Research on cutting force and surface integrity of TC18 titanium alloy by longitudinal ultrasonic vibration assisted milling

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Abstract
In order to study the influence of spindle speed and amplitude on the surface integrity, TC18 titanium alloy samples were milled by the process of conventional milling and longitudinal ultrasonic vibration assisted milling. The experimental data were obtained by dynamometer, thermometer, scanning electron microscope, X-ray diffractometer, and three-dimensional surface topography instrument for observation and analysis. The results show that the spindle speed has a significant effect on the cutting force, cutting temperature, surface morphology, and surface residual stress. Compared with conventional milling, the surface micro-texture produced by longitudinal ultrasonic vibration assisted milling is more regular, and the cutting force and cutting temperature can be reduced by 34.1% and 19.5%, respectively. Then, the surface residual compressive stress and surface roughness can be increased by 50.9% and 163.88%, respectively. In addition, a certain depth of plastic deformation layer can be formed under the surface of ultrasonic vibration machining, and the depth of deformation layer increases with the increase of amplitude, and when the amplitude is 4 μm, the depth of plastic deformation can reach about 5.2 μm. This study lays a theoretical foundation for further research and optimization of ultrasonic milling technology for difficult machining materials.

Keywords Longitudinal ultrasonic vibration assisted milling · TC18 titanium alloy · Cutting force · Surface integrity

1 Introduction
In the modern manufacturing industry, the use range of difficult to machine materials is increasing rapidly. There are still many difficulties and challenges in using traditional processing technologies to process difficult-to-machine materials with high quality, high efficiency, and low cost [1, 2]. TC18 is a kind of near β titanium alloy (α + β) with excellent comprehensive performance, which is widely used in structural parts such as aircraft landing gear and other load-bearing parts in aerospace industry [3–5]. But because of its high-temperature strength, low elastic modulus, low thermal conductivity, and easy chemical reaction with other substances, it is classified as difficult to machine materials [6, 7].

Cutting force and cutting temperature is important physical parameters for the cutting process [8]. The value of the cutting force determines the power consumed during the cutting process and the deformation of the machining process system. At the same time, the cutting force also directly affects the generation of cutting heat and further affects the durability of the tool, which also has a direct impact on the machining accuracy and machining quality [6, 9–11]. In the machining process of titanium alloy, high cutting force, high cutting temperature, and serious cutting vibration will be generated; the production efficiency of traditional machining is greatly reduced [9]. Ultrasonic vibration machining technology is a special machining technology, which applies ultra-high frequency micron-level vibration to the tool or workpiece along a certain direction during the machining process [1, 12]. Ultrasonic vibration...
vibration machining technology can realize intermittent cutting, and in the cutting process, it can effectively reduce the cutting force, reduce the cutting temperature, improve the stability of the machining process, increase the surface residual compressive stress, obtain more regular surface microstructure, and form excellent microstructure (nanocrystalline/fine-grained whole lamellar compact structure) on the surface layer [13–18], which widely used in machining difficult to machine materials [19, 20].

At present, the research on the cutting force and surface integrity of titanium alloy cutting is mostly concentrated on the atypical titanium alloy Ti-6Al-4 V [2, 21–27]. The research on TC18 titanium alloy mainly focuses on the thermal deformation behavior, while the research on milling is rarely reported [3, 28–35]. Therefore, this paper takes TC18 titanium alloy as the research object; CM (conventional milling) and L-UVAM (Longitudinal ultrasonic vibration assisted milling) tests were carried out at different spindle speeds. The main innovation point of this paper lies in the fact that the influence research of the spindle speed on surface integrity. Through the comparison of process CM and L-UVAM, it is concluded that the L-UVAM is beneficial to reduce the cutting force and cutting temperature and increase the surface roughness and residual compressive stress. Finally, the influence of ultrasonic amplitude on surface morphology and plastic deformation layer is further studied. This work laid a foundation for the high-quality manufacturing of TC18 titanium alloy, which has certain research value and significance.

2 Kinematic analysis of tool-workpiece

The L-UVAM applied a longitudinal vibration parallel to the axial direction of the tool through the longitudinal horn to make the front end of the tool intermittent cutting, and the cutting-edge trajectory of longitudinal ultrasonic vibration milling can be obtained. Figure 1 schematically illustrates the processing principle of this method. The coordinate system O-XYZ is fixed on the workpiece, and the kinematics analysis of the L-UVAM cutting-edge is carried out with the P point on the edge of the end mill as the reference point. Its motion is composed of the feed speed in the Y-direction, the ultrasonic vibration in the Z-direction, and the rotation around the tool spindle. In order to facilitate the study, the initial feed direction of the tool is Y-direction, the ultrasonic vibration direction is Z-direction, the end mill radius is R, the feed speed is v_w, the amplitude of the ultrasonic vibration is A, the frequency is f, and the spindle speed is n_s. The trajectory of cutting-edge reference point P can be obtained, and the trajectory equation for any point at the cutting-edge can be expressed as:

\[
\vec{S}(t) = \begin{cases} 
\vec{S}_{x}(t) \\
\vec{S}_{y}(t) \\
\vec{S}_{z}(t) 
\end{cases} = \begin{cases} 
R \sin \left( \frac{2\pi n_s t}{60} \right) + R \cos \left( \frac{2\pi n_s t}{60} \right) \\
v_w t + A \sin(2\pi ft) 
\end{cases}
\]

