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Investigation on Finishing Characteristics of Magnetic Abrasive Finishing Combined with Electrolytic Process

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Abstract: In order to improve the finishing performance of the magnetic abrasive finishing combined with electrolytic (EMAF) process for finishing SUS 304 stainless steel, the finishing characteristics are further studied in this paper. Firstly, the processing characteristics of electrolytic process compounded in EMAF process is investigated more detailed. In the early stage of electrolytic processing, the processing time is subdivided into three stages, each stage is 24 s. It was found that during the processing, the value of surface roughness will be an upward trend in the early stages of processing, and then turn to a downward trend. Then based on the experimental results of electrolytic processing, the optimal time of EMAF processing is discussed. In this part, the ratio of EMAF processing time and MAF processing time within 10 min is explored, and it is found 2 min of EMAF processing and 8 min of MAF processing can obtain better surface roughness. Finally, the MAF processing and EMAF processing under the same experimental conditions are compared, and the experimental result shows that finishing efficiency of EMAF process is higher than that of MAF process. In this study, the best combination of processing time is 2 min EMAF processing + 8 min MAF processing, the processing voltage is 6V, and the concentration of $NaNO_3$ aqueous solution is 20%.

Keywords: EMAF, MAF, Precision Finishing, Surface Roughness

1. Introduction

As a non-traditional precision finishing technology, the MAF (Magnetic Abrasive Finishing) process has been developed for decades [1, 2]. By using the penetrating characteristics of magnetic field, magnetic brush can be formed in the cavity of workpiece. Therefore, the MAF process can be used for finishing the inner cavity of workpiece [3, 4]. In addition, the magnetic brush is formed by the iron powder particles attracting each other in the magnetic field, so the magnetic brush can adapt to the complex surface of workpiece to a certain extent. This property also makes the MAF process can be used to finish tiny grooves on the workpiece surface [5-7]. Due to the above advantages, the parts with complex surface that cannot be finished by traditional processing tools can be finished by MAF process, so it is widely used in aviation, medical, military, and optical industries, etc. [1-6]. Although the MAF process has many advantages that cannot be replaced by traditional processing technology, insufficient finishing efficiency is one of the important factors that affect its large-scale promotion. In order to solve the problem of insufficient finishing efficiency and retain the precision finishing characteristics of MAF process, the EMAF (magnetic abrasive finishing combined with electrolytic) process was proposed [8].

The electrolytic reaction in EMAF process has the characteristics of high processing efficiency and is not affected by material hardness and toughness [9, 10]. Therefore, the EMAF processing utilizes the compounded electrolytic reaction to improve the finishing efficiency than that of the traditional MAF process. In order to make the EMAF process more widely used, after stabilizing the EMAF process for finishing SUS304 stainless steel [11], the feasibility of using EMAF process to finish the surface of aluminum alloy A5052 was also proved [12]. Through previous research, it has been proved that the electrolytic reaction in the EMAF process can improve the processing efficiency.

In order to further improve the finishing performance of EMAF process, the finishing characteristics has been further studied in this study. The processing characteristics of electrolytic process that compounded in EMAF process is investigated firstly. It was found that the surface roughness value did not always decrease with the increase of processing time. During the processing by electrolytic process in EMAF process, the value of surface roughness will be an upward trend in the early stages of processing, and then turn to a downward trend. Since the previous research did not decompose the early stage of the processing time in detail, this result is slightly different from the previous research [8], but is more specific. And Then based on the experimental results of electrolytic processing, the optimal time of EMAF processing is discussed. In order to explore the maximum finishing performance that can be exerted by the combination of EMAF processing and MAF processing, in this part, the ratio of EMAF processing time and MAF processing time within 10 min is explored. It is found that 2 min of EMAF processing and 8 min of MAF processing can obtain better surface roughness and material removal. Finally, the experimental results of MAF processing and EMAF processing at the same experimental conditions are compared, and the finishing characteristics of EMAF process are summarized and analyzed.

2. Processing Principle

2.1. Processing Principle of EMAF Process

The EMAF processing principle is shown in Figure 1. Both the surfaces of workpiece and the electrode of compound processing tool are immersed in the electrolyte. The workpiece is connected to the anode and the electrode of compound processing tool is connected to the cathode of the power supply during EMAF processing. The compound processing tool consists of four magnetic poles and a cross electrode, the magnetic poles are arranged in the same direction and symmetrically distributed in the four areas divided by the cross electrode. The surface of workpiece is processed by the rotation of the compound processing tool and the horizontal feed movement of the X-Y stage.

