Research on ultrasonic vibration–assisted electrical discharge machining SiCp/Al composite

Xiang Gao1,2 · Jucai Li3 · Qixuan Xing1,2 · Qinhe Zhang1,2

Received: 2 September 2021 / Accepted: 9 May 2022 / Published online: 8 June 2022
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Abstract
In this paper, ultrasonic vibration–assisted electrical discharge machining (UEDM) is used to process SiCp/Al composite materials in order to achieve a higher material removal rate (MRR) and lower surface roughness, width overcut, and relative tool wear rate (RTWR). On the basis of studying the erosion mechanism of EDM SiCp/Al composite material, the flow field simulation study was carried out using FLUENT software. The simulation results of the gap flow field show that the ultrasonic vibration of the tool electrode is conducive to the removal of chips, which makes the discharge more stable and improves the machining efficiency. Based on the single-factor experiment, the effects of peak current, reference voltage, pulse width, and pulse interval on MRR, surface roughness, width overcut, and RTWR of the workpiece are studied. Then, based on the orthogonal experiment, the grey relational analysis method was used to optimize the process parameters, and the order of the influence of the 4 process indicators on the comprehensive performance and the optimal processing parameter combination was obtained. The reliability of the process optimization was verified with experiments.

Keywords SiCp/Al composites · EDM · Ultrasonic vibration · Simulation of gap flow field

1 Introduction
SiCp/Al composite material composite materials have significant advantages in terms of specific stiffness, specific strength, solderability, and thermal conductivity, and are widely used in the fields of electronics, automobiles, and aerospace [1, 2]. SiCp/Al composite material is used to manufacture special nuts in the solar cell wing deployment mechanism because of its excellent performance. In order to make the nut lighter, square holes need to be machined on its side, as shown in Fig. 1. However, the SiC particles in SiCp/Al make its machining difficult [3].

Electrical discharge machining (EDM) is a way of processing materials using the heat generated by electrical discharge, so the hardness has little effect on the processing effect [4]. Zhang et al. [5] conducted microhole machining experiments on SiCp/Al composites using EDM and obtained the influence of voltage on machining accuracy and surface roughness. Microholes with 53 μm were successfully processed in the experiment. Liu et al. [6] established a single-pulse discharge model of SiCp/Al composites and analyzed the changes in temperature field and the formation of molten pool during the processing of SiCp/Al composite materials. The experimental results show that if the pulse width increases, the depth-to-diameter ratio of the molten pool will decrease, but the increase of the peak current will reduce the depth-to-diameter ratio of the molten pool. Senapati et al. [7] tested the influence of process parameters on MRR, tool wear rate, and surface roughness through the experiment of EDM machining SiCp/Al composites. In addition, the feasibility of using EDM to process SiCp/Al composites was proved. Although many scholars have proved that EDM can be used to process difficult machining materials such as SiCp/Al, there still exist some problems in the machining process, such as low machining efficiency, unstable discharge, and so on [8–10].
The SiCp/Al composite material contains SiC ceramic particles. The SiC particles have strong thermal resistance, which causes the SiC particles unable to be eroded away but remain in the discharge area of the two electrodes. This will cause the discharge unstable, thereby affecting the processing efficiency. Therefore, improving the chip removal ability is of great significance for EDM [11]. Studies have shown that the chip removal ability of EDM will be significantly improved due to the auxiliary function of ultrasonic vibration. At present, many scholars use ultrasonic vibration to improve the chip removal ability of EDM. Liu et al. [12] simulated the chip removal process of UEDM, and the results showed that the debris in UEDM was greatly reduced compared with EDM. Wang et al. [13] analyzed the material removal mechanism of UEDM based on the principle of heat transfer and analyzed the influence of UEDM on machined surface through the established single-pulse removal model. The conclusion is that the surface roughness will be reduced due to the auxiliary effect of ultrasonic vibration. Shabgard et al. [14] analyzed the effect of applying ultrasonic vibration to the tool electrode on the EDM based on the finite element method. The results show that UEDM can effectively improve the material removal rate compared with EDM. Shervani-Tabar et al. [15] analyzed the dynamic behavior of steam bubbles generated by ultrasonic vibration, and it was proved from different angles that UEDM can improve the material removal rate. In recent years, ultrasonic vibration has been widely used in electrical discharge machining [16].

