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Study on Influence of Ultrasonic Vibration on the Ultra-Precision Turning of Ti6Al4V Alloy Based on Simulation and Experiment

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ABSTRACT Titanium alloy is one of the most important metals widely used in many industrial fields due to its special performance, such as high corrosion resistance and specific-strength. In recent years, titanium alloy has a great application prospect in the optical field. However, the pitiful machinability of titanium alloy material brings great difficulty to its ultra-precision cutting. In this paper, we have proposed the method of ultrasonic-assisted ultra-precision turning (UAUT) to improve the cutting performance of titanium alloy. In addition to exploring the mechanism of ultrasonic cutting, the purpose of this paper is to make a comprehensive comparison between UAUT and conventional ultra-precision turning (CUT) of Ti6Al4V alloy. The orthogonal cutting model was established using the software ABAQUS for revealing the cutting mechanism of titanium alloy. The effect of ultrasonic vibration on the chip morphology, cutting force, residual stress, and cutting temperature in the ultra-precision turning process of titanium alloy has been investigated by the finite-element model. The results of the simulation indicate that UAUT can reduce the cutting force, residual stress, and temperature as compared to that in CUT. The results of the simulation show a great agreement with the experimental results. Furthermore, the comparison of surface roughness and surface morphology between the UAUT and CUT experiments confirmed that the surface quality of the Ti6Al4V sample is improved obviously by ultrasonic vibration. At the same time, the results of the experiments show that the chips became more continuous, and the tool wear was reduced by the UAUT method. This research proved that the UAUT method can greatly improve the cutting performance of titanium alloy.

INDEX TERMS Titanium alloy, ultrasonic vibration, finite element model, ultra-precision turning, tool wear, chip formation, cutting force, cutting temperature, surface roughness, chip morphology.

I. INTRODUCTION

Due to the excellent characteristics of biocompatibility, high specific-strength and high temperature resistance, titanium alloys are extensively used in the fields of ocean, aviation and sport [1], [2]. In recent years, because of other good corrosion resistance and non-magnetic properties, titanium alloys have been increasingly used in medical and health care, such as medical endoscopes and dental optical instruments [3]–[5]. However, some characteristics of titanium alloys, the low heat conduction property and high chemical activity, make the machining performance poor and limit their application in the field of optics field [6]–[8]. Especially in the ultra-precision cutting process of diamond tools, the tool wear is very fast and the surface quality is poor. Aiming at the problems in ultra-precision diamond cutting of titanium alloy, more and more attention has been paid how to improve the tool life and surface integrity of titanium alloys [9]–[16]. Zareena and Veldhuis [9] studied the causes of tool wear in ultra-precision cutting process of titanium alloys

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and presented the method of extending tool life. Sakamoto *et al.* [10] used the diamond tool in ultra-precision machining to make an attempt to cut titanium alloys. Minton *et al.* [11] adopted a diamond coated tool with internal cooling function in the ultra-precision machine to cut titanium alloy and investigated the temperature distribution of tool. Sakamoto *et al.* [12] evaluated the influence of cutting fluid on surface morphology of titanium alloys obtained by ultra-precision machining. Hu and Zhou [13] adopted the experimental method to investigate the wear mechanisms of diamond tool in ultra-precision cutting of Ti6Al4V alloy. Yip [14] used the ultra-precision machine to cut Ti6Al4V alloy and investigated the brittle and ductile transition phenomenon of material. We have also done some research to explore the cutting mechanism of titanium alloys during ultra-precision turning [17]–[19]. At present, tool wear and surface integrity is still the serious problem which constrains the application of titanium alloys in ultra-precision fields.

In recent years, ultrasonic vibration has attracted more and more attention in cutting research. Intermittent cutting is a typical characteristic of ultrasonic assisted cutting. The ultrasonic assisted machining is proved to be an effective way for enhancing machinability and cutting quality of titanium alloys [20]–[25]. Koshimizu [20] found that the semi-dry cutting was the very effective method for ultrasonic vibration cutting of titanium alloys, which can decrease the cutting force obviously. Cakir *et al.* [21] studied the influence of cutting parameters on the ultrasonic vibration turning process of titanium alloys. Patil *et al.* [22] observed the microstructure of machined surfaces and the chips in ultrasonic cutting and non-ultrasonic process and found that ultrasonic vibration can reduce the degree of chip serration. Sui *et al.* [23] made an attempt to study the possibility of high speed ultrasonic vibration to cut titanium alloy. Churi *et al.* [24] presented a rotary ultrasonic machining method to cut the titanium alloy and the results proved that this method is very effective.

Although ultrasonic vibration machining has many advantages, its cutting mechanism needs to be further studied. As an effective research tool, finite element method is largely used in the research of cutting mechanism. Many scholars have established a lots of finite element models for investigating the cutting mechanism of titanium alloys [26]–[32]. Karpat *et al.* [26] presented a new material constitutive model of titanium alloy and used this model in cutting simulation for analyzing the shear localization and chip formation. Karpat [27] integrated a new flow softening equation into the material model of titanium alloy, which can define the temperature-dependent flow softening behavior of material, and used it in the 2D finite element model. Thepsonthi and Özel [28] employed the finite element method to study the chip formation and surveyed the influence of CBN coated micro-end mills on the cutting force and cutting temperature in micro-milling process of titanium alloy Ti6Al4V. Umbrello [29] used the finite element method to explore the conventional and high-speed machining of TiAl6V4 alloy. Chen *et al.* [30] adopted the finite element

TABLE 1. Mass percentages of various elements of TI6AL4V.

Ti	Al	V	S	Sn	C	H	O
94.16	1.13	2.28	0.22	2.20	0.01	0.0013	0.02

TABLE 2. Physical properties of TI6AL4V.

Properties	Vaule
Hardness (HRc)	32
Density (Kg/m3)	4410
Elastic modulus (GPa)	105
Yield strength (Mpa)	1000
Heat conductivity (W/mk)	4
Linear thermal expansion (10-6/ºC)	6.5

model with ductile failure model to study the high speed machining of Ti6Al4V alloy.

In this study, aiming at the difficult machinability of titanium alloy, the ultrasonic vibration was firstly used to assist the ultra-precision turning. In the UAUT, one ultrasonic equipment has been fixed on the ultra-precision machine to make the single point diamond tool vibrate when cutting Ti6Al4V alloy. To explore the mechanisms of improving the surface integrity and decreasing tool wear in the UAUT of titanium alloy, one orthogonal cutting model established by the finite element method for UAUT of Ti6Al4V alloy is presented. In addition, a series of comparison between UAUT and CUT has been carried out to analyze the influence of UAUT. The results indicated that the UAUT can greatly improve the machinability of Ti6Al4V alloy.

II. EXPERIMENTAL SETUP

The material type in this research is a typical titanium alloy Ti6Al4V.The X-ray photoelectron spectroscopy equipment STEREOSCAN 600X is used to obtain the chemical composition of Ti6Al4V alloy and the detailed mass percentages of the various elements are shown in Table 1. The mechanical properties of Ti6Al4V alloy are listed in Table 2.

One CNC ultra-precision machine Nanoform 250 with an ultrasonic tooling system has been used to implement the ultrasonic assisted ultra-precision turning tests. The ultrasonic vibration of the tool can be view as harmonic motion. The displacement of tool in the harmonic motion is given below:

$$y = a\cos wt \tag{1}$$

$$a = 2\pi f \tag{2}$$

where a is the amplitude and f is the frequency of the ultrasonic vibration.

The schematic of the UAUT are shown in Fig.1 and the practical equipment of UAUT is shown in Fig.2. The tool

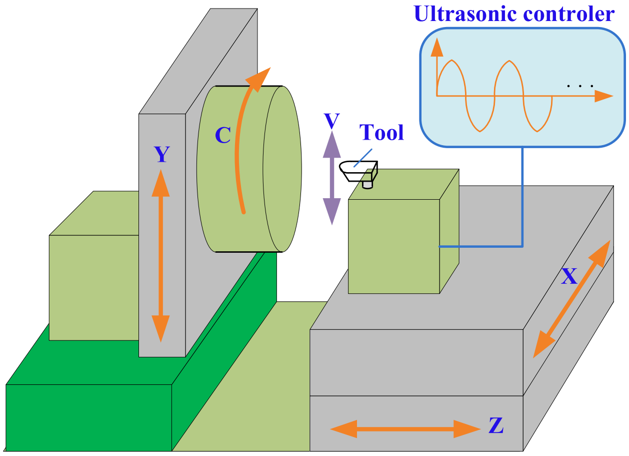


FIGURE 1. Schematic of ultrasonic assisted ultra-precision turning.

