Analytical model of workpiece temperature in axial ultrasonic vibration-assisted milling in situ TiB₂/7050Al MMCs

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Abstract
In recent years, as a new method developed for machining difficult-to-cut materials, ultrasonic vibration-assisted machining technology has been attracting more and more attentions due to its superior properties in reducing cutting temperature. However, analytical models revealing the mechanism and predicting the cutting temperature for ultrasonic vibration-assisted machining are still needed to be developed. In this paper, an analytical model was established to predict the workpiece temperature for ultrasonic vibration-assisted milling of in situ TiB₂/Al MMCs. The heat intensity would be directly determined by the cutting force which was significantly influenced by the ultrasonic vibration motion. Meanwhile, the moving heat source theory was applied for calculating dynamic heat flux and partition ratio. Besides, material properties, tool geometry, cutting parameters, and vibration parameters were taken into account for workpiece temperature modeling. Finally, the developed analytical temperature model was validated by milling experiments with and without ultrasonic vibration on in situ TiB₂/7050Al metal matrix composites. The relative errors between model prediction results and experiments were smaller than 17%, indicating that the proposed model could provide workpiece temperature prediction reliably and accurately. Furthermore, the established analytical model could be used not only in ultrasonic vibration-assisted milling but also in conventional milling for the metal matrix composites.

Keywords Ultrasonic vibration · Cutting temperature · Analytical model · In situ · Al MMCs

1 Introduction

The heat generated in metal cutting process resulting in cutting temperature rising is one of the main physical phenomena, which would have a direct significant effect on the surface quality, residual stress, and machined defects in metal removal processes. For solving the machining problems of difficult-to-cut materials, advanced machining methods were constantly developed and applied such as laser-assisted machining [1] and ultrasonic vibration-assisted machining [2]. In recent decades, the ultrasonic vibration-assisted machining technology has been applied in aviation industry as an effective method for machining difficult-to-cut materials due to its superior advantages in reducing cutting force [3, 4], decreasing cutting temperature [5], and improving surface integrity [6, 7]. Compared with conventional machining method, the motion of cutting tool or workpiece and the material removal process is changed in ultrasonic vibration-assisted machining, which would result in great difference in cutting temperature generation and its effects on machining quality. Therefore, to have a better understanding of cutting temperature in ultrasonic vibration-assisted machining, experimental and analytical modeling researches are quite necessary.

Li et al. [8] conducted an experimental study on rotary ultrasonic drilling Ti6Al4V alloy, it was found that the cutting temperature was reduced by 18.54 ~ 21.68% compared with conventional drilling process. Geng et al. [9] studied the
influence of cutting parameters on cutting temperature during elliptical ultrasonic vibration cutting carbon fiber–reinforced plastic (CFRP) composites. It was found that the decrements of the maximum temperature were 18.8% and 13.1% for the feed rate of 75 μm/rev and 150 μm/rev, respectively. Besides, as feed rate increased from 20 to 80 μm/rev at a certain cutting speed of 165 m/min, the decrements of the maximum temperature increased from 3.8–47%. Based on these results, it was concluded that the cutting temperature was obviously reduced by ultrasonic vibration motion and the feed rate had a much more significant influence on cutting temperature than cutting velocity. Cong et al. [10] carried out experimental investigation on the effect of cutting parameters and ultrasonic parameters on cutting temperature in rotary ultrasonic-assisted machining CFRP. Due to the limitation of cutting temperature measuring methods, the influence of cutting parameters on the cutting temperature was approximately analyzed using the temperature measured near the machined surface. The results showed that the feed rate had the highest effect on cutting temperature. However, it was found from researches of Pálmai [11] and Stephenson et al. [12] that the cutting velocity was the main factor influencing the cutting temperature. Shi et al. [13] concluded from elliptical ultrasonic cutting Ti6Al4V/AI7050 alloy that the vibration frequency was the major factor influencing cutting force and the vibration amplitude was the main factor influencing cutting temperature.

Meanwhile, with increasing development of computer technology, the finite element method based on simulation software was also applied to have an insight of ultrasonic vibration-assisted machining process and cutting temperature generation process. Mitrofanov et al. [14, 15] proposed a thermo-mechanical coupled finite element (FE) model for conventional turning (CT) and ultrasonic-assisted turning (UAT) Inconel 718. It was found that the cutting tool temperature in UAT was about 2 times lower than that in CT. However, temperature of cutting region in UAT was found to be 15% higher than that in CT, which came to the same conclusion by Ahmed et al. [16]. Besides, there were no considerable differences in workpiece temperature between the two cutting methods. For this, Muhammad et al. [17] explained that it needed to consume energy due to the ultrasonic shock, which would result in the temperature in the cutting zone increasing. Patil et al. [18] conducted comparative investigation on Ti6Al4V alloy between CT and UAT methods. It was noted that cutting temperature was reduced by UAT and with increasing from 10 to 30 m/min the difference between the max cutting temperature in UAT and CT was reduced from 48 to 16%.