Although it has been generally recognized that the auxiliary effect of ultrasonic vibration can speed up chip removal and improve processing efficiency [17, 18], but currently, there are few studies on UEDM machining SiCp/Al composite material. In this paper, by studying the effect of process parameters on the processing efficiency when UEDM is processing SiCp/Al, it is beneficial to realize the engineering application of UEDM processing SiCp/Al. And through the optimization of processing parameters, the processing efficiency and processing quality can be improved [19]. Therefore, this research has important practical significance.

In this paper, fluid mechanics simulation software was used to simulate and calculate the medium flow field and the movement of erosion particles in the UEDM. Through simulation calculation, compared with EDM, the working fluid in UEDM flows faster, which helps to reduce the occurrence of short circuit and secondary discharge. Combining single-factor experiment and orthogonal experiment design method, the process experiment research of UEDM machining SiCp/Al composite material square hole was carried out, and the gray correlation analysis method was introduced to find the combination of machining parameters that optimize the comprehensive performance of machining.

### 2 Erosion mechanism of SiCp/Al in EDM

Electrical discharge machining melts and vaporizes the base aluminum in SiCp/Al to make SiC fall off, and finally achieve the purpose of removing material. The processing process mainly includes four stages: dielectric breakdown and formation of discharge channels, dielectric thermal decomposition and erosion of SiCp/Al composites, throwing of erosion products, and deionization of interelectrode dielectrics.

#### 2.1 Dielectric breakdown and formation of discharge channels

When the tool electrode and the SiCp/Al composite material are connected to the voltage, an electric field will be generated between the two electrodes:

\[ E = \frac{U}{D} \]  

In the formula, \( E \) is the electric field intensity, the unit is V/m. \( U \) is the voltage between the poles, the unit is V. \( D \) is the gap between the electrodes, the unit is m. According to the formula, when the voltage \( U \) is constant, the electric field intensity \( E \) increases with the decrease of the distance \( D \) between the electrodes. When the electric field intensity increases to about \( 10^5 \) V/mm, the inter-electrode dielectric is broken down to form a discharge channel. The formation of the discharge channel is shown in Fig. 2.

#### 2.2 Dielectric thermal decomposition and erosion of SiCp/Al composites

After the discharge channel is formed, the charged particles move to the two poles with the effect of the electric
field. High-speed moving charged particles collide with uncharged neutral particles to generate a lot of heat. In addition, the charged particles will hit the tool electrode and the surface of the workpiece. The heat generated in a short time causes the loss of the tool electrode and the corrosion of the SiCp/Al composites remove. Because the melting point and boiling point of the aluminum matrix in the SiCp/Al composite material are lower than that of SiC, the aluminum matrix is first eroded at high temperature during processing. The SiC particles are mainly eroded as the matrix material melts and vaporizes and falls off. As shown in Fig. 3.

**Fig. 2** Formation of discharge channels

**Fig. 3** Thermal decomposition of medium and Erosion of SiCp/Al composite
2.3 Throwing of erosion products

The instantaneous high temperature in the discharge channel melts or even vaporizes the two-pole materials, and the inter-electrode medium is also vaporized. Thermal expansion causes the pressure in the channel to rise sharply. Because the pressure in the channel is greater than the external pressure, the bubbles continue to expand outward, causing most of the aluminum-based material droplets, steam, and SiC particles in the channel to be ejected from the discharge channel, and a small part of the material that has not been ejected re-adheres to the electrode or on the workpiece. After the discharge is completed, the bubble in the channel continues to increase with inertia, causing the pressure in the bubble to be lower than the atmospheric pressure, and the low pressure environment in the bubble causes the molten material and vapor to boil again and be thrown out of the discharge channel. These thrown materials condense into spherical particles due to surface tension and cohesion, and flow out of the discharge gap with the flow of the working fluid. The throwing process is shown in Fig. 4.