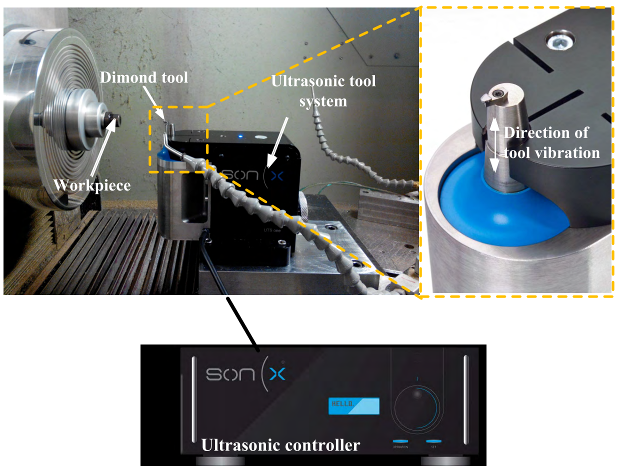


FIGURE 2. Experimental setup for ultra-precision cutting of Ti6Al4V alloy.

TABLE 3. Cutting conditions used in the experiments.

Parameters	Values
Spindle speed	1000 r/min
Feeding speed	20 um/min
Depth of cut	3 um
Diamond tool	rake angle 0°,clearance angle 10°
Ultrasonic frequency	80 KHz
Amplitude	2 um

type used in the cutting experiments is a single point diamond insert. Fig.3 shows the Ti6Al4V alloy samples and the single point diamond tool. The dimension of Ti6Al4V alloy samples is 30 mm in length and 14 mm in diameter. The ultrasonic vibrations generated by a control element are transmitted to the diamond tool in Fig.2. The ultrasonic device causes the tool to vibrate along the direction of cutting velocity. The parameters of ultra-precision turning tests are listed in Table 3.

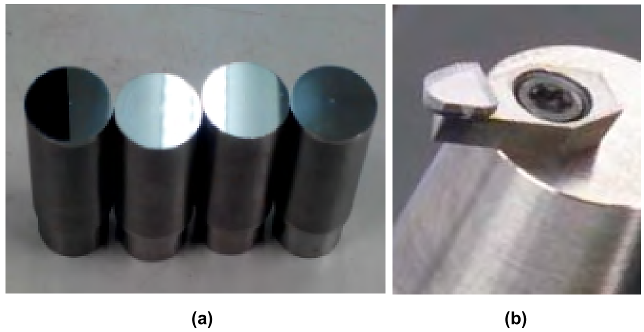


FIGURE 3. Samples and tool in the experiments. (a) Titanium alloy samples. (b) Single point diamond insert.

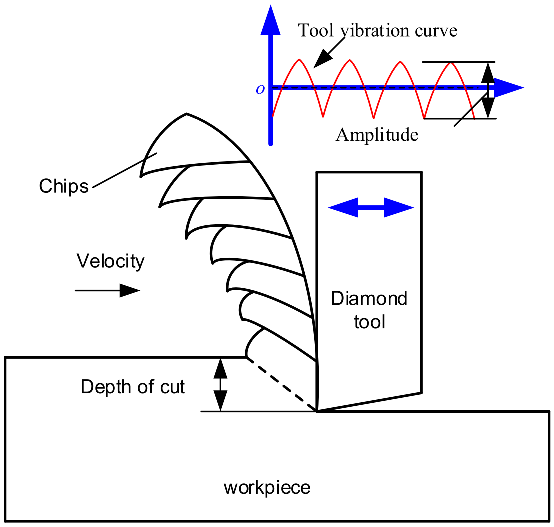


FIGURE 4. Schematic of orthogonal ultrasonic assisted cutting model.

III. FINITE ELEMENT MODELING OF ULTRASONIC ASSISTED MACHINING

A. FINITE ELEMENT MODEL

The orthogonal cutting model is very suitable for revealing chip formation and cutting mechanism of metal materials . The schematic of orthogonal cutting model for the ultrasonic vibration cutting of Ti6Al4V alloy is shown in Fig.4. This diagram shows the relationship between the motion of the cutter and the workpiece.

To reveal the influence of UAUT, one orthogonal finite element model (FEM) for ultrasonic assisted ultra-precision machining of Ti6Al4V alloy was built using the explicit block of the software Abaqus 6.10. The established FEM of UAUT is in Fig.5. The diamond tool was considered to be a rigid-body in cutting simulation. The rake angle and clearance angle of diamond tool were 0° and 10°, respectively. The cutting velocity was 120 mm/s and the depth of cut was 3 μm. The workpiece size is 0.05 mm × 0.012 mm. The simulation initial temperature of tool and workpiece is 20 °C. In this model, tool vibrated along the direction of cutting speed. The workpiece moved at the cutting speed. To enhance the computation efficiency, the meshes in the

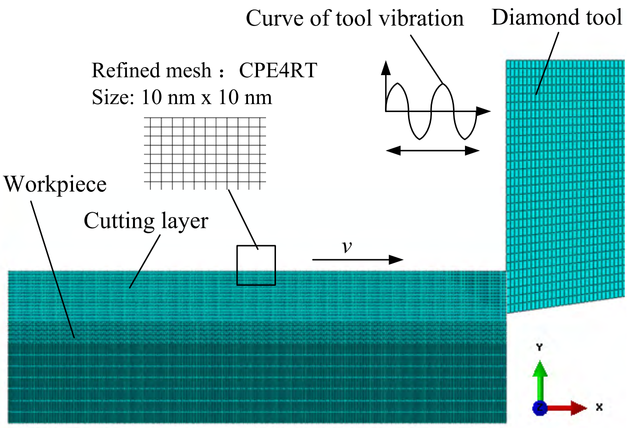


FIGURE 5. FEM of UAUT of Ti6Al4V alloy.

TABLE 4. Constants of Johnson–Cook for TI6Al4V.

A (Mpa)	*B* (Mpa)	*n*	*C*	*m*	*Tr* (°C)	*Tm*(°C)
1000	780	0.47	0.033	1.02	20	1520

cut layer have been refined. CPE4RT element is selected because having both displacement and temperature degrees of freedom. The cutting condition is dry cutting.

B. MATERIAL MODEL

The constitutive relation of materials is the reflection of the material properties, and is one the most important factors for the FEM of the cutting process. In this simulation of UAUT, the Johnson-Cook constitutive model [31] is used to express the stress-strain relationship of Ti6Al4V alloy. This material model is largely used in metal cutting simulation, which combined the effects of strain, temperature and strain rate. The relationship of stress-strain can be expressed using the following equation.

$$\overline{\sigma} = \left[A + B(\overline{\varepsilon}^{pl})^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \tag{3}$$

where $\overline{\sigma}$, $\overline{\varepsilon}^{pl}$, $\dot{\varepsilon}^{pl}$ and $\dot{\varepsilon}_0$ are the equivalent stress,the equivalent plastic strain, the equivalent plastic strain rate and the reference strain rate, respectively. In this paper, $\dot{\varepsilon}_0$ is equal to 1.0/s. T_r is the reference temperature, T_m is the melting point of materials. A, B, n, C and m are yield strength at quasi-static conditions, the index of strain sensitivity, the strain hardening index, the strain rate sensitivity index and temperature sensitivity index, respectively.

This Johnson-Cook model can truly reflect the various mechanical behaviors of metal materials in the cutting process, and the simulation results are in good agreement with the experiments. In addition, this model has the simple form and is very convenient to be used in the simulation. The detailed Johnson-Cook constants of Ti6Al4V alloy are listed in Table 4.

