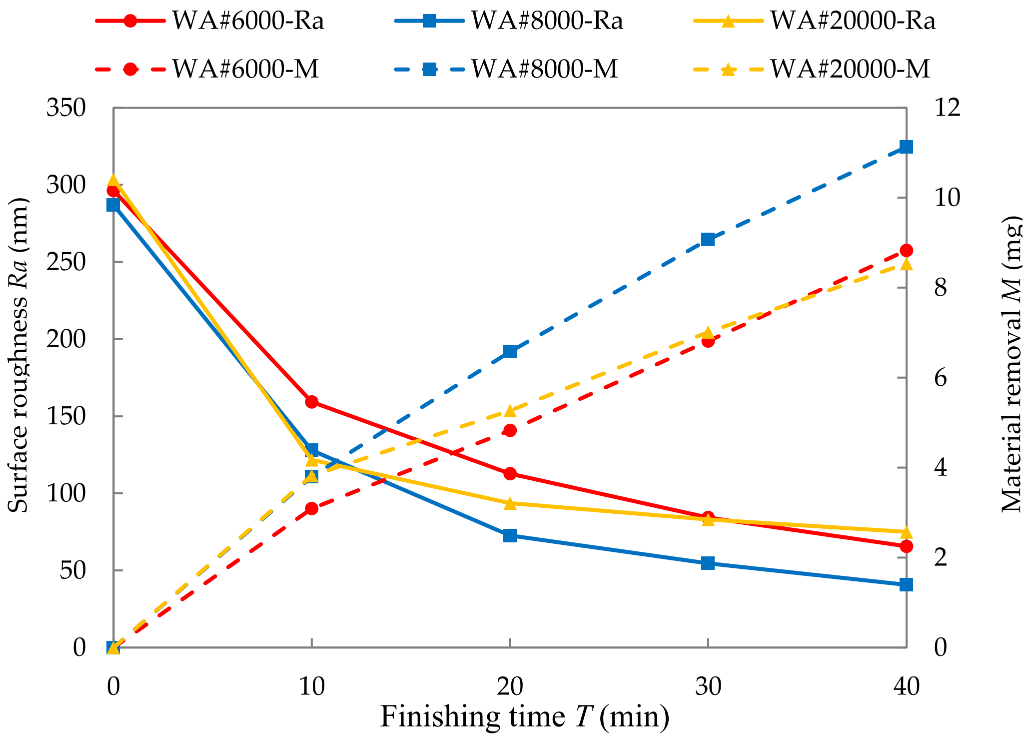
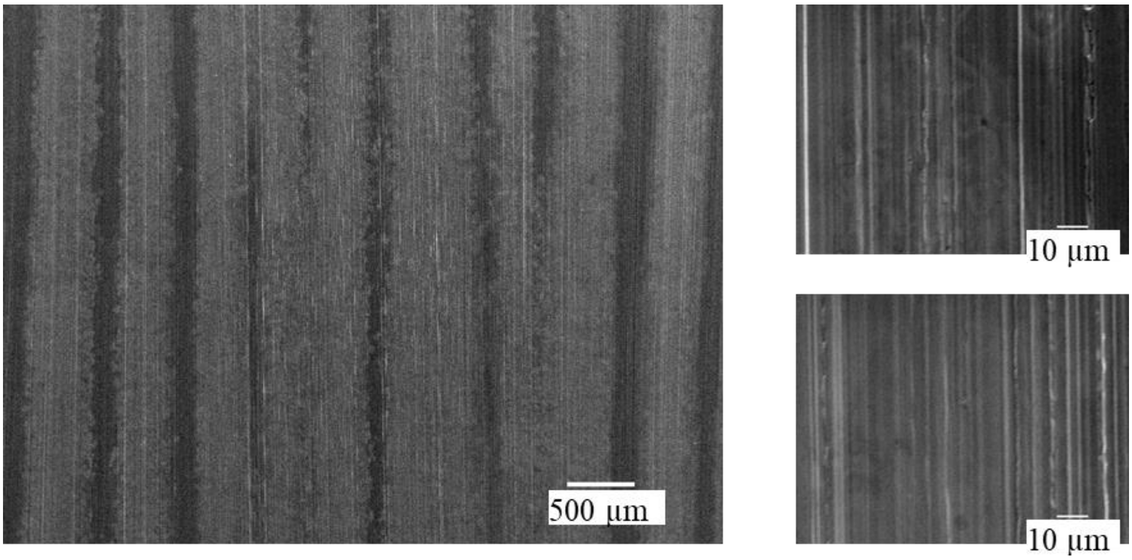
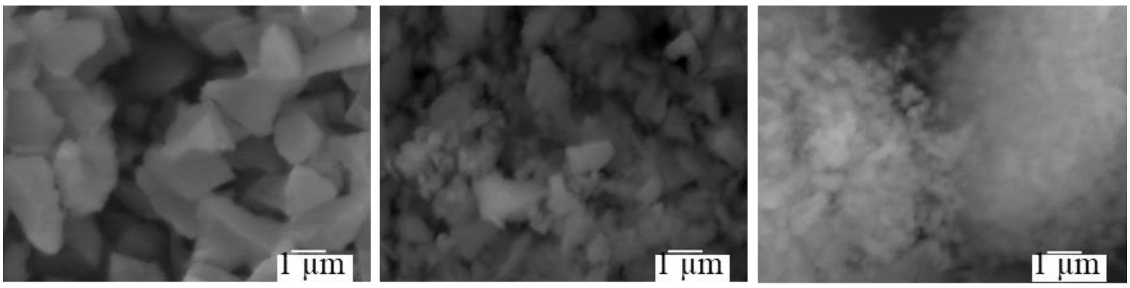


Fig. 4.21 The effect of abrasive particles size on surface roughness and material removal. (Magnetic particles: 149 μm, current waveform: B waveform, frequency: 1 Hz, rotational speed: 350 rpm)

Figure 4.21 shows the effect of APs size on surface roughness and MR. It can be seen that the highest MR and the best surface quality are obtained when using WA#8000 APs. In addition, at 10 min, the MR and surface quality changes of WA#20000 are close to WA#8000. But in the next 30 min, the change rate of surface roughness and MR gradually slows down. In order to explore the reason, the initial workpiece surface and APs were observed, as shown in Figure 4.22. It can be seen from Figure 4.22a that the initial surface of the workpiece has large grooves and is also full of small grooves. Figure 4.22b shows that there are significantly more small particles at WA#20000.



(a)



WA#6000 WA#8000 WA#20000

(b)

Fig. 4.22. SEM images of the workpiece surface and abrasive particles. (a) Workpiece surface; (b) Abrasive particles.

Furthermore, a white light interferometer (Zygo NewView7000 produced by Zygo Corporation, Middlefield, CT, U.S.) was used to observe the surface of the workpiece after finishing, as shown in Figure 4.23. As can be seen in Figure 4.23a, there is no obvious abrasive sliding trace at WA#6000. According to Jain et al. [4], a single AP cutting material needs to meet the following relationship,

$$\mathrm{Fc} \geq \mathrm{A}_s \tau \qquad (4.8)$$

where Fc is the tangential force acting on AP, A_s is the projected area of penetration, and τ is the shear strength of the workpiece material.

At WA#6000, due to the increase of A_s the tangential force required to complete the cut material increases. According to the surface state shown in Figure 4.23a, it can be inferred that because there is not enough tangential force acting on the APs, the APs does not slip but rolls on the surface of the workpiece. Therefore, the finishing efficiency is low.

At WA#8000 and WA#20000, obvious finishing traces can be seen. According to Figures 4.22 and 4.23, in the first 10 min, the peak tip of the workpiece surface will be preferentially removed. During this process, APs enter the gap between the two peaks to cut the peak tip, which mainly depends on the tangential force. In the next 30 min, as small peaks on the surface are gradually removed, material removal in a relatively flat area mainly depends on APs being pressed into the workpiece. During this process, the material removal amount of a single AP mainly depends on the sliding distance and the projected area of the pressed workpiece, which is not only related to the tangential force but also to the normal force. When other conditions are the same, the total normal force is not much different. When the weights of APs are the same, the number of APs is more at WA#20000. The increase in the number of APs disperses the normal force, which reduces the normal force acting on a single AP, thereby reducing the penetration depth. As shown in Figure 4.23b,c as the size of the APs increases, the depth of the finishing mark also increases. Therefore, when the sliding distance is the same, the MR of a single AP increases. This leads to a decrease in the MR of WA#20000 in the following 30 min.

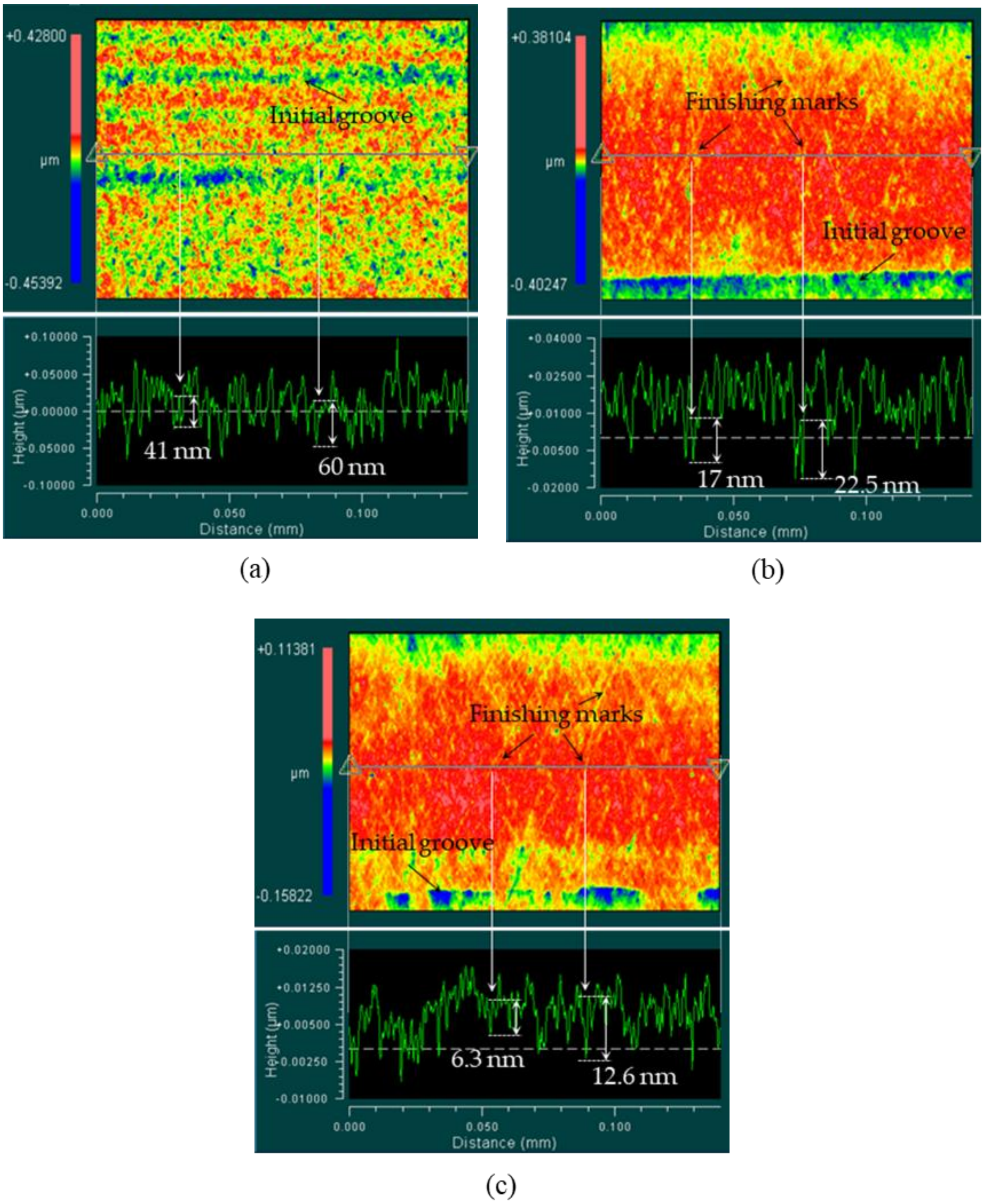


Figure 4.23. The Photographs of the workpiece surface after finishing (White Light Interferometers). (**a**) WA#6000; (**b**) WA#8000; (**c**) WA#20000.

4.3.3.5 Magnetic pole rotation speed

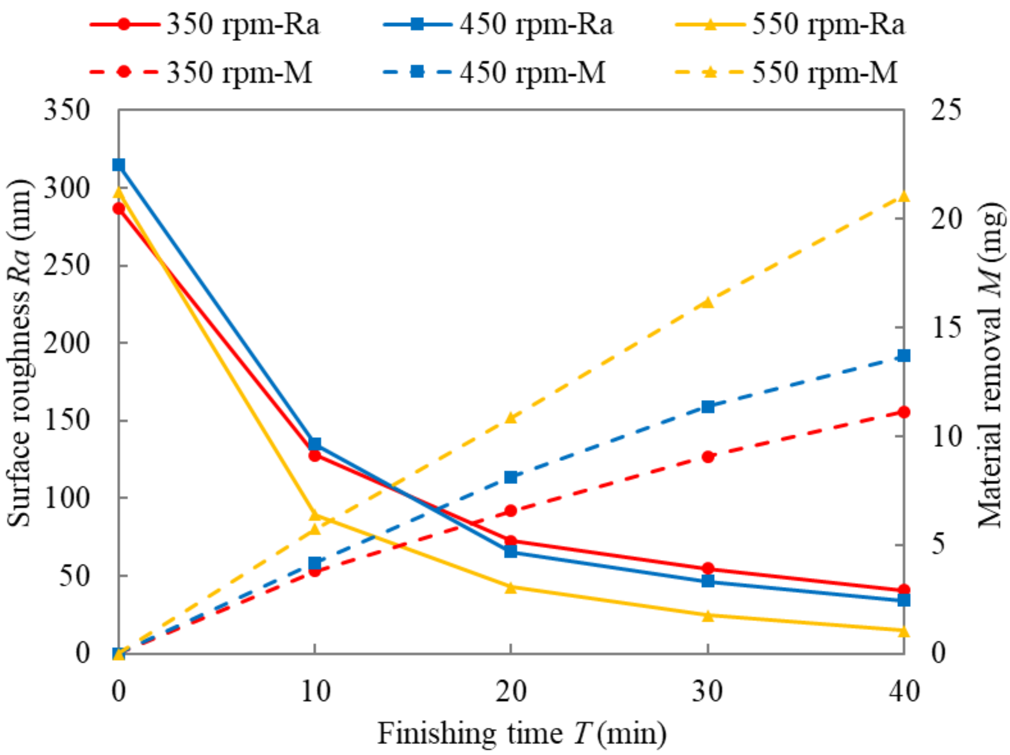


Fig. 4.24. The effect of rotational speed on surface roughness and material removal. (Magnetic particles: 149 μm, current waveform: B waveform, frequency: 1 Hz, abrasive particles: WA#8000)

Figure 4.24 shows the effect of magnetic pole rotation speed on surface roughness and MR. It can be seen that as the rotation speed increases, the finishing efficiency increases. In the abrasive micromachining process, the material removal rate (MRR) can be given by the following equation [5],

$$MRR = C_P \times P \times V \times \rho \qquad (4.9)$$

where P is the normal finishing force acting on the abrasive particle, V is the relative speed between the abrasive particle and the workpiece, ρ is the material density of the workpiece, and C_p is a constant. The increase of the magnetic pole rotation speed increases the relative speed between the APs and the workpiece, so the finishing efficiency is higher.

