Theoretical and micro simulation study on cutting temperature of SiCp/Al by ultrasound vibration cutting

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Abstract. SiCp/Al material is isotropic and belongs to hard machining materials. Cutting temperature has a great influence on the optimization of machining process and tool life. In this paper, the analytical expression of temperature field in ultrasonic vibration turning of SiCp/Al composites is obtained by iteration of heat source method. The dynamic physical simulation model of ultrasonic vibration cutting SiCp/Al cutting temperature is established. Particles are randomly distributed in the matrix, temperature curves of particles above, middle and below the cutting path with time are analysed, the trend of the temperature curve of particles with time is that it increases first, then decreases, then increases, and finally stabilizes.

1. Introduction
Silicon Carbide Particle Reinforced Aluminum Matrix Composite is widely used in the energy sector, aerospace and automotive industries [1]. This material has poor machinability, high cutting temperature, severe tool wear, etc., and belongs to difficult-to-machine materials. Ultrasonic vibration cutting developed in Japan in the late 1950s uses pulsed cutting as its unique cutting feature. It has been proven to effectively reduce cutting forces, can greatly reduce surface roughness, improve machining accuracy and extend tool life. The technology is now more widely used in cutting matrix composites containing hard and brittle reinforcing phases [2,3]. In China, there are very few simulation studies on the cutting temperature field of SiCp/Al composites. Most of them are experimental studies. There is less analysis of the temperature field on the micro level of cutting. This is difficult to explain the mechanism of the temperature generation of SiCp/Al vibration cutting from a microscopic level, so it is necessary to carry out research on the cutting temperature of SiCp/Al composite ultrasonic vibration cutting. He Zhifeng et al conducted a temperature measurement test on dry cutting of 45 hardened steel with coated cemented carbide tools, analyzed the influence of cutting parameters on the cutting temperature, and proved that the cutting speed had the greatest effect, and the cutting temperature was significantly reduced after the coating of the tool [4]. Cheng Xueli used the natural thermocouple method to measure the temperature of SiCp/Al composites under ordinary cutting and ultrasonic cutting, and found that the temperature of ultrasonic vibration cutting was about 20° C lower than that of ordinary turning [5]. Yue Caixu used ABAQUS software to simulate the hard cutting of hardened steel with Polycrystalline Cubic Boron Nitride (PCBN) tools and explored the effect of different cutting edge shapes on the cutting temperature [6]. In the processing of particle-reinforced metal matrix composite materials, ultrasonic vibration cutting technology has a good cutting effect, but the temperature field of metal matrix composites for vibration cutting needs further study.
2. Analysis of temperature field of SiCp / Al composite vibration turning

2.1. Establishment of heat transfer model in vibration turning

In the process of particle-reinforced metal matrix composites, the generation and transfer of cutting heat is affected by many factors. Therefore, the following assumptions are made for the temperature field.

1. The effect of cutting force is not considered during the cutting process, all the work done by the cutting force is converted into cutting heat.
2. The convective heat transfer factor of the workpiece surface and air is not considered.
3. The workpiece is assumed to be a semi-infinite body and is regarded as an adiabatic boundary.

During the cutting process, the cutting heat in the contact area between the rear face of the tool and the workpiece is mainly due to frictional heat generation [7]. The presence of brittle SiC particles in particle-reinforced aluminum-based composite materials increases the proportion of heat generated by friction on the rear face in the cutting heat. The tool cannot be sharp enough in actual condition. The existence of the blunt round radius causes the cutting surface to generate cutting force, which increases the heat of the cutting surface.

As shown in Figure 1, $\phi$ is the shear angle and the point A is the critical point of the separation layer. The material below the separation surface of the workpiece will eventually become the processed surface through the frictional contact between the tool and the cutting surface. The tool arc $AB$ will press and rub the workpiece, and the arc $BC$ will directly contact the workpiece. The arc $AB$ and the arc $BC$ together constitute the length of arc $AC$ of the rear friction zone.

