Crystallographic texture evolution and tribological behavior of machined surface layer in orthogonal cutting of Ti-6Al-4V alloy

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\textbf{A R T I C L E   I N F O}

Article history:
Received 9 July 2019
Accepted 2 August 2019
Available online 22 August 2019

Keywords:
Crystallographic texture evolution
Titanium alloy
Machined surface
Shear texture
Friction property
Anisotropy

\textbf{A B S T R A C T}

The machining-induced crystallographic orientation variation in the plastic deformation layer on the mesoscopic scale usually occurs when severe plastic deformation undergoes in the machined surface layer, which will further affect the macroscopic mechanical performance of the machined parts. The orthogonal cutting experiments of Ti-6Al-4V titanium alloy were carried out to confirm the effectiveness and reliability of the established finite element method (FEM) simulation cutting model with ABAQUS. From the perspective of macroscopic deformation, the shear strain and strain rate history were obtained, and this provided the fundamental data to simulate the machining-induced surface crystallographic texture evolution process using a visco-plastic self-consistent (VPSC) code. The pole figures and orientation distribution function (ODF) maps of crystallographic texture were produced and analyzed using a toolbox of Matlab. In order to validate the existence of crystallographic texture orientation with anisotropy, friction and wear tests were performed to explore the influence of crystallographic texture variation on the macroscopic properties of machined surface. The difference of friction coefficients and wear track width in the cutting direction and vertical cutting direction confirmed the hypothesis, and the machining-induced crystallographic texture evolution will alter the surface integrity and eventually the mechanical behavior of machined parts.

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1. Introduction

The machining-induced crystallographic orientation variation in the plastic deformation layer on the mesoscopic scale usually occurs when severe plastic deformation undergoes in the machined surface layer, which will further affect the macroscopic mechanical performance of the machined parts. Peng et al. [1] reviewed the development, application and feature of titanium alloys in aviation industry, and pointed out that Ti-6Al-4V alloy is a typical $\alpha + \beta$ titanium alloy which has been widely used in many fields, such as aeronautics and military
industries because of the excellent comprehensive properties. Yang [2] investigated the surface integrity in machining of tantalum alloys and optimized the cutting parameters in order to acquire high machined surface integrity. Wang et al. [3] focused on the evolutions of grain size and micro-hardness during chip formation and machined surface generation for Ti-6Al-4V alloy in high-speed machining. Hou et al. [4] performed the experiments in multi-step turning of Ti-6Al-4V alloy and investigated the machined surface integrity of two-step and three-step turning. Song et al. [5] conducted the finite element simulation of single-step cutting, multi-step cutting, pre-stress single-step cutting, and pre-stress multi-step cutting processes, and explained the influence mechanism and coupling effect of multi-step machining and pre-stress machining on the compressive residual stress distribution on machined surface. At present, the investigation on the machining of titanium alloy mainly focuses on the surface integrity, process optimization on the macroscopic scale and grain refinement, but the study on the crystal orientation on the mesoscopic scale is rare.

Texture is the preferred orientation of crystals, and it is the root cause of anisotropy of macroscopic properties. The phase of titanium alloy belongs to the typical hexagonal close-packed (HCP) crystal structure, and the material properties of the pyramidal and the basal planes are different on the microscopic scale. Velasquez et al. [6] summarized an extensive experimental study of the surface integrity and sub-surface microstructure during high speed machining in orthogonal cutting condition. The residual stresses and crystallographic texture caused by machining facilitate the material microstructure evolution of the machined surface layer. Furthermore, the existence of crystallographic texture will enlarge the property difference and form the anisotropy of the properties. Singh and Schwarzer [7] held the view that the texture evolution of titanium and its alloy mainly depends on the mode of deformation, the starting texture and microstructure, temperature and rate of deformation, and the alloying elements. Zhu et al. [8] established the relationship between texture and mechanical property anisotropy in commercially pure titanium sheets. In order to decrease the influence of machining-induced crystallographic texture evolution on the mechanical property anisotropy, the modeling and accurate prediction of crystallographic texture by FEM simulation is necessary to understand the deforming behavior and its correlation with mechanical properties.

