Metallurgical analysis and nanoindentation characterization of Ti–6Al–4V workpiece and chips in high-throughput drilling

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Abstract

The metallurgical analyses, including scanning electron microscopy (SEM), X-ray diffraction (XRD), electron microprobe, and nanoindentation characterization are conducted to study the Ti–6Al–4V hole surface and subsurface and the chips in high-throughput drilling tests. The influence of high temperature, large strain, and high strain rate deformation on the β → α phase transformation and mechanical properties is investigated. Diffusionless β → α phase transformation in the subsurface layer adjacent to the hole surface can be observed in dry drilling, but not in other drilling conditions with the supply of cutting fluid. Nanoindentation tests identify a 15–20 μm high hardness subsurface layer with peak hardness over 9 GPa, relative to the 4–5 GPa bulk material hardness, adjacent to the hole surface in dry drilling. For drilling chips, the β phase is retained under all conditions tested due to rapid cooling. On the chips, the saw-tooth feature and narrow shear bands are only formed at the outmost edge and no significant change of hardness across the shear bands can be found in nanoindentation.

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Keywords: Ti drilling; Chip; Phase transformation; Nanoindentation

1. Introduction

Ti–6Al–4V is a widely used titanium (Ti) alloy in industry, sharing 56% of the Ti market in the US in 1998 [1]. Ti has two crystal structures: the hexagonal closed-pack (HCP) α phase, and body centered cubic (BCC) β phase [1,2]. Pure Ti is 100% α at room temperature. The allotropic transformation from α to β phase takes place at the β transus temperature 883 °C. For Ti–6Al–4V, vanadium (V) is added to pure Ti to stabilize the β phase by lowering the β transus temperature [1,2]. Aluminum (Al) is added to increase the β transus temperature [1,2]. With 6 wt% of Al and 4 wt% V, the β transus temperature of Ti–6Al–4V is 980 °C, beyond which Ti is 100% β [2]. An example of the microstructure of the Ti–6Al–4V used in this study is shown in Fig. 1. The dark region is α phase and the light region is β phase. Because Ti–6Al–4V is a two-phase alloy, it can be heat treated and aged to provide exceptional properties like the high strength–density ratio at elevated temperature [2]. Generally, higher α content results in higher creep resistance and high-temperature strength, while higher β content leads to higher density and room temperature strength [2].

The machinability of Ti–6Al–4V is poor due to the inherent properties of work-material, particularly the low thermal conductivity and high strength [3–6]. To increase productivity and reduce cost, machining Ti at high material removal rate is important and has been studied extensively [7–12]. Drilling is an important machining process and is usually one of the final steps in component fabrication. With the advancement of tool material, tool geometry, and knowledge in process parameter selection, the high-throughput drilling of Ti alloys has been demonstrated to be technically feasible. For example, high-throughput drilling of Ti–6Al–4V at 156 mm³/min material removal rate with up to 183 m/mm cutting speed and 0.75 mm/min feed rate using a 4 mm diameter WC-Co spiral point drill has been demonstrated feasible [13]. Effects of such high material removal rate drilling on the machined surface and chip are investigated in this study.

In high-throughput drilling of Ti–6Al–4V, the workpiece and chips undergo large deformation at high strain rate and temperature, which can alter the microstructure and material properties of the Ti work-material and chips. The high temperature and the following cooling process may cause the β → α phase trans-
formation. Bayoumi and Xie [14] reported the disappearance of β phase in scanning electron microscopic (SEM) and X-ray diffraction (XRD) study of Ti–6Al–4V chips generated in turning. Cantero et al. [15] reported the formation of an “α case” where the β phase is absent adjacent to the hole surface in the dry drilling of Ti–6Al–4V. In high-throughput drilling, the temperature is higher and plastic deformation is more severe than drilling at lower speed and feed rate. One of the goals of this research is to gain better understanding of the phase transformation on surface and subsurface layer of the hole and chip in high-throughput drilling of Ti–6Al–4V.

The change of V concentration due to diffusion has been reported as another cause of the phase transformation in the subsurface layer adjacent to the hole surface in deep-hole drilling of Ti–6Al–4V at a relatively low feed rate, 0.04 m/min [16]. In this study, the feed rate of high-throughput drilling is much higher, 0.75 m/min. Since the drilling time is short, diffusion is unlikely to occur. However, the change in V concentration is investigated in this study.