The relative motion path between the reference point of the outer edge cutting-edge and the workpiece is a spatial curve in L-UVAM and a two-dimensional simple curve in CM (as shown in Fig. 2a). The cutting depth of L-UVAM cutting-edge changes periodically, and its maximum value is greater than that of CM, thus improving the material removal rate and producing high-frequency impact, smearing, and ironing effects on the machined surface. In addition, due to the motion trajectory of the cutting-edge is approximately sinusoidal, the motion trajectory of all cutting-edges interacted to form regular micro-textures, thus obtaining better surface morphology, and Fig. 2b shows multiple trajectory curves.

3 Experimental designs

3.1 Experimental device

In this study, a CNC machining center (Henfux-HFM 700L) with conventional milling and ultrasonic milling functions was adopted. The machine spindle comprises of the piezoelectric actuator, concentrating horn, and tool holder. It is inductively powered by a transmitting coil (fixed to the machine) and a receiving coil (rotating coaxially with the spindle). Ultrasonic vibrations are generated by the piezoelectric actuator in a coaxial direction to the main spindle. Maximum displacement is amplified by the horn before being transferred to the cutting tool [36]. Titanium alloy processing requires good thermal conductivity of tool substrate
material, small roughness of coating surface, and weak affinity between coating material and titanium alloy. In this experiment, four-edge integrated cemented carbide arc end milling cutter (model: TM-4R-D8.0R1.0) produced by Zhuzhou Diamond Tool Co., Ltd, diameter 8 mm, blade length 20 mm, total length 60 mm, coated with AlCrXN coating. This tool is not specially designed to improve the machinability of L-UVAM and will not significantly affect the test results, so it is easier to identify the machining effect. Figure 3 shows the machining device of the milling sample.
Adjust the ultrasonic process parameters in advance, after ultrasonic calibration, select the appropriate parameter setting, fixed ultrasonic device power, ultrasonic vibration always follows the tool axial direction. The sample size is 15 mm × 8 mm × 6 mm; in CM and L-UVAM, each sample surface needs a milling process to achieve the final sample surface. No external cutting fluid is used during the test. Turn on the dynamometer and thermometer before the start of the milling process to ensure that the cutting force and temperature signals are collected throughout the milling test. After milling, stop the force signal acquisition and temperature measurement.

### 3.2 Workpiece material

Make specimens for all tests from the same batch of materials to prevent additional effects due to chemical or metallurgical changes. The raw material alloy is the equiaxed α-structured TC18 titanium alloy bar provided by Chongqing Kingsley Aeronautical Material Technology Co., Ltd. The matrix metallography of the raw material alloy is shown in Fig. 4. The material has good comprehensive properties of strength, plasticity, and corrosion resistance and has low elongation at break and yield strength, and its mechanical properties are shown in Table 1.

![Fig. 4 SEM photos of metallographic organization of TC18 titanium alloy matrix, ×5000](image)

| Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Percentage reduction of area (%) |
|------------------------|----------------------|----------------|----------------------------------|
| 1220                   | 1162                 | 17.4           | 48.4                             |

### 3.3 Experimental parameters

The purpose of this study is to quantitatively analyze the effect of L-UVAM speed on the cutting force and surface integrity of TC18 titanium alloy; on this basis, the influence of ultrasonic amplitude on machined surface morphology and surface microstructure was studied. Tests included CM and L-UVAM, and the feed rate of \( f_z \), cutting depth of \( a_p \), cutting width of \( a_e \), and vibration frequency of \( f \) remain the same. Then, revolution speed \( n_s \) and vibration amplitude \( A \) are variables, and the specific design parameters are shown in Table 2.

### 3.4 Testing method

Piezoelectric crystal dynamometer (Kistler 5080) was used to collect real-time data of the cutting force signals online for CM and L-UVAM, the data acquisition frequency is set to 100 kHz, and the range is set to 150 N. The surface residual stress is obtained by X-ray diffractometer (PROTOCOLXRD), and the detection parameters of residual stress are shown in Table 3. The cutting temperature is obtained by a portable infrared imager (IRI-100). The micro-morphology and surface characteristic parameters of the machined surface were obtained by a desktop scanning electron microscope (COXEM) and a three-dimensional surface topography instrument (NANOVEA ST400).