The material point method and polycrystalline plasticity FEM can simulate and predict the texture reasonably for the metal material of faced centered cubic (FCC), body-centered cubic (BCC) and HCP crystal structure. Miehe and Rosato [9] presents an approach for a fast computational estimate of the texture evolution in FCC polycrystals, and this approach allows a purely kinematic estimate of the texture evolution completely independent of the hardening response of the single crystal grains. Zhang et al. [10] developed a rate-independent polycrystalline plasticity constitutive model considering self and latent hardening to analyze the FCC sheet metal forming process, in which an assignment method of orientation probability was implemented for the direct use of measured ODF data to the crystalline FE modeling. Pi et al. [11] directly utilized the initial orientations obtained by electron backscatter diffraction (EBSD) as the input in the crystal plasticity FEM simulation of mechanical response and texture development of FCC pure Al in uniaxial tensile deformation. Lee et al. [12] used the texture evolution maps as a tool to visualize texture development during upset deformation in body-centered cubic tantalum metal in the crystal plasticity FEM simulation. Lv [13] conducted the texture analysis in commercially pure titanium at room temperature by crystal plasticity FEM simulation, and generated the texture pole figures and ODF maps using Matlab-MTEX toolbox.

Friction property is one of the most important properties of metallic materials, Tian [14] investigated the effect of graphite crystal structure and graphite intercalation compounds on friction properties and the slight variation of crystal microstructure will dramatically influence the micro-mechanical performance of materials. Revankar et al. [15] reported that the surface quality and tribological characteristics of titanium alloy Ti-6Al-4V can be improved by ball burnishing, showing improved friction and wear performance. At present, the investigation on the plastic deformation of metals are mainly focus on the relationship between macroscopic properties and crystal structure on the microscopic and mesoscopic scale. This is beneficial for the deformation mechanism analysis and process modelling of the machined surface generation, which will help controlling the machined surface integrity or quality of machining operations, and enhancing product sustainability in terms of its functional performance.

So in this paper, a comprehensive study of crystallographic textures evolved in the machined subsurface layer of Ti-6Al-4V titanium alloy using the finite element modeling and a visco-plastic self-consistent (VPSC) texture model. And the experimental results are presented wherein the friction coefficient and wear track width for samples cut at different feed rates and cutting speeds. The aim is to attempt to explain the simulated textures in the context of machined surface wear testing results. The connections between macroscopic friction property and mesoscopic crystal orientation of the machined surface of Ti-6Al-4V alloy was investigated. The effect of loading conditions on surface behavior is mainly concerned in order to study the machined surface friction and wear properties of titanium alloy, and internal mechanism analyses are mainly carried out in the macroscopic scale. The new data and analysis results produced will be of value to practicing engineers and help comprehensively advance the scientific understanding of machining-induced surface integrity and its engineering application.

The main contents and technical route are shown in the following Fig. 1. The main results are essentially divided into two part. The first part (sections 2, 3 and 4) focuses on the experimental validated finite element simulation of machined surface deformation, and incorporation of the shear strain and strain rate data into VPSC texture simulation to predict the pole figures and ODF maps in the machined surface layer. The second bit (Section 5) related to standard friction tests conducted on the machined surface in order to validate the existence of crystallographic texture.
2. Orthogonal cutting experiments