Mechanical properties in the hole subsurface can be affected by the combination of phase transformation, thermal softening, and strain hardening during drilling. This layer is usually called the subsurface layer [3,17] or deformed layer [18] underneath the machined surface. The microhardness evaluation of the cross-section of drilled Ti–6Al–4V holes by Cantero et al. [15] found a 125 μm thick hardened subsurface layer. High-throughput drilling is expected to create a narrower subsurface layer due to the shorter drilling time. Microhardness testing is not adequate and nanoindentation evaluation is utilized.

Serrated or saw-tooth type chips are generated in Ti machining. Most of researchers attributed the adiabatic shear band formation for the observed serrated chips [19–25]. Nakayama [26] and Vyas and Shaw [27] proposed that the crack initiated at the chip free face was the cause of serrated chip formation. Sheikh-Ahmad et al. [28] combined these two theories and suggested that flow instability and shear band formation caused the saw-tooth formation at high cutting speed, while at low cutting speed, the cracking followed by shear localization dominated.

The high temperature and shear strain concentrated in the shear bands are expected to influence the mechanical properties. High hardness across the shear band was reported by Sheikh-Ahmad et al. in turning of commercially pure (CP) Ti [28]. Until now, most studies of Ti machining chips were constrained to orthogonal cutting in which the cutting conditions were constant along the tool cutting edge. Drilling has a more complicated material removal process. During the chip formation in drilling, the cutting speed and rake angle vary along the cutting edge of the drill. As a result, complicated chip morphology at different stages of chip formation process is created. The chip morphology and the associated changes in material properties are investigated in high-throughput drilling of Ti–6Al–4V.

In this study, metallurgical studies, including SEM, XRD, electron microprobe, and nanoindentation tests were conducted. Changes in microstructure, phase, chemical composition, and mechanical properties are discussed on the drilled hole surface, subsurface layer, and drilling chips.

2. Experimental setup

2.1. High-throughput drilling of Ti–6Al–4V

High-throughput drilling of a 6.35 mm thick Ti–6Al–4V plate in the as-rolled condition was conducted using a Kennametal spiral point drill with 3.97 mm diameter (K285A01563) and grade K715 WC tool material with 9.5% Co. This drill has a low negative rake angle chisel edge which can reduce the thrust force and make the drill self-centering [29]. Four drilling conditions, marked as Exps. I–IV in Table 1, were performed. The drill feed rate was the same, 0.75 m/min, for all tests in this study. The drilling time was only 0.57 s to penetrate the 6.35 mm Ti–6Al–4V plate. The associated peripheral cutting speed, feed per revolution, and cutting fluid supply in Exps. I–IV are listed in Table 1.

The application of cutting fluid internally from the through-the-drill holes was critical to increase the tool life [13]. The tool life, quantified by the number of holes drilled, is also listed in Table 1. In Exp. I, without using any cutting fluid, only 10 holes could be drilled. Under the same drilling conditions with internal cutting fluid supply, the tool life improved 10 times to 101 holes in Exp. II. The cutting fluid was water-based 5% synthetic CIMTECH 500 metalworking fluid.

In Exps. III and IV, the cutting speed was reduced and feed per revolution was increased while maintaining the same 0.75 m/min feed rate and internal cutting fluid supply. In Exp. III (91 m/min

<table>
<thead>
<tr>
<th>Exp.</th>
<th>183</th>
<th>183</th>
<th>91</th>
<th>61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (m/min)</td>
<td>0.051</td>
<td>0.051</td>
<td>0.102</td>
<td>0.152</td>
</tr>
<tr>
<td>Feed (mm/rev)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cutting fluid supply</td>
<td>10</td>
<td>101</td>
<td>205</td>
<td>164</td>
</tr>
<tr>
<td>Tool life (number of holes)</td>
<td>Percentage of β phase</td>
<td>0</td>
<td>13.6</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 1 Experimental conditions for high-throughput drilling tests with 0.75 m/min feed rate
cutting speed and 0.102 mm/rev), the tool life once again doubled to 205 holes by reducing the cutting speed by half in Exp. II. Further reduction of cutting speed and increase of feed from Exp. III to IV (61 m/min cutting speed and 0.152 mm/rev) did not help to further improve the tool life, which was reduced to 164 holes.

