Study on Thermal Erosion Process of SiC\textsubscript{p}/Al Composite Material in EDM

Yu Liu, Bingchao Wang, Wenchao Zhang, Shengfang Zhang*, Fujian Ma, Dapeng Yang and Zhihua Sha

School of Mechanical Engineering, Dalian Jiaotong University, Dalian, China 116028

*E-mail: zsf@djtu.edu.cn

Abstract. SiC\textsubscript{p}/Al composites are composed of two different material properties of aluminium matrix and SiC particles. In order to deeply study the erosion process of SiC\textsubscript{p}/Al composite in EDM, a single pulse discharge model of SiC\textsubscript{p}/Al composites was established. The melting and solidification model and the volume of fluid (VOF) model in Fluent software were used to simulate the thermal erosion process of EDM. The change of temperature field and the formation of molten pool in the heating process of SiC particles and Al matrix are analysed. The number of SiC particles in molten pool is counted and analysed, and the number of SiC particles in molten pool was counted, the simulation results were verified by the single pulse EDM experiments. The results show that the depth-diameter ratio of the molten pool increases with the increase of the pulse width, and decreases with the increase of the peak current. The number of melted particles in molten pool is basically unchanged.

Keywords: EDM; SiC\textsubscript{p}/Al Composite Material; Thermal erosion process; SiC particle; Depth-diameter ratio

1. Introduction

SiC\textsubscript{p}/Al composite is a typical particle reinforced metal matrix composites (PRMMCs) with excellent properties such as high thermal conductivity, high elastic modulus and high hardness, it is widely used in military and aerospace fields. Due to its non-contact processing, EDM is not limited by the strength and hardness of the material, and has better advantages in the processing of SiC\textsubscript{p}/Al composites. However, EDM machining PRMMCs have serious problems such as severe tool wear and difficult removal of debris, which limits the application of EDM machining PRMMCs. Therefore, it is very necessary to study the erosion mechanism of SiC\textsubscript{p}/Al composites in EDM to solve the problems existing in the EDM of PRMMCs. The processing and discharge process is very short, the processing gap is narrow, which is not conducive to direct detection and observation, it is very suitable for simulate the thermal erosion process of EDM by finite element numerical simulation method. At present, in terms of material thermal erosion, Feng Ruuye et al. have simulated the temperature field of TiC/Ni ceramic EDM, established the random particle distribution model, and explored the change rule of discharge parameters on the erosion volume[1]. Gao Yang et al. conducted thermal analysis on the erosion crater of the discharge, and believed that the heat source in the plasma channel was the main driving force for the erosion of the workpiece material. Under different peak current and pulse width, the model could well predict the changes of the depth and radius of the erosion crater[2]. Weingartner et al. studied the temperature field generated by point heat source, dish heat source and
time-varying heat source through simulation, found that time-varying heat source was more consistent with the actual processing results[3].

In summary, most of the workpiece materials used in the thermal erosion process of EDM are single component materials or the reinforcement particles and matrix are considered as a whole analysis, the properties of the particles and matrix are rarely distinguished. This paper establishes a model in which SiC particles are uniformly distributed in the aluminium matrix, set different material properties to the SiC particles and the aluminium matrix, and using the melting and solidification model to simulate the single pulse discharge thermal erosion process of SiCp/Al composites, it is helpful to explore the regularity of erosion change of discharge craters.

2. Establishment of Single Pulse EDM Model

2.1. Physical model

Figure 1 depicts the single pulse discharge process of SiCp/Al composite material EDM. Under pulse discharge, a plasma channel is formed between tool electrode and workpiece material, which is composed of plasma generated by ionization of dielectric. This process converts the pulsed power into thermal energy and enters the workpiece through heat conduction. At high temperature, the workpiece material is molten and vaporized.

\[ q(r) = \frac{k \cdot \eta \cdot U(t)I(t)}{\pi R^2} \cdot \exp\left(-\frac{k^2 r^2}{R^2(t)}\right) \]  

where, \( U(t) \) (V) is the voltage, \( I(t) \) (A) is the current; \( \eta \) for the energy distribution coefficient of anode workpiece, which is 0.3; \( R(t) \) (m) is \( t \) moment plasma channel radius; \( k \) is the concentration factor of the heat source, which is 3.

