Adopting composite geometric models for the heat conduction simulation of SiC\textsubscript{p}/Al matrix composites in the electrical discharge machining

Jipeng Chen\textsuperscript{1a}, Guojian He\textsuperscript{2}, Lin Gu\textsuperscript{2}

\textsuperscript{1}School of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China
\textsuperscript{2}State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China
\textsuperscript{a} Corresponding author: cjp sjtu@163.com

Abstract. In the heat conduction simulations of electrical discharge machining, SiC\textsubscript{p}/Al composites are generally considered as homogeneous materials for simplification. This paper proposes that the composite geometric models containing SiC reinforcements could be built to improve the homogeneous material model. Three SiC particle equivalent shapes, circle, diamond, and triangle are selected and compared by conducting heat transfer simulations. The results demonstrated that the composite geometric model utilizing a circle SiC particle equivalent shape is better. This paper provides ideas and references for the modeling of composite materials in the heat transfer simulations of electrical discharge machining.

1. Introduction

SiC\textsubscript{p}/Al composites consist of the Al matrix and SiC particle reinforcement. Although SiC\textsubscript{p}/Al composites are finding more and more applications in industries such as automotive, aerospace, and electronics, the machining of these composites is still regarded as a difficult problem. Non-conventional machining processes like electrical discharge machining have been adopted for the machining of SiC\textsubscript{p}/Al composites by many researchers [1-4]. Recently, researchers are trying to simulate heat transfer of the electrical discharge machining SiC\textsubscript{p}/Al composites to study the processing mechanism. For instance, Tang et al. [5] established a thermo-electrical coupling simulation model of powder mixed electrical discharge machining (PMEDM) SiC\textsubscript{p}/Al functionally graded materials. Gu et al. [6] built a heat conduction simulation model of high energy electrical discharge (pulsed arc) machining of SiC\textsubscript{p}/Al composites.

In the above simulation models, the SiC\textsubscript{p}/Al composites are generally considered as homogeneous materials, the thermal properties of the equivalent material are calculated according to the parameters of the matrix material and the reinforcement. One of the disadvantages of the equivalent material model is that it is difficult to consider the interface thermal resistance between the matrix and reinforcement material. To solve this problem, composite geometric models which consist of matrix domain and SiC particle reinforcement domain can be employed. However, the reinforcement SiC particles have tiny irregular shapes which make the construction of composite geometric models very difficult. Chen et al. [7] reported a novel SiC particle-Al matrix cell geometric model to simulate the heat conduction of SiC\textsubscript{p}/Al composites in the electrical discharge machining (single pulsed arc). In that model, a square which contains SiC particle domain and the matrix domain was proposed, and the SiC particle was...
simplified as a circle. In fact, besides circle shape, other equivalent shapes, such as triangle and diamond shapes can also be considered as the representation of SiC particles. This paper aims to reveal the influence of SiC particle equivalent shapes on the heat transfer simulation model of the electrical discharge machining.

2. Composite geometric models
As shown in Fig.1, to imitate the physical structure of SiC/Al composites, the concept of SiC/Al cell was proposed [7]. A SiC/Al cell is composed of two domains, one domain is the matrix and the other is the reinforcement, the reinforcement domain is surrounded by the matrix domain. The combination of cells forms the SiC/Al composite materials. In this study, 3 kinds of SiC equivalent shapes are employed to represent reinforcement domains, namely circle shape, diamond shape, and triangle shape.

![Fig.1 SiC/Al cell with different SiC equivalent shapes](image)

The diameter of the circle ($D_{par}$), the side length of the diamond ($L_{dia}$) and the triangle ($L_{tri}$) are calculated according to SiC fraction and cell area. The area of the circle, diamond, and triangle are the same to make sure they have the same silicon carbide volume fraction.

\[
D_{par} = 2 \sqrt{\frac{f_{vol} \times L_{ce}^2}{\pi}} \quad (1)
\]
\[
L_{dia} = \sqrt{f_{vol} \times L_{ce}} \quad (2)
\]
\[
L_{tri} = 2L_{ce} \sqrt{\frac{f_{vol}}{\sqrt{3}}} \quad (3)
\]

where $L_{ce}$ is the side length of the SiC/Al cell, $f_{vol}$ is the volume fraction of SiC. In this study, $L_{ce}$ and $f_{vol}$ are set as constant, the values are 100 μm and 20 vol. % respectively.