Ti-6Al-4V alloy (α+β titanium alloy, TC4) was chosen as the experimental workpiece, and the experimental condition was dry cutting. The cutting experiments were conducted on a CKD6150H CNC lathe-machining center using a TiAlN coated carbide tool. The rake and relief angle of the tool are 8° and 7°, respectively. Fig. 2 shows the experimental methodology of the orthogonal cutting experiments of the cylindrical end face. The cutting forces were measured by using the Kistler type 9257B three-component piezoelectric Dynamometer as shown in Fig. 2(a). The principle of orthogonal cutting experiment is shown in Fig. 2(b), and the cutting depth (cylinder wall thickness) is 8 mm to obtain the relatively large plane surface for surface measurements. In order to thoroughly investigate the influence of cutting parameters on the cutting performance during titanium alloy machining, several groups of cutting tests under four levels of feed rate and cutting speed were chosen. The feed rates are 0.05, 0.1, 0.15, 0.2 mm/r, and the cutting speeds are 50, 100, 150, 200 m/min, respectively. Then the machining induced surface texture variation and tribological behavior of Ti-6Al-4V alloy in the following sections can be comparably evaluated under low cutting parameters and high cutting parameters.

After the experiment, the machined surface is shown in Fig. 2(c), and the chips were collected and made into specimens. In order to clearly observe the two microstructural phase (α and β) of Ti-6Al-4V titanium alloy, the cross-sections of the chips were inserted, grounded, polished, and then etched in the Kroll’s solution [16] composed of 5 mL HNO₃ + 3 mL HF + 100 mL H₂O. The morphology and microstructure of the cross-sectional chips were observed by the Quanta FEG 250 field-emission scanning electron microscope (SEM) made by FEI Ltd., USA.

3. Analyses of macroscopic plastic deformation of the machined surface

During the machining process of polycrystalline metal materials, severe macroscopic plastic deformation will lead to the microstructure variation. Therefore, it is necessary to analyze the macroscopic plastic deformation in order to study the crystallographic texture. In the paper, the macroscopic plastic deformation of machined surface of titanium alloy was systematically studied by FEM simulation.

![Diagram](image-url)
3.1. Orthogonal cutting simulation

The two dimensional orthogonal cutting model coupled with thermo-mechanical analysis of Ti-6Al-4V alloy was established with ABAQUS software. The tool geometrical parameters and the cutting parameters are the same as the above-mentioned cutting experiments. The bottom and two sides was subjected to displacement constraints. The workpiece was defined as a deformable body, and the tool was defined as a rigid body. They used CPE4RT elements, and the type of analysis step is a general explicit thermodynamic coupling analysis step (Dynamic, Temp-disp, and Explicit). The J-C constitutive model [17] was used to simulate the material flow considering the temperature dependent effect, strain hardening effect and strain rate hardening effect. It is worth noting that the deformation texture evolution at the machined surface strongly depends on the deformation field parameters (particularly the strain and strain path) around the cutting tool tip, and the simulated local deformation field around the tool tip itself will likely depend on the material failure and separation criterion used in the simulation. From the physical standard point of view, a strain-based material failure and separation criterion [18] was used to describe the formation of the chip and material failure, and this can ensure the simulation model reliable to consistent with the actual machining process. In addition, the Coulomb friction model including slip friction contact and bond friction contact with ultimate shear stress [19] was adopted for the contact between cutting tool and workpiece. The cutting model is shown in Fig. 3. And the details of the simulation settings in order to acquire the reliable simulated results can be traced in our previous work [20].

In order to improve the efficiency of the FEM simulation model, the rationality and reliability of the simulation model has to be validated by comparing the experimental measured main cutting force and chip shape characteristics with the FEM simulation results. Fig.4 shows the comparable cutting force results of simulation and experiment. According to the comparisons of cutting forces under different cutting speeds and different feed rates, the simulated values are not much different from the experimental measurements, and the variation of cutting forces is in the same trend. At the same time, the morphologies and their corresponding quantitative characteristic parameters of the chips under different cutting parameters are emerged in Fig. 5 and Table 1. From the chip shape and morphological parameters in terms of saw-tooth chip peak, valley and spacing, the average relative errors of simulated and experimental results are in the 10% ranges, which can reflect that the prediction accuracy of the simulation model meets the requirements of reproducing the cutting process. Therefore, the model can predict the evolution of stress, strain, strain rate and temperature in the cutting process of titanium alloy, and provide a reliable complex physical field distribution.