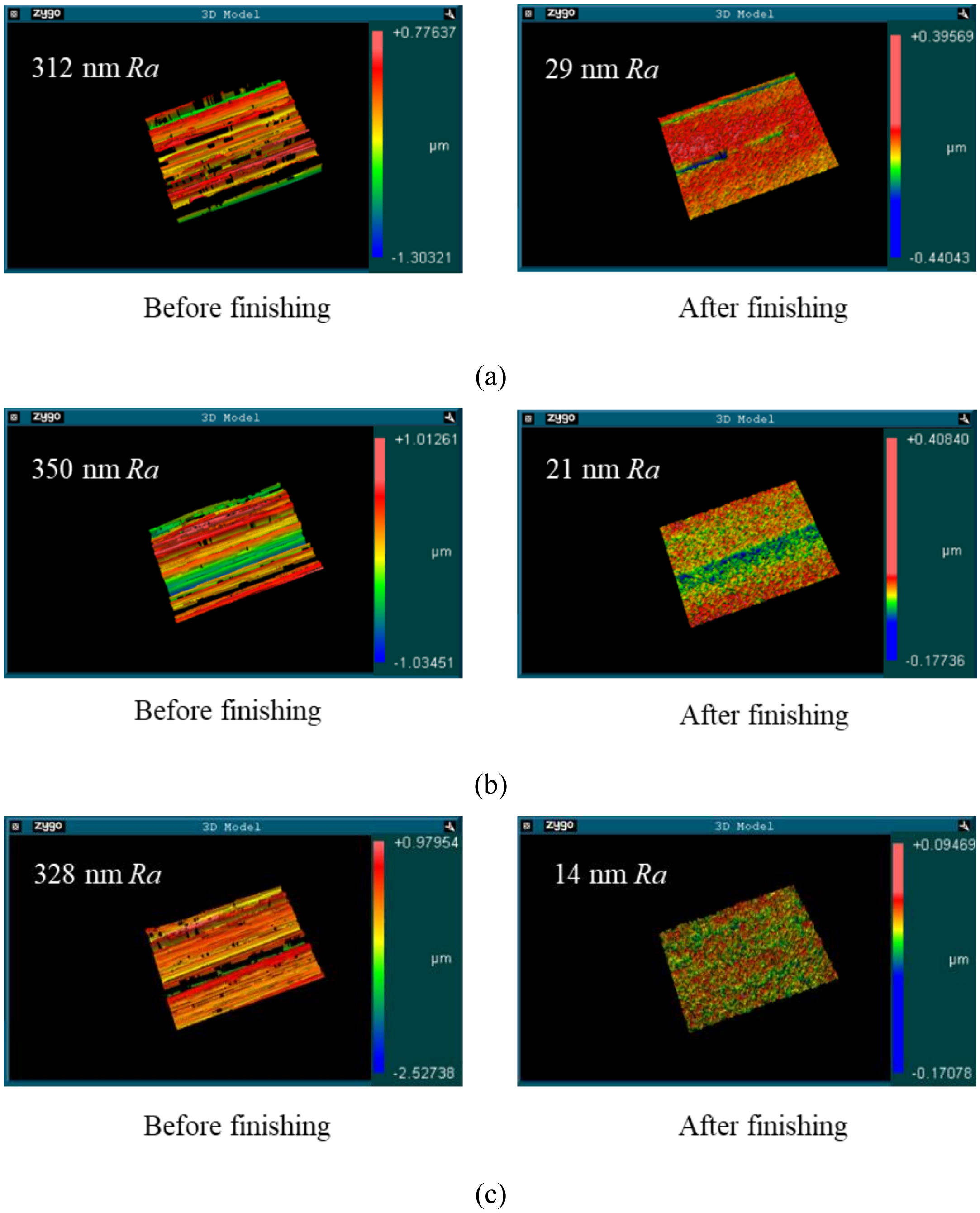


Fig. 4.25. 3D photograph of the workpiece surface before and after finishing. (a) 350 rpm; (b) 450 rpm; (c) 550 rpm.

Figure 4.25 is the 3D photograph of the workpiece surface before and after finishing. It can be seen that the small grooves on the surface after finishing at the three rotational speeds are almost completely removed, but some large grooves are still not removed at 350 rpm and 450 rpm. The best surface quality is obtained when the magnetic pole rotation speed is 550 rpm.

4.4 The influence of full-wave rectified sine wave on finishing characteristics

4.4.1 Observation of magnetic cluster behavior

4.4.1.1 Observation methods and conditions

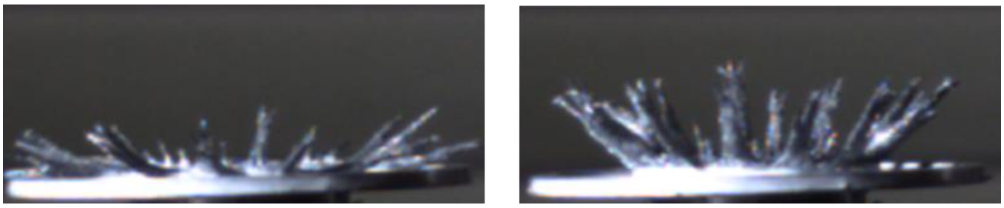
Table 4.5 Measurement conditions

Magnetic particles	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 Electrolytic iron powder, 330 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
Current waveform	A waveform, D waveform
Alternating current	1.9 A (Average)
Magnetic field frequency	1 Hz

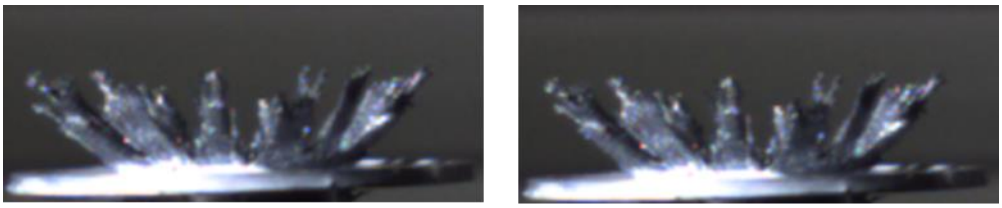
When the direction of the current changes, the most obvious characteristic of the fluctuation behavior of the magnetic cluster is the change of the fluctuation amplitude.

Therefore, we observed the state of the magnetic clusters when the magnetic clusters are in the highest and lowest positions. The measurement conditions are shown in Table 4.5. 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) were used. The rotation speed of the magnetic pole during shooting is 0. Use a high-speed camera to capture the fluctuating behavior of magnetic clusters. The shooting speed of the high speed camera is 1000 FPS.

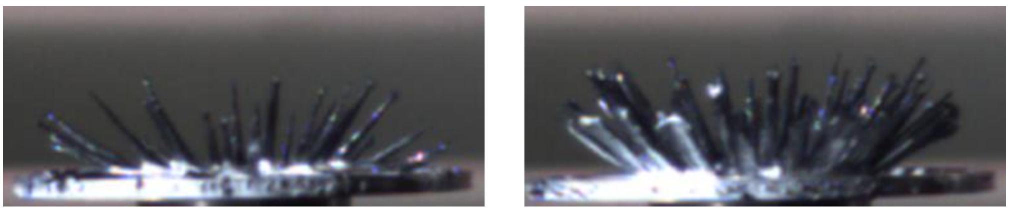
4.4.1.2 Observation results and discussion



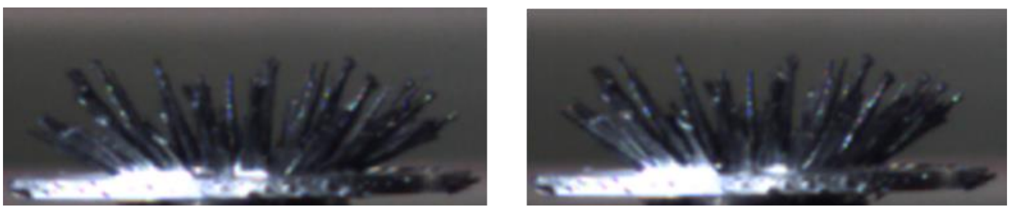
(a) A waveform, 330 μm



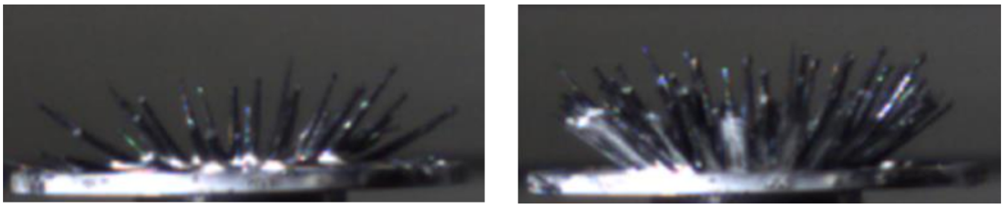
(b) D waveform, 330 μm



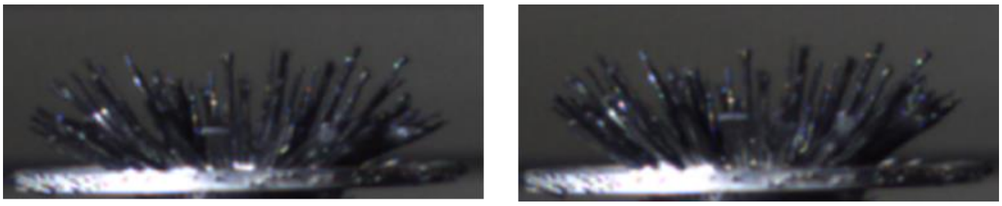
(c) A waveform, 149 μm



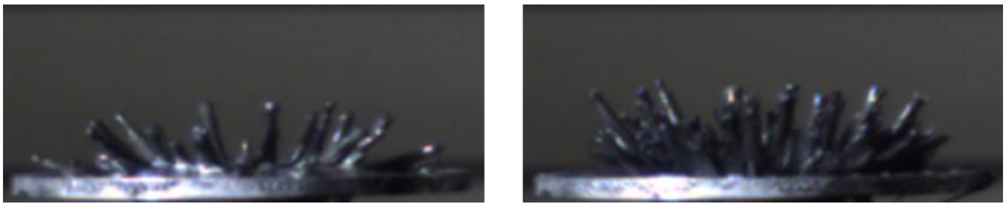
(d) D waveform, 149 μm



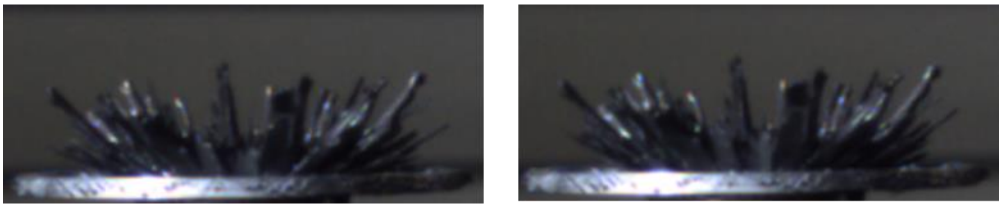
(e) A waveform, 75 μm



(f) D waveform, 75 μm



(g) A waveform, 30 μm



(h) D waveform, 30 μm

Fig. 4.26 The photographs of the magnetic cluster at the lowest and highest positions

Fig. 4.26 shows the photographs of the magnetic cluster at the lowest and highest positions in different magnetic fields. It can be seen that the magnetic clusters formed by magnetic particles of the same size have the same angle at the highest position of the two magnetic fields, while the lowest position differs greatly. In the magnetic field formed by D waveform, the angle of the lowest position is significantly larger than in the magnetic field formed by A waveform. Moreover, in the magnetic field formed by A waveform, the minimum angle of the magnetic cluster formed by the four sizes of magnetic particles can reach 0 degrees due to the change of the direction of the magnetic field. However, when the size of the magnetic particles is 330 μm, the magnetic cluster hardly fluctuates in the magnetic field formed by D waveform. This is because the size of the magnetic particles is larger, and the hysteresis effect is more obvious.

4.4.2 Experimental conditions and method

Table 4.6 Experimental conditions

Workpiece	SUS304 stainless steel plate with the size of 100 ×100 ×1 mm
Magnetic particles	Type A: Electrolytic iron powder, 30 [μm] in mean dia:1.2 [g] Type B:Electrolytic iron powder, 75 [μm] in mean dia:1.2 [g] Type C:Electrolytic iron powder, 149 [μm] in mean dia:1.2 [g] Type D:Electrolytic iron powder, 330 [μm] in mean dia:1.2 [g]
Abrasive particles	WA#8000: 0.3 [g]
Grinding fluid	Oily grinding fluid (Honilo 988): 0.8 [ml]
Rotational speed	350 [rpm]
Feed speed of mobile stage	260 [mm/min]
Working gap	1.5 [mm]
Alternating current	3 [A] (Maximum)
Magnetic field frequency	1 [Hz] (A waveform), 2 [Hz] (D waveform)
Finishing time	10 [min]×6 (60 [min])

The experimental conditions are shown in Table 4.6. SUS304 stainless steel plate is the workpiece. The power supply used in the experiment was 1 Hz alternating current. The D waveform is obtained after full-wave rectification of the power supply. This experiment compared the effects of A waveform and D waveform on processing characteristics in the case of magnetic particles with average diameters of 30 μm, 75 μm, 149 μm, and 330 μm, respectively. The total experiment time is 60 minutes, and the workpiece is cleaned and measured every 10 minutes. The surface of the workpiece is measured by the surface roughness instruments (SURFPAK-SV).