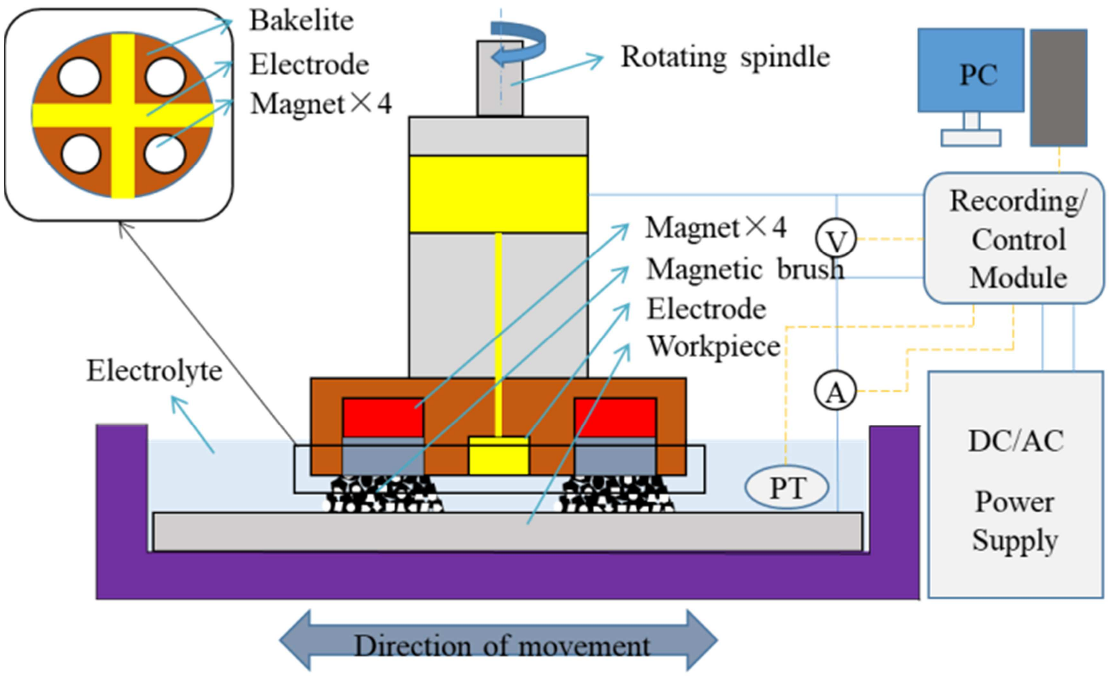


Figure 1. *Schematic of EMAF process.*

The processing of electrolytic process and MAF process act on the workpiece surface at the same time with the rotation and horizontal feed movement of the compound processing tool. The electrolytic reaction is used to efficiently remove the protrusions on surface, and the MAF process is used to further finish the workpiece surface. The processing efficiency of the EMAF process is higher than the traditional MAF process due to the combined electrolytic process is very efficient and is not affected by the properties of the material itself [9-11]. The MAF process that compounded in EMAF process is mainly used to remove the passive film generated during processing and further finishing the surface. So the finishing characteristics of EMAF process not only retains the characteristic of high processing efficiency of the electrolytic process, but also retains the high finishing precision of the MAF process.

The material removal of electrolytic process during the EMAF processing is shown by the (1). Where m is the amount of material removal, η is the current efficiency coefficient, I is the current value (A), t is the energization time (s), A is the atomic weight, F is the faraday constant (96500C) and n is the valence of the electrolysis product [13, 14].