3.2. Plastic deformation analysis of machined surface

The plastic deformation of the machined surface of titanium alloy is mainly the plane shear strain [20]. Based on the simulation, five points were selected on the machined surface of the cutting stable region, as shown in Fig. 6. Each point corresponds to the finish time of serrated chip and represents for the complete formation of serrated chip because of relatively uniform distribution of plastic shear strain. Thus, the variation of the plastic shear strain versus time of the five points was extracted.

Fig. 7 shows the variation of plastic shear strain and strain rate versus time under the cutting speed of 200 m/min, 0.1 mm/r. The variation of plastic shear strain is smooth over time and it gradually increases, eventually reaching 3.03. For the strain rate, the initial change is not obvious, then gradu-
strain of the machined surface ultimately decreases and achieves the highest value of $0.35 \times 10^6$ s$^{-1}$, ultimately reducing to 0. In actual machining process, however, with the continuous movement of the cutting tool, the machined surface experienced the cyclic processes of cut-in, engagement in and cut out of the tool. It is consistent with the variation of plastic shear strain and strain rate mentioned above. The simulated results agree well with the experimental ones in actual cutting process.

The maximum values of plastic shear strain and shear strain rate under different cutting parameters are labeled

<table>
<thead>
<tr>
<th>Cutting parameters</th>
<th>Peak ($\mu$m)</th>
<th>Valley ($\mu$m)</th>
<th>Spacing ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v = 100$ m/min, $f = 0.1$ mm/r</td>
<td>Experiments</td>
<td>118.1</td>
<td>69</td>
</tr>
<tr>
<td>$v = 150$ m/min, $f = 0.1$ mm/r</td>
<td>Simulation (relative error)</td>
<td>113.9 (3.6%)</td>
<td>78.6 (-13.9%)</td>
</tr>
<tr>
<td>$v = 200$ m/min, $f = 0.1$ mm/r</td>
<td>Experiments</td>
<td>115.4</td>
<td>65.7</td>
</tr>
<tr>
<td>$v = 100$ m/min, $f = 0.15$ mm/r</td>
<td>Simulation (relative error)</td>
<td>112.3 (3.1%)</td>
<td>74.4 (-12.2%)</td>
</tr>
<tr>
<td>$v = 100$ m/min, $f = 0.2$ mm/r</td>
<td>Experiments</td>
<td>114.3</td>
<td>63.6</td>
</tr>
<tr>
<td>Simulation (relative error)</td>
<td>109.9 (4.3%)</td>
<td>70.0 (-10.1%)</td>
<td>43.4 (3.3%)</td>
</tr>
<tr>
<td>Experiments</td>
<td>178.3</td>
<td>102.8</td>
<td>66.1</td>
</tr>
<tr>
<td>Simulation (relative error)</td>
<td>166.4 (7.2%)</td>
<td>116.1 (-12.9%)</td>
<td>59.9 (9.4%)</td>
</tr>
<tr>
<td>Experiments</td>
<td>230.4</td>
<td>153.7</td>
<td>82.6</td>
</tr>
<tr>
<td>Simulation (relative error)</td>
<td>218.6 (5.1%)</td>
<td>154.1 (-0.3%)</td>
<td>78.9 (4.5%)</td>
</tr>
</tbody>
</table>

From the variation tendency shown in the two figures, it can be seen that with the increase of cutting speed, the shear strain on the cutting surface of titanium alloy decreases, while the maximum shear strain rate increases (Fig. 8(a)). This is because when the cutting speed increases, the cutting force decreases, the high temperature in the cutting zone can not be taken away, and the strength and hardness of the metal surface are reduced, so the shear strain decreases. The strain rate is increased because the increase of velocity is much larger than the decrease of strain. From Fig. 8(b), it can be seen that with the increase of feed rate, the shear strain in the machined surface layer decreases, and the maximum shear strain rate also decreases. This is because with the increase of feed rate, the temperature of cutting zone increases, the machined surface hardness decreases, and the shear strain decreases. Moreover, the cutting speed remains the same, so the strain rate decreases accordingly.