4.4.3 Experimental results and discussion

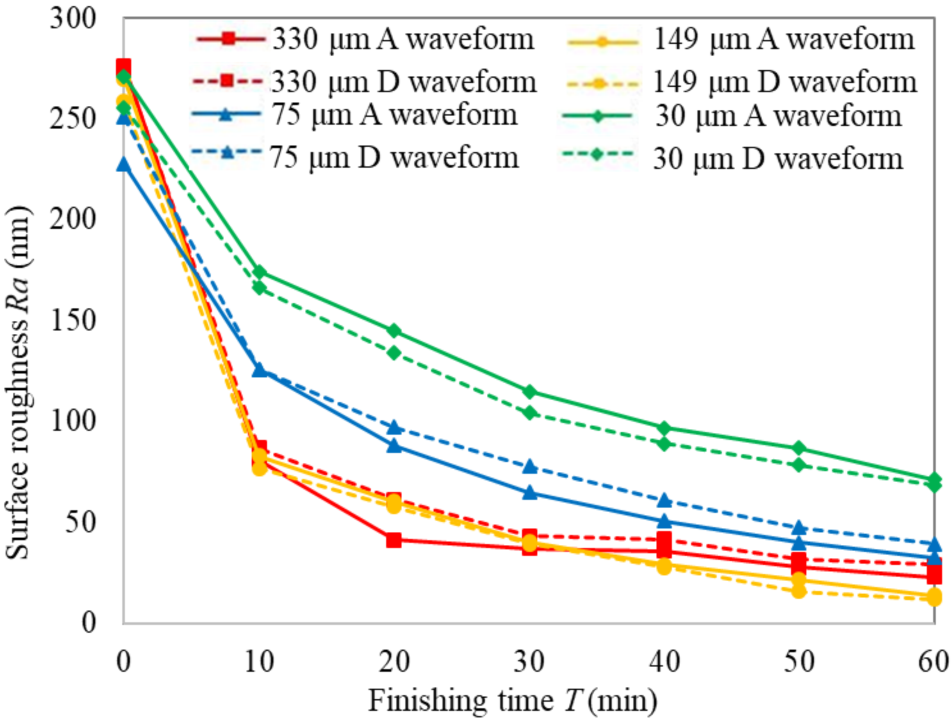


Fig. 4.27 Changes in surface roughness with finishing time

The variation of surface roughness with finishing time is shown in Figure 4.27. It can be seen that when the magnetic particles have the same size, the surface roughness is not much different after 60 minutes of finishing. For the magnetic particles of type A, due to the small finishing force, the surface roughness changes the least. After 60 minutes, the surface roughness is 71.33 nm and 68.33 nm in the case of A waveform and D waveform, respectively. The magnetic particles of type D can see a significant difference at 20 min, and in the case of A waveform, a smoother surface is obtained faster. After 30 min, both in A waveform and D waveform, the surface roughness changed only slightly, and after finishing, the surface was rougher than the magnetic particles of type C. This is because the magnetic particles of type D have a greater finishing force and create new scratches while finishing the surface. Besides, in the case of A waveform and D waveform, within 60 min, the smoothest surface was obtained when magnetic particles of type C.

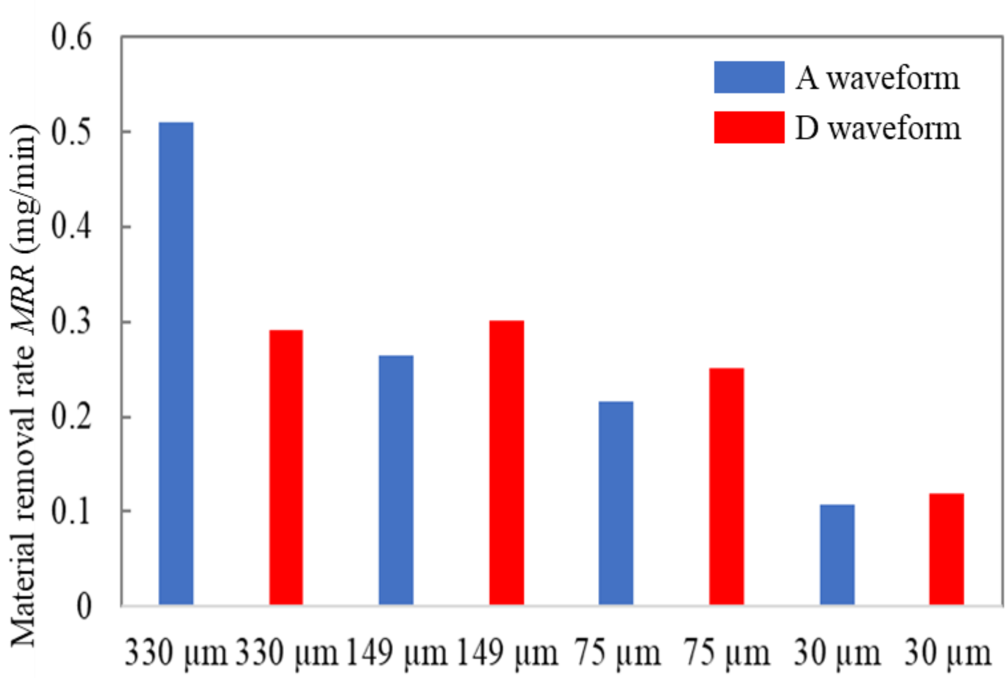
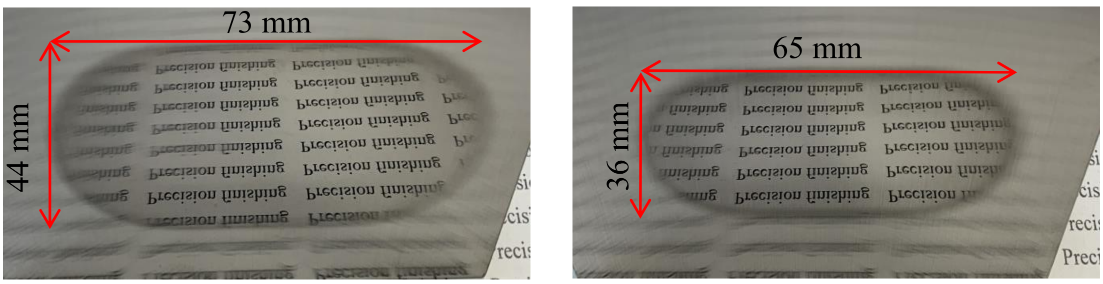


Fig. 4.28 Material removal rate

The material removal rate under different conditions is shown in Figure 4.28. The material removal rate is obtained by Eq. 4.10.

$$MRR = (M_{initial} - M_{final})/T \qquad (4.10)$$

where $M_{initial}$ is the initial weight of the workpiece, M_{final} is the weight of the workpiece after 60 minutes of finishing, and T is the finishing time. It can be seen that for the magnetic particles of type A, B and C, the material removal rate of D waveform is higher than that of A waveform. However, for D-type magnetic particles, the material removal rate of D waveform is lower than that of A waveform. This is because when the magnetic field decreases, the hysteresis effect of large magnetic particles is more significant. Therefore, when the direction of the magnetic field does not change and only the strength of the magnetic field changes periodically, the large magnetic particles are less affected by the change of the magnetic field. According to the observation, in the case of D waveform, the magnetic cluster formed by the D-type magnetic particles hardly fluctuates. Therefore, compared with the case of A waveform, the finishing range is smaller, and the update effect of the abrasive is low. The photograph of the workpiece after finishing using D-type magnetic particles is shown in Fig. 4.29. Through calculation, in the case of A waveform, the area of the finishing area is about 1.36 times that in the case of D waveform. In the case of other particle sizes, the fluctuation of the magnetic cluster is not significantly affected. Therefore, for the magnetic particles of type A, B, and C, in the case of D waveform, the abrasive can be renewed by the fluctuation of the magnetic cluster. At the same time, the average finishing force increases, resulting in higher finishing efficiency.



(a) Alternating current (A waveform) (b) Full-wave rectified current (D waveform)

Fig. 4.29 The photograph of the workpiece after finishing (330 μm)

4.5 The influence of current change mode on finishing characteristics

4.5.1 Experimental conditions and method

Based on the previous investigation, in this section, the influence of the current change mode on the finishing characteristics is investigated. Magnetic particles with an average diameter of 75 μm were used in the experiment. The experimental conditions are shown in Table 4.7.

Table 4.7 Experimental conditions

Workpiece	SUS304 stainless steel plate with the size of 100 mm×100 mm×1 mm
Magnetic particles	Electrolytic iron powder, 75 μm in mean dia:1.2 g
Abrasive particles	WA#8000: 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	1.5 mm
Current	1.9 A (Average)
Finishing time	Single 10 min (40 min)

The workpiece is SUS304 stainless steel plate. The finishing time is 40 minutes, and the workpiece is cleaned and measured every 10 minutes. The current waveform used in the experiment is shown in Fig. 4.3. In different current waveforms, the average current is 1.9 A. Except for C waveform and D waveform, the frequencies of other waveforms are all 1 Hz. The D waveform is obtained after the A waveform is full-wave rectified, so the frequency of the D waveform is 2 Hz. According to the measurement of changes in the magnetic field and finishing force, first, in order to determine the influence of the waveform shape on the finishing characteristics, the A waveform and the B waveform are compared. Secondly, it compares the influence of current direction change (A waveform and D waveform) on finishing characteristics. Finally, the most suitable current waveforms for improving finishing efficiency and surface quality were discussed.

4.5.2 Influence of current waveform shape

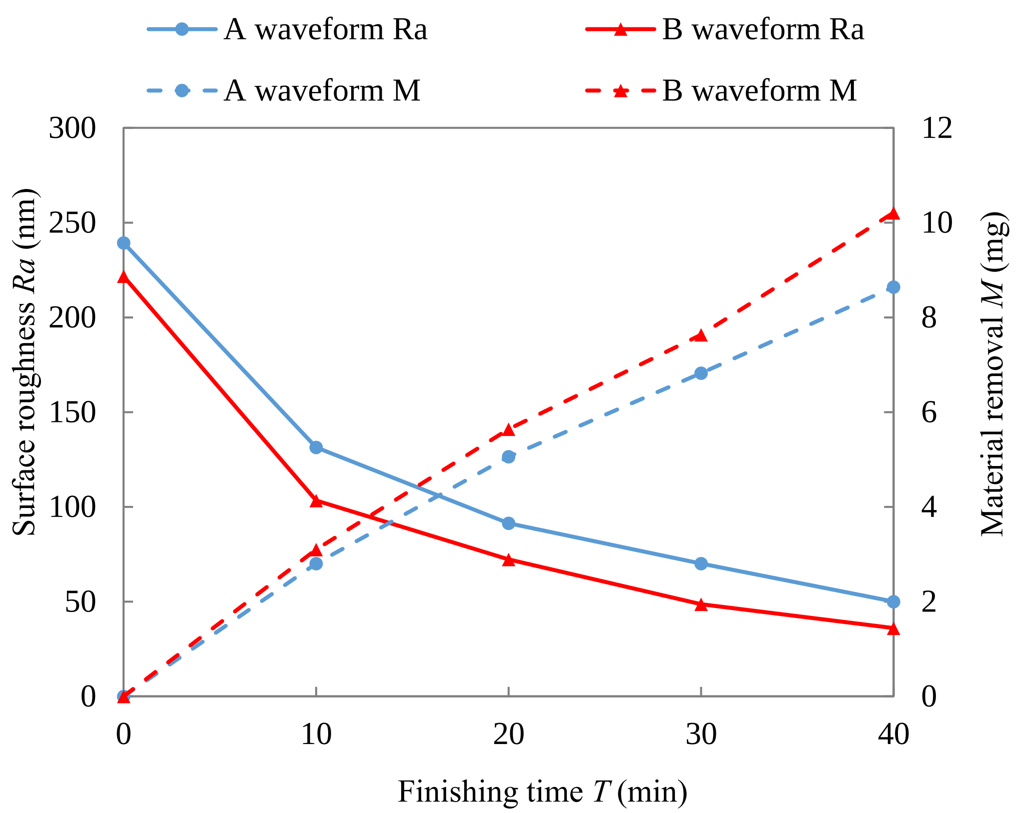


Fig. 4.30 The effect of current waveform shape on material removal and surface roughness

The experimental results are shown in Fig. 4.30. It can be seen that the amount of material removal of the B waveform is more than that of the A waveform. At the same time, better surface quality is obtained in the B waveform. Through the analysis of the magnetic field and finishing force, it can be found that the average magnetic field and average finishing force of the A waveform and the B waveform are about the same. According to the previous analysis, in the B waveform, the magnetic clusters fluctuate faster. When the magnetic particle is 75 um, in the fluctuation period, the duration of the magnetic cluster at the highest position of the A waveform is about 325 ms, and the duration of the magnetic cluster at the highest position of the B waveform is about 384 ms. Obviously, the magnetic cluster stays in the high-efficiency finishing state for a longer time in the B waveform. Therefore, a higher amount of material removal is obtained in the B waveform, and better surface quality is obtained at the same time.

4.5.3 Effect of current direction change

In order to compare the influence of the change of the current direction on the finishing characteristics, the A waveform and the D waveform were compared. The experimental results are shown in Fig. 4.31. It can be seen that the amount of material removed in the D waveform is more than that in the A waveform. This is because the average finishing force in the D waveform is higher than that in the A waveform. The surface quality obtained in the A waveform is slightly better than the D waveform. Based on the previous analysis, it is speculated that the magnetic cluster has different fluctuation amplitude between the A waveform and the D waveform, so the renewal and mixing effect of the abrasive particles is different. According to the previous observations of magnetic clusters, the fluctuation amplitude of the magnetic cluster is larger in the A waveform. This makes in the case of A waveform, the ability of the magnetic cluster to renew and mix the abrasive particles is stronger during the finishing process, and the abrasive distribution is more uniform. Therefore, the surface quality of the A waveform is slightly better than the D waveform.

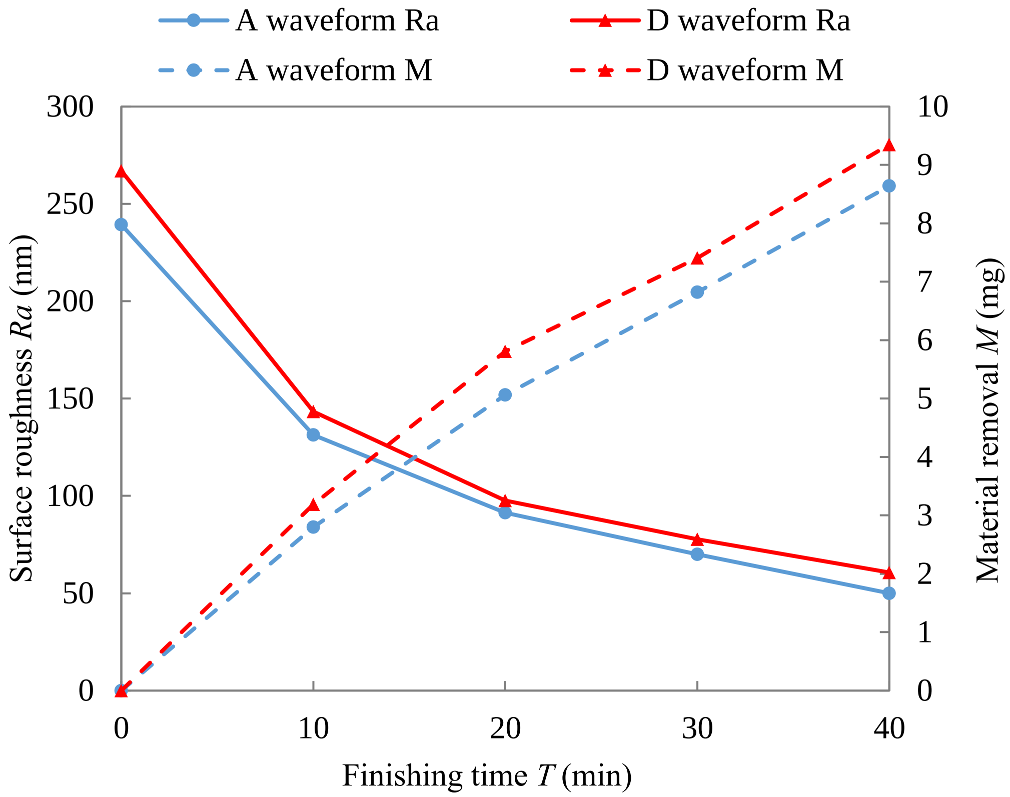


Fig. 4.31 The effect of current direction change on material removal and surface roughness

4.5.4 Explore the optimal current waveform

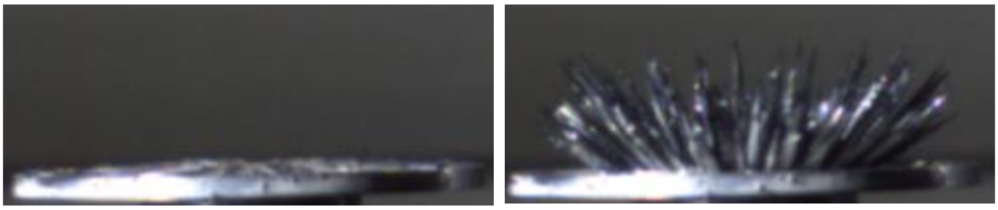
According to the results of the previous two experiments, in the case of a square wave, the magnetic cluster fluctuates up or down faster, so the finishing efficiency is higher than that of a sine wave. At the same time, when the current direction does not change, a higher average finishing force can be obtained, but due to the reduction of the fluctuation range of the magnetic cluster, the renewal and mixing effect of abrasive particles is reduced. Therefore, the experiment uses pulse waveforms to obtain faster magnetic cluster fluctuation speed and higher average finishing force. At the same time, by changing the duty cycle to explore more suitable magnetic cluster fluctuations to further improve the finishing efficiency and surface quality.