TABLE 5. Fracture constants of TI6AL4V alloy.

Constants	Value
D_1	-0.09
D_2	0.25
D_3	-0.5
D_4	0.014
D_5	3.87

C. DAMAGE CRITERION

The chip formation must have the corresponding fracture criteria, which can be used to judge when the material is separated from the workpiece, thus forming chips. There are many material damage criterions which can be applied to realize the chip separation in the cutting simulation. In this paper, the Johnson-Cook material failure criterion [32] was employed. In the simulation, the Johnson-Cook material damage model is based on the value of the equivalent plastic strain at integration points of element. Damage is judged to produce when the value of damage parameter is great than 1. In this model, the damage parameter, w, is described as:

$$w = \sum\left(\frac{\Delta\overline{\varepsilon}^{pl}}{\overline{\varepsilon}_f^{pl}}\right) \tag{4}$$

where $\Delta\overline{\varepsilon}^{pl}$, $\overline{\varepsilon}_f^{pl}$ are the increment of equivalent plastic strain and the failure strain, respectively. In this equation, the failure strain $\overline{\varepsilon}_f^{pl}$, is regarded as dependent on a nondimensional plastic strain rate $\dot{\varepsilon}^{pl}/\dot{\varepsilon}_0$, one dimensionless pressure-deviatoric stress ratio, p/q (where p is the pressure stress and q is the Mises stress). The correlation is assumed to be separable and can be expressed using the following form:

$$\overline{\varepsilon}_f^{pl} = \left[D_1 + D_2\exp\left(D_3\frac{p}{q}\right)\right]\left[1 + D_4\ln\left(\frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0}\right)\right](1 + D_5T^*) \tag{5}$$

$$T^* = \frac{T - T_r}{T_m - T_r} \tag{6}$$

where D_1-D_5 are damage constants obtained below or at the transition temperature, $\dot{\varepsilon}_0$ is the reference strain rate and $\dot{\varepsilon}^{pl}$ is the failure strain. The Johnson-Cook damage criterion constants of Ti6Al4V alloy are listed in Table 5.

D. FRICTIONAL MODEL

Tribological behavior has very significant influence on the metal cutting process. Friction action between the contact interfaces of tool and chip will result in tool wear because of high temperature, high stress and chemical reaction. There are two zones in the contact area of chip and tool, the sliding and sticking zone [33]. In the sliding zone, friction needs to abide by the Coulomb law. But in the sticking zone, the shear stress must be equal to the critical friction stress.

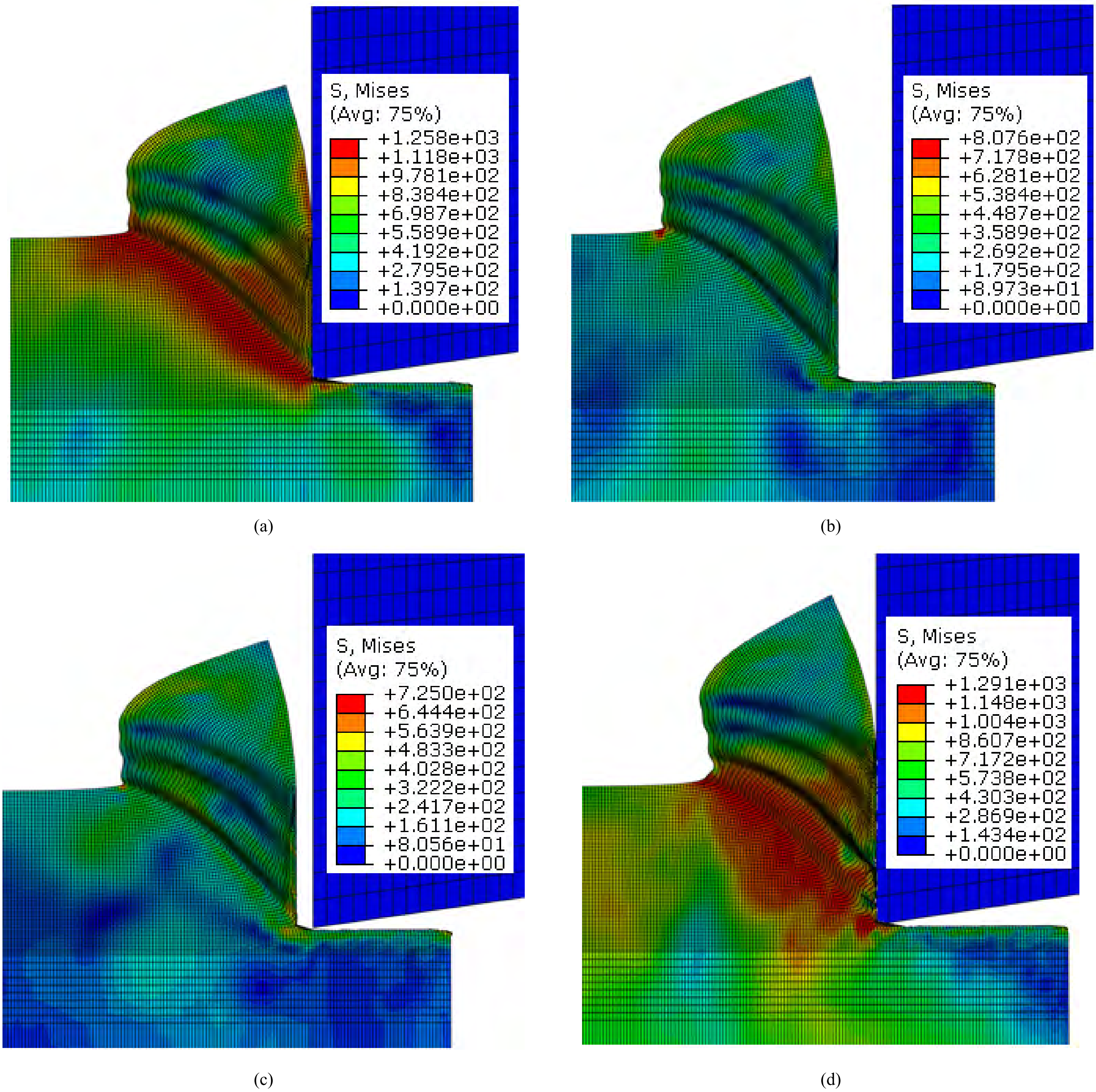


FIGURE 6. **Stress distribution in UAUT. (a) Cutting stage. (b) Backing stage. (c) Approaching stage. (d) Cutting again stage.**

This contacted model between chip and tool is expressed by the following equation:

$$\tau_f = \tau_s, \mu\sigma_n \geq \tau_s \quad \text{(Sticking zone)} \tag{7}$$

$$\tau_f = \mu\sigma_n, \mu\sigma_n < \tau_s \quad \text{(Sliding zone)} \tag{8}$$

where τf is friction force and μ is friction coefficient between workpiece and tool. σ_n is normal stress on contact surface, τ_s is ultimate shear flow stress. By combining the model with the material, the friction status between the chip and rake face can be well reflected. In the cutting simulation, the frictional state will be decided automatically based on the value of contact stress. When the critical friction τ_s is less than the friction stress τ_f, the contact point between the cutting tool and the chip occurs relative sliding. That is, in the sliding friction, when the critical friction τ_s is greater than or equal to the friction stress τ_f, the contact point between the cutting tool and the chip has no relative sliding, in the state of sticking friction. In the cutting simulation of Ti6Al4V alloy, revised Coulomb's law is used to represent the contact action