2.2. Sample preparation

After drilling, each specimen was cut in half axially along each drilled hole, as shown in Fig. 2(a). One of the sectioned specimens was metallographically mounted in epoxy potting and then polished with fine diamond compound for nanoindentation testing and chemical composition analysis. After nanoindentation, the specimens were etched with a solution containing 6 ml HNO₃ and 3 ml HF in 100 ml H₂O to distinguish the α–β phase structure of Ti–6Al–4V in the SEM. The other sectioned specimen was used for XRD. An original Ti–6Al–4V bulk material was also polished and etched to extract the α–β phase information in SEM and for XRD evaluation. The chips, as shown in Fig. 2(b), were cleaned by acetone, metallographically mounted in epoxy, and sectioned and polished for nanoindentation testing and SEM study.

2.3. SEM microstructure observations

The polished and etched hole and chip cross-sections were examined by a Hitachi S-4700 SEM to identify the α–β phase.

2.4. Quantitative analysis of phase content by XRD

A PANalytical XPERT-PRO MPD X-ray diffractometer with Cu tube (generator setting: 40 mA, 45 kV) and proportional detector was used with parallel beam optics, incident parabolic multilayer mirror and diffraction-side 0.09° radial divergence limiting slits, to examine the phase transformation of α–β phase on the cylindrical surfaces of the machined hole. Parallel beam optics were employed to eliminate sample surface displacement effects [30]. The beam width was confined to be less than the hole diameter in order to obtain signal from the cylindrical surfaces only. The scan rate was 15 s/step.

The Rietveld method [31] was utilized for the quantitative XRD analysis of the α–β phase fraction using X’Pert HighScore Plus™ software made by PANalytical. The scan profile is refined with least squares fitting [31]:

\[ S_y = \sum_i w_i (y_i - y_{ci})^2 \]  
where \( w_i = \frac{1}{y_i} \), and \( y_i \) and \( y_{ci} \) are observed and calculated intensities of the spectrum pattern lines at the \( i \)th step, respectively. The calculated intensities \( y_{ci} \) are represented as:

\[ y_{ci} = s \sum_k L_k |F_k|^2 \phi (2\theta_i - 2\theta_k) P_k A + y_{bi} \]  
where \( s \) is the scale factor, \( k \) represents the Miller indices, \( L_k \) contains the Lorentz, polarization, and multiplicity factors, \( F_k \) is the structure factor for the \( k \)th Bragg reflection, \( \phi \) is the reflection profile function, \( 2\theta_i \) is the measured position at the \( i \)th step, \( 2\theta_k \) is the calculated positions of the Bragg peak, \( P_k \) is the preferred orientation function, \( A \) is an absorption factor, and \( y_{bi} \) is the background intensity at the \( i \)th step.

2.5. Analysis of chemical composition by electron microprobe

Wavelength dispersive spectroscopy was used to detect the possible changes in chemical composition, especially the Al as α stabilizer and V as β stabilizer, using a JEOL 8200 electron microprobe. Spectra taken from a region less than 10 μm from the edge of the hole surface were compared with those taken from a region far away from the hole surface.

2.6. Nanoindentation characterization of mechanical properties

The subsurface regions adjacent to the hole surface and the chips were narrow, only a few μm wide. Nano-indentation using the Hysitron triboindenter™ (by Hysitron Inc.) was applied to investigate mechanical properties of the subsurface layer adjacent to the hole surface. Array of indents were made along the direction parallel and perpendicular to the hole axis. The spacing between each indent was 5–12 μm. For each indent, the applied
load was 2 mN. A MTS Nano-indenter™ II was used for chips. To investigate the influence of shear bands on mechanical properties, nanoindentation was conducted on the chips with distinct saw-tooth formations. For each indent, the displacement of the indenter was 150 nm. For both machines, Berkovich diamond indenters were used. The area of indents was less than 1 μm².

The hardness, $H$, is calculated as follows [32,33]:

$$H = \frac{P_{\text{max}}}{A}$$

where $P_{\text{max}}$ is the peak indentation load and $A$ is the projected area of the contact at peak load evaluated from the shape function of the indenter and the maximum indent displacement.

3. Metallurgical analysis of hole surface and subsurface layer

3.1. Microstructural observations

Fig. 3 shows the SEM micrographs of the hole cross-sections of Exp. I and II, which have the same drilling peripheral cutting speed and feed per revolution. In Exp. I (dry drilling), the hole surface is rough with debris welded onto the hole surface and 10–15 μm thick subsurface layer. In this layer, there is a gradation of distinct grain boundaries between $\alpha$ and $\beta$ phases to indiscernible ones from the bulk toward the hole surface. The high magnification micrograph of the subsurface layer shows some tiny acicular or elongated grains. This phenomenon is likely due to two factors: one is the $\beta \rightarrow \alpha$ phase transformation as a result of high temperature and the other is the decrease of grain size due to large plastic deformation. Because the thermal conductivity of Ti–6Al–4V is low, the heat affected zone is expected to be significantly narrower than 125 μm observed in drilling at lower peripheral cutting speed (0.04 m/min) [15].