4.5.4.1 Observation of magnetic cluster behavior

In the pulse waveform, when the current becomes zero, the magnetic cluster will fluctuate downward, and when the current becomes the maximum, the magnetic cluster will fluctuate upward. The time when the current is zero (T_{off}) will affect the fluctuation range of the magnetic cluster. Therefore, we observed the difference in the fluctuation range of magnetic clusters at different duty cycles. The measurement conditions are shown in Table 4.8. The observation method is the same as before, and the fluctuation behavior of magnetic clusters is captured by a high-speed camera. 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) were used. The rotation speed of the magnetic pole during shooting is 0.

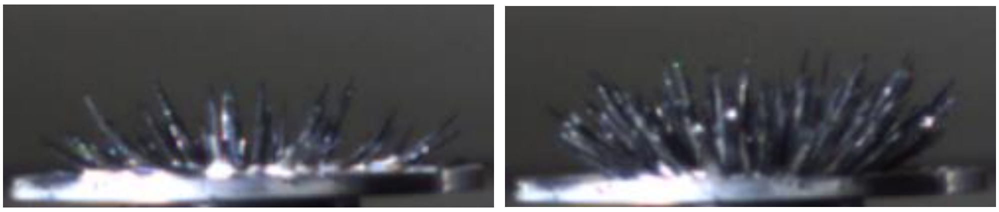
Table 4.8 Measurement conditions

Magnetic particles	Electrolytic iron powder, 75 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
Current waveform	E waveform, F waveform, G waveform, H waveform
Alternating current	1.9 A (Average)
Magnetic field frequency	1 Hz



(1) The lowest position (2) The highest position

(a) E waveform

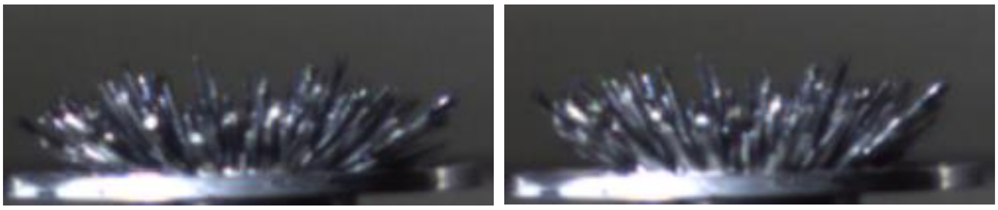


(1) The lowest position (2) The highest position

(b) F waveform

(1) The lowest position (2) The highest position

(c) G waveform



(1) The lowest position (2) The highest position

(d) H waveform

Fig. 4.32 The photographs of the magnetic cluster at the lowest and highest positions

As shown in Figure 4.32, it is the highest position and the lowest position in the magnetic cluster change cycle. It can be seen that in the case of four waveforms, the magnetic cluster is basically the same at the highest position, but is significantly different at the lowest position. As the duty cycle decreases, the amplitude of magnetic cluster fluctuations gradually becomes larger. In the case of the E waveform, the magnetic cluster completely falls back to the tray when it is in the lowest position.

4.5.4.2 Experimental results and discussion

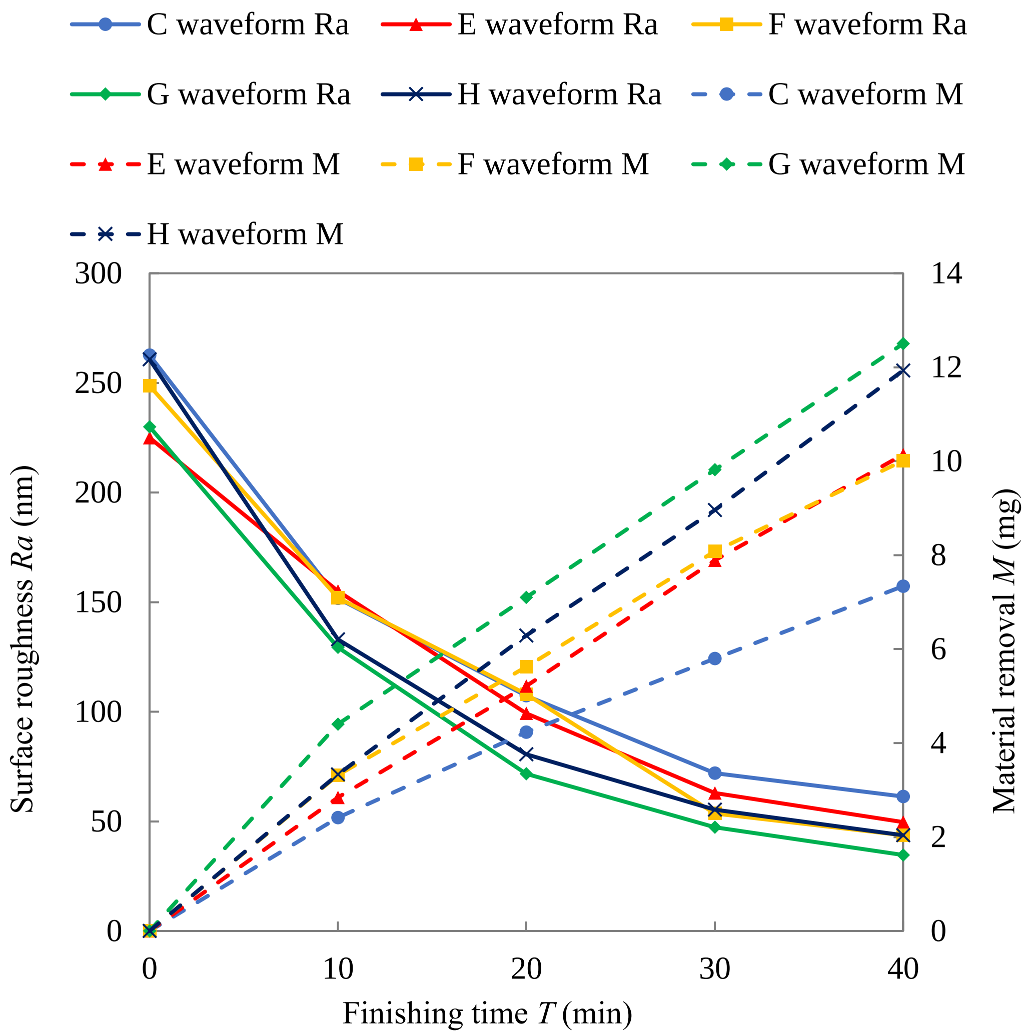
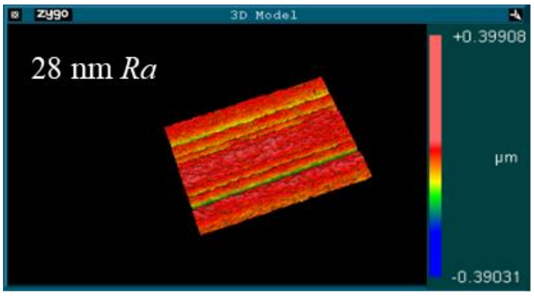


Fig. 4.33 The effect of pulse current on material removal and surface roughness

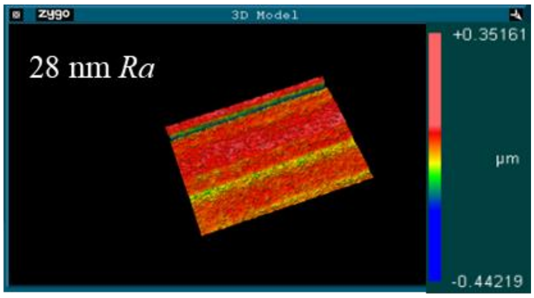
The experimental results are shown in Fig. 4.33. It can be found that in the case of the C waveform, after finishing, the amount of material removal is the lowest and the surface quality is the worst compared to other waveforms. This is because, during the finishing process, the abrasive particles are worn and the abrasive particles are pressed into the magnetic cluster, which causes the abrasive particles in contact with the workpiece to gradually become smaller and reduced. In the case of the C waveform, the magnetic cluster will not fluctuate, so it is difficult to update the abrasive particles in contact with the workpiece, resulting in low finishing efficiency and poor surface quality.

In the case of other waveforms, the magnetic cluster will fluctuate as the current changes. When the current becomes zero, the magnetic cluster will fluctuate downward, and when the current becomes the maximum, the magnetic cluster will fluctuate upward. The time when the current is zero will affect the fluctuation range of the magnetic cluster. As shown in Figure 4.33, it is the highest position and the lowest position in the magnetic cluster change cycle. It can be seen that in the case of four waveforms, the magnetic cluster is basically the same at the highest position, but is significantly different at the lowest position. As the duty cycle decreases, the amplitude of magnetic cluster fluctuations gradually becomes larger. In the case of the E waveform, the magnetic cluster completely falls back to the tray when it is in the lowest position. In addition, according to the previous analysis of the finishing force, as the duty cycle increases, the average finishing force increases.

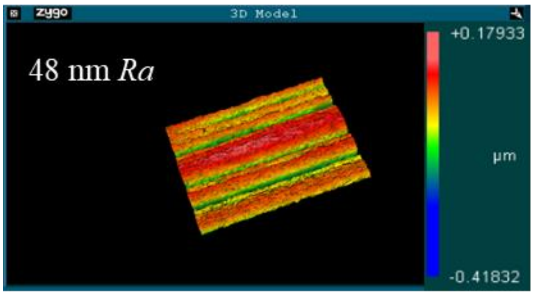
According to Fig. 4.33, the amount of material removal in the G and H waveforms is similar and higher than other waveforms. However, in the case of the G waveform, the surface quality is the best. Therefore, according to the experimental results, in the case of G waveform (duty ratio of 80%), magnetic cluster fluctuation is more suitable for improving finishing efficiency and surface quality.



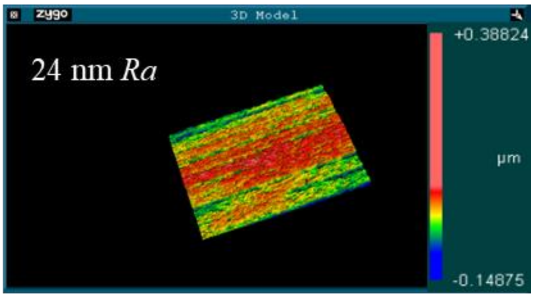
(1) A waveform



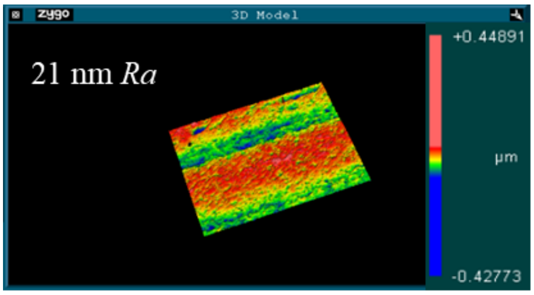
(2) B waveform



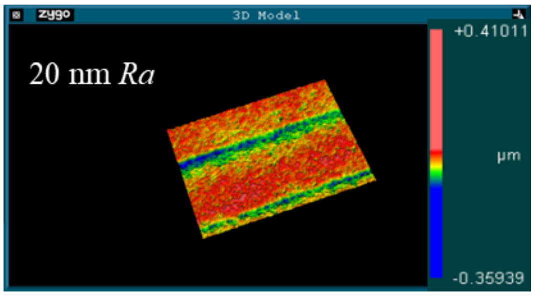
(3) C waveform



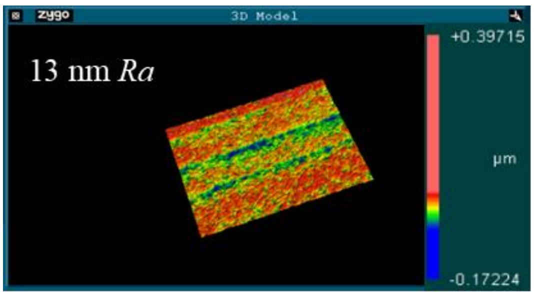
(4) D waveform



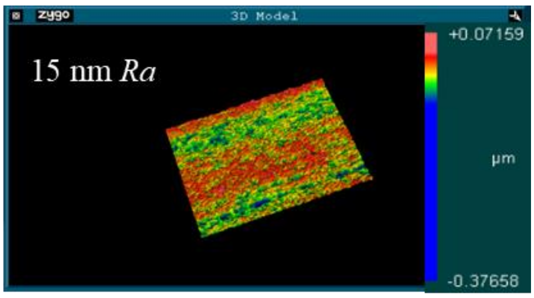
(5) E waveform



(6) F waveform



(7) G waveform



(8) H waveform

Fig. 4.34 3D photo of workpiece surface after finishing

Figure 4.34 is a 3D photo of the surface of the workpiece after finishing under 8 current waveforms obtained by Zygo NewView7300. It can be seen that in the G and H waveforms, the surface quality of the finished workpiece is better than the other 6 waveforms. In the G waveform, the surface roughness is slightly better than the H waveform. Therefore, under the current experimental conditions, the G waveform (duty ratio of 80%) is more suitable for improving finishing efficiency and surface quality.