To fully address the cutting temperature generation in ultrasonic vibration-assisted machining process, analytical mathematical modeling effort has been made. Khajehzadeh et al. [19] developed an average temperature prediction model for the cutting tool in UAT and proposed a cutting velocity model by considering kinematics of cutting process. However, the model building depended on conducting experiments to obtain tool-chip contact lengths of sticking and slipping. Verma et al. [20] proposed an analytical model for temperature rise in workpiece during ultrasonic vibration-assisted milling (UVM). It considered the effect of acoustic softening and intermittent cutting based on Jaeger’s moving heat source theory. The model showed good agreement with experimental results. Chen et al. [21] developed a non-uniform moving heat source model to analyze the heat transfer problem in ultrasonic-assisted cutting Ti6Al4V. The results indicated that the temperature in the machined surface was lower with larger vibration amplitude, while the surface temperature increased with vibration frequency increasing.

From above, although the cutting temperature in ultrasonic vibration-assisted machining has been researched from experiments, simulation to modeling, there is still a few attempts for analytical temperature modeling of workpiece in ultrasonic vibration-assisted milling process. Furthermore, ultrasonic vibration-assisted machining method has shown advantages in reducing tool wear and cutting force, improving machining quality in cutting in situ TiB2/7050Al composites which is a typical difficult-to-cut material [22–25]. Hence, it is quite necessary and important to perform temperature modeling investigation for ultrasonic vibration-assisted milling in situ TiB2/7050Al composites for fully and comprehensively understanding the influence of ultrasonic vibration on machining quality.

Therefore, in this paper, an analytical model of workpiece temperature was proposed in ultrasonic vibration-assisted milling in situ TiB2/7050Al composites. Firstly, a cutting force model was developed by analyzing the coupled effect of tool-chip-workpiece and inertial force with considering ultrasonic vibration motion. Then, based on the heat source theory and cutting theory, the dynamic heat density and the heat partition ratio were analyzed and calculated to establish the temperature model with considering the geometry of the cutting tool and processing parameters. Finally, the proposed model was validated by a series of milling experiments with and without ultrasonic vibration on in situ TiB2/7050Al composites.

## 2 Cutting temperature modeling

### 2.1 Cutting force model

As sinusoidal vibration imposed on the cutting tool, the axial ultrasonic vibration-assisted milling (UVM) differs greatly from conventional milling (CM). As described in Fig. 1, the materials are removed by the cutting tool with vibration of
high frequency and low amplitude during UVM process, the motion of tool is changed due to the application of ultrasonic vibration. Cutting force in UVM is different from that in CM, which has significant influence on cutting temperature.

For deep understanding of the effect of cutting force on the cutting temperature, it is necessary to introduce the main works and differences of cutting force modeling in UVM. Considering the effect of hybrid motion and complex geometry of the cutting tool on the chip thickness, the tool is discretized into many equal slices with the same height \(dz\) along axial direction, each slice participated in cutting is regarded as oblique cutting process, which is shown in Fig. 2a. Based on the equivalent oblique cutting, interaction between the cutting tool and workpiece was analyzed. Especially, due to ultrasonic vibration, the chip between the rake face and the shear plane was gotten acceleration. Therefore, the inertia force in material removal needs to be considered during cutting force modeling, and the forces acted on the chip were analyzed shown in Fig. 2b.

