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Thermal modeling and analysis of thin-walled structures in micro milling

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Abstract: The numerical analytical model has been developed to predict the thermal effect with respect to thin walled structures by micro-milling. In order to investigate the temperature distribution around micro-edge of cutter, it is necessary to considering the friction power, the shearing power, the shear area between the tool micro-edge and materials. Due to the micro-cutting area is more difficult to be measured accurately, the minimum chip thickness as one of critical factors is also introduced. Finite element-based simulation was employed by the Advantedge, which was determined from the machining of Ti-6Al-4V over a range of the uncut chip thicknesses. Results from the proposed model have been successfully accounted for the effects of thermal softening for material.

1. Introduction

Thin-walled structures of highly accurate and miniaturized components with complex shape are becoming increasingly important in diverse field, such as aviation aerospace, biomedicine instruments, and communication systems [1].The cutting temperature, is one of the critical factors which affect the precision of parts, residual stresses, the part distortions, tool wear and so on. FEM based process simulation has been utilized to study machining processes for several years. The main advantage of process simulations remains on the fact that various variables in the machining process including those very difficult to detect by experiments such as temperature, strain, strain rate, stress etc. can be predicted.

Several groups of researchers have been working on the temperature modeling for machining processes. Usuiet et. al. [2] presented a numerical method to calculate the cutting temperature by using the predicted quantities through the energy method. The predicted temperature distribution on the tool face was found to be in good agreement with the obtained experimentally, with regard to the shape of the distribution, the maximum temperature and its location is cutting edge. However, the calculated temperature was lower than the observed one near the cutting edge and the chip leaving point. D. Ulutan, I. Lazoglu and C. Dinc [3] proposed a finite difference method-based model and determined the three-dimensional temperature filed predictions. Lazoglu et al.[4-6] developed various temperature models for different machining operations. Shear energy, friction energy, heat balance, wear et al. were all considered. Thanongsak Thepsonthi and Tu˘grul Özel [7] developed a 3-D FE modeling and simulations of micro milling of Ti-6Al-4V alloy and validated with experiments on chip flow and tool wear. In addition, temperature distribution was also studied at different edge radius size. However, there are still some research problems remain unsolved about FE process simulation such as accuracy of 2-D FE and the influence of uncut chip thickness.

Here in this paper, power model and 2-D finite element modeling are applied for the study temperatures in micro milling. These developed models were used to study the influence of increasing uncut chip thickness of micro milling.

2. Power model

In order to study temperature of micro-milling, a mechanical model of the micro milling process is required for the estimation of heat generation due to the shear friction in the primary and secondary zone. Cutting force and velocities acting on a differential cutting edge along the tool are presented in figure 1. Heat generation in the primary zone due to shearing and friction power in the second deformation zone can be determined as:

$$\begin{cases} P_s = F_s v_s = \dfrac{\tau A v \cos\alpha_e}{\cos(\varphi-\alpha_e)\sin\varphi} \\ P_f = F_f v_f = \dfrac{\tau A v \sin\beta}{\cos(\varphi-\alpha_e)\cos(\varphi+\beta-\alpha_e)} \end{cases} \quad (1)$$

Where P_s, P_f, F_s, F_f, v, τ, β, φ and α_e and A represent the shearing power, friction power, shear force on shear plane, friction force on rake plane, cutting velocity, average shear flow stress, normal friction angle, normal shear angle, and normal rake angle and shear area, respectively.

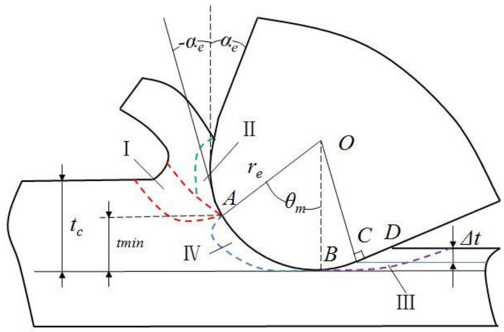


Figure 1. Force and velocity components acting on cutting edge element

In order to calculate the area of the shear plane [8-9], built the thermo-mechanical model and researched the uncut chip thickness. In micro-milling process, cutting edge can no longer be considered sharpen, cutting edge radius is comparable in size to the uncut chip thickness. So the case of $t_c \le r_e$ is just only studied.