4.6 Conclusions

This chapter discusses the influence of current waveform on finishing characteristics. The behavior characteristics of magnetic cluster at different current waveforms are observed and analyzed. The main conclusions are summarized as follows:

1. In a static magnetic field, the direction of the magnetic flux density changes with the current direction, and when the absolute value of the current is the same, the absolute value of the magnetic flux density is basically the same. In addition, the increase rate of the magnetic flux density decreases with the increase of the current.
2. When the direction of the magnetic field changes and the average current is 1.9A, the average magnetic flux density of the sine wave and the square wave is basically the same. By comparing the sine waveform with the sine waveform of the full-wave rectification, it can be concluded that the magnetic flux density will be increased to a certain extent when the direction of the magnetic field remains unchanged. In the pulse waveform, the average value of the magnetic flux density is higher than the average value of the static magnetic field. As the duty cycle increases, the gain rate relative to the static magnetic field gradually decreases.
3. In a static magnetic field, the finishing force increases with the increase of the absolute value of the current. When the absolute value of the current is between 0.9A and 4A, the increase rate of the finishing force decreases with the increase of

the absolute value of the current. In addition, when the absolute value of the current is between 0.9A and 4A, the relationship between the magnetic flux density and the finishing force is approximately linear.

4. When the average current is 1.9A and the current frequency is 1Hz, the maximum finishing force of the sinusoidal waveform is higher than that of the square wave, but the average finishing force is basically the same. When the direction of the current changes, the finishing force is weakened to a certain extent, so the average value of the finishing force is lower than when the current direction does not change. When the pulse current and the average current are the same, the average value of the finishing force increases as the duty cycle increases. When the duty cycle is 90%, the average finishing force is slightly larger than the static magnetic field.
5. When using a square wave, a higher magnetic cluster fluctuation speed can be obtained, and as the size of the MPs decreases, the difference between the magnetic cluster fluctuation speed of the two waveforms is greater.
6. When the current direction changes, the finishing efficiency is improved when the current waveform is a square wave. When the waveform of the alternating current is a square wave, as the size of the MPs increases and the frequency of the magnetic field decreases, the finishing efficiency increases. At the same time, when the APs are WA#8000, the finishing efficiency is higher. In addition, the increase in the rotation speed of the magnetic pole significantly improves the finishing efficiency.
7. In the case of D waveform, the fluctuation of the magnetic cluster decreases. When the average diameter of the magnetic particles is 30 μm, 75 μm and 149 μm, the fluctuation of the magnetic clusters can be maintained. However, when the average diameter of the magnetic particles is 330 μm, the magnetic clusters hardly fluctuate.
8. According to the experimental results, when the average diameter of the magnetic particles is 30 μm, 75 μm and 149 μm, higher finishing efficiency can be obtained

in the case of D waveform. However, when the average diameter of the magnetic particles is 330 μm, the finishing efficiency decreases.

9. When the current waveform is a pulse waveform, the fluctuation amplitude of the magnetic cluster decreases with the increase of the duty cycle. When the average diameter of the magnetic particles is 75 μm, using a pulse current with a duty cycle of 80% can achieve higher finishing efficiency.

References

1. Shinmura T, Aizawa T (1989) Study on internal finishing of non-ferromagnetic tubing by magnetic abrasive machining process. Bull. Jpn. Soc. Precis. Eng. 23(1), 37–41.
2. Zou Y, Xie H, Dong C, Wu J (2018) Study on complex micro surface finishing of alumina ceramic by the magnetic abrasive finishing process using alternating magnetic field. Int. J. Adv. Manuf. Technol. 97(5-8), 2193-2202.
3. Xie H, Zou Y, Dong C, Wu J (2019) Study on the magnetic abrasive finishing process using alternating magnetic field: investigation of mechanism and applied to aluminum alloy plate. Int. J. Adv. Manuf. Technol.102, 1509–1520.
4. Jain VK (2009) Magnetic field assisted abrasive based micro-/nano-finishing. J. Mater. Process. Technol. 209(20), 6022-6038.
5. Cheng K (2002) Abrasive micromachining and microgrinding. In Micromachining of engineering material, McGeough J.; CRC Press: Dekker, New York, pp. 85–123

Chapter V Application of MAF process using an alternating magnetic field

5.1 Introduction

With the development of high-tech industries such as optics, molds, semiconductors, and medical equipment, higher surface finish of parts is required. But for micro-complex surface finishing, conventional polishing tools are difficult to achieve. The magnetic abrasive finishing (MAF) process is a surface finishing process that uses a flexible magnetic brush formed by fine magnetic particles as a polishing tool [1-5]. Therefore, this is considered to be a possible process for finishing complex surfaces. Guo et al. [6] discussed the magnetic field-assisted finishing method for surface finishing of mold insert for injection molding of microfluidic chips. They showed that although the edges became rounded after polishing, the surface roughness was reduced to about 0.11 μm Ra while still maintaining the height of the microstructure. Kim et al. [7] developed an experimental device to apply the MAF process to the finishing of free-form surfaces. They proved that the effective polishing of curved surfaces can be achieved using the two-stage MAF method, and also confirmed that automatic polishing of free-form surfaces can be achieved by this method. Yin et al. [8, 9] improved the deburring efficiency of edges by using the vibration-assisted MAF process. They proposed a method for polishing 3D micro-curved surfaces using vibration-assisted MAF technology, and studied the effects of three vibration modes (horizontal vibration, vertical vibration, and compound vibration) on magnetic field, polishing pressure, abrasive behavior, and polishing performance. Lin et al. [10] polished the free-form surface through the MAF process. The Taguchi experimental design was used to investigate the effects of magnetic field, spindle speed, feed speed, working gap, abrasives and lubricants. After two-stage finishing, the surface roughness Rmax is improved from 2.670 μm to 0.102 μm. Guo et al. [11] proposed a localized vibration-assisted magnetic abrasive polishing (VAMAP) method for the finishing of V-grooves and Fresnel optical elements. They showed that this method can improve the surface roughness of the workpiece from an initial value of more than 10 nm Ra to about 7 nm Ra while the microfeatures of V-groove and Fresnel optics were well maintained. Wang et al. [12] studied the feasibility of using magnetic compound fluid (MCF) slurry to finish linear V-shaped grooves. They proved that the method can effectively improve the surface quality of the V-groove and evaluated the form accuracy. However, when performing complex surface finishing, the change in the gap between the magnetic pole and the workpiece causes a change in the shape of the magnetic brush. In a static magnetic field, the shape of the magnetic brush is difficult to restore, which hinders the finishing of complex surfaces to a certain extent. In order to overcome this problem, we proposed a MAF process that uses an alternating magnetic field. In an alternating magnetic field, the periodic changes of the current will cause the magnetic cluster to fluctuate up and down, which can not only continuously mix and update the abrasive, but also periodically adjust the shape of the magnetic cluster to better fit the surface of the workpiece [13-15].

5.2 Alumina ceramic

5.2.1 Experimental conditions and method

The experimental conditions are shown in Table. 5.1. 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 stainless steel, so 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, 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).

Table. 5.1 Experimental conditions

Workpiece	Alumina ceramic plate 100 mm×100 mm×2.5 mm
Magnetic particles	Electrolytic iron powder, 330 μm in mean dia:1.2 g
Abrasive	Diamond powder,0-1.5 μm in mean dia: 0.3 g Diamond powder,2-3 μm in mean dia: 0.3 g Diamond powder,4-8 μm in mean dia: 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)
Finishing time	20×4 min (80 min)

5.2.2 Experimental results and discussion

Fig. 5.1 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 the 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 nm

Ra, 88.3 nm *Ra*, and 168.6 nm *Ra* for 0–1.5 μm, 2–3 μm, and 4–8 μm diamond powder, respectively. Fig. 5.2 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 size is 0-1.5 μm, the text reflects the most clear, 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 a most smooth surface. To further study this mechanism, the surface was examined using optical surface profiler (NewView 7300).

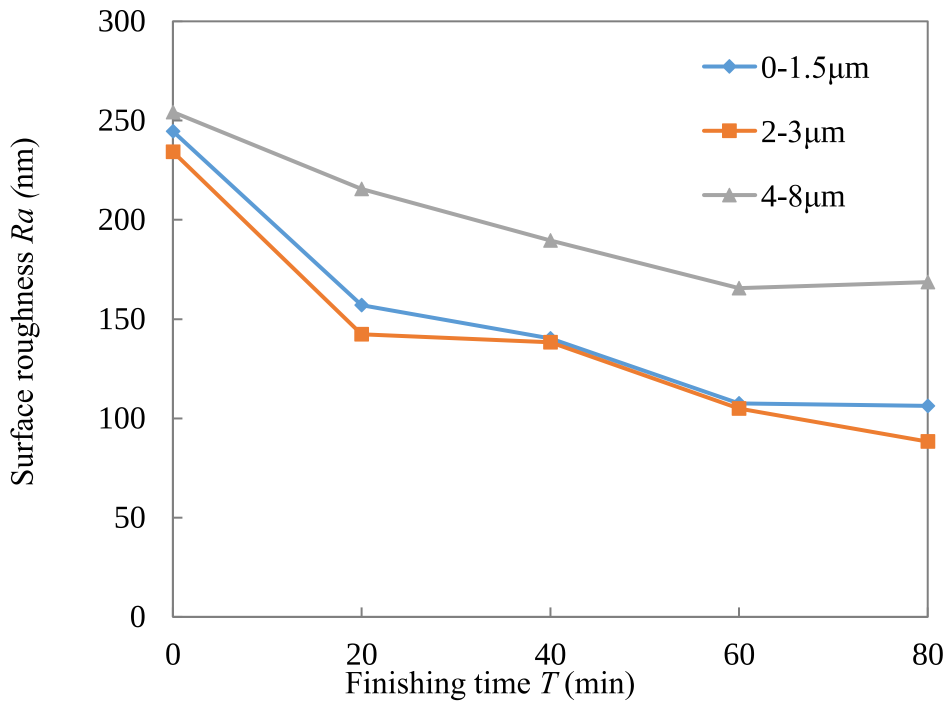


Fig. 5.1. Effects of size of diamond powder on surface roughness

(a) Diamond powder of 0-1.5 μm

(b) Diamond powder of 2-3 μm

(c) Diamond powder of 4-8 μm

Fig. 5.2. Photographs of finishing surface

We randomly take three points on the initial workpiece surface for measurement and compare the measurement results, take the median point as the initial surface measurement point. Fig. 5.3 shows the observation points after the finishing process. According to observe, in the direction perpendicular to the feed movement of the magnetic pole, the finishing effect from the center of the finishing area to both sides of the finishing area is gradually improved. This is because the peak value of magnetic flux density decreases gradually from the outer diameter of magnetic pole to the center of pole, and produced a maximum value at the pole edge. Therefore, on the edge of magnetic pole the workpiece should suffer the most powerful force and the distribution of magnetic particles is the most intensive. Dense magnetic particles are more conducive to the improvement of surface quality. Consequently, the surface finish is better at the edge of the pole than at the center of the pole. Thus, point *A* is selected as the observation point of the central area, and point *B* is selected as the observation point of the edge area.

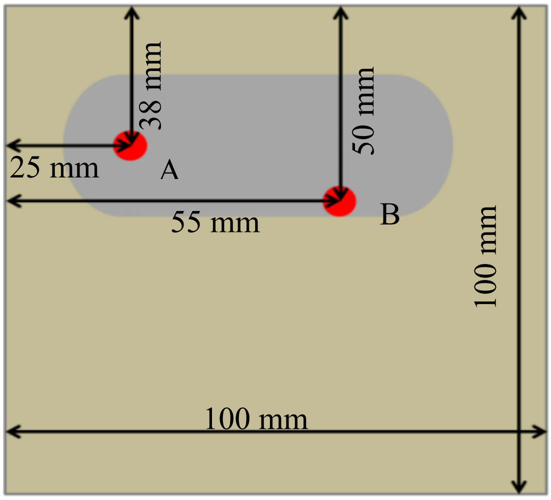
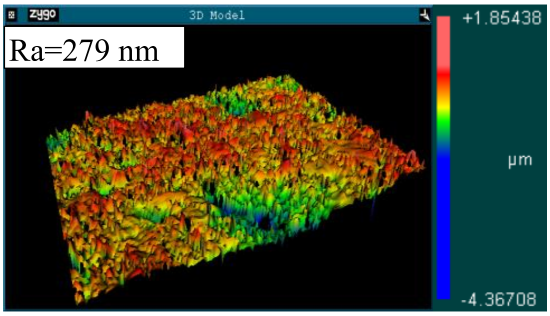
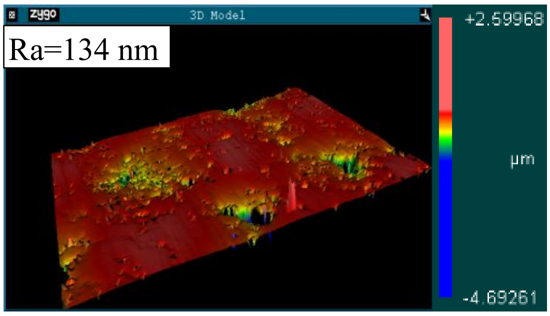


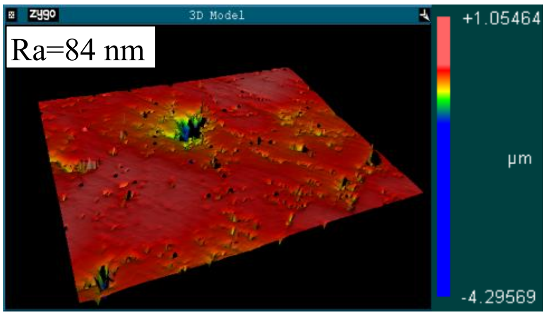
Fig. 5.3. Examine points

Fig. 5.4 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* are improved greatest when the diamond abrasive size is 1-1.5 μm compared with the other two cases. In the case of diamond abrasive size is 2-4 μm, the point *A* surface smoothness is only slightly improved. In the case of diamond abrasive size is 0-1.5 μm, the surface roughness of point *A* and point *B* are 134 nm *Ra* and 84 nm *Ra* respectively, and in the case of diamond abrasive size is 2-3 μm, the surface roughness of point *A* and point *B* are 173 nm *Ra* and 127 nm *Ra*. So when the diamond abrasive diameter is 1-1.5 μm, get the best finishing effect.