According to Newton’s Third Law of Motion, a new force balance relationship by considering the inertia force of chip in the Cartesian coordinate system \(X_n, Y_n, Z_n\) was built, whose components were expressed as follows:

\[
\begin{align*}
F_{\text{r}}' \cos \theta_n - F_{\text{s}}' \cos \theta_n \cos \phi_n &= M_{\text{c}} \cos \alpha_n \\
F_{\text{r}}' \sin \theta_n - F_{\text{s}}' \sin \theta_n \sin \phi_n &= M_{\text{c}} \cos \gamma_n \cos \phi_n \\
-F_{\text{c}}' \sin \theta_n - F_{\text{c}}' \sin \theta_n &= -M_{\text{c}} \sin \eta
\end{align*}
\]

(1)

where \(F'_r\) and \(F'_s\) are the reaction force of the resultant cutting force \(F_r\) on the shear plane and \(F_s\) on the rake face, respectively, and \(M\) is the mass of the chip, \(a_c\) is the chip acceleration, which were given in Ref. [26]. Obviously, the action mechanism of shear plane and rake face on the chip was changed because of ultrasonic vibration. Then, the tangential force \(F_t\), radial force \(F_r\), and axial force \(F_a\) in the one slice could be obtained as follows:
\[
\begin{align*}
F_i &= F_i (\cos \theta_i \cos \theta_r \cos \xi_n + \sin \theta_i \sin \xi_n) \\
F_r &= F_r \cos \theta_n \\
F_a &= F_c (\cos \theta_i \cos \theta_r \cos \xi_n - \sin \theta_i \cos \xi_n)
\end{align*}
\]  

(2)

Cutting force generation and prediction in UVM was calculated as following:

\[
\begin{align*}
F_x(t) &= \sum_{j=1}^{r} \sum_{k=1}^{N} (-F_{r(j,k)} \cos \theta_{j,k}(t) - F_{r(j,k)} \sin \theta_{j,k}(t)) \\
F_y(t) &= \sum_{j=1}^{r} \sum_{k=1}^{N} (F_{r(j,k)} \sin \theta_{j,k}(t) - F_{r(j,k)} \cos \theta_{j,k}(t)) \\
F_z(t) &= \frac{1}{2} R_c \sum_{j=1}^{r} \sum_{k=1}^{N} F_{a(j,k)}
\end{align*}
\]  

(3)

where \(\theta_{j,k}(t)\) is the angular position of the cutting point of the \(j\)th slice in the \(k\)th flute, which was determined by cutting parameters and tool geometry. The index of the slices \(j = 1, 2, 3, \ldots, r\), where \(r\) is the number of the slices. The index of the flutes \(k = 1, 2, 3, \ldots, N\), where \(N\) is the number of teeth of the milling tool. \(R_c\) refers to the cutting tool-workpiece contact rate [27] and its coefficient 1/2 means that the cutting tool-workpiece contact time was half vibration period. The cutting force model is greatly important to provide force data for cutting temperature calculating.

### 2.2 Analysis of heat source

In metal cutting process, cutting edge cuts into the metal layer which was extruded and machined to be chip and formed the machined surface. There are three deformation zones including primary deformation zone, secondary deformation zone, and tertiary deformation zone, which are shown in Fig. 3. The primary deformation zone is the narrow band of plastic deformation between the initial slip plane \(\overline{ON}\) and the ending slip plane \(\overline{OM}\) in the chip forming process. The secondary deformation zone is the plastic deformation zone generated in the contact zone between the bottom of chip flow and the rake face of the cutting tool. The tertiary deformation zone is the deformation zone in the machined surface near the cutting edge.

It is well known that most of the energy generated in the three deformation zones is converted into thermal energy. As presented in Fig. 4, in the primary deformation zone, heat is generated due to the plastic deformation of the workpiece and named shear heat source. In secondary deformation zone, heat is created due to the deformation of chip and the tool-chip interface friction, which is called the frictional heat source. And in tertiary deformation zone, heat produced by tool-workpiece interface rubbing, which is the rubbing heat source.

Generally, most of heat generated by frictional heat source is transformed into cutting tool and chips [28], which has a bit influence on the workpiece temperature [29]. The effect of the rubbing heat source on tool-workpiece interface is minimum, which is determined greatly by tool wear. Then, in this study, the cutting tool was assumed no tool wear and the influence of the rubbing heat source on the workpiece was considered to be negligible. Meanwhile, compared to the heat transferred into workpiece, the heat partition escaping to atmosphere through the boundary could be ignored, meaning that interfaces of tool-workpiece, tool-chip, workpiece-air, chip-air, and tool-air could all be treated as adiabatic.

