Ultra-precision machining of 95W-3.5Ni-1.5Fe alloy by ultrasonic elliptical vibratory turning

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High density tungsten alloy (95W-3.5Ni-1.5Fe) is used in calibrator for precision physics experiment because of its excellent properties. However, tungsten alloy, as a ferrous metal, is difficult to machine using single point diamond turning (SPDT) due to severe tool wear. Thus, in order to realize the ultra-precision machining of tungsten alloy, this study proposed to introduce elliptical vibration into SPDT to retard the tool wear by changing the tool-material contact state and cooling state. The results showed that compared with SPDT, ultrasonic elliptical vibratory turning (UEVT) realized the improvement of tungsten alloy surface roughness Sa from 0.9 µm to 43 nm, the transformation of the machined surface from crushing to nearly damage-free and the reduction of subsurface metamorphic layer thickness from 18 µm to7 µm. In addition, compared with SPDT, the tool life processed by UEVT was extended by 3 times. This study provides a technical reference for the ultra-precision machining of ferrous metals.

NOMENCLATURE

h = cutting depth
v_s = cutting speed
f_r = feed rate
A = ultrasonic amplitude
f = ultrasonic frequency

1. Introduction

High density tungsten alloy (95W-3.5Ni-1.5Fe) is utilized in calibrators for precision physics experiments due to its excellent properties such as high density, high tensile strength, high melting point, corrosion resistance and radiation resistance [1]. Because of the special fields of application, extremely high demands are placed on the quality of the machined surfaces of tungsten alloys. Single point diamond turning (SPDT), as the most widely used ultra-precision machining technology at present, realizes the machining of high-precision parts such as copper alloys, aluminum alloys, single crystal silicon and single crystal germanium [2]. However, tungsten alloy, as ferrous metals, is hard and brittle at room temperature and pressure [3]. In the process of machining tungsten alloys, diamond tool is highly susceptible to graphitization due to high turning force and turning temperature, which leads to severe tool wear and poor machining quality [4]. Therefore, this poses a great challenge to the ultra-precision machining of tungsten alloys.

Ultrasonic elliptical vibratory turning (UEVT) with complete separation between the tool-workpiece, ultrasonic cavitation, changing cutting angle can reduce the cutting force-heat in the machining process [5]. Therefore, ultrasonic elliptical vibration is introduced into SPDT to reduce the turning temperature and consequently suppress tool wear by changing the contact state and cooling state during turning. Based on this, a comparative experiment between SPDT and UEVT of tungsten alloy was carried out in this study to demonstrate the feasibility of UEVT in ultra-precision machining of tungsten alloys by analyzing the surface/subsurface formation and tool wear after turning. This study provides a technical reference for the ultra-precision machining of ferrous metals.

2. Experimental details

Comparative experiments on tungsten alloy machining were carried out on a self-developed ultra-precision machine tool. The UEVT device featured an ultrasonic amplitude P-P of 4 µm and an ultrasonic frequency of 34.1 kHz. The single crystal diamond tool was designed with a rake angle of 0°, a clearance angle of 15° and a nose radius of 1 mm. The machining sample was a 95W-3.5Ni-1.5Fe alloy cylinder that was clamped to the machining tool spindle. The detailed experimental details were shown in Fig. 1. In order to minimize the randomness of the experiments, two processing parameters were selected for the experiments under different machining modes. The experimental parameters were shown in Table 1. Machined surface roughness and surface topography were measured by white light interferometer and scanning electron microscope, respectively. Tool wear after turning was observed by an ultra-deep field microscope.

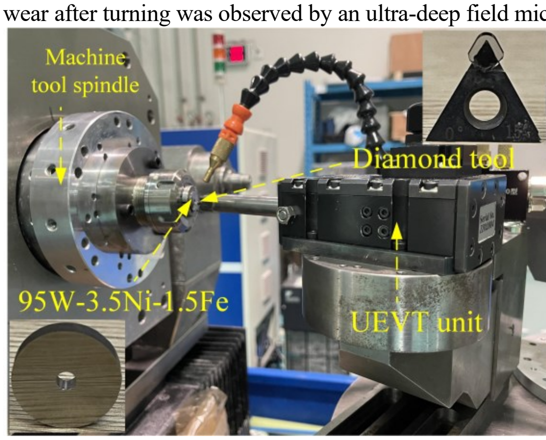

Fig. 1 Experimental details of UEVT of 95W-3.5Ni-1.5Fe alloy using diamond tool.

Table 1 Experimental parameters of SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy.