![Figure 1. Schematic diagram of the cutting area.](image)

The arc length of $AB$ can be obtained from:

$$ MB = \frac{R}{\pi} \left( \frac{\pi}{2} - \omega \right) $$

(1)

In the formula, $R$ is the blunt round radius of the tool tip and the $\omega$ is angle between the combined cutting force and the feed direction. According to the literature [8] the $l_f$ length of the chip contact with the rake face:

$$ l_f = \frac{h \sin \frac{\pi}{4}}{\sin \phi \sin \left( \frac{\pi}{4} + \phi - \gamma_o \right)} $$

(2)

In the formula, $h$ - cutting thickness, $\phi$ - cutting angle, $\gamma_o$ - tool rake angle.

Some scholars observed the wear track on the rear face of the tool after cutting with a microscope and found that the contact $l_f$ length between the rear face and the workpiece surface was less than onetenth of the contact length of the rake face, so the arc $BC$ in this study was taken $1/10 l_f$. So the $l_f$ length of the friction zone of rear face is:
Assume that the friction between the workpiece and the rear face during cutting is adhesive friction. Let the friction stress on the rear face be $\tau_f$, approximately equal to the friction stress on the rake face, $b$ is a cutting width. In this formula, $v_c$ is the cutting speed, that is, the rear face friction speed. Therefore, the heating intensity of the surface temperature field $Q_t$ of the ultrasonic vibration cutting workpiece is:

$$Q_t = W_{f_i} = F_{f_i}v = \tau_f b v_i = \tau_f b v_i \left( \frac{R}{\pi} \left( \frac{\pi}{2} - \omega \right) + \frac{h \sin \frac{\pi}{4}}{10 \sin \phi \sin \left( \frac{\pi}{4} + \phi - \gamma_0 \right)} \right)$$

(4)

As shown in Figure 2, when the temperature field analytical formula is established, for simplicity, this heat source can be regarded as a linear heat source $l$. In the process of ultrasonic vibration cutting, the heat source model is regarded as a moving finite-length heat source. The linear heat source moves along the X-axis direction on the plane ABB_1A_1. Its speed is $v$, the length of the heat source is $L$, and the heat flux is $q(t)$.

![Figure 3. Triangular distribution of heat source density.](image)

Because the ultrasonic vibration cutting has the performance of pulse separation, the heat generation intensity of the tool also changes regularly according to the cutting state of the tool. In order to simplify the calculation, $q$ is approximated as a linear monotonic increase, the heat intensity decreases to zero after the tool cuts out of the workpiece, so the heat source density of ultrasonic vibration cutting adopts a triangular distribution. The triangle-shaped heat source density distribution is shown in Figure 3. The formula for the heat source density of the triangle distribution is $q(t) = Q_L E(t)$, $E(t)$ is the probability density function of the triangle distribution, $T_1$ is the cutting cycle, $f_1$ is the ultrasonic vibration frequency, $\eta$ is the ratio of cutting time to cutting cycle \[9\].

2.2. Modeling of temperature field in vibration turning of SiCp/Al composites

The heat source method is derived by solving the differential equation of heat conduction by Fourier transform method. The premise of using heat source method to establish the heat conduction field model of solid is to determine the heat source. The point heat source in the infinite medium with instantaneous static heating is adopted in this paper. The analytic expression of its temperature field is shown in equation (5):

$$T_M = \frac{Q_d}{c \rho (4\pi \alpha t)^\frac{3}{2}} e^{-\frac{R^2}{4\pi \alpha t}}$$

(5)

In the formula, $T_M$ is the temperature rise at any point $M$, $Q_d$ is the temporal heating intensity of a point reservoir. $c$ is the specific heat capacity of a heat conductor. $\rho$ is the density of a heat conductor. $\alpha$ is the thermal diffusivity of a heat conductor($\alpha = \lambda/cp$). And $\lambda$ is the pyroconductivity. $t$ is the interval.
time between when a point source begins to heat and the observed moment. \( R \) is the distance from any \( M \) to the heat source point. In ultrasonic vibration cutting, the actual situation of the heat source should be the linear heat source with continuous heating. Through the temperature field superposition principle, the cutting temperature field model of ultrasonic vibration cutting can be deduced by integrating it in space and time. Another important prerequisite for the correct use of the heat source method is to properly handle the temperature field boundary, which also leads to the concept of a mirrored heat source to make a finite thermal conductor as close as possible to an infinite thermal conductor [10]. The basis of the temperature field formula of the heat source method is an infinitely large heat conductor. In reality, the goal of ultrasonic vibration cutting is to have a certain limited volume, so the existence of boundaries must be considered.