Hence, in this paper, workpiece temperature rising was assumed to be mainly caused by the shear heat source. Then, based on Komanduri-Hou’s model [30], the heat liberation intensity of the shear heat source could be given as follows:

\[
q_{shear} = \frac{F_s v_s}{L b}
\]  

(4)

where \(F_s\) is the shear force, \(v_s\) is the shear velocity, \(L\) is the length of the shear plane, and \(b\) is the cutting width in the orthogonal cutting.
2.3 Temperature model and heat partition ratio

During UVM process, a new machined surface is formed mainly by the interaction between the bottom cutting edge and the workpiece. Due to the application of ultrasonic vibration, the cutting speed was changed. Verma et al. [27] pointed out that instantaneous cutting velocity generated by ultrasonic vibration did not have much effect on average cutting velocity, and linear velocity of spindle was regarded as the average cutting velocity for calculation of heat generation. So, in this paper, the linear velocity of spindle $v$ could be considered as the average cutting velocity of cutting tool to calculate heat generation. According to Xiong et al. [31], the cutting process of the bottom cutting edge could be equivalent to the orthogonal cutting. However, the cutting speed is different along the bottom cutting edge direction. To address this, the bottom cutting edge is discretized into several elements and every element $dl$ could be regarded as a typical orthogonal cutting process as shown in Fig. 5a.

Moreover, it is assumed that the heat distribution is uniform near the shear plane which is treated as a semi-infinite medium. Under the dry cutting conditions, the workpiece surface was regarded as adiabatic boundaries, which meant that heat exchange was not occurred between the workpiece and the outside, and heat produced by shear heat source was not transmitted but was retained within the workpiece when it reached the workpiece surface. However, the heat transfer theoretical derivation was generally based on infinite heat conductor and no boundary. In order to describe the heat transfer practically, an imaginary shear heat source is introduced to compensate for the loss of heat due to the assumption of the semi-infinite medium of the workpiece [32]. It was assumed the workpiece surface as the mirror, setting up a virtual heat source that was exactly the same as the real shear heat source in a symmetrical position, which is shown in Fig. 5b. And the shear heat intensity could be calculated as following:

$$q_{\text{shear}} = \frac{(F_{c}\cos\phi - F_{u}\sin\phi)v_{c}\cos\alpha}{1000d\csc\phi\cos(\phi - \alpha)}$$  (5)

where $\alpha$ is the rake angle of the cutting tool, $\phi$ was the shear angle which was given out in Ref. [30], and $v_{c}$ was the instantaneous velocity of cutting edge element, which could be calculated as following:

$$v_{c} = \omega \cdot l_{M}$$  (6)

where $\omega$ is angular velocity and $l_{M}$ is the actual length of the bottom edge involved in cutting, which was expressed as following:

$$\begin{cases} l_{M} = \frac{h(\theta)}{\cos_{\text{edge}}} \\ h(\theta) = f_{c}\sin\theta \end{cases}$$  (7)

where $h(\theta)$ is the instantaneous cutting thickness, $\theta_{\text{edge}}$ is the inclination of the bottom edge, $f_{c}$ is the feed rate, and $\theta$ is the instantaneous cutting angle.

Therefore, in this paper, the temperature rise in workpiece is mainly caused by the shear heat source and its imaginary heat source. Then, the temperature of an arbitrary point $M(x,y,z)$ in workpiece in UVM could be expressed with combining effect of the shear heat source and its imaginary heat source as follows:

$$T_{M(x,y,z)} = T_{\text{shear}}^{M(x,y,z)} + T_{\text{image-shear}}^{M(x,y,z)}$$  (8)

where $T_{\text{shear}}^{M(x,y,z)}$ is the temperature caused by the shear plane heat source and $T_{\text{image-shear}}^{M(x,y,z)}$ is the temperature affected by the imaginary shear heat source.

It is well known that the heat partition ratio is quite important to determine the temperature in cutting process. In this paper, the cutting edge was discretized into a number of elements whose cutting was regarded as equivalent oblique cutting. According to Venuvinod’s heat partition ratio calculation of shear plane in equivalent oblique cutting [33], it was assumed average temperature rise of shear plane in the workpiece side was equal to that in the chip side, which could be expressed as following:

$$T_{\text{workpiece-shear}} = T_{\text{chip-shear}}$$  (9)

where $T_{\text{workpiece-shear}}$ and $T_{\text{chip-shear}}$ were the average temperature rise of shear plane in the workpiece side and the chip side, respectively, and Block considered $T_{\text{workpiece-shear}}$ and
\[ T_{\text{chip-shear}} \text{ are merely two different expressions for the mean temperature rise at shear plane [34].} \]

In order to obtain the temperature model and the heat partition ratio, two local coordinate systems \( X_0 O Z_0 \) and \( X_0 O Z_0' \) are built to analyze the cutting temperature on the workpiece side and on the chip side, which are shown in Fig. 6a and Fig. 6b, respectively.

