The Taguchi orthogonal analysis of Ti6Al4V titanium alloy chip morphology in micro-milling

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Abstract. Micro-milling is an efficient machining method, which is suitable for machining miniaturized titanium alloy parts. In this paper, chip morphology in micro-milling of Ti6Al4V titanium alloy was studied experimentally. An orthogonal experiment was established, in which cutting speed, feed per tooth, and axial depth of cut were chosen as the main influencing factors. The effect of milling parameters on chip morphology was analysed via the Taguchi method. The results strongly indicate that the degree of serration of the chip sharply increases with cutting speed, and then is saturated. The calculations of cooling and formation times of adiabatic shear bands under steady-state cutting conditions implied that the dynamic recrystallization occurred in these bands during the Ti6Al4V titanium alloy in micro-milling.

1. Introduction

There is an increasing demand for high-quality miniaturized parts in aerospace, biomedical, information and communication fields. Micro-milling is a suitable method for machining miniaturized parts [1, 2], in which Ti6Al4V titanium alloy is a widely used material [3-5]. The Ti6Al4V titanium alloy has a series of advantages, such as high specific strength, excellent thermal strength and corrosion resistance. Due to the low thermal conductivity of Ti6Al4V titanium alloy, the main shear region collects the heat which is quickly transferred from deformation energy of the material during milling, and the machining temperature rises [6]. Under the coupling of high temperature and high pressure, dynamic recrystallization phenomenon which affects machined surface roughness and chip morphology has been confirmed in conventional high-speed milling of titanium alloy [7]. The spindle speed in micro-milling is much higher than that in conventional milling to ensure enough cutting speed because of the small diameter of micro-milling tool. In some cutting parameters, it also satisfies the condition of adiabatic shear of titanium alloy, and dynamic recrystallization phenomenon occurs [8].

Ti6Al4V titanium alloy is an α+β type titanium alloy. The thermal conductivity of Ti6Al4V titanium alloy is relatively low (l=7.955 W/m·K, which is about 1/10 of the thermal conductivity of aluminum). The coupling of high temperature, high strain and high strain rate promotes the dynamic recrystallization and reduces the internal stress which prevents the material from continuing deformation. Then the adiabatic shear band (ASB) will be formed [9,10]. Adiabatic shear deformation has two characteristics: firstly, the high-speed deformation of the material is close to the adiabatic process from thermodynamic point of view; secondly, the highly localized shear bands have formed [11]. Langer [12,13] extended the thermodynamic dislocation theory to demonstrated ASB. In his theory, ASB was simply a runaway instability originating from structural heterogeneities, and resulting from thermal softening, or the inability for heat to dissipate as quickly as it was generated by plastic deformation. Wan et al. [14] used
an Avrami-type equation to investigate the dynamic recrystallization behavior of a TiAl-based alloy during hot compression tests. The results showed that the dynamic recrystallization volume fraction and grain size decrease with the decrease of deformation temperature or the increase of strain rate. Tian et al. [15] investigated the hot compression and dynamic recrystallization behavior of TiAl alloy by hot compression tests. The results showed that the flow stress during hot compression was affected by deformation temperature and strain rate. Their research can well predict the deformed microstructure of TiAl alloy. Lieou et al. [16] developed the Langer-Bouchbinder-Lookman (LBL) continuum theory of polycrystalline plasticity which included the creation of grain boundaries. Their theory closely matched the results in sheared ultrafine-grained titanium and provided a thermodynamically consistent way to systematically described the formation of shear bands and recrystallized grains therein. Liu et al. [7] investigated the microstructure of chips in high-speed milling of Ti6Al4V titanium alloy and proved that the dynamic recrystallization occurred in ASB when cutting speed was higher than 60 m/min.