3. Simulation utilizing composite geometric models
To compare the performance of the different composite geometrical models in the electrical discharge machining simulations, two-dimensional axisymmetric heat transfer simulations are employed. The simulations use Fourier’s law as governing equations, which is expressed as

\[
q = -k \nabla T \quad (4)
\]
\[
(\partial T/\partial t + u \cdot \nabla T) + \nabla q = -\alpha T \cdot dS/dt + Q \quad (5)
\]

where $k$ is the thermal conductivity (W/(m-K)), $\rho$ is the density (kg/m$^3$), $C_p$ is the specific heat capacity at constant pressure (J/(kg-K)), $u$ is the velocity vector (m/s), $q$ is the heat flux by conduction (W/m$^2$), $\alpha$ is the coefficient of thermal expansion (1/K), $S$ is the second Piola-Kirchhoff stress tensor (Pa), $Q$ is additional heat sources (W/m$^3$).
In the heat transfer simulations, the Gaussian distribution heat flux \( q(r) \) is employed as a heat source, which is expressed as

\[
q(r) = \frac{3}{1 - \exp(-3)} \cdot \frac{f \times U \times I}{\pi r_p^2} \cdot \left[ -3 \left( \frac{r}{r_p} \right)^2 \right]
\]

where \( r \) is the distance from the center of the plasma column, \( f \) is the energy distribution coefficient and a value of 0.39 is generally adopted [8-9]. \( U \) is discharge voltage, \( I \) is discharge current, \( r_p \) is the radius of the plasma heating area. In this study, \( U = 25 \) V, \( I = 100 \) A, and \( r_p = 0.55 \) mm [6-7]. The simulations are conducted based on COMSOL Multiphysics 5.4 software. The three geometrical models with different SiC equivalent shapes are meshed with the same parameters, the minimum mesh size is 0.019 mm and the maximum mesh size is 0.02 mm. The meshed SiC/Al geometrical models are shown in Fig.2. The thermal properties of SiC and Al are from ref. [7], note that this study considers the matrix-reinforcement interface thermal resistance, but do not consider the phase change of both matrix and reinforcement materials to simplify the calculation.

Fig.2 Meshed SiC/Al geometrical models with different SiC equivalent shapes

4. Results and discussion

Fig.3 shows the temperature distribution in SiC/Al composite models with different SiC equivalent shapes. With the same heat source and the same acting time, the temperature in the SiC/Al models is not the same. The surface highest temperature of the circle shape model is much lower than that of the diamond shape and triangle shape model. Lower surface temperature means that the heat applied to the model tends to conduct and diffuse, which means that the circle shape has less effect on the model’s overall thermal diffusivity.

From the observation of the temperature gradient, it is found that different SiC equivalent shapes have an obvious influence on the temperature distribution. This is because these models consider the matrix-reinforcement interface heat resistance, different interface shape changes heat propagation directions which brings the difference of local temperature field. Among them, the circle shape model has less influence on the distortion on the temperature field than that of the diamond shape and triangle shape model.
In the electrical discharge machining, craters are generated on the $\text{SiC}_p/\text{Al}$ workpiece surface when the high-temperature heat source is applied. The formation of the crater is very complicated which includes the melting and evaporation of matrix and reinforcement, among which the melting of aluminum is dominant (melting point 933 K). The crater dimension is an important index to indicate the accuracy of the simulation model.

Fig. 4 shows the crater generated in $\text{SiC}_p/\text{Al}$ composite models with different SiC equivalent shapes. It can be known that the circle shape model generates the smallest crater than the other two models. Since the circle shape has less effect on the heat transfer compared with the other two models, the input heat flux spread faster and form a smaller crater.
Fig. 4 Comparison of crater dimension

In previous work, Gu et al. [6] conducted experiments of electrical discharge machining of 20 vol.% SiC/Al and measured the craters with a confocal microscope. A comparison between the simulation results and experimental results are listed in Table 1.

| Item                  | Crater radius (mm) | Crater depth (mm) |
|-----------------------|--------------------|-------------------|
| Experimental value    | 0.578              | 0.246             |
| Circle shape model    | 0.55               | 0.34              |
| Diamond shape model   | 0.70               | 0.46              |
| Triangle shape model  | 0.71               | 0.48              |

It can be observed that the circle shape model generates a crater which dimension is the closest to the experimental value among the three models. Furthermore, the circle shape model performances better than Gu et al.’s model [6] because considering the interface heat resistance. In brief, the composite geometrical model which employs a circle shape as SiC reinforcement is more accurate, and can be used
in the heat transfer simulations. In addition, this paper explains why a circle shape composite model was adopted by Chen et al.[7] in the heat conduction simulations of machining SiCp/Al composites.

5. Conclusions
Three composite geometric models containing different SiC particle equivalent shapes are built in this paper. The performance of the three models is compared by employing heat transfer simulations. The following conclusions can be drawn:

1) The surface highest temperature of the circle shape model is much lower than that of the diamond shape and triangle shape model, which means that the circle shape has less effect on the model's overall thermal diffusivity.

2) SiC equivalent shapes have an obvious influence on the temperature distribution. Compared with the diamond shape and triangle shape, the circle shape has less impact on the temperature distortion.

3) The circle shape model generates the smallest crater than the diamond shape and triangle shape models.

4) The circle shape model generates a crater whose dimension is closer to the experimental value compared with the diamond shape and triangle shape models.

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