According to Komanduri and Hou [30], the cutting temperature \( T_{\text{workpiece-shear}} \) caused by the shear heat source and the imaginary heat source for point \( M_t(x_t, z_t) \) on the workpiece side could be calculated as follows:

\[
\begin{align*}
T_{\text{workpiece-shear}} &= \frac{B_s}{2\pi c} \int_{0}^{\pi} e^{-\left(\frac{(x_t - l_t \cos \phi)^2}{c^2} + \frac{(z_t - l_t \sin \phi)^2}{c^2}\right)/2} t_{\text{shear}}(R_t + R_{ch}) \, dl_t \\
R_{ch} &= \sqrt{(x_t - l_t \cos \phi)^2 + (z_t + l_t \sin \phi)^2} \\
R_t &= \sqrt{(x_t - l_t \cos \phi)^2 + (2l_t + z_t - l_t \sin \phi)^2}
\end{align*}
\]

where \( B_s \) stands for the fraction of the shear heat source conducted into the workpiece, \( \lambda_s \) is the thermal conductivity of the workpiece, \( a_w \) is the thermal diffusion coefficient of the workpiece, \( K_0^{\text{shear}} \) denotes the modified Bessel function of second kind of order zero and it could be given as:

\[
K_0^{\text{shear}} = \frac{1}{2} \int_{0}^{\pi} e^{-\frac{\left((x_t - l_t \cos \phi)^2 + (z_t + l_t \sin \phi)^2\right)}{c^2}} \, dl_t
\]

where \( t_{\text{shear}} \) was the shear time of cutting edge element, which could be calculated as following:

\[
t_{\text{shear}} = \frac{L \cos \phi}{v_e}
\]

where \( L \) is the length of the shear plane, which was expressed as following:

\[
B_s = \frac{\int_{0}^{\pi} e^{-\left(\frac{(x_t - l_t \sin \phi + l_t \cos (\phi - \alpha))^2}{c^2} + \frac{(z_t - l_t \cos \phi)^2}{c^2}\right)/2a_ch} t_{\text{shear}}(R_t + R_{ch}) \, dl_t}{\int_{0}^{\pi} e^{-\left(\frac{(x_t - l_t \cos \phi)^2}{c^2} + \frac{(z_t - l_t \sin \phi)^2}{c^2}\right)/2a_ch} t_{\text{shear}}(R_t + R_{ch}) \, dl_t + \int_{0}^{\pi} e^{-\left(\frac{(x_t - l_t \cos \phi)^2}{c^2} + \frac{(z_t - l_t \sin \phi + l_t \cos (\phi - \alpha))^2}{c^2}\right)/2a_ch} t_{\text{shear}}(R_t + R_{ch}) \, dl_t}
\]

\[
L = \frac{t_{c}}{\sin \phi}
\]

where \( t_c \) is the uncut chip thickness which could be given as following:

\[
t_c = D + a_p + \sin(2\pi ft)
\]

where \( a_p \) is cutting depth and \( f \) and \( A \) are the vibration frequency and vibration amplitude in ultrasonic vibration-assisted milling.

Then, the cutting temperature \( T_{\text{chip-shear}} \) produced by the shear heat source and the imaginary heat source on the chip side at the point \( M_c(x_c, z_c) \) could be expressed as follows:

\[
T_{\text{chip-shear}} = \frac{1}{2\pi c} \int_{0}^{\pi} e^{-\left(\frac{(x_c - l_c \cos \phi)^2 + (z_c - l_c \sin \phi)^2}{c^2}\right)/2a_{ch}^{\prime}} t_{\text{shear}}^{\prime}(R_c + R_{ch}) \, dl_c
\]

where \( \lambda_{ch} \) is the thermal conductivity of the chip, \( a_{ch}^{\prime} \) is the thermal diffusion coefficient of the chip, \( v_{ch}^{\prime} \) stands for the flow velocity of the chip, \( t_{ch} \) is the contact length of tool-chip, which could be expressed as below:

\[
\begin{align*}
&v_{ch}^{\prime} = \frac{\sin \phi}{\cos(\phi - \alpha)} v_e \\
t_{ch} = (t_c + 3A) \frac{\sin \phi}{\sin \phi - \cos(\phi - \alpha)} \\
t_c = \frac{a_p + \sin(2\pi ft)}{\sin \phi}
\end{align*}
\]

Thus, the heat partition ratio \( B_s \) could be calculated by substituting Eqs. (10) and (15) to Eq. (9), which was shown as follows:

Fig. 6 Schematic of temperature modeling. (a) Heat source and image for the workpiece side. (b) Heat source and image for the chip side
Finally, the workpiece temperature rise could be calculated by substituting the value of $B_s$ in Eq. (10).