$$m = \eta \frac{ItA}{Fn}\ (g) \tag{1}$$

2.2. Principle of Electrolytic Reactions in EMAF Process

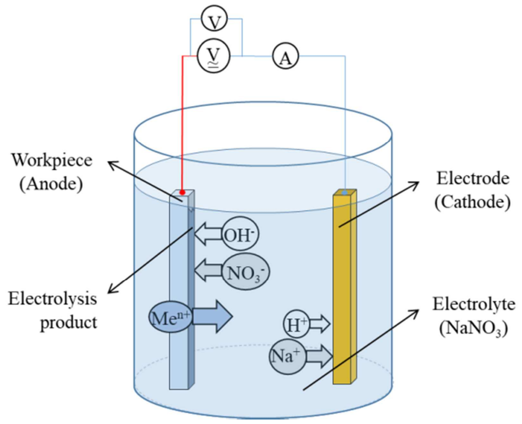


Figure 2. *Schematic of electrolytic reactions during the EMAF process.*

The schematic of electrolytic reactions in the EMAF process is shown in Figure 2. In this study, neutral sodium nitrate aqueous solution is selected as the electrolyte. When the power is on, the main electrolytic reactions that occur during the EMAF process are shown in (2) and (3), [15].

The main electrolytic reaction that occurs on the surface of cathode:

$$2H^+ + 2e^- \rightarrow H_2\uparrow \quad (2)$$

Metal dissolution reaction of workpiece (anode):

$$Me \rightarrow Me^{n+} + ne^- \quad (3)$$

2.3. Principle of Plane MAF Process

In the MAF processing, the magnetic brush is used as a machining tool to finish workpiece, and it is formed between the surfaces of the magnetic pole bottom and the workpiece. The magnetic force F of a single magnetic particle in a magnetic field can be decomposed into a force F_x which along the direction of the magnetic force and F_y which along the direction of magnetic equipotential line, as shown in (4) and (5) [16, 17].

$$F_x = V\chi\mu_0 H(\partial H/\partial x) \quad (4)$$

$$F_y = V\chi\mu_0 H(\partial H/\partial y) \quad (5)$$

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

3. Experimental Setup

3.1. EMAF Processing Experimental Setup

The External view of EMAF experimental setup is shown in Figure 3. The processing area mainly contains the vertical milling machine, X-Y stage, compound processing tool and a Pt100 sensor. The start and stop of the spindle rotation and the stop of the X-Y stage are controlled by a single-chip microcomputer and its attached drive circuit. In addition, the output voltage of the DC power supply is controlled by a single-chip microcomputer and a Frequency-Voltage conversion module.

