Investigation on morphological evolution of chips for Ti6Al4V alloys with the increasing milling speed

Hongguang Liu, Jun Zhang*, Yifei Jiang, Yong He, Xiang Xu, Wanhua Zhao

State Key Laboratory for Manufacturing System Engineering, Xi’an Jiaotong University, Xianning West Road 28, Xi’an 710049, China

* Corresponding author. E-mail address: junzhang@mail.xjtu.edu.cn

Abstract

Titanium alloy, one kind of typically difficult-to-cut materials, is widely used as structural parts in aerospace industry. In this study, orthogonal milling, an experimental way based on Buda’s method to realize orthogonal cutting by milling and different from conventional method to realize high cutting speed for difficult-to-cut materials like ballistic impact, is adopted to reach the cutting speed ranging from 50-500m/min for Ti6Al4V alloy. Cutting forces and cutting temperatures are both measured, and the obtained chips are analyzed by metallurgical treatments. The results show that the serrated degree(Gs) of chips increases first and then decreases with the elevating cutting speed, and continuous-to-serrated transition occurs in one single chip, which is different from the regular rules that Gs remains increasing with elevating cutting speed. But the measured cutting forces and temperatures show the same variation as serrated phenomenon, it may be concluded that cutting forces and temperatures are the critical factors in morphological evolution of chips.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Keywords: Titanium, Chips, Cutting, Formation

1. Introduction

Ti-6Al-4V alloys have been widely used as structural parts in aerospace industry due to their high strength-to-weight ratio, excellent corrosion resistance and good mechanical properties at high temperature[1,2]. During cutting process, the high material removing rate (more than 90%), high strength and extremely low heat conductivity lead to their difficult-to-cut characteristics[3]. So the cutting speeds are usually less than 100m/min, which is mainly attributed to the rapid rise of cutting temperature with the increase of cutting speed, as it will lead to the decrease of tool life and increase of tool vibration[4]. As a result, the machining efficiency of titanium alloys is very low, and researchers have worked for many years to promote the machining efficiency of titanium alloys.

To study chip formation process and the thermodynamics characteristics is an essential way to reveal high speed cutting mechanisms and lay the foundation of high speed machining for titanium alloys. Those characteristics can be expressed by morphological evolution of chips, and different morphology shows different stress state[5]. For titanium alloys, serrated chips are easy to be generated usually regarded as the results of the periodical variation of cutting forces, which will lead to the increase of tool wear and decrease of surface quality. Consequently, to reveal chips formation mechanisms is efficient for realizing high speed machining and helpful for the improvement of tool wear and surface quality[6].

Turning, milling and ballistic impact are the methods mainly used in the research of chips formation mechanisms for titanium alloys. Turning is the most widely used one in the research of relatively low speed cutting as its convenient set-up and constant parameters, Sun et al.[7] analysed the relationship between the frequency of serrated chips and cyclic cutting forces during turning process, and concluded that strain hardening was the key factor causing the increase of cutting forces with the increasing cutting speed; Velasquez et al.[8] explored the metallurgical evolution of chips and got the conclusion that deformation shear bands are the main characteristics under their experimental condition. Ballistic impact is usually used to realize instantly high speed for
difficult-to-cut materials\cite{9}. Gene et al.\cite{10} used this method to reach the cutting speed of 4800m/min for titanium alloys, and found that the chips morphology turns to fragmented at extremely high cutting speed. As titanium alloys are always machined by milling in engineering, it is essential to reveal the morphological evolution of chips during milling process to improve the machining efficiency.

In this study, orthogonal milling, a method to realize orthogonal cutting by milling, is adopted for Ti6Al4V alloys. Cutting forces and temperatures are measured at different cutting speeds, and morphological evolution is analysed for chips. During milling process, serrated degree, cutting forces and temperatures all show a different variation with turning and ballistic impact due to the variation of chip thickness.