Similar with conventional high-speed milling, micro-milling also features high strain and high strain rate. The spindle speed is generally more than 30000 r/min in micro-milling to ensure enough cutting speed. Although the diameter of milling cutter is small (0.1 to 1 mm), the cutting speed can still reach 30 m/min to 240 m/min, which covering the cutting speeds of dynamic recrystallization in conventional high-speed milling of Ti6Al4V titanium alloy. During the micro-milling process, the temperature of ASB rises rapidly. Due to the large amount of relatively low temperature substrates around, the tissue in ASB is subjected to an extremely fast cooling rate. About 90% of the energy which is converted from plastic work cannot be scattered. This process is close to adiabatic process, which satisfies the features of adiabatic shear deformation. Therefore, the dynamic recrystallization will occur in micro-milling of Ti6Al4V titanium alloy, which will affect the workpiece surface roughness and become a limiting factor for the improvement of processing quality.

2. Mater and methods
The Ti6Al4V titanium alloy used in this article was purchased from Bao Ti Group Co., Ltd. (China). Milling experiments were carried on a developed 5-axis micro-milling machine tool, as shown in figure 1. A carbide two-flute micro-end milling cutter with the diameter of 1 mm, helix angle of 30° and a cutting length of 2 mm was used. The cutter was clamped in a high-speed precision spindle with the tool overlap of 19 mm. The workpiece was a rectangular block Ti6Al4V titanium alloy, which was ground to ensure its flatness. Full-immersion slot end milling without cutting fluid was conducted.

![Figure 1. The experimental set-up.](image)

In order to highlight the scale effects in micro-milling, cutting speed, feed per tooth and axial depth of cut (ADOC) were chosen as the main influencing factors and coded as A, B and C, respectively. Table 1 summarizes the levels and values of those influencing factors.
The Taguchi orthogonal array was constructed, according to table 1, as shown in table 2. In order to avoid the effects of tool wear, each set of milling experiment was carried out twice, and the experiment sequence was arranged by the U-type.

The Keyence digital microscope was used to observe chip morphology. The chips needed to be embedded vertically into the insert because this experiment mainly observed the geometries. As the chips were too small in micro-milling, they were difficult to be embedded into the insert individually. Therefore, an amount of chips were deposited on the bottom of the mold, and then the mixture of the polymethyl methacrylate and trimethylolpropane triacrylat was slowly injected. The cured chip specimens were ground and polished, and etched with Kroll reagent (volume ratio, HF: HNO₃: H₂O = 1:2:50) for about 25 seconds. The specimen contained a large amount of chips, in which the vertically embedded chips can be found. If not, it can be continued to repeat the above process until the vertical embedded chips appear.

Chip morphology of each experimental run was observed and photographed. The geometrical parameters which have been observed are shown in figure 2. Chip morphology was assessed qualitatively by the degree of serration $G_s$, which can be expressed by:

$$G_s = (H - h) / H$$ (1)
where $L$ is serration width, $H$ is the maximum serration depth, $h$ is the minimum serration depth, and $\alpha$ is serration angle.

3. Results
The lowest degree of serration was given the degree value of 1 (smoothest) at a scale of 1 to 5 while the highest degree of serration was given the degree value of 5 (sharpest), as shown in figure 3. The remaining degree values between 2 to 4 based on the difference from the smoothest and sharpest conditions.

$$S/N = -10\log\left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)$$

where, $y_i$ is observed data, $n$ is the number of observations. Table 3 shows the results of experiment and their corresponding signal-to-noise ratio.

Table 3. Experimental results and their corresponding S/N ratio.

| No. | Code  | Degree of serration | Calculated S/N ratio |
|-----|-------|---------------------|----------------------|
| 1   | A1B1C1| Run x 3            | -9.542               |
| 2   | A1B2C2| Run 2              | -3.979               |
| 3   | A1B3C3| Run 1              | 0.000                |
| 4   | A2B1C2| Run 3              | -10.969              |
| 5   | A2B2C3| Run 2              | -6.021               |
| 6   | A2B3C1| Run 2              | -3.979               |
| 7   | A3B1C3| Run 4              | -13.118              |
| 8   | A3B2C1| Run 1              | 0.000                |
| 9   | A3B3C2| Run 2              | -8.129               |