2.2. Mathematical model

The heat source distribution of EDM is close to the Gaussian distribution, and the heat flux density in the plasma channel at the point \( r \) away from the center of discharge point can be expressed as[4]:

\[ q(r) = \frac{k \cdot \eta \cdot U(t)I(t)}{\pi R^2} \cdot \exp\left(-\frac{k^2 r^2}{R^2(t)}\right) \]  

2.3. Model Schematics and Boundary Conditions

Figure 2 shows the composite material model of thermal erosion phase. The matrix and the particles are simplified into a two-dimensional model. To reduce the amount of calculation, a symmetric model is established, and only the influence of the heat source on the workpiece is considered. The depth-to-diameter ratio of the discharge crater is generally less than 1, so the length of the model along the radial direction is 250μm, and the length along the depth direction is 100μm. According to Yu Xiaolu et al[5], the particle size of SiC is distributed in 3-8μm, the model has a particle size of 8μm. The uniform distribution model of the particles, the circular area is the particles, and the rest is the aluminium matrix, which respectively gives their respective material properties. The interface boundary is set as the connection between particle and matrix, which can realize data exchange. Table 1 shows material selection and parameter settings.
3. Simulation results and analysis

3.1. Changes of molten pool morphology at different discharge times

Figure 3 shows the formation of the molten pool on the surface of the workpiece during discharge and the presence of the particles. In red, the liquid fraction is 1, representing the completely melted material. In blue, the liquid fraction is 0, indicating that the material is solid. As shown in Figure 3 (a), the matrix material begins to melt at 1μs, and partial particles begin to melt because the melting point of the SiC particle phase is higher than the Al matrix. As the discharge progresses, at 50μs, molten pool tends to be flat, the shape is basically no change, and some particles exist in the molten matrix because they have not reach melting point, as shown in Figure 3 (b).

3.2. Effect of pulse width on thermal erosion of materials

Figure 4 and Figure 5 are the curves of temperature along the radial direction and depth direction at different pulse widths when the peak current is 15A. The smaller the pulse width is, the greater change of temperature is. As the pulse width increases, the highest temperature on the surface of the workpiece first decreases and then rises when the pulse width is 40μs. Because as the radius of the discharge channel expands, the energy gradually decreases, and the temperature decreases. After the optimal pulse width is reached, the discharge channel no longer changes, the heat in the molten pool accumulates, and the temperature begins to rise. The temperature does not change substantially in the radial direction at 15μs, but the temperature in the depth direction drops sharply. This is attributed to the fact that the EDM heat source is mainly a surface heat source, and is approximately Gaussian distribution, the heat source is directly loaded in the radial direction. Due to the large temperature gradient in the depth direction, the temperature changes rapidly in a small range.
Figure 4. Temperature change in radial. Figure 5. Temperature change in depth.

Figure 6 shows the radius and depth of the molten pool increase with pulse width increase, and the change of radius length is large at first and then low with pulse width increased. Because there is thermal convection in the radial direction and heat dissipation of the dielectric, while the depth direction is only thermal conduction. In addition, when the optimal pulse width is reached, the radius of plasma channel remains unchanged, because the temperature of the heat source center is higher than the edge, so the depth direction changes faster than the radius. From Figure 7, the depth-to-diameter ratio of the molten pool increases with pulse width increases, and basically unchanged from 30us to 40μs pulse width.

Figure 6. Molten pool size. Figure 7. Molten pool depth-diameter ratio.

3.3. Effect of peak current on thermal erosion of materials

Figures 8 and 9 are the curves of the temperature in the radial direction and the depth direction at different peak currents with a pulse width of 50us. It can be seen that the temperature in the radial direction and the depth direction increase with the peak current increases. Because discharge current directly affects the value of the heat flux density, and the increase of discharge energy will lead to the increase of overall temperature, but the change of depth direction is small.

Figure 8. Temperature change in radius. Figure 9. Temperature change in depth.