2. Experiments

To reach high cutting speed by orthogonal milling, Buda’s method is adopted, which is a convenient method to realize quick-stop without auxiliary device\cite{11}. A milling cutter with a diameter of 80mm and helix angle of 0° is used, and the workpiece thickness is 3mm. The cemented carbide insert (model: SandvikN331.1A) has a cutting edge of 8mm, which can prove orthogonal cutting realized during up-milling. The rake angle and clearance angle are 0° and 20°, respectively. The experiments are performed on a 5-axis milling machine (model: DMG HSC 75 Linear, maximum rotation speed: 18000rpm) and a 3-axis milling machine (model: BG3-2080M, maximum rotation speed: 2000rpm) with the same cutting parameters, and have got the same results. The schematic of set-up and cutting parameters are shown in Fig. 1 and Table 1, respectively. To avoid the factor of tool wear and obtain the tool wear characteristics at each cutting speed, new inserts would be used each time. Cutting temperatures and forces are measured by infrared thermal camera (model: FLIR SC7300M) and dynamometer (model: Kistler 9265B), respectively, chips are metallurgically treated for subsequent analysis.

3. Results and discussion

3.1. Analysis of cutting forces

Cutting forces in the x, y, z directions are measured and transformed into main force $F_t$ and ploughing force $F_r$, as shown in Fig.1, and the equations can be expressed by\cite{12}:

\[
F_t = -F_x \cos \varphi + F_y \sin \varphi \\
F_r = -F_x \sin \varphi - F_y \cos \varphi \\
F_c = \sqrt{F_x^2 + F_y^2} = \sqrt{F_t^2 + F_r^2}
\]

The variation of cutting forces during cut-in to cut-out process at different cutting speeds is shown in Fig.2. As the chip thickness would increase gradually from cut-in to cut-out, the cutting forces would increase as well. The main cutting force $F_t$ changes the most, showing that chips thickness is the main factor influencing the cutting forces. Meanwhile, the cutting forces would increase to maximum at 250m/min with the increasing cutting speed, and then decrease. Moreover, the proportion of $F_r$ becomes larger, which is larger than $F_t$ at 125m/min and reaches the maximum value at 250m/min, then decreases to the value similar with $F_t$ at 500m/min.

![Fig.1. Schematic of experimental set-up](image)

![Fig.2. Variation of cutting forces at different cutting speeds](image)

Table 1. Cutting parameters

<table>
<thead>
<tr>
<th>Cutting speed (m/min)</th>
<th>50, 80, 125, 250, 375, 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting depth per tooth (mm/tooth)</td>
<td>0.1</td>
</tr>
<tr>
<td>Feed rate (mm/min)</td>
<td>20, 32, 50, 100, 150, 200</td>
</tr>
</tbody>
</table>

The friction of clearance face will increase with the rise of ploughing forces, leading to the increase of tool wear due to the local temperature rise\cite{13}. $F_r$ would decrease when cutting speed continues to increase, as the extrusion between insert and workpiece becomes lower, while the vibration becomes higher. The results could be supported by tools break-up, as shown in Fig.3. Under dry milling condition, inserts break-up mainly focus in clearance face at 50m/min and 80m/min when the feed distance is 40mm; break-up would occur by severe friction of clearance face, where residual materials melt at high temperature and built-up edge appears at 125m/min and 250m/min when cutter feeds 20mm; inserts would break up due to the inserts cleavage when feed distance is only 10mm at 375m/min and 500m/min. It can be concluded that titanium
alloys could not be machined at medium cutting speeds due to the strength and impact toughness limit of cutting tools.

<table>
<thead>
<tr>
<th>V=50m/min</th>
<th>V=80m/min</th>
<th>V=125m/min</th>
<th>V=250m/min</th>
<th>V=375 m/min</th>
<th>V=500m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake Face</td>
<td>Clearance Face</td>
<td>Rake Face</td>
<td>Clearance Face</td>
<td>Rake Face</td>
<td>Clearance Face</td>
</tr>
</tbody>
</table>

Fig.3. Tool wear of rake face and clearance face at different milling speeds

3.2. Morphological evolution in a single chip

Serrated chips would be easily produced during machining process of titanium alloys, while the periodical segmentation and shear bands could be observed between segmentations compared with original microstructures, as shown in Fig. 4. For quantitative characterization of serrated chips, the serrated degree \( G_s \) of chips is defined by researchers as:

\[
G_s = \frac{H - h}{H}
\]

where, \( H \) and \( h \) are the heights from the bottom of chips to the bottom and top of the segmentation, respectively.