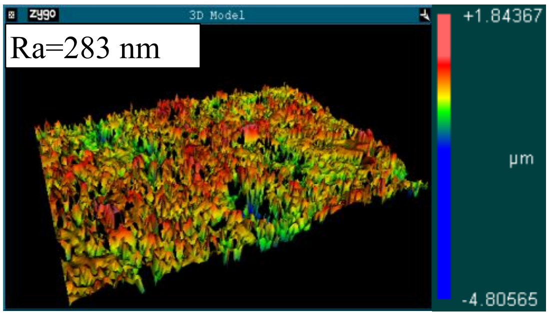
Before finishing × 50



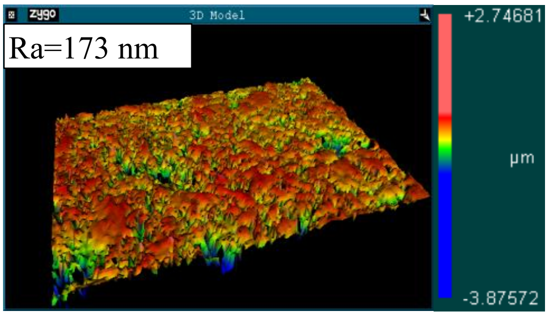


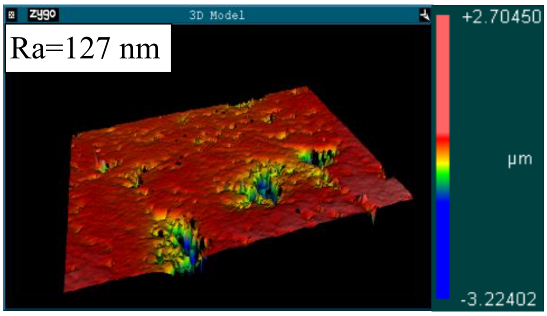
After finishing A　　After finishing B

(1) Diamond powder of 0-1.5 µm



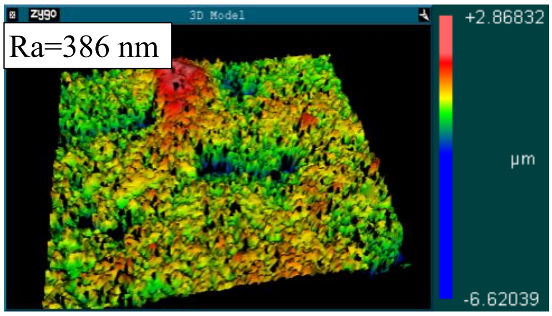
Before finishing



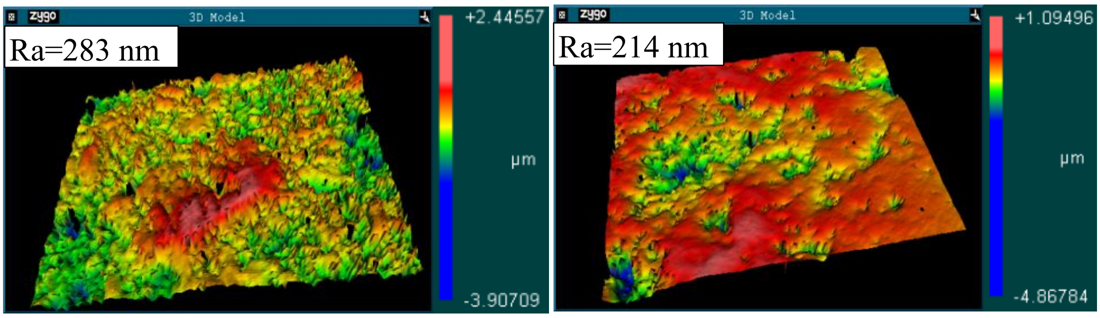


After finishing A　　After finishing B

(2) Diamond powder of 2-3 µm



Before finishing



After finishing A　　　　After finishing B

(3) Diamond powder of 4-8 µm

Fig. 5.4. Surface image of before and after finishing with the different sizes of diamond abrasives

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 is 0-1.5 µm, the workpiece surface roughness improved the highest.

5.3 Finishing the miniature groove

5.3.1 Processing principle and experimental device

Figure 5.5 shows the processing principle. The magnetic particles, abrasive particles, and the grinding fluid are uniformly mixed in a certain proportion to form magnetic compound fluid. Place the magnetic compound fluid in the tray. The magnetic particles in the magnetic compound fluid are attracted by the magnetic pole to form the magnetic cluster and carry abrasive particles to press the workpiece. The coil is supplied with alternating current to generate an alternating magnetic field. A permanent magnet is placed above the axis of the pole I. When the current supplied to the coil changes, the magnetic field in the finishing area changes accordingly. Furthermore, the magnetic cluster will periodically fluctuate, which helps the shape of the magnetic cluster to recover after contacting the surface of the workpiece. In addition, the pole I can perform rotational movement and feed movement. At the same time, pole II can feed motion at the same speed as pole I, so as to keep it above the axis of pole I. The relative movement between the magnetic cluster and the workpiece can be realized by the movement of the magnetic poles, thereby realizing surface finishing.

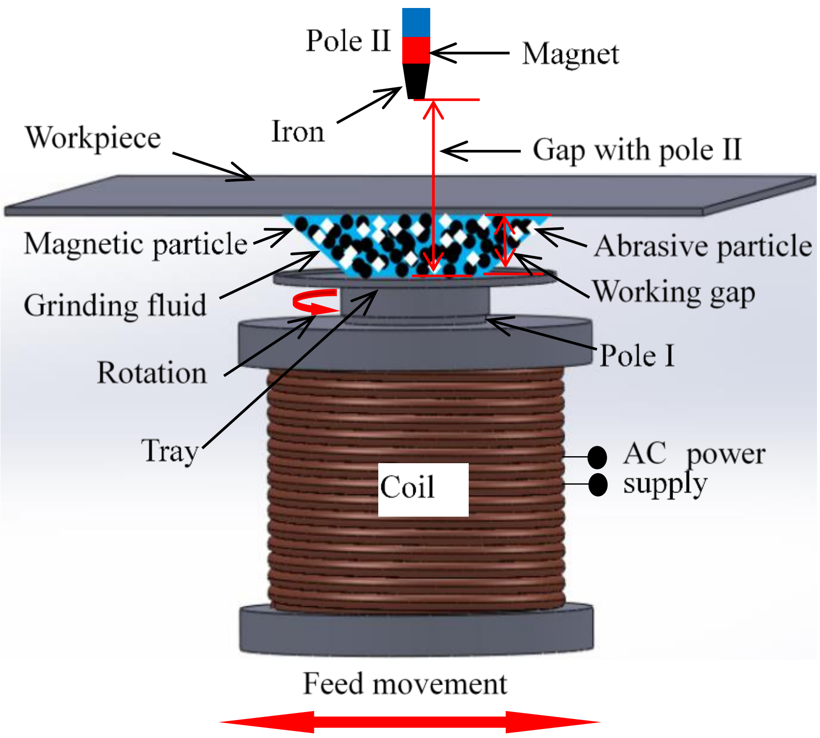


Fig. 5.5 Schematic of processing principle

Figure 5.6 shows the appearance of the experimental device. The pole I can be driven by motor II to rotate. At the same time, the pole I, the coil, and the pole II are all fixed on the mobile stage and driven by motor I for feeding motion. The speed control system can adjust the speed of the motors according to the needs of the experiment. The magnetic particles, abrasive particles, and grinding fluid are uniformly mixed in a certain proportion and placed in the tray. Magnetic particles are attracted by the magnetic poles to form magnetic cluster and move with the magnetic poles. This causes the magnetic cluster to move relative to the surface of the workpiece, thereby realizing the finishing of the workpiece.

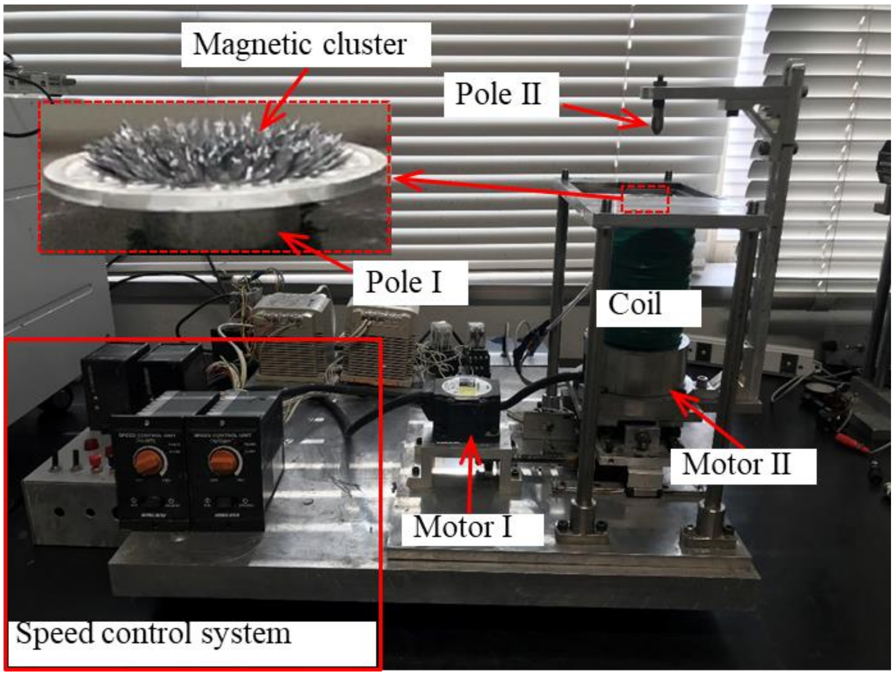


Fig. 5.6 The appearance of the experimental device

The pole II is shown in Fig. 5.7, which consists of a cylindrical magnet and an iron pole. The length of the magnet is 10 mm and the diameter is 10 mm. The total length of the iron pole is 13 mm, the diameter of the connecting surface with the magnet is 10 mm, and the diameter of the other surface is 4 mm. The length of the cylindrical part is 8 mm.

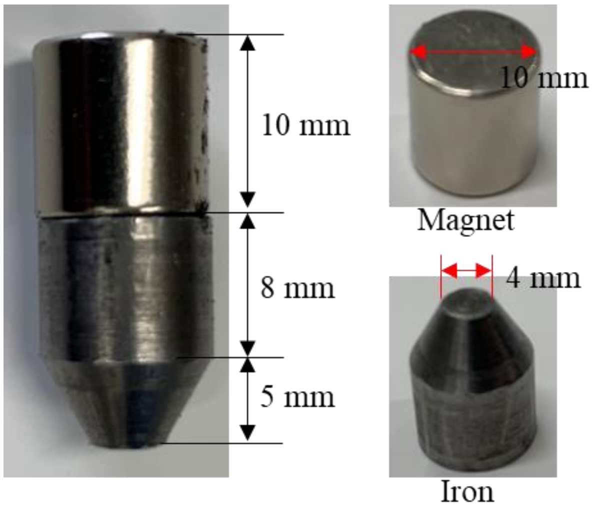


Fig. 5.7 The upper magnetic pole (Pole II)

5.3.2 Magnetic field analysis

In order to analyze the change of the magnetic field in the finishing area, when the alternating magnetic field and the static magnetic field are used simultaneously. The model was constructed using Magnet7 software, and the magnetic field in the finishing area was simulated. The simulation model is shown in Fig. 5.8. The coil, pole I, and pole II are all the same as the actual size. The number of coil turns is 2000. The gap between the pole I and the pole II is 12 mm. The mesh size is 1 mm. The simulation analysis assumes that the magnetic field changes synchronously with the current and ignores the hysteresis effect. Therefore, the alternating magnetic field analysis is replaced by multiple static simulation analyses with different directions and current values. As shown in Fig. 5.9, the current value is set and simulated every 0.1 s.

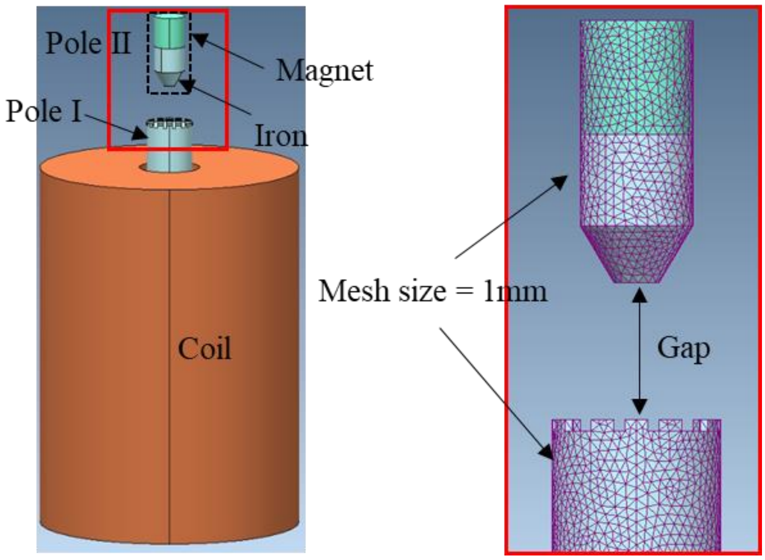


Fig. 5.8 Simulation model

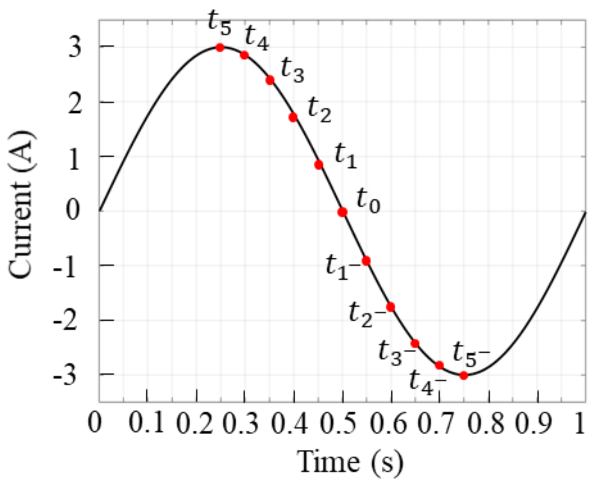


Fig. 5.9 Relationship between sampling point and current

The simulation result is shown in Fig. 5.10. It can be seen from the figure that as the current supplied to the coil changes, the magnetic field of the finishing area changes simultaneously. During the period from t_5 to t_0, the magnetization directions of the two magnetic poles are the same, and as the current increases, the magnetic flux density between the two magnetic poles gradually increases. During the period from t_0 to t_{5^-}, the direction of the current changes, and the direction of the magnetic flux density near the lower magnetic pole area changes. Since the magnetization directions of the two magnetic poles are opposite, the magnetic field between the two magnetic poles is weak compared to the case of the same magnetization direction (t_5 to t_0).