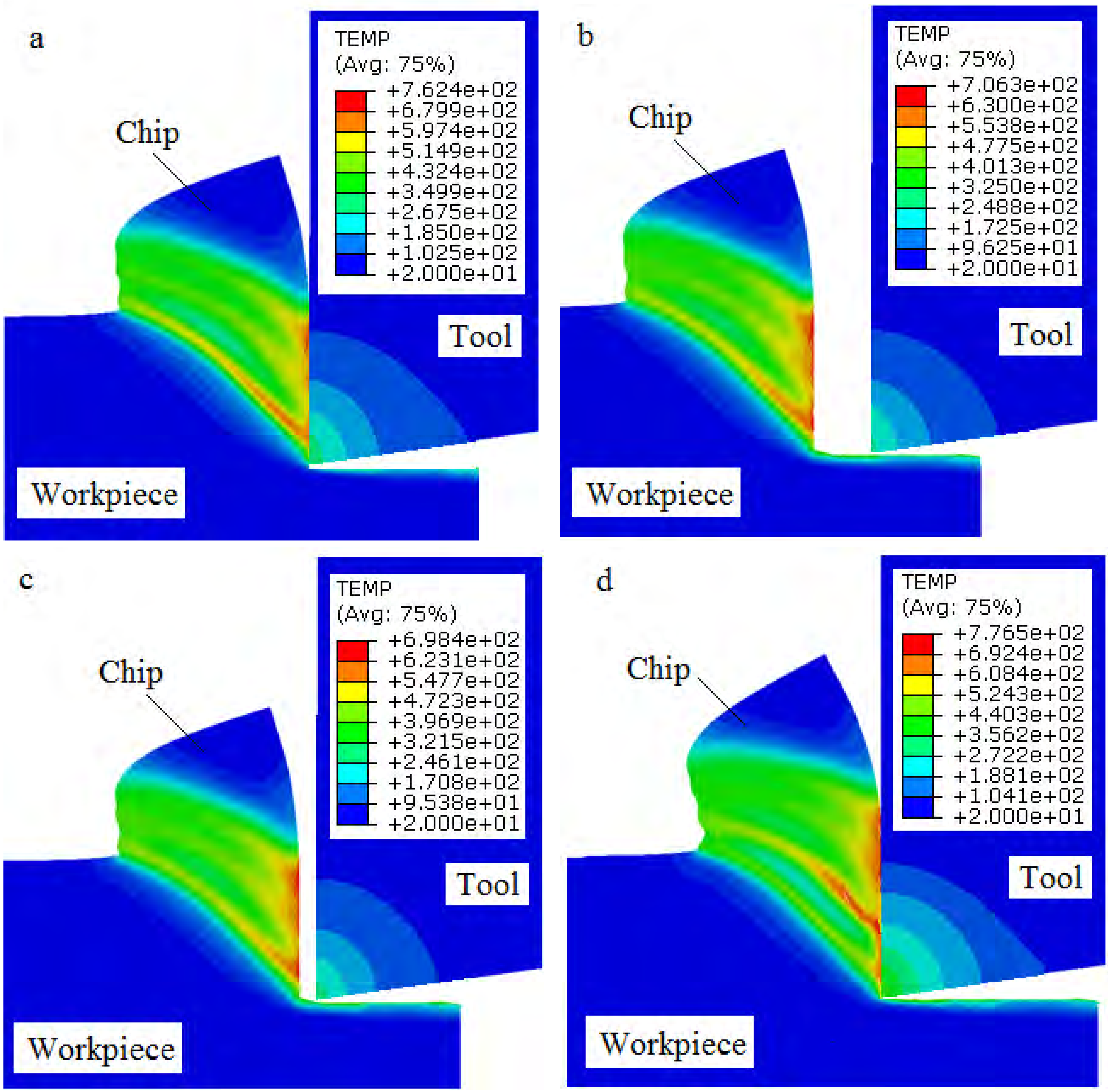


FIGURE 7. Temperature distribution during one vibration cycle.

between chip and rake face. Critical shear friction stress can be expressed as follows:

$$\tau_c = \min(\mu\sigma_n, \tau_s) \tag{9}$$

where, τ_c is critical shear friction stress of sliding on the contact surface. In the simulation, the frictional coefficient is set to be 0.25.

E. HEAT TRANSFER MODEL

The cutting heat mainly comes from the plastic deformation of materials and the friction at the interface between the cutter and the chip. The plastic deformation of the material in the cutting process is mainly concentrated in the primary shear region and most of deformation energy is converted into heat. Part of the friction heat is passed into the workpiece and the other part is passed into the tool. The heat transfer at the interface is generally considered to be evenly distributed between the chip and the tool. In order to really reflect the thermo-mechanical behavior of Ti6Al4V alloy in the UAUT, the thermal conduction model needs to be founded for the simulation. The heat transfer between chip and tool in simulation is defined as:

$$q = k(\theta_a - \theta_b) \tag{10}$$

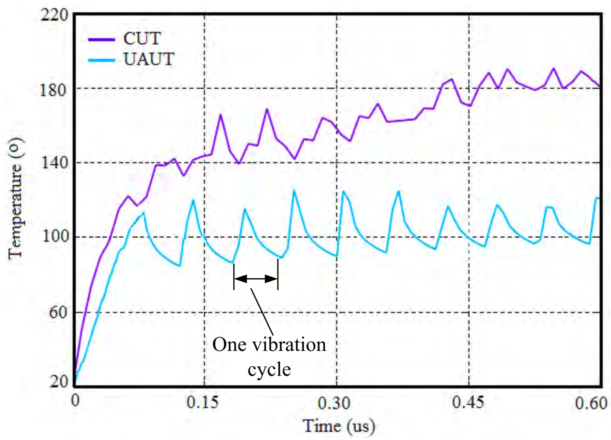


FIGURE 8. Temperature curve of tool.

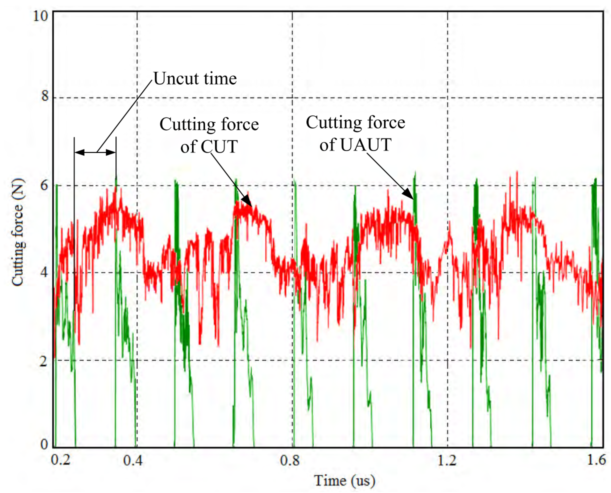


FIGURE 9. Comparison of cutting force between UAUT and CUT.

where q is the heat flux per unit area across the tool-chip interface from node a at one surface to node b at the other surface, k is the gap conductance. In the cutting process, node a is on the chip surface and node b is located on the rake face contacting with the chip, or the position on the rake surface with a surface normal that intersects the node a when the tool and chip is not in contact. The gap conductance between tool and chip can be expressed as:

$$k = k(\theta, d, p, |\dot{m}|, f_r) \tag{11}$$

where d is the gap between node a and node b, p is the contact pressure transmitted crossing the interface between node a and node b, $\theta = \frac{1}{2}(\theta_a + \theta_b)$ is the average surface temperature between node a and node b, $|\dot{m}| = \frac{1}{2}(|\dot{m}|_a + |\dot{m}|_b)$ is the average value of the mass flow rates per unit area of the interface at node a and node b, $f_r = \frac{1}{2}(f_r^a + f_r^b)$ is the average value of any predefined field variables at node a and node b. During the cutting simulation, it is assumed that 90% of the dissipated energy is converted to heat and the heat is divided equally between the chip and rake face.