4. Simulation and analyses of crystallographic texture in the machined surface layer

The crystal plastic deformation behavior was simulated by using the VPSC codes. In the program, it is assumed that the grain orientations are randomly distributed. The crystal ori-
Fig. 7 – Variation of plastic shear strain and strain rate versus time ($v = 200 \text{ m/min}, f = 0.1 \text{ mm/r}$).

Fig. 8 – Plastic shear strain and maximum shear strain rate versus different cutting parameters.

4.1. Plastic deformation mechanism of titanium alloy

Generally, the plastic deformation mechanism of metal materials can be divided into two types: the slip mechanism produced by dislocation movement and twin mechanism produced by twinning. By studying the plastic deformation behavior of $\alpha + \beta$ titanium alloy, it is found that the $\alpha$ phase plays a dominant role in the deformation [21]. Moreover, in the $\alpha$ phase, the main slip systems due to dislocation movement can be divided into two types: $<a>$ slip system and $<c+a>$ slip system. Table 2 shows the complete slip system in $\alpha$ phase for $\alpha + \beta$ titanium alloy.

The critical shear stresses (CRSS) of various slip systems in crystals are not same at room temperature generally [24]. A large number of research results show that the dislocation slip of $<a>$ sliding system is the main slip mechanism of $\alpha + \beta$ type titanium alloy. In addition, the $<c+a>$ sliding also produces plastic deformation parallel to the $c$ axis. Only in this way can the material’s continuous deformation condition be ensured [25]. Moreover, the texture results depend on the choice of slip systems, a justification for choosing only a selected slip system is necessary. In order to simplify the calculation, the $<a>$ slip system and the first type of $<c+a>$ slip system are chosen as the deformation slip system of titanium alloy, and the slip hardening parameters of $<a>$ slip system are shown in Table 3. The CRSS of first type of $<c+a>$ slip system is 690 MPa [26].

4.2. Simulation and analysis of crystallographic texture

The machined surface of titanium alloy has undergone severe plastic deformation, mainly shear strain, and a small amount of extrusion deformation at the same time. Some investigations have been made on the variation of crystal orientation of HCP materials under shear condition. Beausir et al. [28] studied the texture of HCP materials undergoing the pure shear deformation, using viscoplastic crystal plasticity method of full constrains. The results show that there are five kinds of typical shear textures after deformation: B fiber texture $(0^\circ, 90^\circ, 060^\circ)$, P fiber texture $(0^\circ, 090^\circ, 30^\circ)$, Y fiber texture $(0^\circ, 30^\circ)$,
Table 2 – Complete slip system in α phase for α + β titanium alloy [22,23].

<table>
<thead>
<tr>
<th>Slip type</th>
<th>Slip system</th>
<th>Slip direction</th>
<th>Slip surface</th>
<th>Number of slip system</th>
<th>Independent slip system</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;a&gt;</td>
<td>Basal</td>
<td>&lt;11–20&gt;</td>
<td>(0001)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Prismatic</td>
<td>&lt;11–20&gt;</td>
<td>(10–10)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pyramidal</td>
<td>&lt;11–20&gt;</td>
<td>(10–11)</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>First type</td>
<td>&lt;11–23&gt;</td>
<td>(10–11)</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Second type</td>
<td>&lt;11–23&gt;</td>
<td>(11–22)</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3 – Hardening parameter of <a> slip system [27].