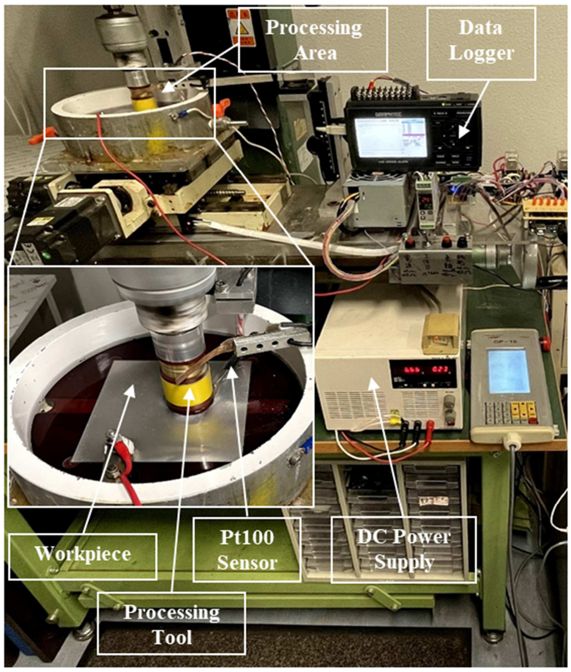


Figure 3. *EMAF experimental setup.*

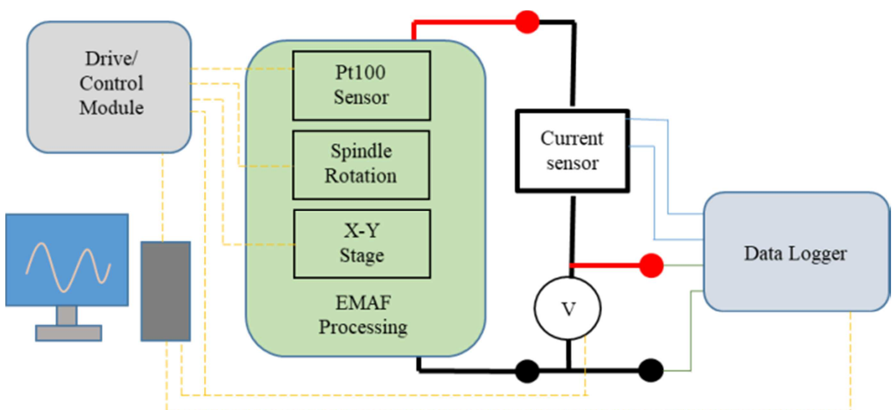


Figure 4. *Schematic of EMAF processing set up.*

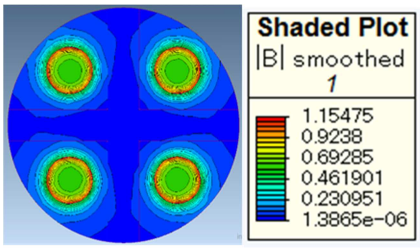
3.2. Schematic of EMAF Processing Setup

The Schematic of EMAF set up is shown in Figure 4. As shown in the schematic diagram, the drive and control device mainly integrates control modules such as single-chip microcomputer, drive, relay, frequency to voltage conversion module and programmer of X-Y stage, etc. The start and stop of the spindle, the stop of the X-Y stage, voltage output of DC-power supply are controlled during processing by program. The temperature of the electrolyte during processing is monitored by a Pt100 temperature sensor, and the temperature change is recorded by a data logger. By compiling the program, the processing requirements of different stages can be realized.

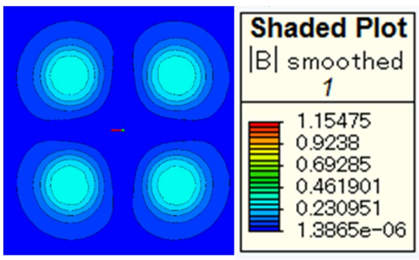
In addition, the voltage and current changes during processing will also be recorded by the data logger, so as to find abnormal conditions during processing.

3.3. Simulation of Magnetic Induction

The simulation results of compound processing tool in Figure 5 are mainly used to investigate the distribution of magnetic induction on the surface of processing tools and workpiece. Since the different magnetic induction intensity will affect the shape of the magnetic brush and the finishing pressure, the reasonable design and layout of the com-pounded processing tool can be preliminarily determined based on the simulation results.



(a) Magnetic induction on the surface of compound processing tool



(b) Magnetic induction on the surface of the workpiece (working gap 1 mm)

Figure 5. *Simulation results of magnetic induction.*

The simulation result of magnetic induction that on the compound processing tool surface is shown in Figure 5(a). The result shows that at the edges of magnetic poles the magnetic induction is the largest. In the middle part of the magnetic pole the magnetic induction is slightly weaker. The magnetic induction outside the magnetic pole debilitates rapidly. The magnetic brush cannot provide enough finishing pressure if the magnetic induction is not strong enough. Figure 5(b) shows the magnetic induction on the workpiece surface when the working gap is 1 mm. It can be seen from the simulation results that the magnetic induction on the workpiece surface is obviously weaker than that on the processing tool surface. According to (4) and (5), the finishing pressure provided by the magnetic brush is greater when it is closer to the processing tool.

4. Experimental Conditions and Results

4.1. Processing Characteristics of Electrolytic Process

The electrolytic reaction plays an important role in the EMAF process. During EMAF processing, the electrolysis reaction is mainly used to accelerate material removal to improve the EMAF processing efficiency. Therefore, it is necessary to explore the processing characteristics of the electrolytic process, and comprehensively determine the processing parameters of the subsequent composite EMAF processing according to the change of material removal (MR) amount and surface roughness (SR) value.

4.1.1. Experimental Conditions of Electrolytic Process

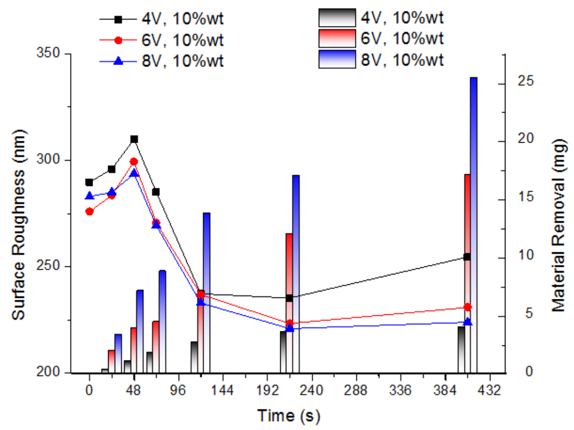
Table 1. *Experimental Conditions of Electrolytic process.*