The engaged radius of round nose can be divided in two parts defined, respectively, by the angle θ and π-2ψ, see figure 2(a) with:

$$\begin{cases} \theta = \cos^{-1}\left(f_z/2r_e\right) - sin^{-1}\left(r_e - t_c/r_e\right) \\ \psi = cos^{-1}\left(f_z/2r_e\right) \end{cases} \quad (2)$$

The angle θ *is* subdivided into N cutting edge elements characterized by the incremental angle $\Delta\theta = \theta/N$ and by the index j such as $1 \le j \le N$. Figure 2(b) gives a treatment of discretization with N=3.

As shown in figure 2(*b*), the cutting edge element *j* can be defined by $\Delta\theta$, w_r^j, β_j, d_j, w_j^r

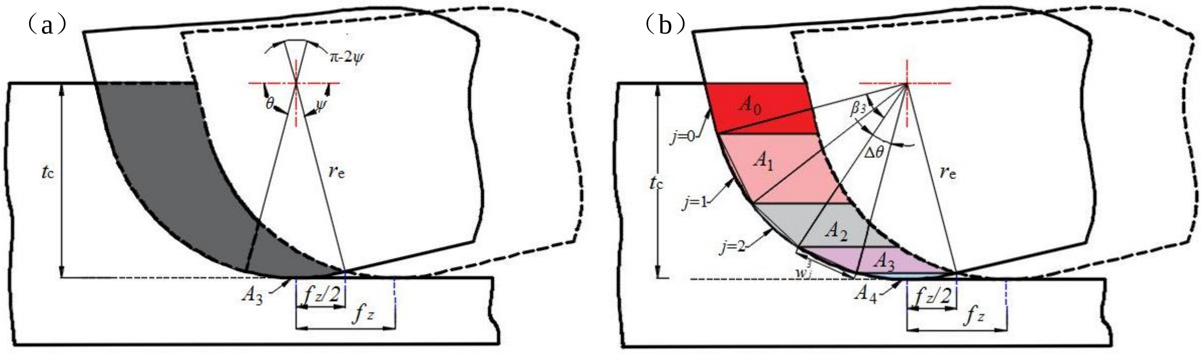
$$\begin{cases} \Delta\theta = \dfrac{\theta}{N}, d_j = w_r^j sin\left(\dfrac{\pi}{2} - \beta_j - \dfrac{\Delta\theta}{2}\right) \\ w_r^j = 2r_e sin\dfrac{\Delta\theta}{2},\ \beta_j = \cos^{-1}\left(\dfrac{f_z}{2r_e}\right) - \theta + (j-1)\Delta\theta \end{cases} \quad 1 \le j \le N \tag{3}$$

Where, β_j, w_r^j and d_j represent the angle position, width of cut and depth of the cut corresponding to the cutting edge element *j*.

In figure 2(*b*), the area of shear associated to the *j*th cutting edge element is defined as

$$A_j = \begin{cases} f_z t_{c_j} \\ \dfrac{r_e^2}{2}\left[\pi - 2cos^{-1}\left(\dfrac{f_z}{2r_e}\right) - sin\left(2cos^{-1}\left(\dfrac{f_z}{2r_e}\right)\right)\right] \end{cases} \begin{cases} 0 \le j \le N \\ j = N+1 \end{cases} \tag{4}$$

By considering equation (3) and equation (4) and after some algebraic manipulation the following expressions are obtained.



(*a*) The undiscretized model (*b*) The model of discretization

Figure 2. Subdivision of the rounded nose and the area (*N*=3 in the figure)

$$A_j = \begin{cases} 2r_e f_z sin\dfrac{\Delta\theta}{2} sin\left(\dfrac{\pi}{2} - \beta_j - \dfrac{\Delta\theta}{2}\right) \\ r_e^2\left[\dfrac{\pi}{2} - cos^{-1}\left(\dfrac{f_z}{2r_e}\right) - \dfrac{f_z}{2}\left(r_e^2 - \dfrac{f_z^2}{4}\right)^{1/2}\right] \end{cases} \begin{cases} 0 \le j \le N \\ j = N+1 \end{cases} \tag{5}$$

From figure 2, by using equation (5) can get

$$A = r_e^2\left[\frac{\pi}{2} - arccos\left(\frac{f_z}{2r_e}\right)\right] + \frac{f_z}{2}\left(r_e^2 - \frac{f_z^2}{4}\right)^{1/2} + f\left(t_c - r_e\right) \tag{6}$$

So the total power, which is the sum of shear and friction power, can be written as $P = P_s + P_f = c$A. Where *c* is a constant, the value is given as follow

$$c = \frac{\tau v}{cos(\varphi - \alpha_e)}\left(\frac{sin\beta}{cos(\varphi + \beta - \alpha_e)} + \frac{cos\alpha_e}{sin\beta}\right) \tag{7}$$

In this paper, we supposed $P_0 = P/c = A$.