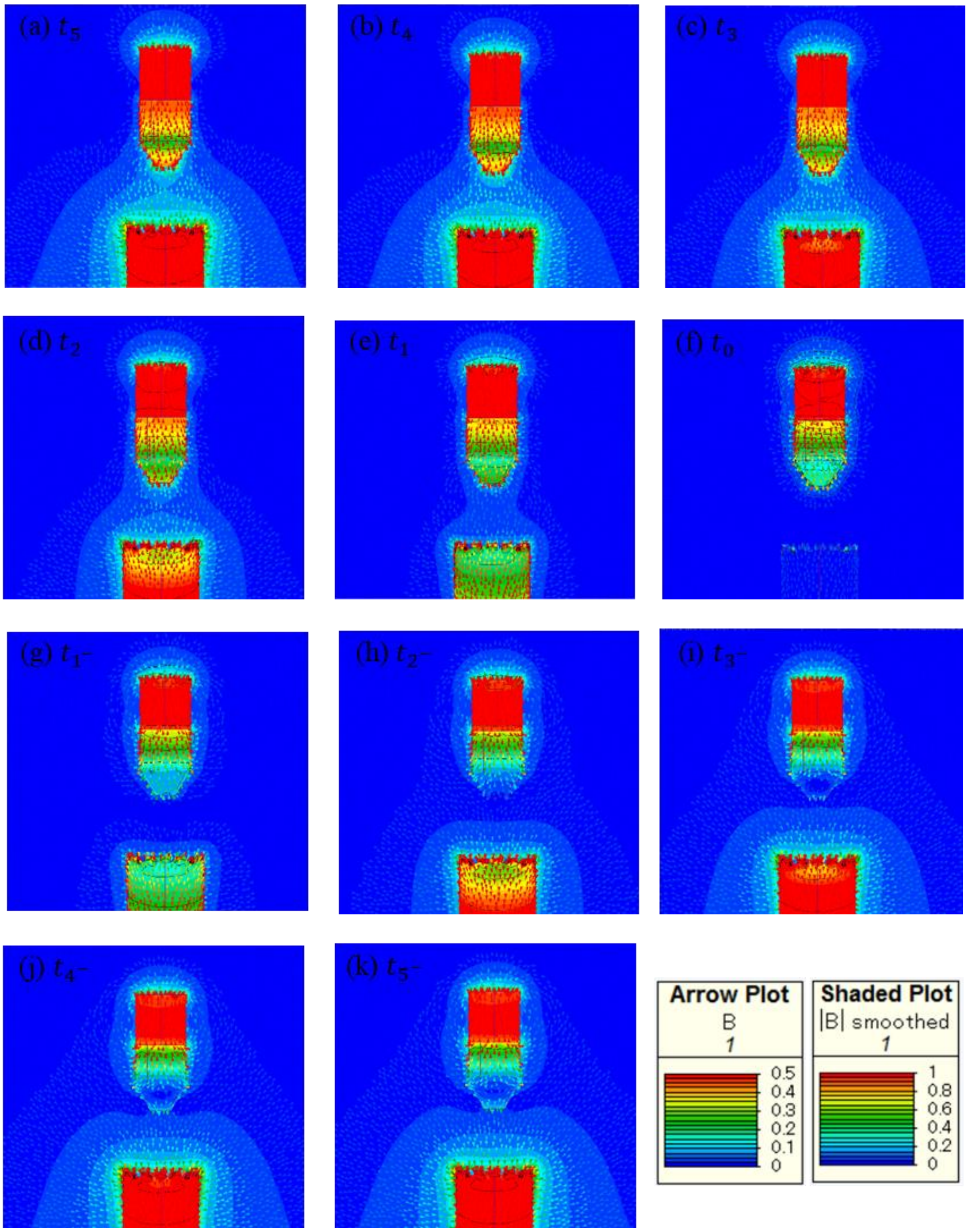


Fig. 5.10 Simulation result

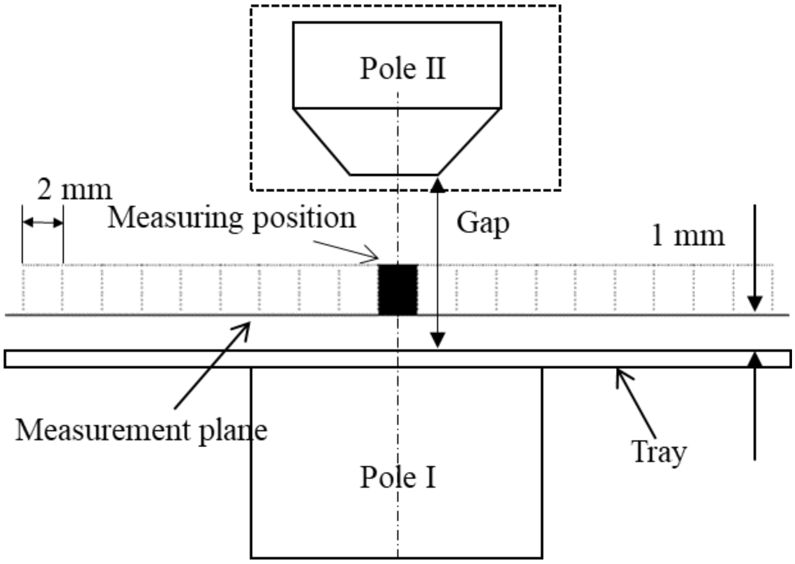


Fig. 5.11 Measuring position

In order to understand the influence of the combination of alternating magnetic field and static magnetic field on the magnetic field distribution in the finishing area, we measured the magnetic flux density distribution in the processing area. In this study, we use AC power with a peak current of 3 A and an average value of 1.9 A. We measured the maximum and minimum magnetic flux density at different positions when the current frequency was 1 Hz. The measuring position is shown in Fig. 5.11. The measuring instrument is manufactured by EMIC, the model is T-401. Take the center of the magnetic pole as the origin, and measure the magnetic flux density every 2 mm from the center to both sides. The measuring plane is parallel to the tray and the distance is 1 mm. The magnetic flux density distribution of the case with and without permanent magnet pole (pole II) was measured respectively. When using permanent magnet pole, the gap between the two poles is 12 mm.

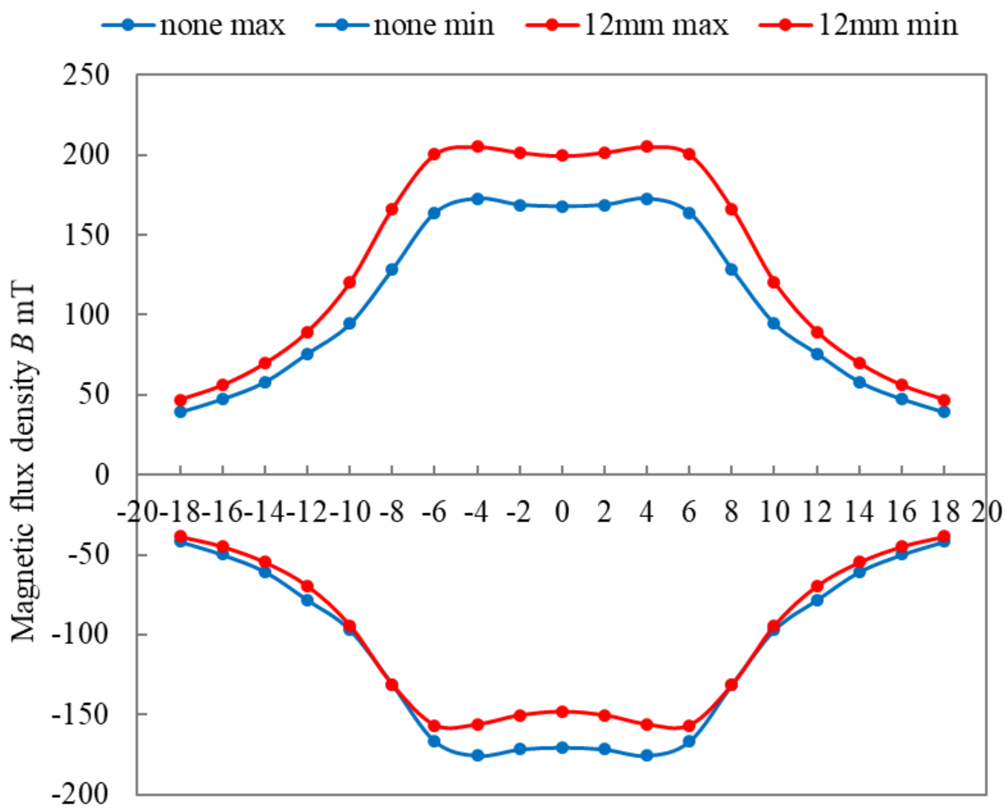


Fig. 5.12 Measurement result

The measurement result is shown in Figure 5.12. According to the measurement result, the magnetic flux density obtains the maximum value near the edge of the pole I in both cases. The magnetic flux density in the measurement plane is enhanced when the magnetization direction is the same (ie, N-S), and weakened when the magnetization direction is opposite (ie, N-N). However, the average magnetic flux density in one cycle is enhanced.

5.3.3 Experimental conditions and methods

The experimental conditions are shown in Table 5.2. The workpiece is SUS304 stainless steel plate. The workpiece is distributed with three grooves with a width of 1 mm and a depth of 0.3 mm. As shown in Fig. 5.13, the 2# groove is located in the center of the finishing area, and the 1# groove is close to the edge of the finishing area, and the distance from the 2# groove is 10 mm. The distance between 3# groove and 2# groove is 5 mm. The magnetic compound fluid is composed of magnetic particles with an average diameter of 149 µm, WA#8000 abrasive particles, and oily abrasive fluid. The working gap during finishing is 1 mm, and the gap between the lower magnetic pole and the upper magnetic pole is 12 mm. The current frequency is 1 Hz. The total finishing time is 40 minutes, and the workpiece is measured every 10 minutes.

Table 5.2 Experimental conditions

Workpiece	SUS304 stainless steel plate with the size of 100 mm×100 mm×1 mm With grooves (depth 0.3mm, width 1mm)
Magnetic particles	Electrolytic iron powder, 149 µm in mean dia:1.2 g
Abrasive particles	WA#8000: 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
Gap with iron	12mm
Alternating current	1.9 A (Average)
Magnetic field frequency	1 Hz
Finishing time	40 min (single 10 min)

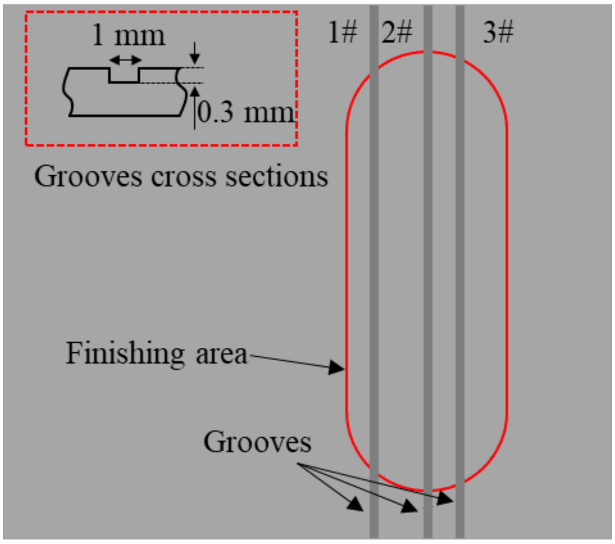


Fig. 5.13 Groove position

5.3.4 Experimental results and discussion

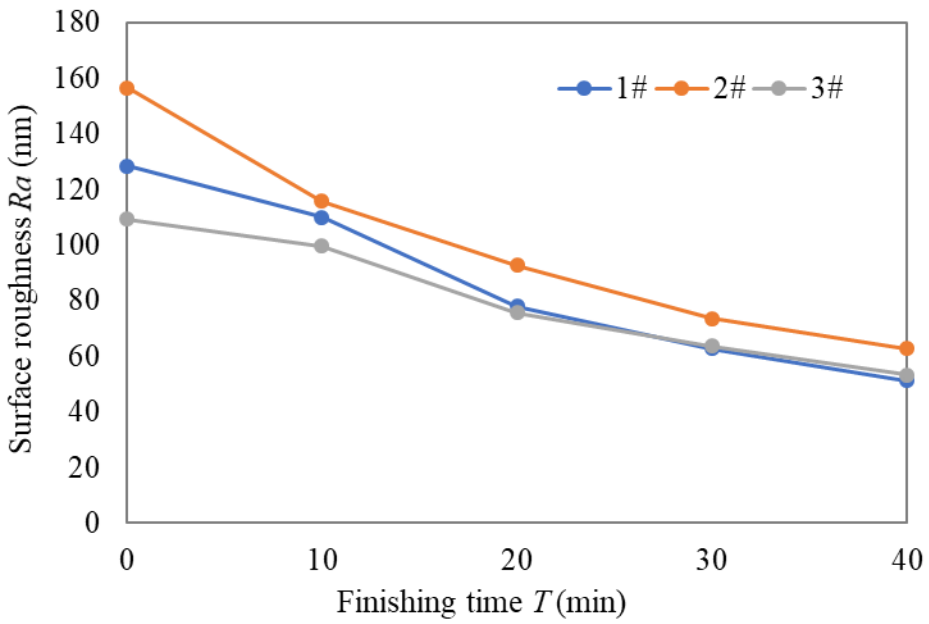
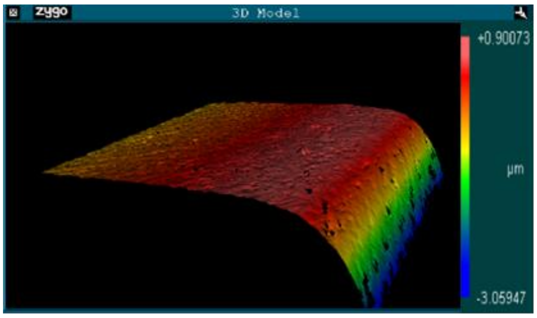


Fig. 5.14 The surface roughness of the groove bottom changes with time

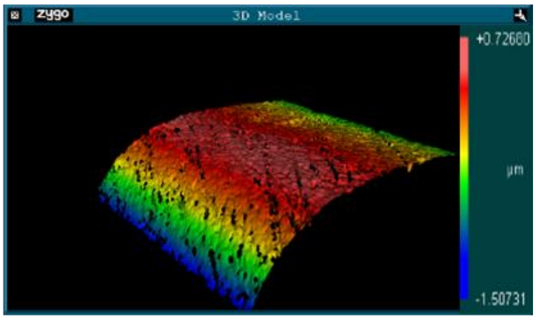
The experimental results are shown in Figure 5.14. It can be seen that the surface roughness of the bottom of the three grooves has been improved. The surface roughness *Ra* of groove 1# is improved from 128.33 nm to 51.33 nm. The surface roughness *Ra* of groove 2# is improved from 156.67 nm to 62.67 nm. The surface roughness *Ra* of groove 3# is improved from 109.33 nm to 53.33 nm.

Fig. 5.15 Photos of the bottom and edges of the groove before and after finishing

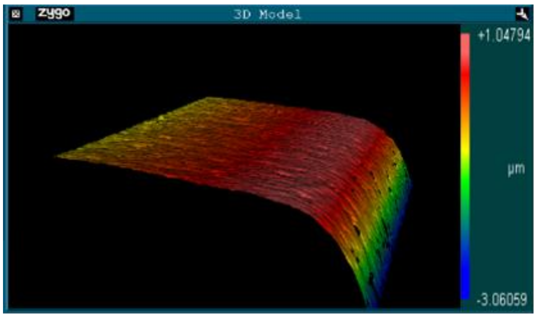
Figure 5.15 shows the photos of the bottom and edges of the groove before and after finishing. It can be seen that the edge of the groove is greatly improved after finishing, and the burr is completely removed. The bottom surface of the groove has also been improved to a certain extent, but because the moving speed of the magnetic clusters in the groove is reduced, the finishing efficiency is lower than the plane outside the groove. In order to investigate the change of the groove edge shape, the white light interferometer (Zygo NewView7000) was used to measure the groove edge shape.