<table>
<thead>
<tr>
<th>Slip system</th>
<th>Initial hardening modulus (MPa)</th>
<th>Initial value of yield strength (MPa)</th>
<th>Saturation value of yield strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal</td>
<td>631.2</td>
<td>420</td>
<td>462</td>
</tr>
<tr>
<td>Prismatic</td>
<td>436.2</td>
<td>370</td>
<td>407</td>
</tr>
<tr>
<td>Pyramidal</td>
<td>436.2</td>
<td>490</td>
<td>539</td>
</tr>
</tbody>
</table>

Fig. 9 – Texture pole figures of the machined surface under different cutting speeds (f = 0.1 mm/r).
Fig. 10 – Texture pole figures of the machined surface under different feed rates ($v = 100$ m/min).

4.2.1. Texture pole figures
The pole figure is a two-dimensional image, which is stereographic projection from the intersection point of the crystal plane and the reference sphere in the equatorial plane (corresponding to a characteristic surface of the specimen). Figs. 8 and 9 shows the machined surface texture pole figures of titanium alloy under different cutting speed conditions and different feed rate conditions, respectively. From the (0001), (0110), (1122) pole figures shown in Fig. 9, it is found that the texture is obvious and concentrative and it is mainly cylindrical texture (0110 texture, $\theta = 90^\circ$). Besides, there exist obvious small differences in shear texture and peak texture density across the range of machining conditions. It has the highest density along the X direction (the cutting direction), compared to the Y direction (perpendicular to the cutting direction).

Fig. 10 illustrates the texture pole figures of the machined surface under different feed rates when the cutting speed is $v = 100$ m/min. From the figures, it is found that the typical shear texture density decreases gradually with the increase of feed rate from the pole figures. This is because the plastic shear strain and strain rate decreases with the increase of feed rate at the same time (seen in Fig. 8(b)). The results also show that the typical shear textures were formed on the machined surface, and the density of cylindrical texture along the cutting direction was the highest. In addition, the shear texture...
density decreased with the increase in cutting speed and feed rate.

4.2.2. Orientation distribution function maps

Pole figure is 2D stereographic projection in the polar surface for the orientation in space, but it cannot exhaustively describe the spatial orientation of the crystal, which is the reason of erroneous and missing judgment. Therefore, the three-dimensional function is used to express the orientation distribution of the crystal, which is called orientation distribution function (ODF).

Figs. 11 and 12 show the ODF maps of texture on the machined surface of titanium alloy under different cutting speeds and different feed rate conditions, respectively. From the ODF maps, it is found that typical shear textures (B, P, Y, C₁ and C₂ fiber texture) formed in the machined surface layer. In these textures, the density of Y fiber texture is highest and the density of P fiber texture is lowest.

Fig. 11 – ODF maps of texture on the machined surface under different cutting speeds (f = 0.1 mm/r).
It is also found that the texture density decreases gradually with the increase in cutting speed from the pole figures (Fig. 9) and ODF maps (Fig. 11). This should be attributable that with the increase in cutting speed, the shear strain decreases gradually although the strain rate increases under the comprehensive effects of mechanical stress field and temperature field. The typical shear texture density decreases gradually with the increase of feed rate from the pole figures (Fig. 10) and ODF maps (Fig. 12). This is because the plastic shear strain and strain rate decreases with the increase of feed rate at the same time (seen in Fig. 8(b)).

5. Tribological behavior of machined surface layer

In order to investigate the effect of typical shear texture on the macroscopic properties, friction experiments were carried out
on the machined surfaces of titanium alloy along the cutting direction and perpendicular to the cutting direction. Then the wear testing results can be explained in the context of the simulated textures, also the existence of typical shear textures can be confirmed by the wear and friction properties of the machined surfaces.

