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ARTICLE

# Surface Morphology and Affected Layer in Disc-milling Grooving of Titanium Alloy

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**Abstract:** Disc-milling grooving experiment was carried out to measure milling force and temperature for titanium alloy samples. After machining, surface roughness, surface topography, residual stress, microstructure and microhardness under different milling conditions were analyzed. The results show that the surface roughness of the center on milling surface is lower than that of the edge; moreover, the surface roughness decreases with the increase of the spindle speed, but increases with the increase of depth of cut and feed speed. The residual compressive stress is produced on the machined surface and subsurface, and gradually declines to zero with increase of the depth. The microstructure of lattice tensile deformation is found along feed direction under the effect of milling force, progressing from the initial equiaxed structure to long flake lattice. The metallographic structure of plastic deformation zone changes with the temperature, transforming from the initial equiaxed microstructure to a lamellar microstructure when the temperature is up to $\beta$-phase transition temperature. The combination of mechanical and thermal loads increases the microhardness on the machined surface and subsurface.

**Key words:** titanium alloy; disc-milling; surface roughness; surface topography; microhardness; microstructure

The titanium alloy is widely used in aerospace, aviation, navigation, automobile and other industries because of its advantages like small density, high intensity, high temperature resistance and good corrosion resistance [1]. However, the machining quality and efficiency are limited by the unique characteristics of titanium alloy like low thermal conductivity, small elastic modulus and high chemical activity, which can bring a high cutting temperature, great cutting force and a small distortion coefficient. Meanwhile the sticking phenomenon and tool wear are severe in the process of machining [2]. Noticeable changes happen in the microstructure and microhardness on the machined surface in high speed milling titanium alloy. Serious plastic deformation and work hardening are observed when improper cutting factors are employed, leading to adverse effects on fatigue life of materials [2,3].

Recently, multitude researches were conducted on the surface integrity for high speed milling titanium alloy. A large number of experiments show that small residual stress and a hardened layer can be obtained by high speed milling of titanium alloy [4,5]. Du et al.[6] studied the surface morphology and microstructure of TC4 titanium alloy under high-speed milling. The results showed that the milling surface quality becomes better with increasing the spindle speed. Yang et al.[7] researched the effect of high-speed milling parameters on surface integrity of TC4 titanium alloy. The results showed that the effect of spindle speed on surface roughness, surface topography and microhardness is obvious, and the effect of axial cutting depth on surface roughness, surface topography is remarkable. Yang et al.[8] carried out two-dimensional simulation of TC4 titanium alloy in the high-speed milling process. They found that the highest temperature in the cutting zone locates on tool chip interface at a distance of 0.01~0.02 mm from the tool tip.

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The influence of the milling speed on the cutting temperature is significant. Sridhar et al.[9] focused on the effect of machining parameters and heat treatment on the residual stress in titanium alloy IMI-834. The residual compressive stresses are found to be dependent upon the milling parameters. Yao et al.[10] researched residual stress in high speed milling of titanium TC11 alloy under different cooling conditions, tool rake angles and milling parameters. The results showed that emulsion cooling gets the highest surface residual compressive stress and the dry cutting gets the lowest. With the increase of cutting tool rake angle, surface residual compressive stress increases. Daymi et al.[11] investigated the effect of machining condition on surface integrity of TC4 alloy using a high speed ball end milling process with various milling parameters, in a dry condition on a vertical five-axis CNC machine. Wu et al.[12] studied the formation mechanism and influence of cutting parameters on residual stress in flank milling of TB6 through orthogonal experiments. Experiments result showed that the cutting temperature varies between 300 and 518 °C, while residual compressive stress on the machined surface is from −199.8 MPa to −41.7 MPa. Residual tensile stress occurs on subsurface with increasing milling parameters excessively. Yang et al.[13] focused on the machined surface integrity of TC11 titanium alloy under different cutting conditions. It is shown that surface residual stress is compressive, and decreases with increasing the milling speed in both feed and stepover directions. When the milling speed increases, surface roughness increases obviously. The microstructure of surface layer does not change obviously. Daymi et al.[14] researched surface integrity in high speed end milling of TC4 under dry condition. The machined surface roughness, residual stress, microhardness and microstructure were observed.

Some research of cutting types like end milling and face milling has been carried out to study the surface integrity in high speed milling titanium alloy. Based on the best of our knowledge, few studies have been dedicated to disc milling at low speed, especially research on the thermal-mechanical coupling effect on surface morphology and the affected layer. Disc milling is widely used in machining for its capability to provide large cutting force and high milling efficiency. It is quite a new method applied in large-size blade and blisk machining. The grooving efficiency for blisk is greatly improved using a disc milling approach verified by experiments. However, the problem of deeper plastic deformation layers caused by big milling force and high temperature, which has a significant influence on fatigue life of parts, is not studied yet.

Therefore, the disc milling grooving was studied in the present research, and the surface morphology and the affected layer were focused on. First, the milling force and temperature were measured. Based on the results, the thermal-mechanical coupling effect on surface roughness, surface topography, residual stress, microstructure and microhardness was analyzed to study the formation mechanism of surface morphology and the affected layer. The results provide the experimental basis for technological parameter optimization and controlling the surface integrity of disc milling grooving for blisk.

## 1 Experiment

Titanium alloy (Ti6Al4V) was chosen as the experiment material in the present study, which is one kind of $\alpha + \beta$ phase titanium alloy. It has many advanced properties such as comprehensive mechanics performance, great specific strength and low thermal conductivity which extend its application in aviation. The main chemical composition and mechanical properties are shown in Table 1 and Table 2, respectively. The tested hardness of material is 33~35 HR.

XH716 VMC was used as the milling machine, staggered teeth disc cutter with three edges was applied for climb milling under wet cutting condition. The parameters of the disc cutter are shown in Table 3. In order to obtain the milling force and temperature in different milling parameters (spindle speed, depth of cut and feed speed), the specific processing parameters of disc milling are shown in Table 4.

Milling temperature was measured by a semi-artificial thermocouple composed of TC4 alloy ($\varphi$ 0.03 mm) and constantan ($\varphi$ 0.03 mm). Milling force was tested in three directions of $x$, $y$ and $z$ by a dynamic piezoelectric dynamometer. The wave of milling force was recorded by DEWESOFT. Milling temperature and milling force would provide a theory basis to the alternation of machined surface. Measurement results are shown in Table 4. The milling schematic diagram is shown in Fig.1.

TR240 rough meter was applied to measure surface roughness. Five points were chosen along the milling direction on milling surface, and surface roughness of each point was measured to acquire $R_{a1}$, $R_{a2}$, $R_{a3}$, $R_{a4}$ and $R_{a5}$. Sampling length of measuring was 0.8 mm and assessment was 5.6 mm. Then these five values were averaged.

The three-dimensional surface topography was detected by optical VECOO 3D surface topography tester NT100. The surface morphology was measured by QUANTA 200 scanning electron microscope (SEM) in a secondary electron (SE) mode.

The microstructure was observed by metallurgical optical microscope S6D. In this step, the sample was firstly cut along the affected layer direction to make the embedded samples, and then the embedded samples were ground and polished with a metallographic grinder. Before observation, the embedded samples were etched for 5~10 s using a corrodent matched by HF : $HNO_3$ : $H_2O$ = 1 : 1 : 20.