Item	Experimental Conditions
Workpiece	SUS 304 stainless steel plane (100 × 100 × 1 mm)
Electrolyte	$NaNO_3$ aqueous solution 10% wt, 20% wt, 30% wt
Processing voltage	4V, 6V, 8V
Working gap	1 mm
Stage feed speed	5 mm/s
Tool rotation speed	450 rpm
Total processing time	408 s

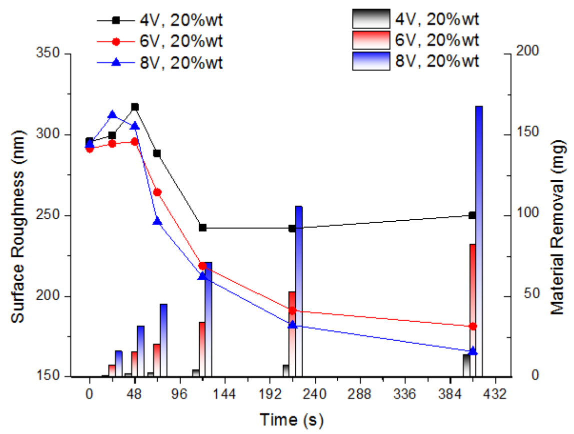
As shown in Table 1, in this part of the experiment, 4V, 6V, 8V DC voltage are used for exploration. $NaNO_3$ neutral aqueous solution with concentrations of 10%, 20% and 30% are selected as the electrolyte. The changes of material removal (MR) and surface roughness (SR) is investigated in this experiment. Due to the limitation of the workpiece size and the feed speed of the X-Y stage, the one-way movement time of the X-Y stage is 12 s, and the time of each reciprocating cycle is 24 s. The processing time in this experiment is a multiple of 24 s, and the total processing time is 408 s.

4.1.2. Experimental Results of Electrolytic Process

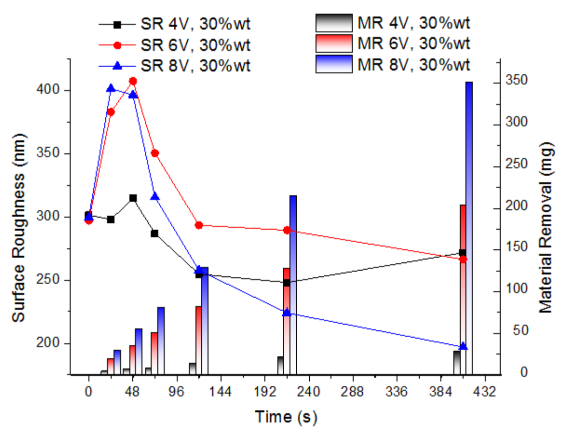
When the 10% concentration of $NaNO_3$ aqueous solution is used for electrolytic processing, the experimental results are shown in Figure 6 (a). From the perspective of the change of surface roughness, whether it is 4V, 6V or 8V voltage is used for electrolytic processing, the average surface roughness value increases during 0 - 48s, and then gradually decreases. After 216s electrolytic processing, the average surface roughness value rises slowly. From the change of material removal, as the processing time increases, the material removal increases. And as the processing voltage increases, the amount of material removal increases corresponding to the same processing time. When the electrolyte concentration is 20% and 30%, the corresponding experimental results are shown in Figures 6(b) and (c). In the early stage of electrolytic processing, the average surface roughness value also has a trend of first rising and then falling. The change law of material removal also increases with the increase of processing voltage. In this experiment, no matter which concentration of electrolyte is used for processing, the amount of material removal when using 4V voltage is significantly less than that of 6V and 8V.



(a) Concentration of $NaNO_3$ 10%



(b) Concentration of $NaNO_3$ 20%



(c) Concentration of $NaNO_3$ 30%

Figure 6. *Experimental results of Electrolytic process.*

From the change of surface roughness, the surface roughness value first increases and then gradually decreases in the early stage of processing. This is because the protrusions on the surface of the workpiece preferentially discharge during the early stage of electrolytic processing, uneven dissolution occurs and resulting in an increase in surface roughness. As the processing progresses, the surface gradually becomes uniform so the surface roughness value decreases. From the change in the amount of material removal, as the processing voltage increases, the processing current becomes larger. So according to (1), as the current increases per unit time, the corresponding material removal increases.