### 2.4 Prediction of temperature in workpiece

In this study, the cutting temperature rise by shear heat source is obtained through analyzing the temperature field of the orthogonal cutting process. UVM is a complicated 3D cutting process and it is quite necessary to consider the effect of tool geometry and cutting parameters. Besides, the cutting temperature is significantly determined by the cutting force calculated with Eq. (2). Then, in order to obtain the temperature rise of an arbitrary point $M(x, y, z)$ in the workpiece, a coordinate transformation from $xyz$ to $x_t y_t z_t$ is needed as following:

$$
\begin{bmatrix}
  x_t \\
  y_t \\
  z_t
\end{bmatrix}
= \begin{bmatrix}
  \cos \theta_{Ax}(t) & 0 & -\sin \theta_{Ax}(t) & 0 \\
  0 & 1 & 0 & 0 \\
  \sin \theta_{Ax}(t) & 0 & \cos \theta_{Ax}(t) & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}
+ \begin{bmatrix}
  -R \sin \theta_{Ax}(t) & 0 & 0 \\
  0 & R(\cos \theta_{Ax}(t) - 1) & 0
\end{bmatrix}
\begin{bmatrix}
  1 \\
  0 \\
  0
\end{bmatrix}
$$

At last, the cutting temperature could be calculated by Eq. (10). Due to a lot of complicated computations, the software MATLAB is used to write a program for this job and the programming, the flowchart is shown in Fig. 7.

Meanwhile, the specific computational procedure is as follows:

1. Input the necessary parameters including cutting parameters, vibration parameters, tool geometric parameters, materials physical properties, and integration parameters.
2. Calculate the entering and exiting angle, then calculate the instantaneous immersion angle, and store these data for subsequent calculations.
3. According to the cutting force model to calculate instantaneous cutting force and store the data for calculating cutting temperature.
4. Based on the cutting force data to calculate the intensity of shear heat source, then calculate the shear angle, heat partition ratio, and shear time.
5. According to the cutting temperature model to calculate the temperature rise of one point in the workpiece and output cutting temperature data.

### Table 1 Mechanical and physical properties of TiB$_2$/7050Al MMCs [31]

| Density (g/cm$^3$) | Yield strength (MPa) | Thermal conductivity (W/(m·K)) | Thermal diffusion coefficient (cm$^2$/s) | Specific heat (J/(kg·K)) | Melt temperature (°C) |
|------------------|----------------------|-------------------------------|----------------------------------------|--------------------------|------------------------|
| 2.9              | 639                  | 112                           | 0.451                                  | 860                      | 476                    |

Fig. 7 The flowchart of cutting temperature calculation
Experimental design

In order to validate the cutting temperature model, a set of down milling experiments were performed on the material of 6 wt% in situ TiB₂/7050Al MMCs which was provided by Shanghai Jiao Tong University, mechanical and physical properties of the material are shown in Table 1, and the microstructure of in situ TiB₂/7050Al MMCs is shown in Fig. 8. The size of specimen used for milling tests was 40 × 30 × 8 mm. The cutting tools used were TiAlN coated carbide end milling tools with diameter of 7 mm and 4 flutes, whose specifications are shown in Table 2.

All experiments were done on a CY-VMC850 machine with and without ultrasonic vibration under dry machining condition as shown in Fig. 9.

The whole experimental setup is mainly composed of three parts including ultrasonic vibration system, machining system, and data acquisition system. In the ultrasonic vibration system, the ultrasonic generator could be controlled to switch between ultrasonic vibration-assisted machining and conventional machining. During experiments, the vibration frequency was 30 kHz, and the vibration amplitude was 4 μm. The detailed cutting temperature model validating is listed in Table 3, the effect of cutting parameters on machined surface temperature is designed in Table 4, and the cutting force model is validated in Table 5. Cutting temperature on the machined surface was measured using semi-thermocouple and temperature below the machined surface was measured by K-type thermocouple. Distance

| Table 2 Specifications of coated carbide milling tool |
|-----------------------------------------------|
| Diameter | Rake angle | Nose radius | Flank angle | Helix angle | Bottom edge inclination |
|---------|------------|-------------|-------------|-------------|------------------------|
| 7 mm    | 5°         | 0.2 mm      | 8°          | 40°         | 4°                     |