Value	SPDT	UEVT
cutting depth h/μm	3, 5	3, 5
cutting speed v_s/m·min^{-1}	5, 1	20, 25
feed rate f_r/μm·r^{-1}	14.1	0.7
ultrasonic amplitude A/μm	–	2
ultrasonic frequency f/kHz	–	34.1

3. Results and discussion

3.1 Analysis of surface/subsurface formation

Fig. 2 illustrates the comparison of machined surface roughness induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy. As shown in the figure, the surface roughness Sa induced by SPDT are 891 nm and 971 nm (Fig. 2(a) and (b)), respectively, which are much higher than the surface roughness of 43 nm and 61 nm induced by UEVT (Fig. 2(c) and (d)). Meanwhile, the machined surface textures induced by SPDT present obvious traces of tool extrusion and surface craters. The machined surface textures induced by UEVT show the trajectory of regular tool vibration, which is favorable to improve the surface roughness. In order to further analyze the material removal formation under different machining methods, the machined surface morphology is presented in Fig. 3.

Fig. 3 illustrates the comparison of the machined surface topography induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy. As can be seen from Fig. 3(a) and (b), the machined surfaces induced by SPDT show obvious brittle peeling and extrusion crushing, as well as tool turning traces. In contrast, the machined surfaces induced by UEVT exhibit clear traces of plastic removal and the tungsten particles are also nearly undamaged (Fig. 3(c) and (d)). By comparing the surface morphology in Fig. 3, it can be seen that the tungsten alloy under SPDT mainly shows brittle removal, while the material under UEVT presents plastic removal. This is why the surface roughness varies so much between the two machining methods.

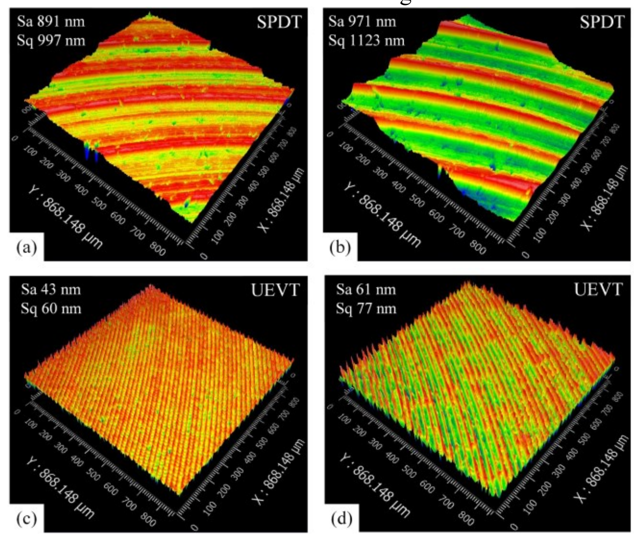

Fig. 2 Comparison of machined surface roughness Sa induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy: (a)(b) SDPT, (c)(d) UEVT.

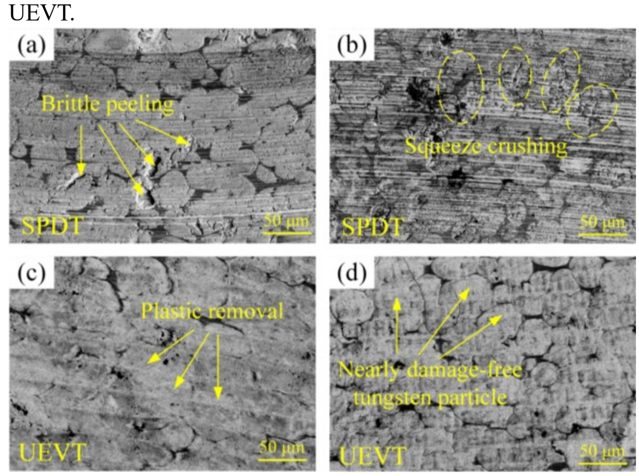

Fig. 3 Comparison of machined surface topography induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy: (a)(b) SDPT, (c)(d) UEVT.

Fig. 4 demonstrates the comparison of subsurface metamorphic layer thicknesses induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy. The characterization of the machined subsurface condition is derived from the truncation of the turned workpiece. From Fig. 4(a) and (b), the thicknesses of the subsurface metamorphic layers induced by SPDT are 18 μm and 21 μm, respectively, while the thicknesses of the subsurface metamorphic layers induced by UEVT are 7 μm and 12 μm, respectively. The thickness of the subsurface metamorphic layer under SPDT is twice that under UEVT. The generation of subsurface metamorphic layers is attributed to the phenomenon of grain refinement after machining [6]. By observing Fig. 4, the tungsten grains in the metamorphic layer under SPDT are severely fragmented, while the tungsten grains in the metamorphic layer under UEVT are significantly elongated. Elongated grains are more favorable for the formation of uniform grain refinement than broken grains.