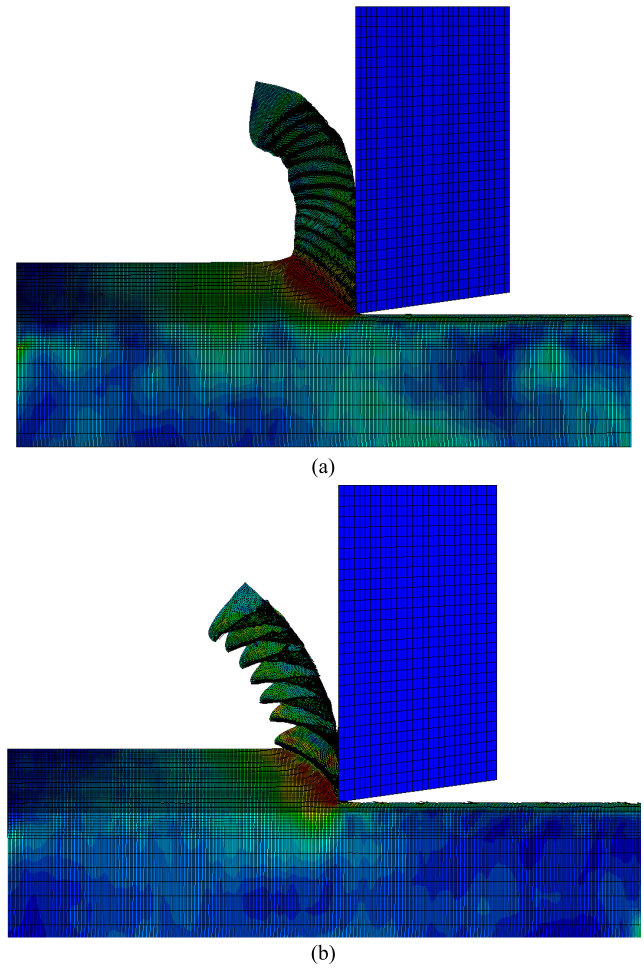


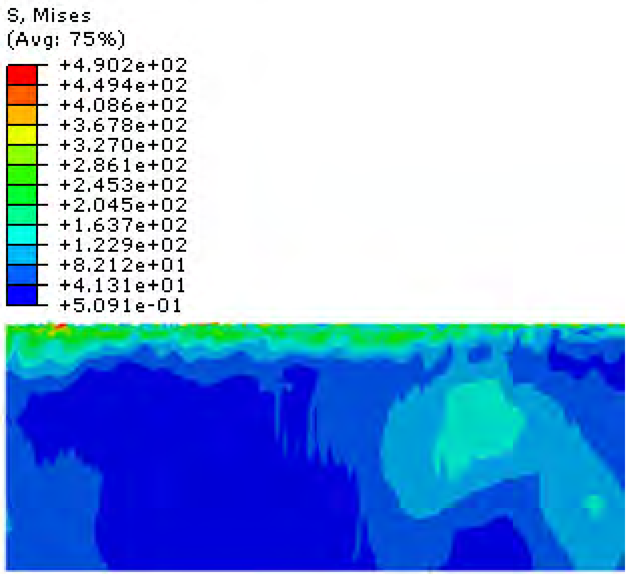
FIGURE 10. Comparison of chip formation. (a) UAUT. (b) CUT.

IV. RESULTS AND DISCUSSIONS

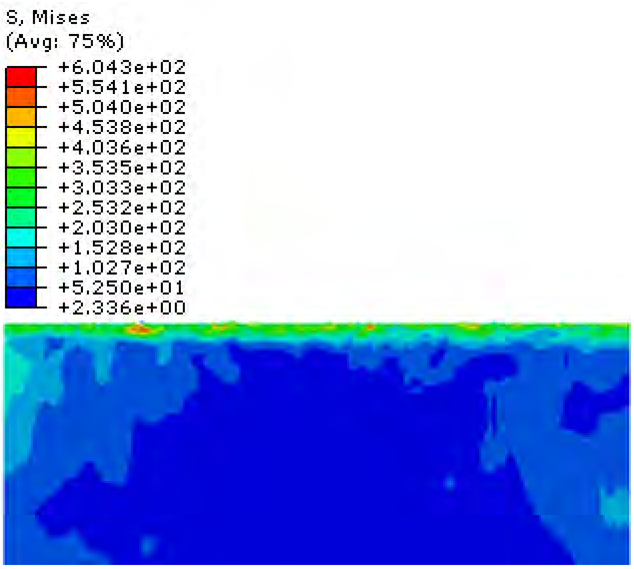
A. NUMERICAL SIMULATION OF CUTTING PROCESS

The metal cutting process will produce a lot of heat due to plastic deformation, and which will affect the change of material properties in the shear zone. Cutting process is a thermal mechanical coupling process and the mechanical and thermal solutions need to be calculated synchronously rather than separately. In the cutting simulation, the stress calculation is dependent on the temperature distribution and the temperature distribution depends on the stress solution. So the ''Dynamic Temperature-displacement, Explicit'' analysis step in software ABAQUS is selected. The UAUT of Ti6Al4V alloy has been simulated by the orthogonal FEM. Fig.6 is the stress distribution in an ultrasonic cutting cycle in UAUT. One ultrasonic cutting cycle included 3 stages: cutting, backing, approaching. In the simulation, the stress state of workpiece in UAUT **is** unstable and changes with the moving of tool during one ultrasonic vibration period. And the stress value fluctuates widely because of the formation of serrated chips. It can be seen that the intensity of chip serration is reduced.

Most of the deformation energy in the cutting process is converted into heat. Cutting temperature is one of the most

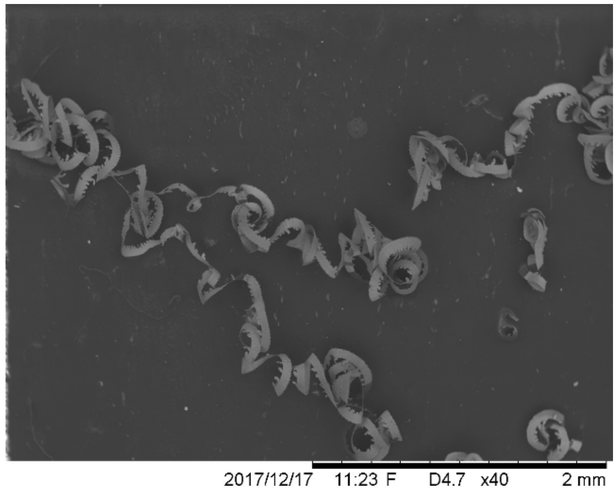


(a)

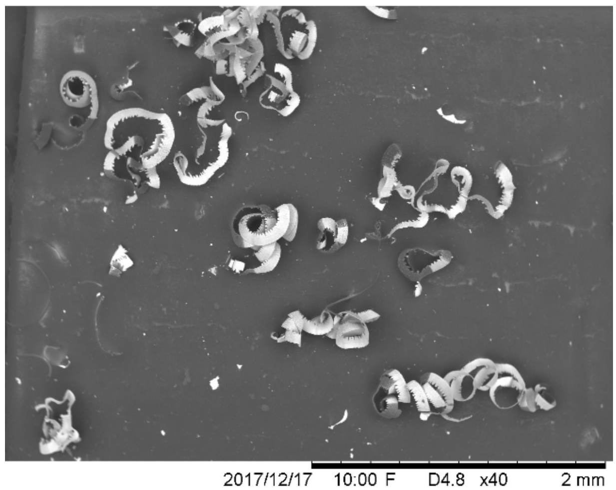


(b)

FIGURE 11. Comparison of residual stress on the cutting surface. (a) Distribution of residual stress obtained by UAUT. (b) Distribution of residual stress obtained by CUT.



(a)



(b)

FIGURE 12. SEM photos of chip shape. (a) Chip shape of UAUT. (b) Chip shape of CUT.

significant physical variables in the cutting process, which can affect tool life and cutting quality. The temperature distribution in tool-chip contact interface obtained by cutting simulation during one vibration cycle in UAUT is shown in Fig.7. In UAUT process, there exists the cutting time and the non-cutting time. This intermittent contact of tool and workpiece results in a decrease in thermal conduction between the chip and the tool, and an increase in heat transfer to the environment. Because the tool will be away from the chip for some time during every cycle of ultrasonic vibration, the cutting temperature on the tool decreases significantly. Because the heat in the shear zone has enough time to be conducted, the heat softening zone cools rapidly and no obvious adiabatic shear zone occurred. The thermal softening effect and adiabatic effect are reduced by ultrasonic vibration and the chip morphology tends to be continuous rather than serrated.