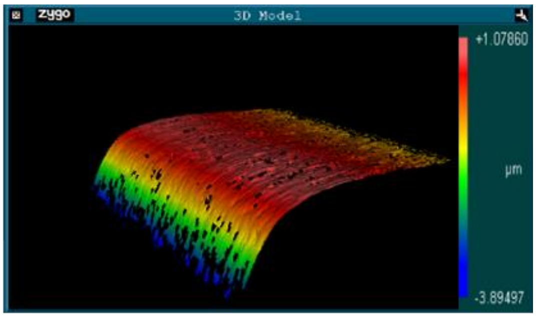
(a) 1#, Edge-L



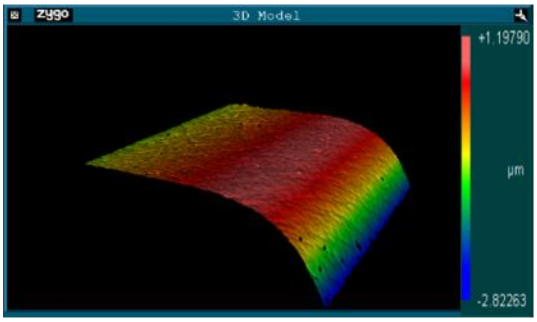
(b) 1#, Edge-R



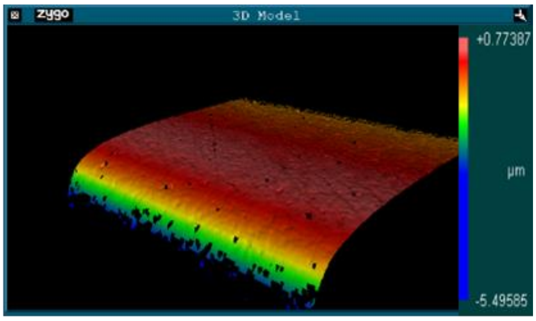
(c) 2#, Edge-L



(d) 2#, Edge-R



(e) 3#, Edge-L



(f) 3#, Edge-R

Fig. 5.16 3D photos of the edges of the grooves after finishing

Figure 5.16 shows the 3D photos of the left and right edges of the three grooves after finishing. It can be seen that there is a slight change in the shape of the groove edge. The edge of the groove is rounded to varying degrees after finishing. This phenomenon is more obvious at the left edge of groove 3# and the right edge of groove 1#. However, the overall structure of the groove is maintained well. The above results show that this process is feasible for finishing the inner surface of the micro grooves. At the same time, the process has a significant effect on edge deburring.

5.4 Conclusions

In this chapter, the industrial application of MAF process using alternating magnetic field is studied. The main conclusions are as follows.

1. Experimental results prove that this process can realize the finishing of alumina ceramic plates, and the surface roughness of alumina ceramic workpieces can be increased from 244.6 nm *Ra* to 106.3 nm *Ra*.
2. The combined use of alternating magnetic field and static magnetic field can maintain the characteristics of alternating magnetic field and increase the magnetic flux density in the finishing area.
3. The feasibility of the alternating magnetic field MAF process in the finishing of microgrooves is discussed, and it is proved that this process can finish the surface of the micro grooves (depth 0.3 mm, width 1 mm).
4. Experimental results show that the process has excellent deburring effect.

References

1. Wang Y, Hu DJ (2005) Study on the inner surface finishing of tubing by magnetic abrasive finishing. International Journal of Machine Tools and Manufacture 45(1):43-49.
2. Jain NK, Jain VK, Jha S (2007) Parametric optimization of advanced fine-finishing processes. Int J Adv Manuf Technol 34:1191–1213.
3. Shinmura T, Takazawa K, Hatano E, Matsunaga M, Matsuo T (1990) Study on Magnetic Abrasive Finishing. CIRP Annals 39(1):325-328.
4. Shinmura T, Aizawa T (1989) Study on magnetic abrasive finishing process-development of plane finishing apparatus using a stationary type electromagnet. Bull Jpn Soc Precis Eng 23(3):236-239.
5. Shinmura T, Aizawa T (1988) Development of Plane Magnetic Abrasive Finishing Apparatus and its Finishing Performance (2nd Report) Finishing Apparatus using a Stationary Type Electromagnet. J Jpn Soc Prec Eng 54(5):928–933 (in Japanese).
6. Guo J, Liu K, Wang Z, Tnay GL (2017) Magnetic field-assisted finishing of a mold insert with curved microstructures for injection molding of microfluidic chips. Tribology International, 114, 306-314.
7. Kim JD, Choi MS (1997) Study on magnetic polishing of free-form surfaces. International Journal of Machine Tools and Manufacture, 37(8), 1179-1187.
8. Yin SH, Shinmura T (2004) Vertical vibration-assisted magnetic abrasive finishing and deburring for magnesium alloy. Int J Mach Tool Manuf 44:1297-1303.
9. Yin SH, Shinmura T (2004) A comparative study: polishing characteristics and its mechanisms of three vibration modes in vibration-assisted magnetic abrasive polishing. Int J Mach Tool Manuf 44:383-390.

10. Lin CT, Yang LD, Chow HM (2007) Study of magnetic abrasive finishing in free-form surface operations using the Taguchi method. Int J Adv Manuf Technol 34, 122–130.
11. Guo J, Jong HJH, Kang R, Guo D (2018) Novel localized vibration-assisted magnetic abrasive polishing method using loose abrasives for V-groove and Fresnel optics finishing. Optics express, 26(9), 11608-11619.
12. Wang Y, Wu Y, Nomura M (2016) Feasibility study on surface finishing of miniature V-grooves with magnetic compound fluid slurry. Precision Engineering, 45, 67-78.
13. Wu JZ, Zou YH, Sugiyama H (2015) Study on ultra-precision magnetic abrasive finishing process using low frequency alternating magnetic field. Journal of Magnetism and Magnetic Materials 386:50-59
14. Zou YH, Xie HJ, Dong CW, Wu JZ (2018) Study on complex micro surface finishing of alumina ceramic by the magnetic abrasive finishing process using alternating magnetic field. Int J Adv Manuf Technol 97(5-8):2193-2202
15. Xie HJ, Zou YH, Dong CW, Wu JZ (2019) Study on the magnetic abrasive finishing process using alternating magnetic field: investigation of mechanism and applied to aluminum alloy plate. Int J Adv Manuf Technol. 102(5-8): 1509-1520.

Chapter VI　Conclusions

In order to overcome the shortcomings of the conventional MAF process, for example, it is difficult for the magnetic clusters to recover their shape after contacting the workpiece during the finishing process, and the uneven distribution of abrasive particles leads to poor surface accuracy and reduced finishing efficiency. The MAF process using an alternating magnetic field is proposed. This process makes the magnetic clusters fluctuate through the use of periodically changing currents. Through the fluctuation of the magnetic cluster, the abrasive particles in contact with the workpiece are replaced, thereby renewing the abrasive particles in contact with the workpiece, ensuring the stability of the grinding tool. Therefore, the finishing efficiency can be improved and a stable finishing process can be realized. In this paper, the finishing mechanism of the MAF process using an alternating magnetic field is discussed. The influence of current change on magnetic flux density is measured and analyzed. The relationship between finishing force and magnetic flux density and the influence of current change on finishing force are analyzed. Moreover, the feasibility of high-efficiency ultra-precision finishing of aluminum alloy materials was investigated through experiments. In order to further improve the finishing efficiency and surface quality, the influence of the current waveform on the finishing characteristics was investigated. In addition, the application of MAF process using alternating magnetic field is discussed. The main research contents and conclusions of each chapter are as follows:

Chapter 1

In chapter 1, the research background and research in this field are introduced. The research purpose of this research is described and the chapters of this article are introduced.

Chapter 2

In chapter 2, the processing principle of conventional MAF is introduced. The processing principle and experimental device of the MAF process using an alternating magnetic field are explained. Moreover, mathematical models and measurements prove that the changing frequency of the magnetic force and finishing force in the alternating magnetic field is twice the frequency of the current. In addition, the simulation results show that the grooved magnetic pole used in this study can improve the edge effect to a certain extent.

Chapter 3

In chapter 3, the ultra-precision finishing of the 5052 aluminum alloy workpiece by the MAF process using the alternating magnetic field is investigated. The measurement results show that the magnetic flux density is unevenly distributed in the finishing area, and the strongest magnetic flux density is at the edge of the magnetic pole. In addition, as the average diameter of the magnetic particles increases, the finishing force increases. The current frequency has almost no effect on the maximum finishing force, but the average finishing force decreases as the current frequency increases. 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 more uniform mixing of the magnetic particles with the abrasive particles. 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 an 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. The experimental results show that the MAF process using an alternating magnetic field can realize ultra-precision finishing of 5052 aluminum alloy plate. The surface roughness of the workpiece improved from 318 nm Ra to 3 nm Ra within 15min.

Chapter 4

In chapter 4, the influence of the current waveform on the magnetic field, finishing force, and finishing characteristics is discussed.

Comparison of sine wave and square wave draws the following conclusions. (1) When the current frequency is 1Hz and the average current is 1.9A, the average magnetic flux density of sine wave and square wave is basically the same. Under the same conditions, the maximum finishing force of a sine wave is higher than that of a square wave, but the average finishing force is basically the same. (2) Observation of the behavior of magnetic clusters shows that when square waves are used, higher magnetic cluster fluctuation speeds can be obtained, and as the size of magnetic particles decreases, the difference between the magnetic cluster fluctuation speeds of the two waveforms is greater . (3) The experimental results show that when the current waveform is a square wave, a finishing efficiency higher than that of a sine wave can be obtained. In addition, as the size of the MP increases and the frequency of the magnetic field decreases, the finishing efficiency increases. At the same time, when the AP is WA#8000, the sorting efficiency is higher. In addition, the increase of the magnetic pole rotation speed significantly improves the finishing efficiency.

The following conclusions can be obtained by comparing the sine waveform with the full-wave rectified sine waveform. (1) In the case of a full-wave rectified sine waveform (the direction of the magnetic field remains unchanged), the average magnetic flux density will increase to a certain extent. The corresponding average finishing force is also higher than that of the sine wave. (2) Observation of the behavior of magnetic clusters shows that in the case of a full-wave rectified sine waveform, the fluctuation of magnetic clusters is reduced. When the average diameter of the magnetic particles is 30 µm, 75 µm and 149 µm, the fluctuation of the magnetic clusters can be maintained. However, when the average diameter of the magnetic particles is 330 µm, the magnetic clusters hardly fluctuate. (3) The experimental results show that when the average diameter of the magnetic particles is 30µm, 75µm and 149µm, a higher finishing efficiency can be obtained in the case of a full-wave rectified sine waveform. However, when the average diameter of the magnetic particles is 330 µm, the finishing efficiency is reduced.

The following conclusions can be obtained by comparing the above waveform with the pulse waveform. (1) In the pulse waveform, the average value of the magnetic flux density is higher than the average value of the static magnetic field (DC). As the duty cycle increases, the gain rate relative to the static magnetic field gradually decreases. Correspondingly, when the average current is the same, the average finishing force increases as the duty cycle increases. (2) Observation of the behavior of magnetic clusters shows that in the case of pulse waveform, the fluctuation amplitude of magnetic clusters decreases as the duty cycle increases. (3) The experimental results show that when the average diameter of the magnetic particles is 75µm, the current frequency is 1Hz, and the average current is 1.9 A, the pulse current with a duty cycle of 80% achieves the highest finishing efficiency (compared to the above eight current waveform).

Chapter 5

In chapter 5, the industrial application of MAF process using alternating magnetic field is studied. First, the feasibility of this process for finishing alumina ceramics was verified. Experimental results prove that this process can realize the finishing of alumina ceramic plates, and the surface roughness of alumina ceramic workpieces can be increased from 244.6 nm *Ra* to 106.3 nm *Ra*. Secondly, the application of the alternating magnetic field MAF process in the finishing of microgrooves is discussed. The experimental results show that this process can finish the surface of the micro groove (0.3 mm deep and 1 mm wide), and has excellent finishing effect on the edge of the groove.

Chapter 6

In chapter 6, the main conclusions of this research are summarized.

Acknowledgement

I am grateful to those who have offered me encouragement and support over the past several years. It would be impossible to accomplish this work without the kindhearted help and full-hearted support of many people.

First and foremost, I express my deepest gratitude to my advisor, Associate Professor Yanhua Zou, for her consistent and illuminating instruction. Through countless discussions and daily work with her, I have not only learned a lot about the magnetic abrasive finishing process but also her rigorous attitude towards scientific research will provide guidance for the rest of my life and future research work.

I would like to express my heartfelt gratitude to Professor Yoshimasa Takayama, Associate Professor Ryunosuke Sato, Professor Yutaka Mabuchi and Professor Hiroaki Hasegawa for their willingness to serve as members of my thesis defense committee.

I would like to acknowledge the financial support of the Rotary Yoneyama Memorial Foundation of Japan to my study and living in Japan. I would also like to thank my counselor, Ms. Toshi Wakairo, and all members of the Tochigi Rotary Club for their kindness and sharing interesting information about Japan.

The gratitude is also extended to some supports from Creative Department for Innovation (CDI) of Utsunomiya University and mechanical processing factories of Utsunomiya University for this research.

I also want to express my special gratitude to my wife (Ms. Linlin Mu). She is not only the love of my life but also my best friend. Thank you for all of your love and support.

Last but not least, my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years. I also owe my sincere gratitude to my friends and my fellow classmates who gave me their help and time in listening to me and helping me work out my problems during the difficult course of the thesis.

Contributed papers related to this study

Articles

1. Yanhua Zou, Huijun Xie, Chaowen Dong, Jinzhong Wu, Study on complex micro surface finishing of alumina ceramic by the magnetic abrasive finishing process using alternating magnetic field, The International Journal of Advanced Manufacturing Technology, 2018, 97, 2193-2202.
2. Huijun Xie, Yanhua Zou, Chaowen Dong, Jinzhong Wu, Study on the magnetic abrasive finishing process using alternating magnetic field: investigation of mechanism and applied to aluminum alloy plate, The International Journal of Advanced Manufacturing Technology, 2019, 102, 1509-1520.
3. Huijun Xie, Yanhua Zou, Investigation on Finishing Characteristics of Magnetic Abrasive Finishing Process Using an Alternating Magnetic Field. Machines 2020, 8, 75.

International conference

1. Huijun Xie, Yanhua Zou. Study on ultra-precision processing of aluminum alloy plates through magnetic abrasive finishing process with alternating magnetic field. 14th China-Japan International Conference on Ultra-Precision Machining Process, September 2018, Harbin China.
2. Huijun Xie, Yanhua Zou, Study on the Magnetic Abrasive Finishing Process Using an Alternating Magnetic Field - Discussion on the application of full-wave rectifier current-, 3rd International Conference on Metal Material Processes and Manufacturing, June 2020, Singapore (Webinar).

Domestic conference

1. 謝 恵君, 鄒 艶華, 変動磁場を利用した超精密磁気研磨法に関する研究ーアルミニウム合金材料の超精密仕上げー, 茨城講演会講演論文集, 8 月, 2018.
2. 謝 恵君, 鄒 艶華, 変動磁場を利用した超精密磁気研磨法に関する研究ー加工メカニズムの検討ー, 2019 年度砥粒加工学会学術講演会, 8 月, 2019.
3. 謝 恵君, 鄒 艶華, 変動磁場を利用した超精密磁気研磨法に関する研究ー磁気クラスタの挙動観察及び加工特性の検討ー, 2020 年度精密工学会秋季大会学術講演会, 9 月, 2020.

Awards

1. Best Paper Award, Awarded on the 15th China-Japan International Conference on Ultra-Precision Machining Process (CJUMP 2018), 2018.
2. Young Researcher Award, Awarded on the 15th China-Japan International Conference on Ultra-Precision Machining Process (CJUMP 2018), 2018.
3. Best Paper Award, Awarded on the 3rd International Conference on Metal Material Processes and Manufacturing (ICMMPM2020), 2020.