4.2. EMAF Processing Experiment

4.2.1. Experimental Conditions of EMAF Process

In the EMAF experiment part, 20% $NaNO_3$ aqueous solution is selected. This is because according to the above experiment, when using 20% concentration of $NaNO_3$ aqueous solution for electrolytic processing, the final surface roughness value is lower than that of other experimental conditions. And the experimental conditions of EMAF process is shown in Table 2.

Table 2. *Experimental Conditions of EMAF process.*

Item	Experimental Conditions
Workpiece	SUS 304 stainless steel plane (100 × 100 × 1 mm)
Electrolyte	$NaNO_3$ 20% wt
Processing voltage	4 V, 6 V, 8V
Working gap	1 mm
Stage feed speed	5 mm/s
Tool rotation speed	450 rpm
Magnetic particles	330 μm Electrolytic iron powder
Abrasive	WA#8000
Cutting fluid	Water soluble (EMAF), Oily (MAF)
Processing time	2 min EMAF + 8 min MAF, 4 min EMAF + 6 min MAF, 6 min EMAF + 4 min MAF, 8 min EMAF + 2 min MAF, 10 min EMAF.

The 4V, 6V and 8V processing voltage is selected for EMAF processing and the EMAF processing time is 2min. Because when the 8V voltage is used for processing, the current value is relatively large, and long-term processing is likely to cause the electrode of the processing tool to be burned, so the composite processing time is set to 2min.

4.2.2. Experimental Results of EMAF Process

When the $NaNO_3$ aqueous solution is 20%, the EMAF processing time is 2 min and the MAF processing time is 8 min, the experimental results are shown in Figure 7. From the change of the average surface roughness value, compared with MAF processing (3 min – 10 min), the surface roughness value decreases faster during EMAF processing. After the first 2 min of EMAF processing, the surface roughness value has dropped from more than Ra 300 nm to around Ra 150 nm. After another 8min of MAF processing, the minimum surface roughness value Ra 31 nm is obtained when the EMAF processing voltage is 6V.

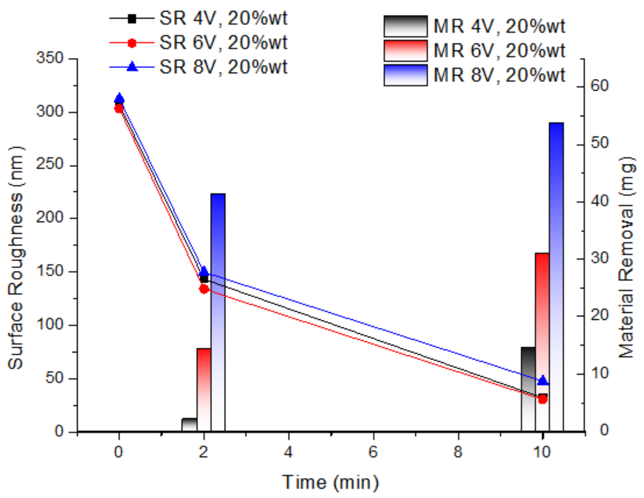


Figure 7. *EMAF Experimental results, processing voltage 4V, 6V and 8V.*

From the change of material removal, when the 6V and 8V voltage is used for EMAF processing, the material removal rate is significantly higher than the subsequent MAF processing. But when the EMAF processing voltage is 4V, compared with subsequent MAF processing the processing efficiency is not significantly improved. The reason is when the processing voltage is 4V, the electrolytic reaction effect is relatively weak, and the voltage just exceeds the decomposition voltage of electrolytic cell in this experimental system. So the amount of material removed by the electrolytic process is very small. Besides, due to the influence of the electrolyte, the abrasive is easily dispersed in the electrolyte during EMAF processing, which will also reduce the processing efficiency of MAF process.

According to the above experimental results, since the optimal surface roughness value is obtained by using the processing voltage of 6V. In the following experiment, 6V processing voltage will be used, the concentration of $NaNO_3$ aqueous solution is 20%, and the EMAF processing time is 2min, 4min, 6min, 8min and 10min, respectively. The processing effect of EMAF processing at different times is explored, and the experimental results is shown in Figure 8.