Figure 10 shows both the radius and the depth increase with current increases, but the radius changes significantly, while the depth does not change after 15A. This is because when the current increases, and the surface temperature of the workpiece rises and material melts, the coefficient of thermal conductivity gradually decreases, while the radial direction not only transfers heat from the molten matrix, heat source acts directly on the surface of the material, so the temperature along the radial direction keeps increasing, but the depth is not changed when it increases to a certain value. The
curve of the depth-to-diameter ratio of the surface molten pool under different peak current conditions is shown in Figure 11. The peak current increases, the depth-to-diameter ratio decreases continuously.

3.4. Changes and statistics of particles in molten pool
Figure 12 shows the variation of the particles inside the molten pool at different discharge moments. The results show that at 0.6μs the two particles near the discharge center begin to melt, and becomes an irregular circular shape. At 40μs, it is found that the third and fourth particles also began to melt and is melted completely at 70μs. Comparing the edge of the crater at 40μs and 70μs, it can be seen that the bottom of the crater is not flat at 40μs. This is because the particles on the edge of the crater did not reach the melting point, and the particles were between the molten pool and the solid matrix, making the bottom of the crater not flat.

Figure 13 shows the change curve of the number of particles in the molten pool under different peak currents when the pulse width is 50μs. As the peak current increases, the number of particles in the molten pool also gradually increases, because the area of the molten pool becomes larger with current increasing. However, there are two particles that are melt completely when the current is 5A. And there are still only two particles when the current is 25A, which means that the amount of molten particles do not change with the increase of the peak current. In actual processing, if the number of particles increase in the molten pool, it will hinder or even stop the next discharge, which is not conducive to the discharge. Therefore, proper current reduction is beneficial to the erosion of the material.

4. Experimental results and analysis
The experiments using single pulse EDM power supply, table 2 shows the selection of machining parameters.
The experimental results are shown in Figure 14. The maximum depth of the crater is 17μm and the width is 196μm. Comparing the simulation results obtained by the same simulation parameters, the crater diameter is basically the same, and the depth of the experimental processing is smaller than that of simulation. Because the debris exists in the molten pool during the actual processing, making the processing depth affected, but these factors are not considered in the simulation, and the simulation results are basically reasonable within the allowable error range.

![Crater morphology](image1)

(a) The crater morphology of the experimental results.

![Experimental measurement results](image2)

(b) Experimental measurement results.

![Simulation results](image3)

(c) Simulation results.

**Figure 14.** Comparison of EDM experiments and simulation results.

### 5. Conclusion

In this paper, considering the composite properties of SiC<sub>p</sub>/Al materials, the model of SiC<sub>p</sub>/Al composites with uniform distribution of SiC particles was established. The material thermal erosion process of single pulse EDM was simulated and the simulation was verified by experiments. The results show that the temperature in the workpiece decreases first and then increases with the increase of pulse width, increases with the increase of peak current. The depth-to-diameter ratio increases with the increase of pulse width, and decreases with the increase of peak current. The number of melted particles are basically unchanged and reducing the current appropriately will benefit the discharge in the processing.

### Acknowledgments

The financial support from the National Natural Science Foundation of China under grant no. 51875074, Scientific Research Platform Foundation of Liaoning Province under grant no. JDL2016006, and General Program of Natural Science Foundation of Liaoning Province under grant no.20180550425 is acknowledged.

### References

[1] Feng Ruiye. Study on Temperature Filed Simulation During Electro-Discharge Machining of TiC/Ni Cermet. *J. Electric Machining & Mould*, 2016(2):1-5

[2] Gao Yang, Liu Lin, *et al*. Finite Element Thermal Analysis of EDM Crater *J. Electric Machining & Mould*, 2008(2): 8-11.

[3] E. Weingärtner, F. Kuster, *et al*. Modeling and simulation of electrical discharge machining *J. Procedia Cirp*, 2012, 2(7): 74-78

[4] Zhang Qingfen. Modeling and simulation of SiCp/Al composite EDM *D. Harbin Institute of Technology*, 2011.

[5] Yu Xiaolu, Zhang Haitao, *et al*. Quantitative Research of Statistical Characters of Particle in SiC Particle Reinforced Aluminum Matrix Composit *J. China Materials Science Technology & Equipment*, 2011(4):30-32.