**Figure 4.** Mirror temperature source.

**Figure 5.** Temperature field model of finite long line heat source.

As shown in Figure 4, \( Q \) is the real heat source, its mirror heat source is \( Q' \), take the adiabatic boundary as the axis of symmetry and mirror the true heat source. The heat intensity of the mirror heat source and the real heat source satisfies the following conditions \( q' = nq \). This study in the study of ultrasonic vibration cutting, in the condition of dry cutting, without considering the heat exchange between air and surface as adiabatic boundary, thus the heat intensity of mirror heat source is two times of real heat source.

As shown in Figure 5, the actual heat source in the tool-workpiece contact area is a narrow band heat source, if \( L \) is discretized in the \( Z \) direction into an infinite number of tiny elements. The temperature rise at point \( M \) under the influence of the heat source can be obtained by the action of the small element line heat source \( dz \), which is approximately regarded as a point heat source.

\[
\frac{dT}{\rho(4\pi \alpha t)^\frac{3}{2}} = \frac{Q_2 dz}{c} e^{\frac{-x'^2+y'^2+z'^2}{4\alpha t}}
\]  

\[ (6) \]

The temperature raise of the heat source in line \( L \) of the whole section to point \( M \) can be obtained by integrating both sides of equation (6), and order

\[
\eta = \frac{z-z_0}{\sqrt{4\alpha t}}
\]

\[ (7) \]

\[
\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\eta^2} d\eta
\]

\[ (8) \]

Finally, the temperature field formula of finite heat source is obtained as follows:

\[
T_{\text{ave}} = \frac{Q_2}{2c\rho(4\pi \alpha t)^\frac{3}{2}} \left[ \text{erf} \left( \frac{z}{\sqrt{4\alpha t}} \right) - \text{erf} \left( \frac{z-L}{\sqrt{4\alpha t}} \right) \right] e^{\frac{-x'^2+y'^2+z'^2}{4\alpha t}}
\]

\[ (9) \]

The heat distribution correction coefficient is \( K \) introduced to characterize the proportion of heat transferred into the workpiece. \( K \) value ranges from 3\% to 9\%. The coordinate (0,0,0) is substituted into the formula, because the error function erf(x) is an odd function, so in the above formula is simplified to:
The formula (9) can be used to analyze the surface temperature field of particle reinforced composite material in ultrasonic vibration cutting. It can be seen from the formula that the calculation of cutting temperature field is related to the material properties of the workpiece, cutting speed, cutting time, etc.

3. Simulation model establishment

For materials with low volume fraction (such as below 30%), the particles are basically random distribution. In the simulation, the random distribution of particles can truly reproduce the microstructure of the composite, the interaction between particles can also be fully considered [11]. Changing tool vertical height to simulate cutting depth, the rake angle and rear angle of the tool are 5° and 0° respectively, and the blunt round radius of the tool tip is 4μm. The typical particle reinforced composite with a volume fraction of about 20% is taken as the research object, and the workpiece is 240μm × 120μm in the simulation process, as shown in Figure 6.

According to the research, the change of SiCp/Al composite material properties can be ignored when the temperature is below 100°C, so the influence of material property changes caused by temperature changes on cutting temperature is ignored in this model [12]. The research of particle reinforced composites adopts elastic-plastic constitutive equation and uses classical J-C viscoplastic constitutive model to simulate the characteristics of matrix materials [13]. The four nodes of the mesh element type in the shape of quadrilateral element (CPE4RT) have hourglass control, which can solve the temperature-displacement coupling reduced integral thermal coupling. The grid unit type is a temperature-displacement coupled three-node plane strain thermal coupling triangular unit (CPE3T).