2.4 Deionization of interelectrode dielectrics

After a pulse discharge is over, the dielectric capacity of the medium in the discharge channel cannot be recovered quickly, and a certain gap time is required for the deionization of the inter-electrode medium. In the process of EDM SiCp/Al composites, if the eroded bipolar metal material and the shed SiC particles do not have enough time to discharge the discharge gap, it will also affect the stability of the machining. Therefore, when processing EDM SiCp/Al composites with EDM, there should be sufficient pulse interval. The deionization process is shown in Fig. 5.

3 Simulation of gap flow field

In UEDM, the ultrasonic vibration of the tool electrode is usually better for the chip removal because it will promote the flow of the working medium. This paper carried out the flow field simulation of the machining gap to verify the effect and feasibility of UEDM processing SiCp/Al using the FLUENT simulation software.

3.1 Simulation model and condition setting

3.1.1 Calculation of machining gap

The size of the discharge gap will affect the discharge parameters in UEDM, so it is difficult to accurately measure. The empirical formula for the bottom clearance value is as follows [20]:

![Fig. 4 Throwing of erosion products](image-url)
In this formula, $K_V$ is the coefficient related to the dielectric constant of the working fluid, where the working fluid is kerosene, taking $5 \times 10^{-2}$. $V$ is the open-circuit voltage, taking the value 100 V. $K_R$ is the coefficient related to the processing material, which takes the value $2.5 \times 10^2$ according to the processing material. $A_m$ is the mechanical gap, which is 3 μm. $\varepsilon_0$ is the single pulse discharge energy; the formula is as follows:

$$S = K_V \cdot V + K_R \cdot \varepsilon_0^{0.4} + A_m$$  \hspace{1cm} (2)

In this formula, $K_V$ is the coefficient related to the dielectric constant of the working fluid, where the working fluid is kerosene, taking $5 \times 10^{-2}$. $V$ is the open-circuit voltage, taking the value 100 V. $K_R$ is the coefficient related to the processing material, which takes the value $2.5 \times 10^2$ according to the processing material. $A_m$ is the mechanical gap, which is 3 μm. $\varepsilon_0$ is the single pulse discharge energy; the formula is as follows:

$$\varepsilon_0 = \int_0^{\varepsilon_0} u(t) \cdot i(t) \, dt \approx u_e \cdot i_e \cdot t_e$$  \hspace{1cm} (3)

where $u_e$ is the spark discharge sustain voltage, which is 25 V; $i_e$ is the pulse peak current, which is 37A; $t_e$ is the pulse width, which is 100 μs.

According to the above parameters and formulas, the machining gap is calculated to be 104.5 μm. This chapter is a numerical simulation of the effect of the gap flow field and the movement of the erosion particles, so the discharge breakdown and other factors are not considered. The bottom machining gap is set to 100 μm, and the side machining gap is set to 200 μm.

### 3.1.2 Mesh model creation

The length of the tool electrode is 15.6 mm, and the gap flow field with a processing depth of 3 mm is simulated using WORKBENCH software. When the flow field is simulated, different areas will be divided into different meshes. The part close to the tool electrode is the main area of this simulation and the speed and pressure of this part change greatly, so the grid is relatively fine, and the grid size of other parts is appropriately increased. Figure 6 shows the established mesh model.

### 3.2 Simulation results and analysis

#### 3.2.1 The effect of tool vibration on the velocity of the flow field

The following is the displacement formula of the tool electrode:

$$s = A \sin(\omega t)$$  \hspace{1cm} (4)

$$\omega = 2\pi f$$  \hspace{1cm} (5)

In this formula, $s$ is the displacement of the tool electrode; $A$ is the peak of the tool electrode displacement, and here is 3μm; $f$ is the electrode vibration frequency, and its value is 28.3 kHz. $\omega$ is the angular frequency of electrode vibration.