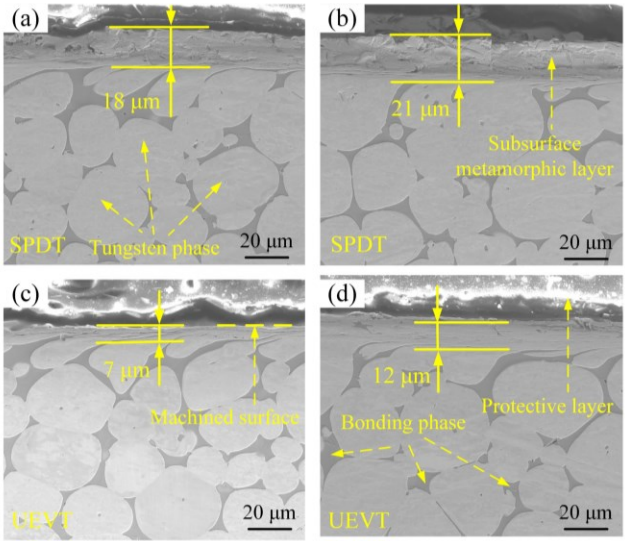

Fig. 4 Comparison of subsurface metamorphic layer thickness induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy: (a)(b) SPDT, (c)(d) UEVT.

3.2 Analysis of tool wear

Fig. 5 shows the comparison of tool wear induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy, where the tool wear is measured after 500 m of turning. Fig. 5(a) and (b) represent the cutting edge retreat and the flank face wear of tool induced by SPDT, respectively. Fig. 5(c) and (d) represent the tool wear under UEVT. As can be seen in Fig. 5, the cutting edge retreat and flank face wear of tool under SPDT are much larger than the tool wear under UEVT. Compared to SPDT, tool life under UEVT is extended by three times. In addition, according to the tool wear in Fig. 5, it can be seen that the mechanical wear of the tool exists in the SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy.

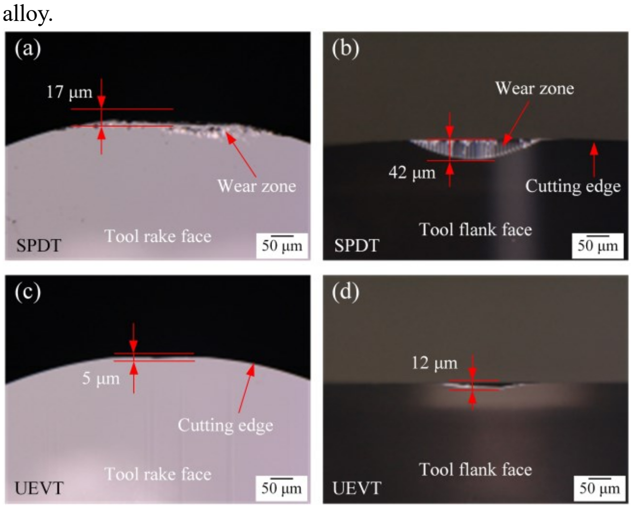

Fig. 5 Comparison of tool wear induced by SPDT and UEVT of 95W-3.5Ni-1.5Fe alloy: (a)(b) SDPT, (c)(d) UEVT.

3. Conclusions

In this study, the ultra-precision machining of 95W-3.5Ni-1.5Fe alloy is realized by comparatively analyzing the surface/subsurface formation and tool wear induced by UEVT and SPDT, which results in the following main conclusions.

UEVT achieves the machined surface with roughness Sa 43 nm, while the surface roughness Sa induced by SPDT is 891 nm. The tungsten particles on the machined surfaces induced by UEVT show nearly no damage, which suggests plastic removal. However, the machined surfaces induced by SPDT show significant brittle peeling and extrusion crushing, which indicates brittle removal. The thickness of the subsurface metamorphic layer under UEVT (7 μm) is smaller than under SPDT (18 μm). For tool wear, including the cutting edge retreat and flank face wear, the tool life induced by UEVT is extended by 3 times compared with SPDT.

This study provides a technical reference for the ultra-precision machining of ferrous metals.

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