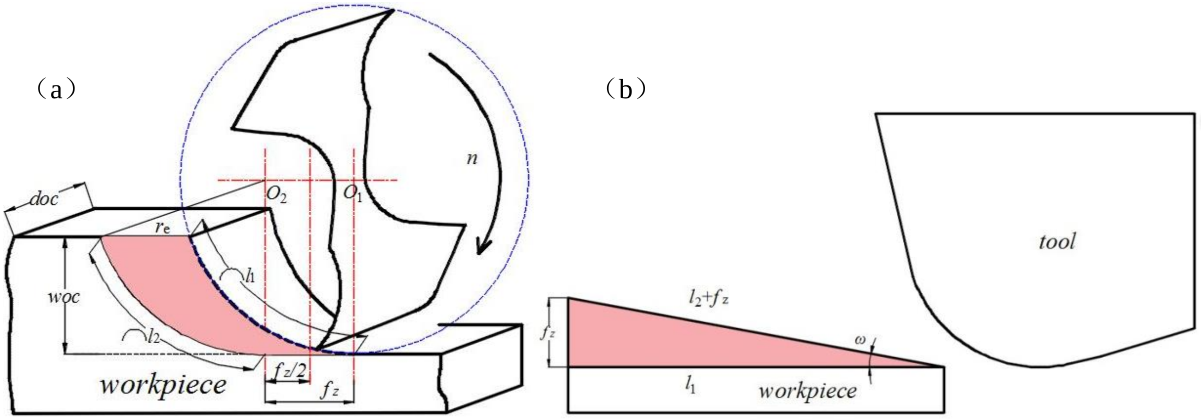
3. 2-D finite element modeling

To construct the 2-D FE model for micro up milling of Ti-6Al-4V alloy, AdvantEdge was utilized. AdvantEdge does not need to define the separation line, chip and workpiece separation criteria and assume the chip shape in advance. So it can better avoid the grid re-division and distortion, which making the workpiece and chip to maintained a good contact state, the calculation easy to converge and promised the accuracy and efficiency [10].

AdvantEdge adopted Power Law constitutive model. It was defined by three multiplicative terms namely strain hardening, rate sensitivity and thermal softening as shown in equation (8)

$$\sigma\left(\varepsilon^{p},\dot{\varepsilon},T\right)=\mathrm{g}\left(\varepsilon^{p}\right)\times\Gamma\left(\dot{\varepsilon}\right)\times\Theta\left(T\right) \tag{8}$$

Where, $\mathrm{g}(\varepsilon^p)$ is strain hardening, $\Gamma(\dot{\varepsilon})$ is strain rate sensitivity and $\Theta(T)$ is thermal softening.



(*a*) 3-D finite element simulation (*b*) 2-D finite element simulation

Figure 3. FE model for half-immersion up micro milling schematic diagram

The figure 3 shows a schematic diagram of the milling model. From the figure 3(a), it can be noticed that the cutting quantity is indicated by shading part. Unlike other software for up milling, when converting 3-D to 2-D finite element simulation, AdvantEdge have as realistic a model as possible.

In the figure 3(b), f_t, l_1, l_2 represent the feed, arc length corresponding to the angle of rotation δ, respectively. N is the number of teeth. The relation between them can be written as:

$$l_1 = l_2 = \frac{\pi r_e}{180}\delta \text{ , } f_t = \frac{f_z N}{2\pi}\delta \tag{9}$$

Equation (9) indicated that at the same time, there is different feed when δ is changing. However, every project actually has same feed while t_c is changing. Big t_c just took more time to complete the project. This is agreement with the process. Therefore the model, we built in AdvantEdge, is true.

In the simulation, the tool diameter is 0.5mm with a rake angle of -5° and the edge radius of 3μm. The configurations of the simulation cutting parameters are spindle speed（n）of 20000rpm, cutting depth（a_p）of 0.1mm, feed per tooth（f_z）of 5μm, and uncut chip thickness（t_c）of 1.5μm, 2.0μm, 2.5μm and 3.0μm.