Excessive cutting temperature will make the tool wear fast and reduce the tool life. To investigate the change of tool temperature, one point at distances of 2.0 um from the tool-tip was selected and the temperature curve of this point during the whole UAUT and CUT is as shown in Fig.8. It can be seen that tool temperature in UAUT is much lower than the temperature in CUT. The result proved that the ultrasonic vibration can decrease the cutting temperature of tool.

The contrast of the primary cutting forces in UAUT and CUT of Ti6Al4V alloy is shown in Fig.9. The ultrasonic vibration imposed on the diamond tool results in the discontinuity and reduction of cutting force in the UAUT. This phenomenon is due to the reduction of the contact rate of tool and workpiece. Therefore, intermittent cutting helps to reduce cutting force and extend tool life due to the existing of non-cutting time.

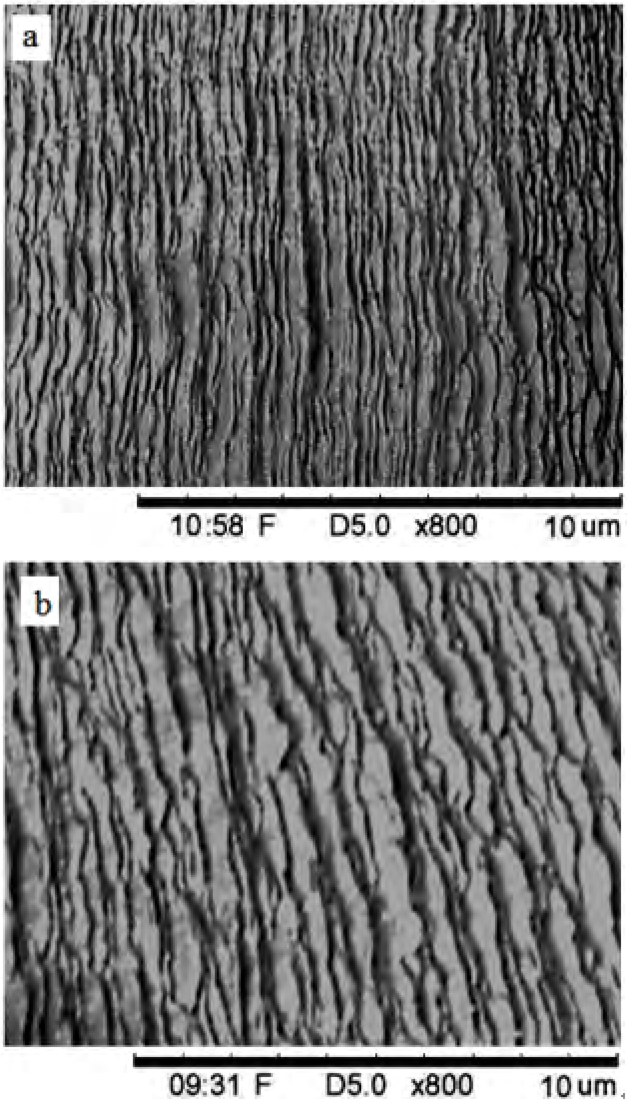


FIGURE 13. SEM photos of chip morphology during (a) UAUT and (b) CUT.

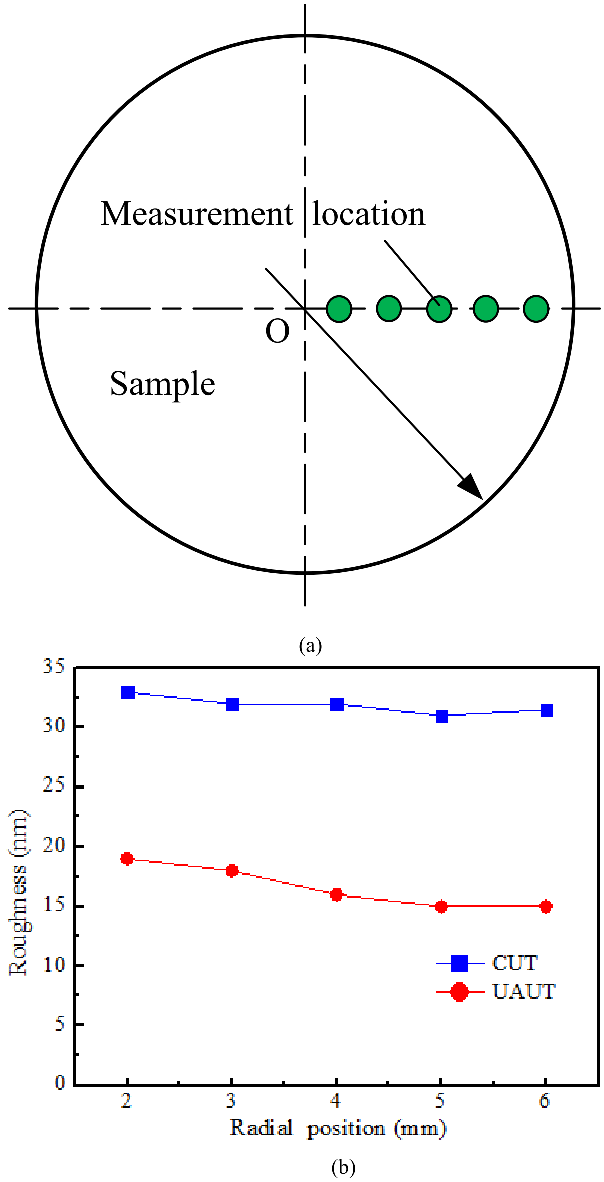


FIGURE 14. Roughness values obtained at various radial positions. (a) Measurement positions of roughness. (b) Comparison of roughness value.

In UAUT, tool vibration causes the large fluctuations of cutting force, so the cutting force value is very lower than that in CUT. As shown in Fig.9, about 42% decrease in cutting forces during UAUT as compared to that in CUT. Lower cutting force means lower energy consumption in UAUT, which indicates that heat occurred in the cutting process decreases. In addition, because the repeated retreats of tool in the cutting process can reduce the friction action between tool chip and tool, which is helpful to reduce the formation of built-up edge. As a result, the cutting heat and cutting force is further reduced. These advantages of vibration cutting help to compensate the difficulty of cutting caused by the poor thermal conductivity of titanium alloys.

Fig.10 is the chip morphology of UAUT and CUT in the simulation. The chip is serrated in CUT, but the chip of UAUT is close to continuous. The continuous chip can reduce the vibration of the machine and improve the surface quality. This is because ultrasonic vibration reduces the adiabatic effect of the titanium alloy material.

The plastic deformation and phase change occurred inside the material due to the action of cutting force and heat is the main reasons of residual stress. It is very important to study the distribution of residual stress on the machined surface for improving the cutting quality of workpiece. Fig.11 shows that the distribution of residual stress on the machined surface of titanium alloy Ti6Al4V obtained in UAUT and CUT. The comparison confirms that ultrasonic vibration also reduces the residual stress on the machined surface. Because the ultrasonic assisted ultra-precision turning is a discontinuous cutting, the temperature and stress are released when the tool and chip are separated. As a result, the residual stress on the machined surface in is lower than that of the