4. Analysis of simulation results

Based on the established micro-model of particle reinforced composites, the variation of cutting temperature of each component in the micro-level particle reinforced composites is analyzed. In the following, the curves of cutting temperature of particles and matrix under three different cutting paths are analyzed. Particles are randomly distributed in the workpiece. Take the first particle as an example. The schematic diagram of three different cutting paths of particles is shown in Figure 7.

4.1. Analysis of temperature curve under condition of particles above cutting path

The finite element model of particles above the cutting path is designed. The cutting schematic diagram of particles above the cutting path (Figure 7(a)). Figure 8(a) shows the temperature curve and temperature field in the matrix, when the particles are above the cutting path, the cutting temperature tends to rise first, then fall and finally flatten. From 0μs to 13μs, the tool has impacted the matrix, and when t=13μs, the temperature of the matrix reaches the highest. After the impact of vibration has a temperature rise, the matrix material has been converted into chips.

\[
T = \frac{KQ}{2c\rho \pi a} \int_0^\infty E(t) \left( \frac{L}{4\alpha t} \right) \frac{\nu^2}{\alpha} \exp \left( -\frac{\nu^2}{4\alpha} \right) dt.
\]
As shown in Figure 8(b), it is cutting temperature curve in the particles. When the tool first contacts the workpiece, the particle temperature begins to rise. When \( t = 17\mu s \), the temperature of the particles is the highest at this time. When the particles separate from the cutter, the cutter is farthest away from the particles, the heat of the particles diffuses to the surrounding matrix. Then a part of the heat is taken away by the tool tip, which results in a drop in the temperature of the particles themselves. When \( t = 58\mu s \), the cutter continues cutting in the second cutting cycle, the temperature will rise again. Therefore, the impact of vibration on the temperature rise of the particles has a periodic effect.

### 4.2. Analysis of temperature curve under condition of particles in the middle of cutting path

As shown in Figure 9, the temperature variation curves of particles and matrix are analyzed under condition of particles in the middle of the cutting path (Figure 7(b)). Figure 9(a) shows that the change law of the matrix temperature curve is almost the same as Section 4.1. In Figure 9(b), the particle temperature changes with the periodic movement of the tool, but the maximum temperature of each cycle is increasing. This indicates that the cutting particles generate higher heat.
4.3. Analysis of temperature curve under condition of particles below cutting path

The schematic diagram of the cutting process in which particles are located below the cutting path (Figure 7(c)). The temperature variation curves of particles and matrix with time are analysed as shown in Figure 10. The particle temperature changes with the periodic movement of the tool are almost the same as Section 4.2. The temperature of the matrix has increased with the change of the tool cycle. This shows that greater force is required to achieve cutting due to the role of the particles on the rear face, so a higher temperature is generated in the matrix.

In the ultrasonic vibration cutting process, the particles are located in three different cutting paths. The rising temperature in the first deformation zone is mainly concentrated around the particles. The temperature of Al matrix is higher than that of SiC particles. This is because SiC particles have higher thermal conductivity than Al matrix, and the heat is more easily transmitted to the matrix.

To sum up, by comparing the curves of cutting temperature for particles above, in the middle and below the cutting paths, it is found that in the ultrasonic vibration cutting process, the cutting temperature of the particles under the cutting path are obviously smaller than the other two positions. This is because the cutting tool mainly cuts Al matrix in the cutting process and breaking particles generates more heat because of high specific strength, specific stiffness and high temperature resistance of SiCp/Al composites.

5. Conclusion

In this paper, the research conclusions are as follows: 1) The heat conduction model of ultrasonic vibration turning process is established, and the analytical formula of temperature field of SiCp/Al composite ultrasonic vibration turning is obtained. 2) In the first vibration cutting cycle, the temperature of Al matrix is higher than that of SiC particles. In the second vibration cutting cycle, the temperature of SiC particles is higher than that of Al matrix. In the ultrasonic vibration cutting process of the same particle, the temperature variation curve trend of the particle in three different cutting paths with time is firstly increased, then decreased, then increased and finally stabilized.

Acknowledgements

The authors greatly appreciate the funding support from The Liaoning Natural Science Foundation (2015010131).

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