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Study of surface integrity in ultrasonic elliptical vibration assisted cutting of Ti-6Al-4V titanium alloy

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Abstract

Ti-6Al-4V titanium alloy has been widely used in aerospace engineering, biomedical engineering and marine engineering because of its unique mechanical, thermal and chemical properties. However, the current cutting technologies are difficult to achieve ultra-precision machining of Ti-6Al-4V titanium alloy. The ultrasonic elliptical vibration assisted cutting (UEVC) is considered as a promising technology for achieving the ultra-precision machining of difficult-to-machine alloy. In this study, the UEVC technology is used to study the machinability of Ti-6Al-4V titanium alloy with polycrystalline diamond tool. Firstly, the UEVC principle was presented. Then, the comparative investigation of the conventional machining with the UEVC machining was performed. The surface damage and the surface roughness are the focus in this paper. The measurement results indicated that an ultra-precision machining of Ti-6Al-4V titanium alloy is difficult to achieve by conventional cutting process. In contrast, an almost flawless machined surface with roughness value Ra of 25.1 nm is obtained by using the UEVC technology.

Keywords: Ultrasonic elliptical vibration cutting; surface quality; Ti-6Al-4V titanium alloy; polycrystalline diamond tool

1. Introduction

Ti-6Al-4V titanium alloy has been widely in many fields due to its unique mechanical, thermal and chemical properties[1]. However, due to the low thermal conductivity, low elastic modulus and high chemical activity of Ti-6Al-4V alloy, the ultra-precision machining of Ti-6Al-4V alloy has always been a technical challenge. In the conventional cutting (CC) of Ti-6Al-4V alloy, there are mass of cutting heat trapped at the tool-workpiece interface, thus, a high turning temperature is generated, which induce adhesive tool wear and short tool life. The ultrasonic elliptical vibration assisted cutting (UEVC) technology can decrease the average cutting force, reduce cutting temperature, extend tool life and improve the machined surface quality, thus, the UEVC technology may provides a solution for this problem [2]. The UEVC technology is a promising machining technology, which has been successfully applied to the ultra-precision machining of hardened steel [3], tungsten alloy [4], inconel 718 [5], and tungsten carbide [6]. In this study, the UEVC technology is used to study the machinability of Ti-6Al-4V titanium alloy by using polycrystalline diamond (PCD) tool. The comparative investigation of surface damage and surface roughness of the machined surfence under UEVC and CC process is performed.

2. Material and methods

2.1. The UEVC principle

Fig. 1 shows the schematic illustration the UEVC principle. The cutting tool tip is controlled to vibrate elliptically in the xoz plane, which is formed by the nominal cutting direction and the cutting depth direction. The vibration locus of the cutting tool are described as follows:

$$x(t) = a\cos(2\pi ft) \quad (1)$$

$$z(t) = b\cos(2\pi ft + \varphi) \quad (2)$$

where a and b are vibration amplitudes in x-direction and z-direction, respectively. φ is the phase shift and f is the vibration frequency of cutting tool. The nominal cutting speed is always set to be lower than the maximum vibration speed in cutting direction, namely, $V_c < 2\pi fa$, which can ensures an intermittent cutting.

In each elliptical vibration cycle, times t_0, t_1, t_2, t_3 and t_4 are defined as follows: the tool starts to cut the workpiece at time t_0. At time t_1, the tool arrives at the lowest point of the vibration locus. At time t_2, the instantaneous uncut chip thickness is greatest in the total cutting cycle, but it always smaller than the nominal depth of cut (a_p). Then, the friction between tool and workpiece begin to reverse at time t_3, and the tool separates from workpiece at time t_4. Thus, during each vibration cycle, the tool only contacts the workpiece during a short time period (t_4-t_0), and the friction between tool and workpice is reversed during the time period (t_4-t_3). The intermittent cutting, the reduction of cutting thickness and the reversed friction are the most important characteristics of UEVC technology [7].

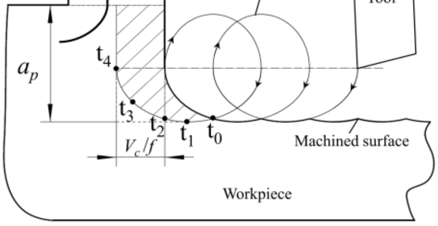

Figure 1. Illustration of the UEVC principle

2.2. Experimental setup

The experimental setup of the cutting experiment as shown in Fig. 2. A home-made precision machine tool was used, and it mainly consisted of two horizontal hydrostatic sideways and an aerostatic spindle. The workpiece was affixed to the spindle axis. The UEVC device was positioned on the z-axis via a high-precision adjustment platform. In this study, The UEVC device was set to work at the resonant frequency of 29.75 kHz with the amplitude in cutting direction of 6 µm and in cutting depth direction of 4 µm. More details on the UEVC device can be found in our previous work [8].In addition, the PCD tool has a nose radius of 0.8 mm, a rake angle of 0 and a clearance angle of 11. The workpiece material was Ti-6Al-4V titanium alloy with a diameter of 50 mm and a height of 20 mm. The machining parameters in CC process was set as: spindle speed of 480 r/min, cutting depth of 5 μm, feed speed of 5 μm/r. In UEVC process, cutting depth and feed speed were the same as in CC process, but, spindle speed was set as 8 r/min for achieving an ultra-precise machining [9]. After the completion of cutting experiment, a optical microscope and an atomic force microscope (AFM) were used to measure the machined surface. It should be noted that, in the study, the tool wear was not considered because the machining area was set to be small.