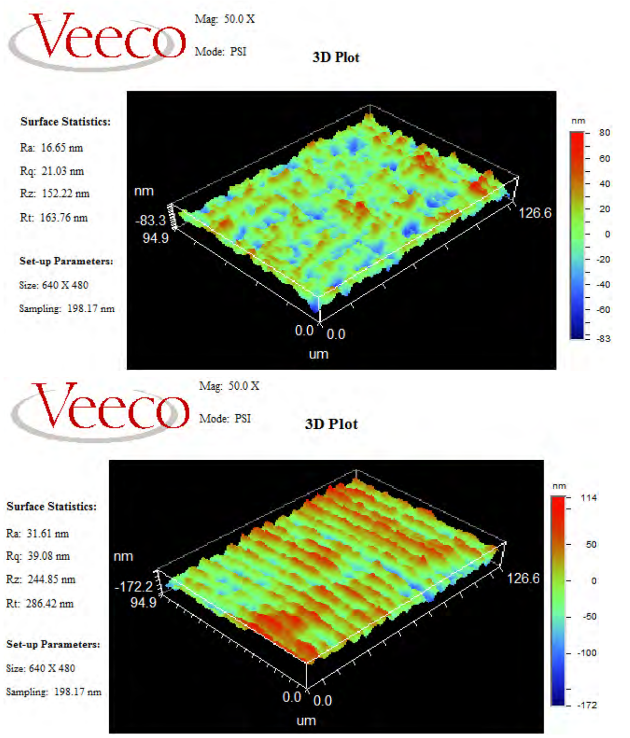
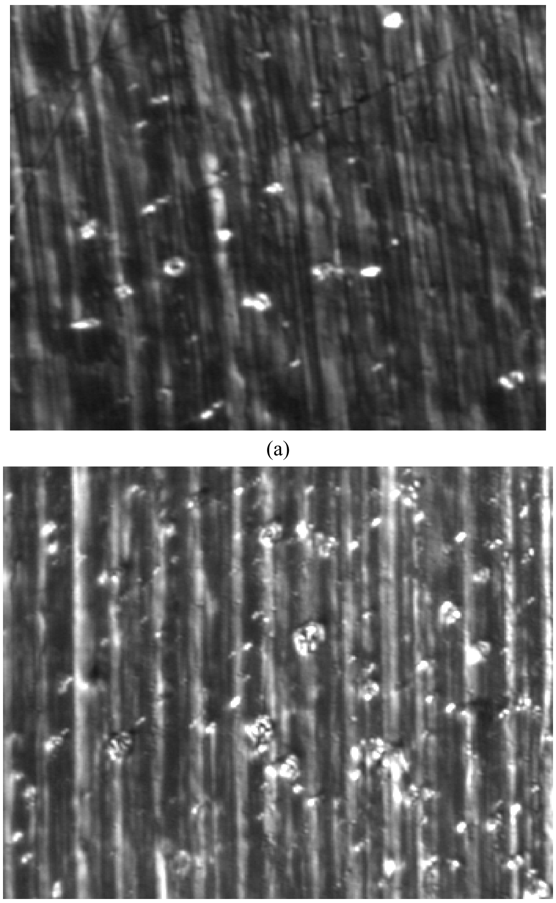


FIGURE 15. 3D roughness profiles of UAUT and CUT. (a) Surface roughness profile of UAUT. (b) Surface roughness profile of UAUT.



(a)

(b)

FIGURE 16. SEM image of surface morphology. (a) UAUT. (b) CUT.

non-ultrasonic cutting. The results proved that ultrasonic vibration method can improve the machinability of Ti6Al4V in the ultra-precision turning with diamond tool.

B. COMPARISON OF UAUT AND CUT

A Hitachi TM 3000 scanning electron microscope (SEM) was used to observe the morphology of chips connected in the UAUT and CUT experiments. The chip shape is as shown in Fig.12. It can be seen that the chips obtained by UAUT is more continuous, while the chips obtained by CUT tends to be fragmented.Fig.13 shows the micro morphology of chips in UAUT and in CUT. It is observed that the intensity of chip serration is reduced in UAUT, which has a good agreement with the result of simulation. The results of experiments manifest that chip serration have been suppressed by UAUT and prove that cutting process of UAUT is more stable. The results also agree well with the cutting force analysis.

The surface roughness was measured using a precision optical profiler Wyko NT8000. Because the cutting speed varies with the radial position of sample when the tool moves from outside to the center of the sample, five measuring positions were selected and located 2.0, 3.0, 4.0, 5.0 and 6.0 mm away from the sample center as shown in Fig.14a.The comparison of surface roughness of the Ti6Al4V samples is shown in Fig.14b. For each measurement position, the measuring region is 95 $\times$ 127 μm. It can be seen that the roughness value of sample by UAUT is lower than it by CUT, which showing a great improvement. Furthermore, the surface roughness values of titanium alloy sample by UAUT are more stable for various locations as compared with the CUT. Therefore, the results of comparison confirmed that the ultrasonic vibration can improve the surface quality of titanium alloy in ultra-precision turning.

To further analyze the surface state, the optical profiler Wyko NT8000 was used to achieve the 3D surface morphologies of samples. The measured position is located 4.0 mm away from the sample center and the 3D surface morphologies are shown in Fig.15. Using the same magnification, it is obvious that the cutting surface obtained by UAUT is smoother than it by CUT. At the same time, it shows that the feed marks on the cutting surface obtained by CUT are more severe than it by UAUT. The results manifest that elastic recovery in turning process was reduced by UAUT. The SEM images of surface morphology in UAUT and CUT are shown in Fig.16. It can be seen that ultrasonic vibration is beneficial to reduce the burrs on the machined surface of Ti6Al4V alloy. And the surface quality obtained by UAUT is obviously better than it by CUT.

Fig.17 is the shapes of tool wear for the single point diamond tool after UAUT and CUT. The above results have shown that UAUT can reduce cutting force and cutting temperature, which are helpful to reduce tool

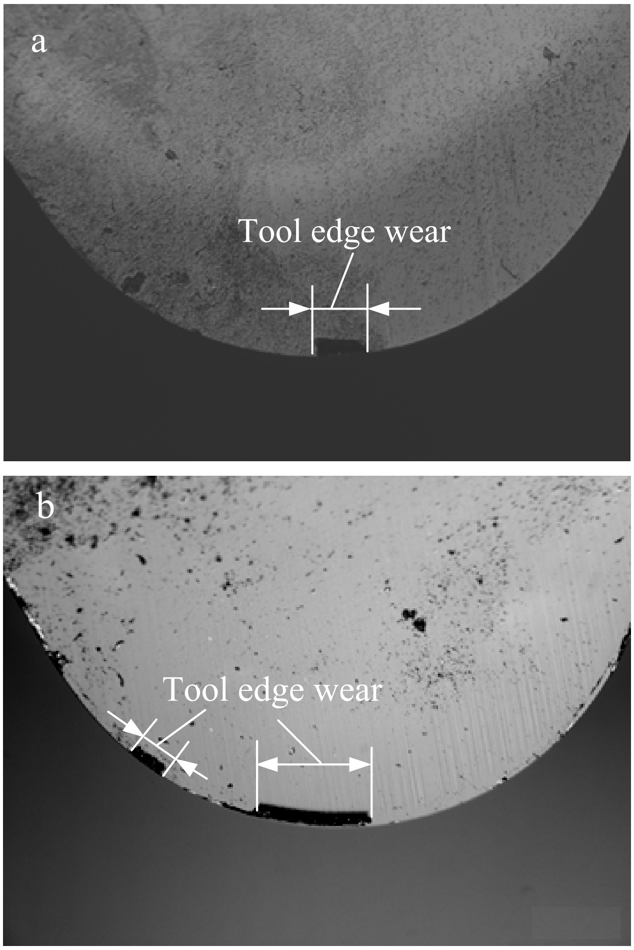


FIGURE 17. Photographs of a tool rake face (a) UAUT (b) CUT (cutting time 25 min).

wear. The comparison of tool wear also proves that UAUT can reduce tool wear in ultra-precision turning of Ti6Al4V.

V. CONCLUSIONS

A new ultrasonic tool equipment is adopted to assist the ultra-precision turning of Ti6Al4V alloy and improve cutting integrity of material. FEM and UAUT were performed to analyze the influence of ultrasonic vibration on the ultra-precision cutting of Ti6Al4V alloy. The research shows that the UAUT can reduce the cutting force, cutting temperature and obtain the lower residual stress in ultra-precision machining of Ti6Al4V. The surface integrity of Ti6Al4V samples using UAUT was better than using CUT. The results of FEM confirmed that UAUT make the cutting process more stable and chip more continuous. The results of experiments are in good agreement with the results of numerical simulation. At the same time, the results of the experiments show that the chips became more continuous and tool wear was reduced by UAUT method. This research proved that UAUT method can greatly improve the cutting performance of titanium alloys.

REFERENCES

[1] M. Cotterell and G. Byrne, "Dynamics of chip formation during orthogonal cutting of titanium alloy Ti–6Al–4V," *CIRP Ann.-Manuf. Technol.*, vol. 57, no. 1, pp. 93–96, 2008.