In Exp. II, the $\beta$ structure is observable at regions very close to the hole surface, suggesting that the extent of the $\beta \rightarrow \alpha$ phase transformation is significantly reduced due to the better cooling with internal cutting fluid supply. The subsurface layer is about only 3 μm. As shown in the high magnification micrograph, the grain structure within the subsurface layer is elongated parallel with the hole edge, indicating the severe plastic deformation. Although not shown, the micrographs of Exp. III and IV showed similar features and dimensions as those in Exp. II.

![Fig. 3. SEM micrographs of the polished and etched cross-sections with drilled holes in Exps. I (dry) and II (internal cutting fluid supply).](image)

![Fig. 4. X-ray diffraction patterns of the as-polished bulk material and hole surface of Exp. I (intensity plotted as square root of counts to help distinguish the weak peaks from the background).](image)
3.2. Quantitative XRD analysis of the $\beta \rightarrow \alpha$ phase transformation

X-ray diffraction analysis results of as-polished bulk material and drilled hole surface of Exp. I are shown in Fig. 4. The X-ray diffraction pattern of the as-polished bulk material shows the BCC $\beta$ phase has a (1 1 0) preferred orientation/texture. The HCP or phase is also textured on the (1 0 0) and (0 0 2) planes.

In Exp. I (dry drilling), compared to the pattern of as-polished bulk material, the $\alpha$ peaks are clearly broader due to the decreased size of crystallite and likely rms strains (i.e., nanotains) [34], resulting from the severe plastic deformation in the subsurface layer. Drilling process also changes the original texture and makes the $\alpha$ crystallites in the material more randomly distributed. The peaks corresponding to $\alpha$ (1 0 0) and (0 0 2) planes are weakened relative to the (1 0 1) planes. All peaks corresponding to $\beta$ phase disappear. Because the most
prominent changes are concentrated in the range of 30° and 45° 2θ diffraction angle, the close-up view of the XRD patterns along with the fitted profiles of the bulk material and four drilled hole surfaces of Exps. I–IV are shown in Fig. 5 for mutual comparison.

Quantitative analysis by Rietveld method shows 7.3% β in the bulk material, as labeled in Fig. 5. In Exp. I, the β is reduced to 0%. The X-ray penetration depth is estimated to vary from 4 to 12 μm at 30–90° 2θ, respectively, for 95% of the total diffraction intensity. There are two possible causes for the disappearance of β peaks. The main cause is the transformation of a large portion of the β to α phase. The other cause is that the residual broadened β peaks are submerged by broadened neighboring or peaks and become indiscernible.

The amount of β phase increases to 13.6, 7.8, and 11.4% with the introduction of cutting fluid for Exps. II–IV, respectively. These values are higher than the 7.3% β phase in the bulk material and indicates that only a small amount, if any, of the β phase transformed to α on the hole surface during drilling due to the better cooling with cutting fluid. Because of the broadened α peaks, the peaks corresponding to β are not obvious in XRD patterns of Exps. II–IV as in Fig. 5. Since only one or two tests were conducted for each hole, quantitative results may not be determinative, but the difference between Exps. I and II is manifested.

### 3.3. Chemical composition analysis

The Al and V contents were measured at seven points randomly chosen within a region less than 10 μm from the hole surface and seven points in the region far from the hole surface (i.e., the bulk) in Exps. I and II. For comparison, the Al and V contents were also measured in the bulk material. Table 2 summarizes results of average and standard deviation of the Al and V contents. No statistically significant change of Al and V composition can be observed between regions close to and far away from the hole surface, which supports the hypothesis that the β phase decomposition under dry drilling condition is a diffusionless transformation (the transformation without chemical composition change). The same diffusionless transformation for the decomposition of β phase is also observed in the heat treatment of Ti–6Al–4V [2]. Any β → α transformation is more likely due to the high temperature. This matches with the same conclusion observed in turning of Ti–6Al–4V [14] but is different from the result reported in Ref. [16] for drilling of Ti–6Al–4V at low feed rate.