The derivative function of formula (3) is the velocity of the tool electrode, and the formula is as follows:

$$v = 2\pi fA \cos(2\pi ft)$$  \hspace{1cm} (6)

The change of the flow field velocity in the machining gap at different moments of the vibration cycle is shown
in Fig. 7. When $t$ is $(0, \pi/2)$ or $(3\pi/2, 2\pi)$, the tool electrode is far away from the surface of the workpiece, the bottom gap increases, and the liquid medium flows into the gap. Then, the working fluid in the gap flows out. The fluid velocity in the machining gap has the same changing law as the electrode velocity, which can be seen from Fig. 7. The auxiliary effect of ultrasonic vibration will affect the speed of the working fluid in the gap, which is conducive to the discharge of debris.

### 3.2.2 The effect of tool vibration on the debris

The distribution of debris at different times during the UEDM process is shown in Fig. 8. We can see from Fig. 8 that the debris is distributed at the bottom of the machining gap due to gravity when the ultrasonic vibration of the tool electrode stops. After ultrasonic vibration was applied to the tool electrode, the debris begins to move due to the disturbance of the working fluid and will finally be discharged.

### 4 Experiment setup and methods

#### 4.1 Experiment platform

This experiment was carried out on the AgieCharmilles EDM machine SF201. The vertical resolution of the Z-axis of the machine tool is 1 μm, the resonance frequency of the ultrasonic vibration spindle is 28.3 kHz, and the amplitude is 3 μm. In this paper, the experiment of SiCp/Al composite forming square hole processing was carried out on this platform. Table 1 is the basic parameter in this experiment.

#### 4.2 Design of single-factor experimental

Through single-factor experiments, we studied the effects of peak current, reference voltage, pulse interval, and pulse width on MRR, surface roughness, width overcut, and RTWR. Table 2 shows the value of each factor level of the single-factor experiment. The basic level is peak current 37 A, reference voltage 70 V, pulse interval 75 μs, and pulse width 100 μs. Each set of experimental data is tested three times to ensure the reliability of the results.

#### 4.3 Design of orthogonal experiment

An orthogonal experiment can use a relatively small number of experiments to obtain better results and achieve the purpose of the experiment. Optimization based on orthogonal experiments usually has better results. The orthogonal experiment in this paper is carried out on the basis of single-factor experiment; Table 3 lists the parameters’ values. Table 4 shows the test parameters of the orthogonal experiment.

According to the data in Table 4, three trials for each set of data.

### 5 Results and analysis of single-factor test

#### 5.1 Effect of peak current on UEDM

Under the premise that other experimental conditions remain unchanged, change the magnitude of the peak current to study its influence on MRR, surface roughness, width overcut, and RTWR. Figure 9 is the relationship curve between peak current and UEDM index. We can see from the figure that after the peak current increases, the MMR, surface roughness, width overcut and RTWR also increase. Figure 10 shows the microscopic surface morphology of the square holes formed by UEDM in SiCp/Al composites when the peak currents are different.

As the peak current increases, the energy of a single pulse discharge increases. Therefore, the energy obtained by the surface of the workpiece per unit time becomes more. In addition, the pits on the surface of the workpiece will be larger or deeper, resulting in the increase of MRR and surface roughness. With the increase of the peak current, the particles of erosion produced per unit time increase, making it difficult for the particles of erosion to exit the discharge gap from the side. The phenomenon of secondary discharge increases, the width overcut will also become larger. The difficulty in discharging the erosion particles will cause a
Fig. 7  Flow field velocity change diagram of a single ultrasonic vibration cycle. a $t = \pi/10$. b $t = 3\pi/10$. c $t = \pi/2$. d $t = 3\pi/5$. e $t = 4\pi/5$. f $t = \pi$. g $t = 11\pi/10$. h $t = 13\pi/10$. i $t = 3\pi/2$. j $t = 8\pi/5$. k $t = 9\pi/5$. l $t = 2\pi$. 
(g) $t = \frac{11\pi}{10}$

(h) $t = \frac{13\pi}{10}$

(i) $t = \frac{3\pi}{2}$

(j) $t = \frac{8\pi}{5}$

(k) $t = \frac{9\pi}{5}$

(l) $t = 2\pi$

Fig. 7 (continued)
large amount of accumulation of erosion particles and the tool electrode to frequently produce secondary discharges, and therefore increasing the RTWR.