[2] C.-F. Wyen and K. Wegener, "Influence of cutting edge radius on cutting forces in machining titanium," *CIRP Ann.-Manuf. Technol.*, vol. 59, no. 1, pp. 93–96, 2010.

[3] H. Yasui, A. Shinozaki, A. Toyama, S. Sakamoto, and Y. Kajiwara, "Effect of low cutting speed on ultra-precision cutting of titanium alloy with coated-cemented-carbide tool," *Int. J. Jpn. Soc. Precis. Eng.*, vol. 74, no. 4, pp. 359–363, 2006.

[4] X. Liu, P. K. Chu, and C. Ding, "Surface modification of titanium, titanium alloys, and related materials for biomedical applications," *Mater. Sci. Eng. R, Rep.*, vol. 47, nos. 3–4, pp. 49–121, 2004.

[5] M. Niinomi, "Mechanical properties of biomedical titanium alloys," *Mater. Sci. Eng. A*, vol. 243, nos. 1–2, pp. 231–236, 1998.

[6] E. O. Ezugwu and Z. M. Wang, "Titanium alloys and their machinability—A review," *J. Mater. Process. Technol.*, vol. 68, no. 3, pp. 262–274, 1997.

[7] P.-J. Arrazola, A. Garay, L.-M. Iriarte, M. Armendia, S. Marya, and F. Le Maître, "Machinability of titanium alloys (Ti6Al4V and Ti555.3)," *J. Mater. Process. Technol.*, vol. 209, no. 5, pp. 2223–2230, 2009.

[8] J. P. Colafemina, R. G. Jasinevicius, and J. G. Duduch, "Surface integrity of ultra-precision diamond turned Ti (commercially pure) and Ti alloy (Ti-6Al-4V)," *Proc. Inst. Mech. Eng. B, J. Eng. Manuf.*, vol. 221, no. 6, pp. 999–1006, 2007.

[9] A. R. Zareena and S. C. Veldhuis, "Tool wear mechanisms and tool life enhancement in ultra-precision machining of titanium," *J. Mater. Process. Technol.*, vol. 212, no. 3, pp. 560–570, 2012.

[10] S. Sakamoto, A. Shinozaki, and H. Yasui, "Possibility of ultra-precision cutting of titanium alloy with diamond tool," in *Proc. ASPE Annu.*, 2005, pp. 1–4.

[11] T. Minton, S. Ghani, F. Sammler, R. Bateman, P. Fürstmann, and M. Roeder, "Temperature of internally-cooled diamond-coated tools for dry-cutting titanium," *Int. J. Mach. Tools Manuf.*, vol. 75, no. 12, pp. 27–35, 2013.

[12] S. Sakamoto, H. Yasui, and M. Kawada, "Effect of cutting fluid on surface roughness formed by ultra-precision cutting of titanium metal," *J. Jpn. Soc. Precis. Eng.*, vol. 69, no. 3, pp. 402–406, 2003.

[13] L. Hu and M. Zhou, "Experimental study on the wear of single crystal diamond tools in ultra-precision cutting of titanium alloy," *Key Eng. Mater.*, vol. 693, pp. 1015–1021, Apr. 2016.

[14] W. S. Yip and S. To, "Ductile and brittle transition behavior of titanium alloys in ultra-precision machining," *Sci. Rep.*, vol. 8, Mar. 2018, Art. no. 3934.

[15] N. S. Kwak, J. Y. Kim, and D. G. Park, "A research on ultra precision machining for Ti-6AL-4V alloy based biomedical applications using nanopositioning mechanism," *J. Nano Res.*, vol. 25, no. 12, pp. 157–173, 2013.

[16] L. H. Hu and M. Zhou, "Experimental study on the wear of single crystal diamond tools in ultra-precision cutting of titanium alloy," *Key Eng. Mater.*, vol. 693, pp. 1015–1021, May 2016.

[17] H. B. Wu and S. To, "Effects of electropulsing treatment on material properties and ultra-precision machining of titanium alloy," *Int. J. Adv. Manuf. Technol.*, vol. 82, nos. 9–12, pp. 2029–2036, 2016.

[18] R. Xiong and H. Wu, "Study on cutting mechanism of Ti6Al4V in ultra-precision machining," *Int. J. Adv. Manuf. Technol.*, vol. 86, nos. 5–8, pp. 1311–1317, 2016.

[19] Y. Lou and H. Wu, "Improving machinability of titanium alloy by electro-pulsing treatment in ultra-precision machining," *Int. J. Adv. Manuf. Technol.*, vol. 93, nos. 5–8, pp. 2299–2304, 2017.

[20] F. H. Cakir, S. Gurgen, M. A. Sofuoglu, O. N. Celik, and M. C. Kushan, "Finite element modeling of ultrasonic assisted turning of Ti6Al4V alloy," *Procedia-Social Behav. Sci.*, vol. 195, pp. 2839–2848, Jul. 2015.

[21] S. Patil, S. Joshi, A. Tewari, and S. S. Joshi, "Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V," *Ultrasonics*, vol. 54, no. 2, pp. 694–705, 2014.

[22] H. Sui, X. Zhang, D. Zhang, X. Jiang, and R. Wu, "Feasibility study of high-speed ultrasonic vibration cutting titanium alloy," *J. Mater. Process. Technol.*, vol. 247, pp. 111–120, Sep. 2017.

[23] N. J. Churi, Z. J. Pei, and C. Treadwell, "Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): Effects of tool variables," *Int. J. Precis. Technol.*, vol. 1, no. 1, pp. 85–96, 2007.

[24] R. Muhammad, A. Maurotto, M. Demiral, A. Roy, and V. V. Silberschmidt, "Thermally enhanced ultrasonically assisted machining of Ti alloy," *CIRP J. Manuf. Sci. Technol.*, vol. 7, no. 2, pp. 159–167, 2014.

[25] M. Calamaz, D. Coupard, and F. Girot, "A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al–4V," *Int. J. Mach. Tools Manuf.*, vol. 48, nos. 3–4, pp. 275–288, 2008.

[26] Y. Karpat, "Temperature dependent flow softening of titanium alloy Ti6Al4V: An investigation using finite element simulation of machining," *J. Mater. Process. Technol.*, vol. 211, no. 4, pp. 737–749, 2011.

[27] T. Thepsonthi and T. Özel, "Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V titanium alloy: Effects of cBN coating on tool wear," *J. Mater. Process. Technol.*, vol. 213, no. 4, pp. 532–542, 2013.

[28] D. Umbrello, "Finite element simulation of conventional and high speed machining of Ti6Al4V alloy," *J. Mater. Process. Technol.*, vol. 196, nos. 1–3, pp. 79–87, 2007.

[29] G. Chen, C. Ren, X. Yang, X. Jin, and T. Guo, "Finite element simulation of high-speed machining of titanium alloy (Ti–6Al–4V) based on ductile failure model," *Int. J. Adv. Manuf. Technol.*, vol. 56, nos. 9–12, pp. 1027–1038, 2011.

[30] T. Obikawa and E. Usui, "Computational machining of titanium alloy–finite element modeling and a few results," *J. Manuf. Sci. Eng.*, vol. 118, no. 2, pp. 208–215, 1996.

[31] Y. Zhu, W. Zeng, X. Ma, Q. Tai, Z. Li, and X. Li, "Determination of the friction factor of Ti-6Al-4V titanium alloy in hot forging by means of ring-compression test using FEM," *Tribology Int.*, vol. 44, no. 12, pp. 2074–2080, 2011.

[32] G. R. Johnson, W. H. Cook, G. Johnson, and W. Cook, "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures," in *Proc. 7th Int. Symp. Ballistics*, 1983, pp. 541–547.

[33] G. R. Johnson and W. H. Cook, "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and Pressures," *Eng. Fracture Mech.*, vol. 21, no. 1, pp. 31–48, 1985.

[34] N. N. Zorev, "Inter-relationship between shear processes occurring along tool face and shear plane in metal cutting," *Int. Res. Prod. Eng., ASME*, pp. 42–49, 1963.

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