4. Discussion
4.1. Chip morphology
The results in table 4 and figure 4 show that cutting speed significantly affects the degree of serration of chip morphology. The increased cutting speed resulted in higher degree of serration. When cutting speed
was low, the valve of degree of serration was small. The chips were in the form of strips, and their thickness changed little. As the cutting speed increased, the thermoplastic of Ti6Al4V titanium alloy was destabilized due to dynamic recrystallization which resulted in the increased value of degree of serration. When cutting speed was greater than 125.6 m/min, softening effect of the material increased, that caused the value of degree of serration increased [7]. When the cutting speed reached 188.4 m/min, dynamic recrystallization softening effect increased slowly due to the chips carried off most of the cutting heat. The degree of serration gradually increased and stabilized. As feed per tooth increased, the work hardening dominated. Dynamic recrystallization softening effect was not obvious, and the degree of serration was greatly reduced. When feed per tooth was larger than 0.6 μm, the cutting was gradually stabilized, and the degree of serration was slightly lowered. ADOC had little effect on the degree of serration. However, the smaller the ADOC, the more easily the chips were broken. Cutting force increases with the ADOC, which makes the work hardening more obvious and the dynamic recrystallization softening effect is weaker, and the degree of serration is lowered.

Table 4. Mean S/N ratio for the degree of serration.

| Parameter                  | Code | Mean S/N ratio | Level 1 | Level 2 | Level 3 | Max-Min |
|----------------------------|------|----------------|---------|---------|---------|---------|
| Cutting speed (m min⁻¹)    | A    | -4.507         | -6.990  | -7.082  | 2.575   |
| Feed per tooth (μm)       | B    | -11.210        | -3.333  | -4.036  | 7.877   |
| ADOC (μm)                 | C    | -4.507         | -7.693  | -6.379  | 3.186   |

Figure 4. Mean S/N ratio for the degree of serration.

Figure 5. Milling chips in different cutting speed (m min⁻¹). (a) Cutting speed of 62.8, (b) Cutting speed of 125.6 and (c) Cutting speed of 188.4.

Some milling chips in different cutting speed are shown in figure 5. When cutting speed was low, the deformation inside the chip was performed as a uniform sliding. As cutting speed increased, ASBs were generated in the chips and the deformations were concentrated in some narrow shear bands. Slip
lines in the shear bands were densely distributed, and internals of shear bands were elongated into thin strips along the shear zone. The entire shear zones showed the signs of large plastic deformation had been appeared. When cutting speed was further increased, slip lines in the chips became short and dense, and the tissue in the shear bands had a tendency to become thinner. The distances between the bands became had narrowed, and the center of the bands formed some refinement tissue which was non-deformed. Some small dot-like shapes were faintly visible which portend dynamic recrystallization occurred.

4.2. Dynamic recrystallization in ASB
The FEM simulation results show that the maximum temperature in micro-milling of Ti6Al4V titanium alloy reached is 845.3°C, similar to the one calculated for conventional milling [17]. The transformation temperature of Ti6Al4V titanium alloy in this research is 995°C. During the shear deformation process, the temperature in ASB did not reach the transformation temperature. According to the heat transfer lumped parameter method [7], the temperature of ASB decreased to environmental temperature (25°C) was estimated to be about 1 ms. The formation time of the ASB can be calculated by the following formula [18]:

$$t = \frac{(L + a_c \cos \gamma_0) \sin \alpha \cos(\alpha - \gamma_0) - H \cos \gamma_0}{v}$$

(3)

where, $L$, $H$ and $a_c$ are respectively serration width, the maximum serration depth and serration angle, as shown in figure 3; $v$ is cutting speed; $a_c$ is ADOC; $\gamma_0$ is the rake angle of the cutter which is 10° in this paper. According to the average value of the measurement results, the formation times of ASB can be calculated, as shown in table 5. The formation times of the ASB were much shorter than the cooling time, which can be used as the evidence for dynamic recrystallization. Therefore, dynamic recrystallization occurred in the ASB in each experimental setup.