### 5.2 Effect of reference voltage on UEDM

Under the premise that other experimental conditions remain unchanged, the size of the reference voltage change, and its influence on the MRR, surface roughness, width overcut, and RTWR is studied. Figure 11 is the relationship curve between the reference voltage and the UEDM index. We can see from the figure that as the reference voltage increases, the workpiece MRR, surface roughness, and width overcut are gradually reduced, while the RTWR gradually increases. Figure 12 is the microscopic surface morphology of UEDM square holes formed in SiCp/Al composite materials at different reference voltages.

As the reference voltage increases, the gap between the two poles increases, and the number of open circuits during processing increases, so that the effective pulse discharge per unit time decreases and the MRR of the workpiece decreases. In addition, the increase of the gap between the two poles is also conducive to the discharge of erosion particles, reducing short-circuit arcing and other phenomena, so that the surface quality of the workpiece becomes better, and the roughness value is reduced accordingly.

**Table 1** Experimental parameters

| Project                  | Value or condition                                      |
|-------------------------|---------------------------------------------------------|
| Workpiece               | 20% volume fraction of SiCp/Al composite plate          |
| Tool electrode          | Copper with a bottom size of 15.6 mm x 13.6 mm         |
| Working fluid           | Spark oil                                               |
| Liquid supply method    | Immersion                                               |
| Processing polarity     | Electrode connected to negative electrode               |
| Processing depth        | 4 mm                                                    |

**Table 2** Factor level table

| Processing parameters   | Basic level   | Each parameter level |
|-------------------------|---------------|----------------------|
| Peak current (A)        | 37            | 5.6, 18.4, 37, 50, 64|
| The reference voltage (V)| 70            | 52, 60, 65, 70, 80   |
| Pulse interval (μs)     | 75            | 32, 56, 75, 130, 240 |
| Pulse Width (μs)        | 100           | 56, 100, 300, 750, 1800 |
removal conditions are getting better, and the secondary discharge phenomenon caused by the accumulation of erosion in the discharge gap is reduced, resulting in the reduction of width overcut. With the increase of the reference voltage, the discharge gap between the two poles increases. During discharge, the charged particles in the discharge channel have a longer distance to obtain a greater speed, which makes the kinetic energy of the charged particles increase. Because the mass of positive ions is much greater than that of electrons, the kinetic energy obtained by positive ions is much greater than that of electrons. Therefore, when the reference voltage increases, the increase in the loss of the positive ions to the electrode is greater than the increase in the erosion of the workpiece by the electrons so that the RTWR increases.

### Table 3  Factor level table

| Level | Pulse width (μs) | Pulse interval (μs) | Peak current (A) | The reference voltage (V) |
|-------|------------------|---------------------|------------------|--------------------------|
| 1     | 56               | 32                  | 18.4             | 60                       |
| 2     | 320              | 75                  | 37               | 70                       |
| 3     | 1800             | 240                 | 64               | 80                       |

### Table 4  Orthogonal test scheme

| Serial number | Pulse width (μs) | Pulse interval (μs) | Peak current (A) | The reference voltage (V) |
|---------------|------------------|---------------------|------------------|--------------------------|
| 1             | 56               | 32                  | 18.4             | 60                       |
| 2             | 56               | 75                  | 37               | 70                       |
| 3             | 56               | 240                 | 64               | 80                       |
| 4             | 320              | 32                  | 37               | 80                       |
| 5             | 320              | 75                  | 64               | 60                       |
| 6             | 320              | 240                 | 18.4             | 70                       |
| 7             | 1800             | 32                  | 64               | 70                       |
| 8             | 1800             | 75                  | 18.4             | 80                       |
| 9             | 1800             | 240                 | 37               | 60                       |