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>Comparison of Al and V content in the chemical analysis of cross-sectional subsurface layer (within 10 μm from the hole surface) in Exps. I and II and the bulk material</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Bulk</th>
<th>Exp. I</th>
<th>Exp. II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (%)</td>
<td>6.7</td>
<td>6.7</td>
<td>6.5</td>
</tr>
<tr>
<td>V (%)</td>
<td>4.0</td>
<td>4.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Fig. 7. Nanoindentation hardness profile of subsurface adjacent to the hole edge in Exps. I–IV.

### 3.4. Nanoindentation hardness

Fig. 6 shows the nanoindent and associated hardness values of the hole cross-section in Exp. I, which has a 15–20 μm subsurface layer of almost 0% β phase (Fig. 3). Fig. 6(a) shows a matrix
of indents in directions roughly parallel and perpendicular to the hole axis. The spacing between each indent is about 8–12 μm. Another set of nanoindentations with a line of nanoindents close to the hole surface is shown in Fig. 6(b). Higher hardness values are found at indents closer to the hole surface. Adjacent to the hole surface, the hardness can reach 10.0 GPa. All indents are under the same 2 mN load.

Fig. 7 compares the nanoindentation hardness, \( H \), versus distance from the hole surface in Exps. I–IV. The layer of high hardness exists in all conditions, but the extent and the depth of high hardness layer are different. The highest hardness exists under the dry drilling condition in Exp. I. At the region less than 5 μm from the hole surface, the hardness is over 8 GPa, which is about twice the hardness measured in the bulk. The high hardness layer is about 15–20 μm wide, which is in reasonable agreement with the microstructural observations of Exp. I as in Fig. 3. The thickness of hardened layer is significantly narrower than prior results observed in drilling at moderate speed [15] and demonstrates a benefit of high-throughput drilling. The existence of this hardened layer is the result that plastic deformation outweighs the thermal softening. The high-temperature \( \beta \rightarrow \alpha \) phase transformation as stated in Section 3.2 may also contribute to the formation of this layer [3,15]. Beyond this layer, the hardness is stabilized around 4.1–5 GPa.

When the cutting fluid is supplied at the same cutting speed and feed (Exp. II), the peak hardness reduces to 5–5.5 GPa in the subsurface layer close to the hole edge. This hardness is only slightly higher than that of the bulk material. The thickness of hardened layer is also reduced to between 5 and 15 μm. Relative to the results of Exp. I, the benefit of cutting fluid to lubricate the tool–chip interface and reduce the temperature and plastic deformation on the hole surface is apparent. For Exps. III and IV, no significant change in the hardness profile from Exp. II is observed. The peak hardness remains in the range of 5–5.5 GPa.

![SEM micrographs of chip morphology in Exp. I](image-url)

(a) (b) (c)

Fig. 8. SEM micrographs of chip morphology in Exp. I: (a) spiral cone chip, (b) outer edge of the chip, and (c) inner side of the chip.
as in Exp. II. The thickness of machining affected layer are about 5 μm, which is smaller than that of Exp. II. The decrease of layer thickness is possibly the result of smaller plastic deformation and a lower strain hardening effect at high feed and lower cutting speed.

4. Drilling chips

In Section 3, significant differences in hardness and depth of subsurface layer are observed between dry drilling (Exp. I) and drilling with supply of cutting fluid (Exp. II) at 183 m/min high cutting speed and 0.051 mm/rev feed. With the supply of cutting fluid, different cutting speeds and feeds in Exps. II–IV do not influence the product quality metallurgically. As a result, only chips in Exps. I and II are investigated.

4.1. Chip morphology

In all Ti–6Al–4V drilling experiments in this study, the spiral point drill generates the same chip morphology: a continuous chip with spiral cone followed by folded long ribbon [13]. The spiral cone is generated at the start of drilling from the beginning of contact to the full engagement of drill cutting edge with workpiece. Due to the increased resistance to eject the chip, the spiral cone is changed to folded ribbon chip with the increase of drilling depth.

Serrated chip formation with the saw-tooth shape surface is commonly observed in orthogonal turning of Ti alloys [17–23]. Surprisingly, as shown in Fig. 8, the saw-tooth is not a common feature on the chip surface in high speed drilling of Ti–6Al–4V. As labeled as the point F in Fig. 8(a) and magnified in Fig. 8(b), the saw teeth can be seen only at the outmost edge of the chip. This region is generated by the outmost point on the drill cutting edge. This saw teeth region is less than 50 μm from the chip edge. It is only a very small part of the whole chip.