From the change rate of the average surface roughness value, compared with the MAF processing, the surface roughness value of the EMAF processing decrease faster. From the material removal rate, the material removal rate of EMAF processing is significantly higher than that of MAF processing. After 10 minutes of processing, the combination of "2 min EMAF + 8 min MAF" and "4 min EMAF + 6 min MAF" achieved lower average surface roughness values, *Ra* 31nm and *Ra* 39 nm, respectively. This is because if the combined processing time is too long, the electrolytic process in the EMAF process is likely to cause uneven corrosion on the surface, which is disadvantageous to the subsequent MAF processing.

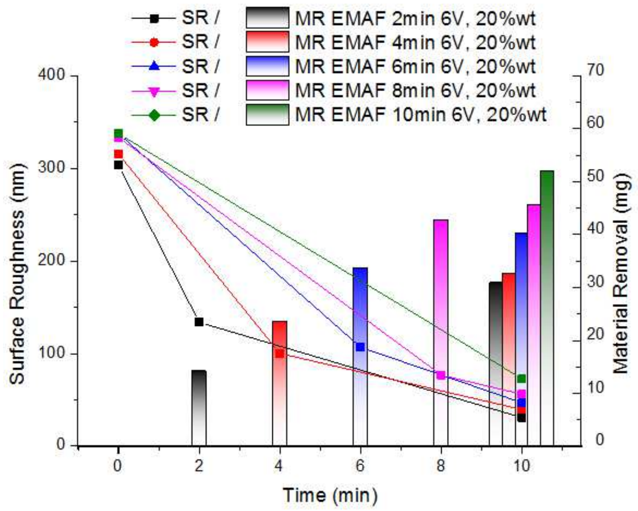


Figure 8. *Experimental results of EMAF process, processing voltage 6V.*

4.3. Comparative Experiment of EMAF Processing and MAF Processing

This part of the experiment is mainly to further compare and analyze the finishing characteristics of EMAF process and the MAF process. The two optimal combinations "2 min EMAF + 8 min MAF" and "4 min EMAF + 6 min MAF" in the previous experiment were used to compare with MAF processing.

4.3.1. Experimental Conditions of Comparative Experiment

In this part of the experiment, two types of the MAF processing are explored. The type 1 is the MAF processing experiment at EMAF processing conditions. In this case, except that no voltage is applied, other conditions are the same as EMAF processing. And the workpiece is also immersed in the electrolyte and a water-soluble cutting fluid is used. The type 2 is that the traditional MAF processing uses oily cutting fluid without the influence of electrolyte. The other experimental conditions are the same as Table 2.

4.3.2. Experimental Results of Comparative Experiment

Figure 9 shows the results of comparative processing experiments between EMAF process and MAF process. From the experimental results, it can be concluded that after 10 minutes of processing, the final surface roughness value and the amount of material removal obtained by the EMAF process are better than those of the MAF process. From the amount of material removal rate, compared with MAF processing, EMAF processing can achieve a significantly higher material removal rate.

Further comparing the MAF processing at the two experimental conditions, it can be seen that due to the influence of the electrolyte, the MAF processing efficiency at the EMAF processing conditions (type 1, water-soluble cutting fluid) is significantly lower. Both the amount of material removal and the average surface roughness value are worse than traditional MAF processing (type 2, oily cutting fluid).

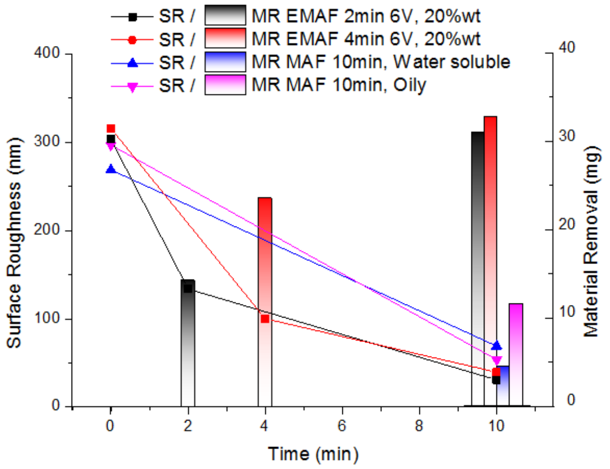
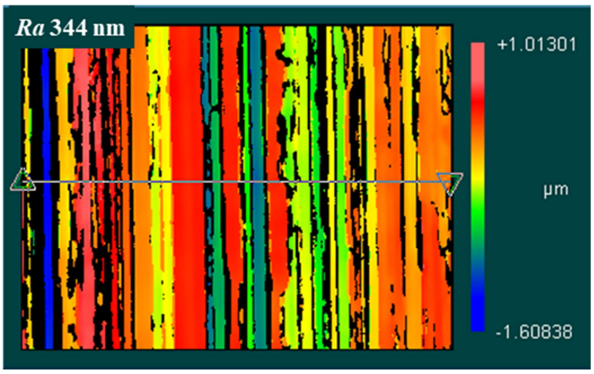