### 5.3 Effect of pulse interval on UEDM

In UEDM, the pulse interval will affect the deionization effect of working fluid between the electrodes. Under the premise that other experimental conditions remain unchanged, change the size of the pulse interval, and study its influence on MRR, surface roughness, width overcut, and RTWR. Figure 13 is the relationship curve between pulse interval and UEDM index. It can be seen from the
Fig. 10  Microtopography at different currents. a Peak current 5.6 A. b Peak current 18.4 A. c Peak current 37 A. d Peak current 50 A. e Peak current 64 A
figure that the MRR, surface roughness, and width overcut of the workpiece gradually decrease with the increase of the pulse interval. RTWR shows a wavy change with the pulse interval, but the overall change is small. Taking into account the influence of the error, the pulse interval in this experiment has little effect on RTWR. Figure 14 is the microscopic surface morphology of the square hole formed by UEDM in SiCp/Al composite material under different pulse interval values.

As the pulse interval increases, the number of pulse discharges decreases, which results in a decrease in MRR. With the increase of the pulse interval, the deionization becomes sufficient. The eroded aluminum matrix material and SiC particles also have more time to drain the processing gap, and the abnormal processing phenomena such as short circuit and arc drawing are reduced. The more stable is the processing, the smaller are the surface roughness and width overcut of the material. When the pulse interval continues to increase to 75 μs, the deionization and the discharge of the erosion will be relatively sufficient, which will cause the increase of the pulse interval to have a relatively small effect on the width overcut of the workpiece and surface roughness.

5.4 Effect of pulse interval on UEDM

Figure 15 is the relationship curve between pulse width and MRR, surface roughness, width overcut, and RTWR. It can be seen from the figure that as the pulse width increases, the MRR first increases and then decreases, the surface roughness and width overcut gradually increase, and the RTWR first decreases and then increases. Figure 16 is the microscopic surface morphology of the square hole formed by UEDM in SiCp/Al composite material at different pulse width values.

When the pulse width is in a smaller range, as the pulse width increases, the pulse discharge time per unit time is prolonged, the surface of the workpiece can get more heat, and the MRR of the workpiece increases. But with the pulse width continues to increase, under the heat generated by the long-term pulse discharge, the low-melting aluminum matrix material will melt in a large amount, and many SiC
Fig. 12 Microtopography at different voltages. a The reference voltage 52 V. b The reference voltage 60 V. c The reference voltage 65 V. d The reference voltage 70 V. e The reference voltage 80 V
particles will fall out of the matrix. A large amount of erosions in the discharge gap makes the discharge state worse. Frequent occurrence of abnormal discharge phenomenon causes the MRR to decrease. Therefore, as the pulse width increases, the MRR first increases and then decreases. As the pulse width increases, the energy of a single pulse discharge increases, and the amount of erosion processed by a single discharge increases. The pits on the surface of the workpiece will be larger or deeper, which will eventually lead to the roughness of the processed surface increasing accordingly. At the same time, as the pulse width increases, the number of materials to be eroded increases, and frequent secondary discharges lead to an increase in the amount of width overcut. From Fig. 15, when the pulse width is 300 μs, the RTWR reaches the minimum.

6 Orthogonal test results and parameter optimization

Table 5 shows the experimental results.

6.1 Parameter optimization based on the gray relational analysis method

6.1.1 Calculate the gray correlation value

In the actual production process of UEDM forming holes in SiCp/Al composites, not only one of the above-mentioned test indicators is investigated separately, but the comprehensiveness between the various test indicators should be investigated. Therefore, this experiment is based on the gray relational analysis method to find the best combination of process parameters for the comprehensive advantages of the four process indicators. The larger the gray correlation value, the better the performance.