After the test, the machined surface and side section of the workpiece are embedded into the sample, and the cross section of the sample is mechanically grinded and polished. Using corrosion reagent (5% HNO₃ + 3% HF + 92% H₂O) etching for about 20 s, the microstructure perpendicular to the cross section of the machined surface along the feed direction was observed with a scanning electron microscope to characterize the effect of amplitude on the grain structure.

### 4 Results and discussion

#### 4.1 Surface morphology

Figure 5 shows the surface morphology of CM and L-UVAM observed by the SEM and 3D surface topography instrument. The image shows that the CM surface has obvious tool marks, the lateral plastic flow of the material on the machined surface is relatively serious, and the surface morphology is irregular and with obvious plow-like scratches. With the increase of cutting speed, the feature of overlapping tool marks decreases gradually (as shown in Fig. 5a–e). The surface texture of L-UVAM is more regular, and there are uniform vibration machining traces on the machined surface. The feed trace is covered by the ultrasonic vibration cutting trace. At low speed, the machined surface has obvious
“riblike” micro-texture and waved macro-morphology due to the dominant effect of high-frequency impact performance. Then, with the increase of cutting speed, the ironing effect of the cutting-edge on the machined surface is more obvious, so the corresponding milling surface texture is more regular, and when the spindle speed reaches 2400 rpm, the “riblike” micro-texture on the surface gradually turns into evenly arranged fish scale-like bionic structure (as shown in Fig. 5f~j). The experimental results show that with the increase of cutting speed, the microstructure becomes more obvious and the distribution becomes more regular. This micro-texture plays a positive role in improving the surface adhesion property for coatings and the surface lubrication property.

4.2 Effect of spindle speed on cutting force, cutting temperature, roughness, and surface residual stress

According to the kinematic characteristics of ultrasonic milling, the cutting force of the L-UVAM increases with the increase of the spindle speed (as shown in Fig. 6a), and at the same spindle speed, the cutting force (Fz) of L-UVAM is lower than that of CM. When the spindle speed is 1600 rpm, the cutting force of L-UVAM decreases by 34.1% compared with CM. With the increase of spindle speed, this decreasing percentage shows a trend of gradual decrease. The reason is that after ultrasonic vibration is applied, the cutting force signal changes from a simple curve to a dense pulse beam, which causes the cutting force signal of the L-UVAM to change from a continuous signal to a pulsed force signal, showing obvious oscillation characteristics (as shown in Fig. 7). The changing cutting depth and the pulling action of the tool on the cutting debris cause oscillating friction between the debris and the tool. This frictional resistance is transformed into a force that is beneficial to the cutting process, thereby effectively reducing the surface cutting force, but as the speed increases, the reduction effect of ultrasonic-assisted cutting force will be significantly reduced (as shown in Fig. 6a) [37, 38].

As shown in Fig. 6b, the cutting temperature of L-UVAM and CM both increase with the increase of the spindle speed as the speed increases in the range of 1600–2400 rpm. And then, when the spindle speed is higher than 2400 rpm, the cutting temperature of these two processes has an upward trend. Furthermore, at the same speed, the cutting temperature of process L-UVAM is obviously lower than that of process CM, and the maximum cutting temperature of process L-UVAM can be reduced by 19.5% compared with process CM. The reason is that while the ultrasonic assists in reducing the cutting force, it effectively increases the diffusion time and diffusion space of the cutting temperature, and also increases the air flow between the tool and the workpiece, and promotes the temperature diffusion on the surface, resulting in the reduction of the surface temperature for the L-UVAM. Thus, the cutting temperature of this process is significantly lower than that of the process of CM.

Figure 6c shows the relationship between spindle speed and surface roughness (Sq) of samples processed by process CM and L-UVAM. For the CM processed sample, as the spindle speed increases, the surface roughness does not appear significant changes, while the surface roughness of L-UVAM processed sample increases with the increase of spindle speed, and the maximum surface roughness of L-UVAM processed sample can increase by 163.88% compared with that of CM processed sample. Combined with the SEM image and 3D morphology observation results in Fig. 5, there are obvious tool marks on CM sample’s surface, while there are not only tool marks but also obvious impact ironing marks on L-UVAM sample’s surface due to the ultrasonic vibration. Then, with the increase of cutting

| Table 2 | Experimental parameter settings |
|---------|--------------------------------|
| No | Milling parameters | Vibration parameters |
| | Revolution speed (rpm) | Feed per tooth (mm/z) | Depth of cut (mm) | Cutting width (mm) | Frequency (kHz) | Amplitude (μm) |
| 1 | 1600, 2000, 2400, 2800, 3200 | 0.015 | 0.2 | 6 | 33.9 | 2 |
| 2 | 1600 | 0.015 | 0.2 | 6 | 33.9 | 0, 2, 4 |