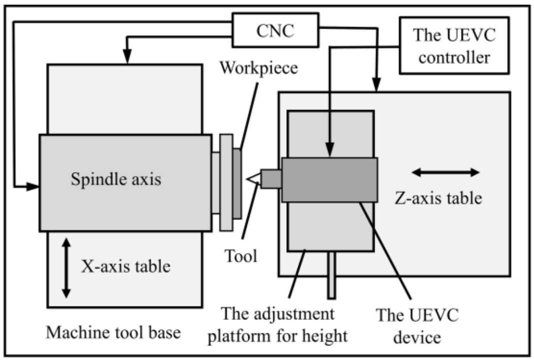

Figure 2. Illustration of experimental setup

3. Results and discussion

Fig. 3 shows the optical micrograph of machined surface under different machining methods. As shown in Fig. 3 (a), there are a lot of uncut materials bonded to the machined surface. These uncut materials were believed to be caused by the random vibration of cutting tool during CC process. The high cutting temperatures was considered to be the main inducement of the vibration of cutting tool. As we all known, Ti-6Al-4V alloy has a small deformation coefficient, so, the distance of the sliding friction of the chips with the tool rake face is fairly long. Moreover, the thermal conductivity of Ti-6Al-4V alloy is also small, thus, the generated cutting heat was difficult to dissipated and it easy concentrated in the cutting zone. Therefore, the cutting temperature was high during CC process. In contrast, a clear and smooth machined surface was obtained under UEVC process, as shown in Fig. 3 (b). This may be explained the intermittent cutting and the reduction of cutting thickness exist in UEVC process, which can provide a lower cutting heat and more favorable heat dissipation condition. In addition, the reversed friction can promote the smooth discharge of chips, which takes away a lot of cutting heat. Thus, the cutting temperature was lower compared to CC process. And, above all, the cutting tool flutter was suppressed and the cutting process was performed smoothly.

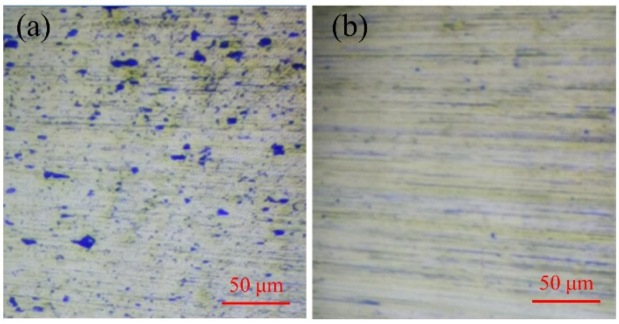

Figure 3. Comparison of optical micrograph of machined surface: (a) CC and (b) UEVC.

Fig. 4 shows the AFM detection results of machined surface under different machining methods. As shown in Fig. 4 (a), surface defects such as uncut materials and material flow can be clearly seen, which increases the roughness value of the machined surface. And, the roughness of the machined surface was 62.3 nm. Moreover, these surface defects deteriorate the serviceability of the part. Thus, CC process is not considered to be a applicative cutting process for ultra-precision machining of Ti-6Al-4V titanium alloy. However, as shown in Fig. 4 (b), a smooth machined surface without any defect was obtained in UEVC process, which roughness value was 25.1 nm. Thus, the ultra-precision machining of Ti-6Al-4V titanium alloy can be realized by using UEVC technology.

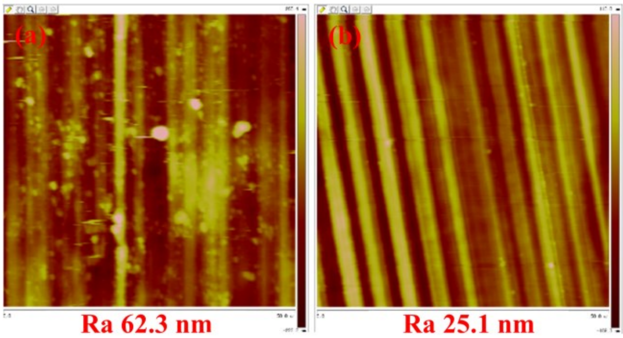

Figure 4. Comparison of AFM detection results of machined surface: (a) CC and (b) UEVC.

4. Conclusions

In this study, a comparative investigation of the machinability of Ti-6Al-4V titanium alloy under CC and UEVC process was performed. The experimental results indicate a clear and smooth machined surface was obtained by using UEVC technology, and its roughness value was 25.1 nm. However, due to the random vibration of cutting tool induced by the high cutting temperature in CC process, many surface defects have been found on the machined surfence, which deteriorated the quality of the machined surface. Further investigations will focus on the optimization of processing parameters of ultra-precision cutting titanium alloy with UEVC technology.

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