5.1. **Friction tests**

Fig. 13 shows the experimental equipment and friction specimens in the friction tests. The cutting path of titanium alloy is circular and the original machined surface is circular, so it is cut into 12 × 8 mm small pieces as shown in Fig. 13(b). In order to investigate the friction properties along the different directions, the circular arc is approximated as a straight line in the small samples cut at different feed rates and cutting speeds, and defined as the cutting direction and perpendicular to the cutting direction respectively as shown in Fig. 13(b). The experimental instrument is UMT-2 type multifunctional friction and wear test machine, using ball-disc contact reciprocating motion method, as shown in Fig. 13(a). The frictional ball is a bearing steel ball (GCr15, 36-40HR). The load F is 20 N, the cycle time t is 15 min, the speed V is 10 mm/s, and the distance L is 4 mm.

5.2. **Analyses of friction process**

Fig. 14 exhibits the curve of friction coefficient of the machined surface of titanium alloy along the direction perpendicular to cutting direction under the cutting conditions of \( v = 100 \text{ m/min}, f = 0.1 \text{ mm/r} \). According to the variation of friction coefficient versus time, the whole friction process can be divided into four stages:

5.2.1. **Running-in stage**

Due to the effect of machined surface topography, the friction coefficient rises with a certain fluctuation in this stage.

5.2.2. **Stable wear stage**

The friction coefficient is stable and minimum due to the effect of plastic deformation layer in this stage. This should be attributed to severe plastic deformation in the machined surface, the grain refinement and the enhancement of the surface hardness.

5.2.3. **Transition wear stage**

Due to the transition from plastic deformation to matrix, the friction coefficient rises with a large fluctuation in this stage.

5.2.4. **Substrate wear stage**

Due to the wear of substrate, the friction coefficient is large with a serve fluctuation.

5.3. **Friction coefficient**

In order to eliminate the effects of machined surface morphology and substrate material property on the friction process, the second stage, which is the smooth and stable wear stage of the plastic deformation layer, is mainly incorporated in the frictional analyses. Fig. 15 shows the comparison of friction coefficient along the cutting direction and perpendicular to the cutting direction. The results indicate that the friction coefficient of the former is always smaller than the friction coefficient of the latter. There is always a difference between the friction coefficients in two directions, which shows that the friction coefficient is anisotropic.

During the machining process of polycrystalline metal materials, the macroscopic plastic deformation is inevitably
accompanied by the change of microscopic and mesoscopic crystallographic structure, which will affect the material macroscopic properties. As an important component of the metal structure on the mesoscopic scale, texture is the root cause of anisotropy. Therefore, the existence of the typical texture in the machined surface of titanium alloy has a certain influence on the macroscopic friction properties and makes the friction coefficient anisotropic.

The α phase of titanium alloy belongs to the typical HCP crystal structure, so the material properties of the pyramidal and the basal planes are different on the microscopic scale. And the existence of texture will enlarge the property difference and form the anisotropy of the property. Manteet et al. [29] studied the nanoindentation of single crystal titanium, it is found that the hardness of the basal plane is 1.60 ± 1 GPa, while the hardness of the pyramidal plane is 1.90 ± 1 GPa. Therefore, on the microscopic and macroscopic scale, the hardness of the pyramidal and the basal planes is different. The machined surface has mainly formed typical shear texture, and the X direction (parallel to the cutting direction) has the highest density of cylindrical texture. So, it can be inferred that the hardness along the cutting direction is slightly larger than the hardness along the direction perpendicular to cutting direction. Generally speaking, the higher the hardness is, the higher the surface abrasion resistance is, and the smaller the friction coefficient is. Finally, the friction coefficient along the cutting direction is always smaller than the friction coefficient along the direction perpendicular to cutting direction, which shows that the friction coefficient is anisotropic.