The gray correlation coefficient and gray correlation values are shown in Table 6.

Obtained from Table 6, when the pulse width is 56 μs, the pulse interval is 32 μs, the peak current is 18.4 A, and the reference voltage is 60 V, the gray correlation value reaches the maximum, which is 0.8481.
Fig. 14 Microtopography of different pulse intervals. a Pulse interval 32 μs. b Pulse interval 56 μs. c Pulse interval 75 μs. d Pulse interval 130 μs. e Pulse interval 240 μs
6.1.2 Analysis of optimal processing parameters

According to the principle of the gray correlation analysis method, if gray relational value is the maximum value, it indicates that the process parameter makes the maximum correlation of various process indicators at this level, that is, the level is considered the four indicators reached the optimal. Respectively add up the correlation values of each process parameter at each level in Table 6 and then calculate the average value, and obtain the average value of each level under each process parameter in turn, as shown in Table 7.

According to Table 7, when the peak current is 18.4 A, the reference voltage is 60 V, the pulse interval is 75 μs, and the pulse width is 56 μs. This group of processing parameters is the optimal processing parameters. In addition, the order of the impact on the overall performance from large to small is pulse width, peak current, pulse to pulse, and reference voltage.

6.2 Verification experiment

The parameters of the verification experiment are the optimal combination of processing parameters found by the gray relational analysis method. In the verification test, the factors other than the four processing parameters are strictly controlled to be the same as the orthogonal test settings. Through data analysis before and after processing, the results are: the MRR of the workpiece is 21.192 mm³/min, the surface roughness $Ra$ is 8.114 µm, the width overcut is 235 µm, and the RTWR is 5.285%. Calculating the gray correlation value of the results obtained from the verification experiment, the calculated value reaches the maximum. The gray correlation value reaches 0.8511, which is greater than the maximum gray correlation value of 0.8481 obtained by the orthogonal experiment. Therefore, the optimized parameter combination is the optimal processing parameter combination scheme.
Fig. 16 Microtopography at different pulse widths. a Pulse width 56 μs. b Pulse width 100 μs. c Pulse width 320 μs. d Pulse width 750 μs. e Pulse width 1800 μs
This paper analyzes the influence of ultrasonic vibration on EDM from the machining mechanism, and carried out theoretical analysis and simulation calculation on the flow field of machining gap. With the aid of ultrasonic vibration, the single-factor test of SiCp/Al composite forming machining was carried out on the UEDM test platform. The effects of peak current, reference voltage, pulse interval and pulse width on MRR, width overcut, surface roughness and the RTWR were explored. Through orthogonal experiment, combined with gray correlation method, the combination of processing parameters that makes the comprehensive performance of processing indexes reach the best is obtained. The specific conclusions are as follows:

1. The erosion mechanism of EDM SiCp/Al composite material was studied. The effect of tool electrode on the discharge channel, discharge gap, erosion material discharge, and machined surface in EDM after ultrasonic vibration is analyzed. The analysis results show that the periodic ultrasonic vibration of the tool electrode can effectively reduce the occurrence of unstable processing, and can improve the processing efficiency and the surface quality of the workpiece.

| Serial number | Material removal rate (mm³/min) | Surface roughness (μm) | Width overcut (μm) | Relative loss rate of electrode (%) |
|---------------|--------------------------------|------------------------|-------------------|-----------------------------------|
| 1             | 21.383                         | 8.546                  | 243               | 5.01                              |
| 2             | 42.628                         | 9.78                   | 244               | 11.41                             |
| 3             | 22.098                         | 10.55                  | 228               | 20.36                             |
| 4             | 51.891                         | 14.848                 | 347               | 8.34                              |
| 5             | 121.837                        | 17.605                 | 360               | 10.63                             |
| 6             | 21.462                         | 13.668                 | 303               | 4.51                              |
| 7             | 69.371                         | 19.238                 | 502               | 17.66                             |
| 8             | 8.962                          | 14.41                  | 353               | 5.61                              |
| 9             | 48.032                         | 16.739                 | 490               | 12                                |