3 Experimental design

Fig. 8 Microstructure of in situ TiB₂/7050Al MMCs. (a) Cross section, (b) Longitudinal section

Fig. 9 Schematic diagram of experimental setup
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Table 3 Experimental parameters for cutting temperature model validating

| No | Cutting speed \( \nu \) (m/min) | Feed rate \( f_z \) (mm/z) | Cutting depth \( a_p \) (mm) | Amplitude \( A \) (μm) | Frequency \( f \) (kHz) | DMST (mm) |
|----|-------------------------------|------------------------|---------------------------|-------------------|-------------------|----------|
| #1 | 20                           | 0.06                   | 0.8                       | 4                 | 30                | 0.1      |
| #2 | 20                           | 0.06                   | 0.8                       | 0                 | 0                 | 0.1      |
| #3 | 35                           | 0.04                   | 0.4                       | 4                 | 30                | 0.2      |
| #4 | 35                           | 0.04                   | 0.4                       | 0                 | 0                 | 0.2      |
| #5 | 15                           | 0.05                   | 0.5                       | 4                 | 30                | 0        |
| #6 | 15                           | 0.05                   | 0.5                       | 0                 | 0                 | 0        |
| #7 | 30                           | 0.05                   | 0.5                       | 4                 | 30                | 0        |
| #8 | 30                           | 0.05                   | 0.5                       | 0                 | 0                 | 0        |
| #9 | 30                           | 0.03                   | 0.5                       | 4                 | 30                | 0        |
| #10| 30                           | 0.03                   | 0.5                       | 0                 | 0                 | 0        |

Table 4 Cutting parameters for effect on machined surface temperature in UVM

| No | Cutting speed \( \nu \) (m/min) | Feed rate \( f_z \) (mm/z) | Cutting depth \( a_p \) (mm) | Amplitude \( A \) (μm) | Frequency \( f \) (kHz) |
|----|-------------------------------|------------------------|---------------------------|-------------------|-------------------|
| #11| 15                           | 0.05                   | 0.5                       | 4                 | 30                |
| #12| 30                           |                        |                           |                   |                   |
| #13| 45                           |                        |                           |                   |                   |
| #14| 30                           | 0.03                   | 0.5                       | 4                 | 30                |
| #15| 15                           | 0.05                   |                           |                   |                   |
| #16| 0.07                         |                        |                           |                   |                   |
| #17| 30                           | 0.05                   | 0.2                       | 4                 | 30                |
| #18| 0.5                          |                        |                           |                   |                   |
| #19| 0.8                          |                        |                           |                   |                   |

from machined surface of thermocouple (DMST) is set to be 0.1 mm and 0.2 mm, which is shown in Fig. 10.

4 Results and discussions

The predicted and measured cutting forces are shown in Fig. 11. The results indicated peak cutting force and variation trend of prediction was in good agreement with that of measurement. It could be proved that the cutting force model had good accuracy and could provide force data for temperature calculating.

The proposed cutting temperature model for ultrasonic vibration-assisted milling is validated by a series of experiments on in situ TiB\(_2\)/7050Al MMCs and the results of validation are shown in Table 6 and Fig. 12. Tests #1 to #4 were performed for the subsurface temperature and the machined surface temperature is measured from tests #5 to #10.

It could be seen from Table 6 and Fig. 12 that the model prediction results are in good agreement with that of experiments. The proposed model is validated to be of good reliability and accuracy with the relative errors being smaller than 17%. Besides, the good agreement for conventional milling experiments, whose frequency and amplitude are set to be 0, indicates that the developed cutting temperature model could be used for both ultrasonic vibration-assisted milling and conventional milling.

In this study, the main error source might include three parts: the simplification error of the model, cumulative error of the model, and measurement error. During modeling, the cutting temperature model developed is mainly taken into consideration the influence of heat source in the primary shear zone without the heat transferring into the atmosphere, which would result in the simplification error. Besides, cutting force and heat partition ratio are obtained by analytical model, which would lead to the accumulation of model error. And the measurement error might come from the measuring instruments and observing data. But from Table 4 except for test #4, the relative errors between proposed model and measured results range from 6.69 to 16.44%, which are all smaller than 17%, showing a good prediction agreement.