| No. | $v$ (m min$^{-1}$) | $a_c$ (μm) | $H$ (μm) | $h$ (μm) | $L$ (μm) | $A$ (deg) | $t$ (ms) |
|-----|----------------|-------------|-----------|----------|----------|-----------|---------|
| 1   | 62.8           | 30          | 5.08      | 2.12     | 1.34     | 60        | 0.036 |
| 2   | 62.8           | 60          | 4.75      | 2.67     | 1.44     | 50        | 0.055 |
| 3   | 62.8           | 90          | 4.94      | 3.07     | 1.03     | 60        | 0.114 |
| 4   | 125.6          | 60          | 5.38      | 1.46     | 2.11     | 60        | 0.038 |
| 5   | 125.6          | 90          | 2.92      | 1.51     | 1.87     | 60        | 0.059 |
| 6   | 125.6          | 30          | 7.63      | 5.50     | 1.17     | 60        | 0.017 |
| 7   | 188.4          | 90          | 8.66      | 2.36     | 2.89     | 60        | 0.038 |
| 8   | 188.4          | 30          | 7.18      | 5.76     | 1.56     | 50        | 0.008 |
| 9   | 188.4          | 60          | 4.97      | 2.45     | 1.07     | 60        | 0.025 |

5. Conclusions
Miniaturized titanium alloy parts have broad application prospects in spacecraft. However, poor quality and processing difficulties seriously constrain their development. In this paper, an orthogonal experiment was established to analyze the chip morphology. Then, dynamic recrystallization was discussed. Based on the work performed, the following conclusions can be drawn:

- The chip was flat along with the low cutting speed. As cutting speed increased, the softening effect of the material increased and the degree of serration increased. Further increased the cutting speed, the dynamic recrystallization softening effect was enhanced slowly, the deformation in the chip was basically uniform.

- The formation times of ASB were calculated by chip morphology, which were much shorter than the cooling time of ASB. Dynamic recrystallization was mainly determined by the cutting speed, and the cutting parameters in this paper had caused dynamic recrystallization.
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References
[1] Liu Y, Li P F, Liu K and Zhang Y M 2017 Int. J. Adv. Manuf. Tech. 90 405-12
[2] Yang S C, Liu W W, Zhang Y H and Wan Q 2017 Int. J. Adv. Manuf. Tech. 96 1579-89
[3] Thepsonthi T and Özel T 2016 Prod. Eng. 10 575-86
[4] Kuram E and Ozcelik B 2017 Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 231 228-42
[5] Mamedov A and Lazoglu I 2016 J. Mater. Process Tech. 229 659-667
[6] Germain G, Morel A and Braham-Bouchnak T 2013 J. Eng. Mater. Technol. Trans. ASME 135 1104-14
[7] Liu L J, Lv M, Wu W G and Zhu X J 2015 Jixie Gongcheng Xuebao 51 196-205
[8] Thepsonthi T and Özel T 2012 Trans. North Am. Manuf. Res. Inst. SME 40
[9] Liu H G, Zhang J, Xu X and Zhao W H 2018 J. Mater. Process. Technol. 257 132-40
[10] Luo J, Wang L F, Li M Q, Ge C J, Ma X X and Yang Y T 2016 Rare Met. 25 598-605
[11] Bai Y L 1990 Res. Mechanica 31 133-203
[12] Langer J S 2016 Phys. Rev. E 94 1-6
[13] Langer J S 2017 Phys. Rev. E 95 1-8
[14] Wan Z P, Sun Y, Hu L X and Yu H H 2017 Mater. Des. 122 11-20
[15] Tian S W, Jiang H T, Guo W Q, Zhang G H and Zeng S W 2019 Internet. 112 9-19
[16] Lieou C K C and Bronkhorst C A 2018 Int. J. Plast. 111 107-21
[17] Pratap T, Patra K and Dyakonov A A 2015 Procedia. Eng. 129 134-9
[18] Dirikolu M H, Childs T H C and Maekawa K 2001 Int. J. Mech. Sci. 43 2699-713