| Test number | Gray correlation coefficient | Material removal rate | Surface roughness | Width overcut | Relative loss rate of electrode |
|-------------|------------------------------|-----------------------|-------------------|---------------|--------------------------------|
| 1           | 0.4885                       | 1                     | 0.9395            | 0.9642        | 0.8481                         |
| 2           | 0.5478                       | 0.8805                | 0.9357            | 0.6613        | 0.7563                         |
| 3           | 0.4903                       | 0.8193                | 1                 | 0.4595        | 0.6923                         |
| 4           | 0.5784                       | 0.5905                | 0.6618            | 0.7786        | 0.6523                         |
| 5           | 1                            | 0.5008                | 0.6383            | 0.6876        | 0.7067                         |
| 6           | 0.4887                       | 0.6396                | 0.7564            | 1             | 0.7212                         |
| 7           | 0.6465                       | 0.4595                | 0.4595            | 0.5061        | 0.5179                         |
| 8           | 0.4595                       | 0.6078                | 0.6507            | 0.9245        | 0.6606                         |
| 9           | 0.5652                       | 0.5259                | 0.4706            | 0.6427        | 0.5511                         |

| Process parameters | Average of gray correlation degree | Max–min |
|--------------------|-----------------------------------|---------|
|                    | Level 1   | Level 2   | Level 3   |         |
| Pulse width (μs)   | 0.7656    | 0.6934    | 0.5765    | 0.1891  |
| Pulse interval (μs)| 0.6728    | 0.7079    | 0.6549    | 0.0530  |
| Peak current (A)   | 0.7433    | 0.6532    | 0.6390    | 0.1043  |
| The reference voltage (V) | 0.7020 | 0.6651    | 0.6684    | 0.0369  |

7 Conclusion

This paper analyzes the influence of ultrasonic vibration on EDM from the machining mechanism, and carried out theoretical analysis and simulation calculation on the flow field of machining gap. With the aid of ultrasonic vibration, the single-factor test of SiCp/Al composite forming machining was carried out on the UEDM test platform. The effects of peak current, reference voltage, pulse interval and pulse width on MRR, width overcut, surface roughness and the RTWR were explored. Through orthogonal experiment, combined with gray correlation method, the combination of processing parameters that makes the comprehensive performance of processing indexes reach the best is obtained. The specific conclusions are as follows:

1. The erosion mechanism of EDM SiCp/Al composite material was studied. The effect of tool electrode on the discharge channel, discharge gap, erosion material discharge, and machined surface in EDM after ultrasonic vibration is analyzed. The analysis results show that the periodic ultrasonic vibration of the tool electrode can effectively reduce the occurrence of unstable processing, and can improve the processing efficiency and the surface quality of the workpiece.
2. With the help of FLUENT, the law of the velocity change of the flow field in the machining gap and the discharge of the erosion particles are solved. It is concluded that the ultrasonic vibration of the tool electrode can accelerate the flow rate of the working fluid in the discharge gap, promote the removal of erosion particles from the processing gap, and prevent erosion particles from accumulating in the discharge gap.

3. On the UEDM test platform, single-factor experiment of forming square holes in SiCp/Al composites was carried out. The research results show that with the increase of the peak current, the MRR, surface roughness, and width overcut and RTWR show a gradually increasing trend. With the increase of the reference voltage, the MRR, surface roughness, and width overcut show a gradually decreasing trend, while the RTWR is gradually decreasing.

4. Based on the single factor test, the orthogonal test of UEDM machining SiCp/Al composite material hole was carried out, and the combination of gray correlation analysis method was used to find the combination of processing parameters that maximized the comprehensive performance of the four processing indicators. The peak current is 18.4 A, the reference voltage is 60 V, the pulse interval is 75 μs, and the pulse width is 56 μs, which is the optimal combination of processing parameters.

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