| Table 3 | Measuring parameters of residual stress |
|---------|---------------------------------------|
| Content | Parameters |
| Tube voltage (kV) | 25 ~ 30 |
| Tube current (mA) | 25 |
| Target and radiation | Cu Kα |
| Filter | Ni |
| Aperture size | 1 mm × 5 mm |
| Diffraction crystal and Bragg angle | Ti-213, 142° |
| Beta angle | ± 19° |
| Normal inclination range | ± 42° |
| X-ray elasticity modulus | \( S_2/2 = 11.8879 \times 10^{-6} \) | \(-S_1 = 2.97 \times 10^{-6}\) |
speed, the impact ironing marks on material surface are more obvious, so the $S_q$ of L-UVAM processed sample is greater than that of CM processed sample.

Figure 6d shows the change trend of surface residual stress for CM sample’s surface and L-UVAM sample’s surface. It illustrates that the surface residual compressive stress of these surfaces is both gradually decrease with the increases of the spindle speed. Further analysis shows that ultrasonic machining is beneficial to increase the residual compressive stress on the surface, and at the spindle speed of 2000 rpm, the surface residual compressive stress of L-UVAM processed sample increases by 50.9% compared...
Fig. 6  CM process and L-UVAM process under different spindle speeds: a axial component force and axial component force decrease percentage; b cutting temperature and cutting temperature decrease percentage; c surface profile height root mean square deviation Sq; d surface residual stress and residual stress increase percentage

Fig. 7  CM and L-UVAM a cutting force characteristics; b cutting force spectrum characteristics
with that of CM processed sample. The main reason is that ultrasonic processing is beneficial to reduce the cutting force and cutting temperature, and the lower cutting force and cutting temperature of the L-UVAM sample’s surface reduce the plastic bulging effect and thermal effect in the formation of residual stress, and at the same time, the L-UVAM sample is caused by the impact ironing of the longitudinal high-frequency ultrasonic vibration, the value of the residual compressive stress on the surface is greater than that of the CM sample.
4.3 Effect of amplitude on surface morphology and microstructure

To study the effect of ultrasonic vibration on the surface topography, the SEM images of different samples with different processing parameters are observed (as shown in Fig. 8a–c). With the increase of ultrasonic amplitude, the tool ironing traces left on the machined surface increase as expected, the main reason is that large ultrasonic amplitude makes the pulse cutting effect of intermittent cutting more obvious, the residual height on the machined surface is larger, and finally leads to the surface vibration cutting traces more obvious. In order to further study the effect of ultrasonic vibration on the grain structure, we observed the cross-sectional structure of the sample (as shown in Fig. 8d to f). It can be seen that the thermal–mechanical coupling in the cutting process leads to the distortion of the grain boundary of the surface material of the work piece, and the grains are elongated and refined along the cutting direction, and however, no subsurface defects such as cracks or tearing were observed. Under the impact energy of ultrasonic vibration, a certain depth of plastic deformation layer will be formed on the machined surface. Because the maximum impact energy of the tool is proportional to the ultrasonic amplitude, the depth of plastic deformation layer increases with the increase of the amplitude, and the degree of grain deformation becomes more obvious with the increase of the amplitude. When the amplitude is 4 μm, the depth of the deformation layer can reach about 5.2 μm.

5 Conclusion

In this paper, the influence of ultrasonic milling on cutting force, cutting temperature, surface residual stress, and surface morphology was studied, and compared with the traditional milling process, the conclusions were as follows:

1. In general, ultrasonic-assisted milling is beneficial to reduce cutting force and cutting temperature and increase surface residual compressive stress. Compared with the CM, the cutting force of the L-UVAM can be reduced by 34.1%, the cutting temperature can be reduced by 19.5%, and the machined surface residual compressive stress can be increased by 50.9%.

2. Ultrasonic vibration has an important influence on the surface morphology and grain structure. Compared with the CM sample, the surface of the L-UVAM sample can obtain a more regular microscopic morphology and higher roughness. Then, a certain depth of plastic deformation layer will be formed on the surface of ultrasonic milling, and the plastic deformation layer will increase with the increase of amplitude.

3. This research systematically studied the influence of ultrasonic-assisted milling process on material surface cutting force, cutting temperature, surface morphology, and grain structure and had laid a certain theoretical foundation for further research and optimization of surface ultrasonic milling process.

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Declarations

Ethics approval The authors state that the present work is in compliance with the ethical standards.

Conflict of interest The authors declare no competing interests.

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