Fig. 16 shows the differences of friction coefficient along the two directions under the different cutting speed and feed rate. Fig. 16(a) indicates that the difference gradually enlarges with the increase of cutting speed. On the one hand, the existence of shear texture is the fundamental reason for the anisotropy of friction coefficient. Moreover, the texture density decreases gradually with the increase of cutting speed as shown in Fig. 9. The anisotropy level of the friction coefficient along the two directions should decreases. On the other hand, the grain refinement increases with the increase in cutting speed, which expands the difference of friction coefficient and play a major role. Therefore, the difference of friction coefficient finally increases with the increase in cutting speed. Fig. 16(b) indicates that the difference gradually diminishes with the increase in feed rate. The main reason is that the texture density and grain refinement gradually decreases with the increase in feed rate.

5.4. Wear track width

A tool microscope was used to measure the wear track width (as shown in Fig. 17), and a comparative analysis was made with the different cutting speeds as shown in Fig. 18. Fig. 18 indicates that the wear track width along the cutting direction is always smaller than the wear track width along the direction perpendicular to cutting direction. On the one hand, the machined surface morphology of titanium alloy is different along the different direction, and there has a peak shape along the direction perpendicular to cutting direction. On the other
hand, the friction coefficient along the cutting direction is always smaller than the friction coefficient along the direction perpendicular to cutting direction because of the existence of typical shear texture, which plays a major role.

Since there are peak texture density differences observed across the range of conditions, and this should be responsible for the macro-scale differences in friction coefficient and wear track width. Then the relationship between small texture differences and mechanical properties can be distinguished. So the differences in mechanical properties should be correlated with the small differences in textures. Thus, the crystallographic texture evolved in the machined surface layer was validated through friction experiments.

6. Conclusions

In this paper, the orthogonal cutting experiments of Ti-6Al-4 V alloy were carried out, the macroscopic plastic deformation and mesosopic texture were analyzed by the FEM simulation and VPSC codes, respectively. Finally, the friction experiments were conducted along the cutting direction and perpendicular to the cutting direction to investigate the relationship between crystallographic texture and macroscopic friction property. The main conclusions are deduced as follows:

1) On the macroscopic scale, the machined surface of titanium alloy mainly undergoes shear strain, and the variations of shear strain and strain rate versus time was obtained.
2) On the mesosopic scale, the crystallographic texture evolution during the machining process was expressed by pole figures and ODF diagrams. The machined surface emerges typical shear textures: B, P, Y and C1, C2 fiber textures, and exhibits the highest density in the X direction (the cutting direction). In addition, the texture density gradually decreases with the increase in cutting speed and feed rate. As the cutting speed increases, the strain rate increases under the combined action of the mechanical stress field and the thermal stress field, but the shear strain gradually weakens, which eventually leads to the decrease of the texture density of the machined surface. As the feed rate increases, the surface texture density decreases gradually, mainly due to the simultaneous reduction of the shear strain and strain rate of the machined surface.
3) The friction coefficient along the cutting direction is always smaller than that along the direction perpendicular to cutting direction, which shows the friction coefficient is anisotropic. This is the obvious evidence to the existence of typical shear textures according to the machining direction. Moreover, the difference of friction coefficient increases with the increase in cutting speed, and decreases gradually with the increase in feed rate. In addition, there is a difference in the wear track width along the two directions.

Future work can be focused on the experimental validation of crystallographic texture. Since the measurement of slip system activity within the deformation zone is highly difficult, slip systems that are most likely to be active can perhaps be deduced from “first-order” evaluation of the temperature field (from FEM simulation) and looking at the temperature-dependence of CRSS for different systems. In order to verify the simulation results of crystallographic texture evolution, and to find the enhanced proof to the existence of texture directly through experimental comparisons of texture for inferring key information on slip activity, further experimental research on microstructural texture measurements using the EBSD technique is in progress.
Conflicts of interest
The authors declare no conflicts of interest.

Acknowledgments
The authors would like to acknowledge the financial support of the National Natural Science Foundation of China (51605260), the Key Research and Development Program of Shandong Province - Public Welfare Special (2017GGX30144, 2018GGX103043), and the Young Scholars Program of Shandong University (2018WLJH57).

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