Other than this narrow region, the saw-tooth formation becomes indiscernible. The free surface on the chip degrades to lamellae [24], as shown by an example point G in Fig. 8(a) and its close-up view in Fig. 8(c). This observation is different from Ti chips formed in turning [17–23]. Contrary to the orthogonal cutting, chips in drilling are not generated uniformly along the cutting edge. The rake and inclination angles as well

Fig. 9. SEM micrographs of chips in: (a) Exp. I (dry drilling), (b) Exp. II (internal cutting fluid supply), and (c) close-up view of regions H (Exp. I) and J (Exp. II).
as the cutting speed vary along the drill cutting edge. Near the
center of the drill, the strain rate is low, where plowing of the
work-material occurs. The strain rate and cutting parameters
in this region are not likely reaching the critical cutting con-
dition to initiate the chip saw teeth formation. This and the
continuously changing cutting conditions along the drill cut-
ing edge likely inhibit the serrated chip formation in drilling
of Ti–6Al–4V. At the outmost region of the drill cutting edge,
the chip is less affected by the changing cutting speed and tool
geometry. This can explain the saw teeth formation in this narrow
region.

4.2. Microstructural observations

SEM micrographs of chip cross-sections are shown in Fig. 9.
Both the saw teeth (outmost of edge of the chip) and small lamel-
lae regions of the chip are examined. As shown in Fig. 9(a and
b), the light β phase can be observed in both Exps. I and II.
Even in dry drilling (Exp. I), which expects to have high tem-
perature in the contact surface with the tool, the β phase still
exists. Under high cooling rate, the β → α phase transformation
is retarded [2]. The high cooling rate in chip is likely the rea-
son for the β phase in retained and distributed across the whole
chip.

Fig. 9(c) shows the close-up view of the chip free edge in
Exps. I and II, as marked by H and J in Figs. 9(a and b),
respectively. The narrow shear bands initiate from the valley
of saw-tooth chips are observed in both drilling conditions. The
grain structures are elongated along the both sides of shear bands,
clearly identifying the severe plastic shear deformation.

4.3. Nanoindentation hardness

Nanoindentation on the chip cross-sections was conducted
before etching to minimize the influence of chemical etching.
The thermal softening and strain hardening are two competing
factors which determine the hardness of an indent in the chip.
Fig. 10(a) shows an example of indents on a chip before etching.
The spacing between each indent was about 5 μm. After inden-
tation, the sample was etched to expose the crystal structure and
determine if the indent is close to the shear band. An example of
etched chip sample is shown in Fig. 10(b). Two indents close to
the shear band are marked by circles in Fig. 10(b). There is no
significant difference of hardness between these two and other
indents.

Over 140 and 60 indents were made in a similar configuration
on the saw-tooth chip cross-sections in Exps. I and II, respec-
tively. These indentation results show that the shear band does
not change the nanoindentation hardness in the drilled chip of
Ti–6Al–4V. This result is different form that observed of CP Ti
chip at low cutting speed turning [28]. At low cutting speed, the
thermal effect is weak, so the strain hardening effect dominates.
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5. Concluding remarks

Metallurgical studies, including SEM, XRD, electron micro-
probe, and nanoindentation tests were conducted on the hole
surface and subsurface and the chips in high-throughput drilling
of Ti–6Al–4V. High-throughput drilling decreased the size of
crystallite and likely rms strains, changed the original texture
and made the α crystallites in the material more randomly dis-
tributed. In dry drilling, the transformation of BCC β phase into
HCP α phase was identified in a 10–15 μm wide subsurface layer adjacent to the hole surface by SEM and XRD analysis.
This transformation was proved to be diffusionless, i.e., without chemical composition change. High hardness was found in
this layer by nanoindentation testing. No obvious β → α phase
transformation occurred with the supply of cutting fluid. The
high hardness layer was also narrower than that of dry drilling.
Unlike chips formed in orthogonal cutting, drilling chips had complicated morphology. The saw-tooth feature only formed
at the outmost region of the drill cutting edge, mainly due to
the variable cutting speed along the cutting edge. Narrow
shear bands could be observed in the cross-sections of chips
with distinct saw teeth, but no significant change of mechani-
cal properties along the chips was found using nanoindentation
tests.
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