Figure 13 shows the temperature contours behind the cutting edge under different depth below the machined surface. It could be seen that the subsurface temperature field of workpiece is distributed behind the cutting edge, and the

Table 5 Experimental parameters for cutting force model validating

| No | Cutting speed \( \nu \) (m/min) | Feed rate \( f_z \) (mm/z) | Cutting depth \( a_p \) (mm) | Cutting width \( a_e \) (mm) | Amplitude \( A \) (μm) | Frequency \( f \) (kHz) |
|----|-------------------------------|------------------------|---------------------------|-------------------|-------------------|-------------------|
| #20| 43.96                         | 0.1                    | 1.0                       | 2.5               | 4                 | 21                |
| #21| 43.96                         | 0.1                    | 1.0                       | 2.5               | 0                 | 0                 |
The maximum temperature is not located below the cutting tool nose, whose location is 0.0 point along the cutting direction. Besides, viewing from tests #1 and #3 or tests #2 and #4, the high-temperature region is becoming far away from the cutting tool nose with the increasing of the depth below the machined surface. It indicates that the workpiece temperature of the subsurface is determined by the conduction time of shear heat source.

As shown in Fig. 14, by comparing the measured cutting temperature of UVM and CM, it could be found that the cutting temperature is reduced by about 14.55% with ultrasonic vibration. There might be two reasons for this: First, the cutting force is reduced due to the ultrasonic vibration, which would result in total energy of heat generation reducing and then cutting temperature is decreased. Second, contact between the cutting tool and the workpiece is changed by the ultrasonic vibration, which would decrease heat conduction time.

In addition, the influence of cutting parameters on the machined surface cutting temperature in UVM is shown in Fig. 15. It could be found that the cutting parameters have
important effect on the cutting temperature. It was increased with the cutting speed, feed rate, and cutting depth increasing under a certain vibration frequency and amplitude. And cutting speed has a maximum effect on the workpiece temperature, followed by cutting depth, and feed rate has the minimum influence on it. Besides, it is interesting to be noted that the influence of cutting parameters on the temperature rising ratio is different. Obviously, with the cutting depth increasing, the rising ratio was increased significantly. That was because that the material volume removed was increased, which would result in an increasing of the work done. However, with increase of cutting speed and feed rate, the rising ratio was opposite to that of increasing cutting depth. Firstly, cutting force is reduced with cutting speed increasing [26], which would result in a decreasing of work done by force. Besides, increase of cutting speed leads to heat transfer time reduction. These might be the reasons for the temperature rising ratio became slow. In addition, feed rate has an effect on the material volume removed, but

![Fig. 12 Relative error between the predicted and experimental cutting temperature](image)

![Fig. 13 Temperature contours at different depths below the machined surface](image)

(a) Test #1  (b) Test #2  
(c) Test #3  (d) Test #4
Compared to that by cutting depth, it was small and the temperature rising ratio was not significant.

5 Conclusions

In this paper, an analytical cutting temperature prediction model was developed for axial ultrasonic vibration-assisted milling in situ TiB₂/7050Al composites. A set of experiments were carried out to verify the model with and without ultrasonic vibration. Based on the results and analysis, the following conclusions could be made:

1. The heat partition ratio was built based on the moving heat source theory, which considered the effect of ultrasonic vibration, cutting parameters, tool geometry, and material properties. With verification, the proposed cutting temperature model shows a good agreement with...
experiments with the relative errors being smaller than
17%.
(2) Under the influence of heat conduction time from shear
heat source to workpiece, it was found that the sub-
surface temperature field of workpiece was distributed
behind the cutting edge and with increasing the depth
below the machined surface, the high temperature
region was becoming far away from the cutting tool
nose.
(3) From comparison with CM, it was found that the cut-
ing temperature could be significantly reduced by
about 14.55% with UVM. With increasing cutting
speed, feed rate, and cutting depth, the cutting tem-
perature increased accordingly. The cutting speed has the
highest effect on the workpiece temperature, followed
by cutting depth, and the feed rate has the minimum
influence. Besides, it could be found that temperature-
rising ratio decreases with cutting speed and feed rate
increasing while increasing obviously with cutting depth.

In the future study work, the coupling effect of force-
temperature on the integrity for ultrasonic vibration-assisted
machining in situ TiB2/7050Al composites would be investi-
gated and analyzed.

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investigation, calculating, and analysis. Wenhui Wang: materials and
equipment support. Ruisong Jiang: investigation. Yifeng Xiong: super-
vision, review and editing, review of experimental setup. Kunyang Lin:
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Data availability All authors confirm that the data supporting the find-
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Code availability Not applicable.

Declarations

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Consent to participate All authors voluntarily agree to participate in
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