Figure 9. *Experimental results of Comparative Experiment.*

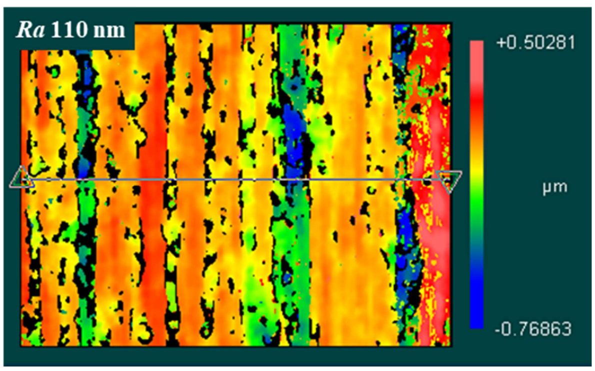
4.4. Surface Topography Before and After Processing

The 3D topography of the workpiece surface before and after processing measured by Zygo NewView7300 is shown in Figure 10.

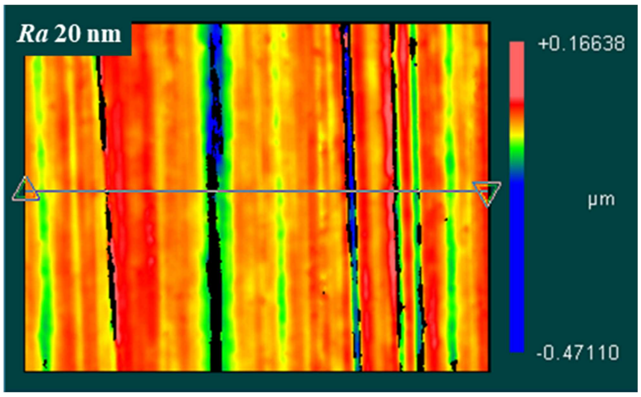
It can be seen from the Figure 10(a), that the surface of the unfinished workpiece is relatively rough and there are obvious grooves on the surface. The surface after 2 min EMAF processing is shown in Figure 10(b), the surface becomes smoother, but there is passive film remains on the surface. The surface after 2 min EMAF + 8 min MAF processing is shown in Figure 10(c). After 8 min of MAF processing, the surface became smooth and the surface roughness value dropped from *Ra* 344 nm to *Ra* 20 nm.



(a) Before finishing



(b) After 2min EMAF processing



(c) After 2min EMAF + 8min MAF processing

Figure 10. *3D topography before and after finishing.*

5. Discussion

The finishing characteristics of EMAF processing is further explored in this paper. The processing characteristics of electrolytic process in the EMAF process has been explored in more detail. Besides, the optimal EMAF processing time of the combination of 2 min EMAF+8 min MAF processing is confirmed. Furthermore, the EMAF process has higher finishing performance than the traditional MAF process is proved. This study provides a basis for further improving the surface uniformity of EMAF processing. In the future research, the processing parameters should be further optimized to reduce the occurrence of pitting corrosion. For example, pulse voltage can be used instead of DC voltage for EMAF processing.

6. Conclusion

After a series of exploratory experiments to explore the finishing characteristics of EMAF process, the experimental results are as follows:

At the suitable processing parameters, using the EMAF process can obtain higher processing efficiency and better surface roughness than that of traditional MAF process.

During EMAF processing, due to the existence of electrolyte in the processing area, the processing performance of the MAF process will be weakened.

In this study, the best combination of processing time is 2 min EMAF processing + 8 min MAF processing, the processing voltage is 6V, and the concentration of $NaNO_3$ aqueous solution is 20%.

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