4. Results

The simulation for total power of the workpiece as shown in figure 4, which is the sum of friction and shearing power. Equation (1) indicated that power is increased with the increasing shear area. That is to say, taking into equation (6) account, total power increased with uncut chip thickness, which can be seen from figure 5.

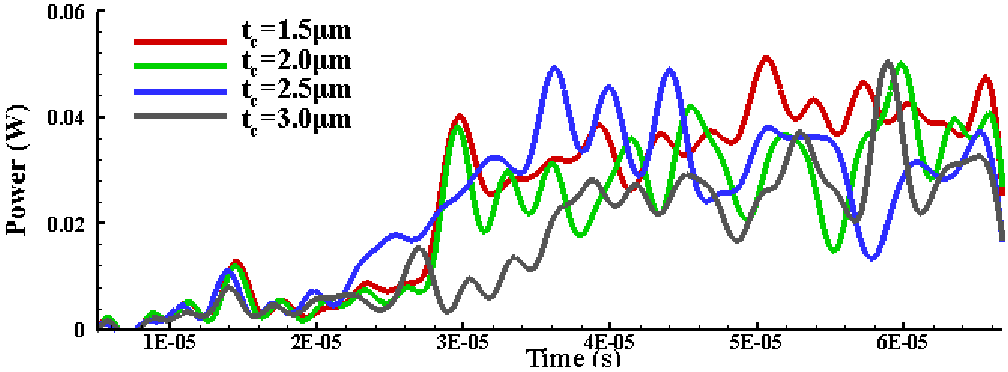


Figure 4. The total power for simulation

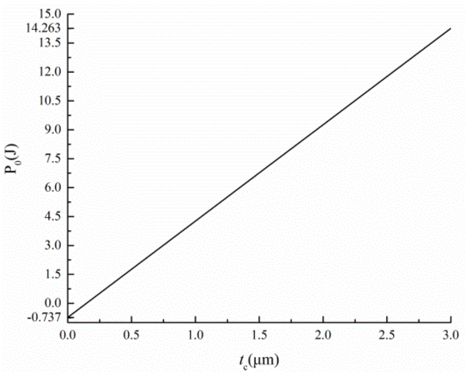


Figure 5. The total power for analysis results

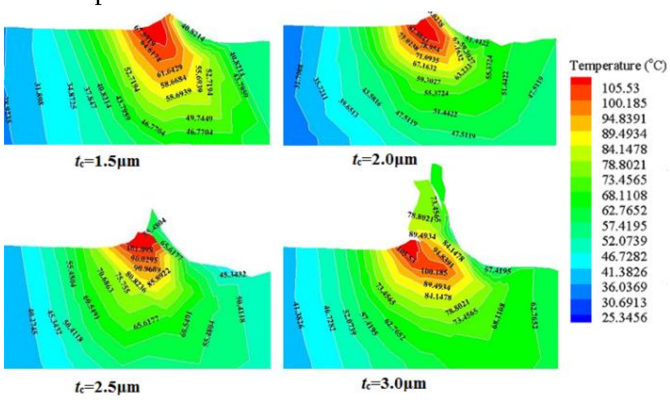


Figure 6. Workpiece temperature cloud at different uncut chip thickness

The workpiece's temperature cloud with different uncut chip thickness (t_c) as shown in figure 6. It can be noticed that chip formed was significantly influenced by the t_c. The larger t_c is, the lager chip is. The highest temperature is distributed in the primary deformation. And there is obvious temperature stratification phenomenon when close to the main deformation zone. But the most unfavorable point is the whole workpiece temperature is increasing, which will cause residual stresses and thermal deformation [11]. Therefore, to master the law of temperature changes and optimization of processing parameters is very necessary. According to this paper, although selecting bigger uncut chip thickness increased machining time, the workpiece will have a better improvement.

5. Conclusions

In this study, power model and 2-D FE simulations of micro milling have been developed. The developed model uses a semi analytical approach for calculating the power in the primary and secondary deformation zones. The results showed that the bigger uncut chip thickness is, the higger power and temperature are. Thermal-mechanical distribution of zone machined will reduced when the uncut chip thickness is larger than the minumum chip thickness.

Acknowledgments

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