Fig.4. Serrated chips and measured parameters

In this study, chips morphology is not totally serrated at 50m/min and 80m/min with a transition state from continuous to serrated. For example, the chips thickness would increase gradually from cut-in to cut-out at 80m/min, as shown in Fig.5. The morphology is continuous at first, then turns into the transition state, finally becomes totally serrated chips. It can be attributed to two aspects: 1) the increasing uncut chip thickness leads to the increase of cutting forces, as shown in Fig.2, which makes the shear deformation easier to occur; 2) the heat conductivity of titanium alloys is quite low (only 19W/mK), leading to the occurrence of adiabatic shear bands due to the heat accumulation along cutting direction\(^{[14]}\). As chips morphology has shown the condition of cutting forces and temperatures, short chips should be produced for reducing tool wear and improving surface quality.

Fig.5. Morphological evolution in a single chip at 80m/min

3.3. Morphological evolution of chips with increasing cutting speed

As mentioned in section 3.2, serrated degree could be varied from one end to another in a same chip, so the average value is used to characterize the serrated degree of a whole chip; the peak values in smooth variation area between cut-in and cut-out are used to characterize the cutting temperatures and forces at different cutting speeds, respectively. As shown in Fig.6, serrated degree, cutting forces and temperatures all show the variation that increase first and then decrease with the increasing cutting speed.

Sutter and List\(^{[15]}\) have found that the serrated degree arises with the increase of cutting speeds, and finally becomes fragmented chips by ballistic impact. But the impact process can only present the variation of chips at one moment, which is different from the real machining. Moreover, although the chips formation at extremely high cutting speeds has been thoroughly investigated, some problems still remain unsolved at relatively low cutting speeds that can be realized by current spindle and tools technology. In this study, chips formation mechanism from 50m/min to 500m/min has been investigated, and the morphology of chip obtained at 250m/min is similar to that obtained by Sutter at 1200m/min. Cutting forces and temperatures influence little on chips morphology at 50m/min and 80m/min, but the accumulation of deformation and rising temperature finally lead to segmentation at chips end. Chips morphology turns into serrated at 125m/min and 250m/min due to the increase of cutting forces and temperatures with the appearance of adiabatic shear bands. But cutting forces and temperatures will decrease when cutting speeds elevated to
375m/min and 500m/min, while morphology remains serrated with decreasing serrated degree, and cutting forces are lower than that at low cutting speeds. From Fig.6, adiabatic shear bands remain to appear in spite of the decrease of serrated degree at high cutting speeds. Moreover, compared to the cutting forces, the temperature does not decrease rapidly, which means that low cutting forces and high cutting temperatures appear simultaneously at the high cutting speeds, leading to the decreased serrated degree. Consequently, it can be deduced that thermal softening is so severe at high cutting speed that serrated chips appear easily, but serrated degree will decrease because of low cutting forces.

**Fig.6. Evolution of cutting forces, cutting temperature and serrated degree with the increasing cutting speed**

### 4. Conclusions

In this study, Ti6Al4V alloys are machined at the cutting speeds from 50-500m/min by orthogonal milling, and the morphological evolution of chips and its relationship with cutting forces and temperature are investigated, which shows that serrated degree, cutting forces and cutting temperature all increase first and then decrease, and the speed of the inflection point is relatively low. It can be deduced that titanium alloys can be machined at cutting speeds more than 500m/min by milling process, but the fracture mechanism may change with increasing cutting speed. At low cutting speeds, slip deformation plays the most important role, and heat accumulation leads to the occurrence of locally serrated chips; at high cutting speeds, adiabatic shear becomes the dominating mechanism, which leads to the formation of fully serrated chips. But the quick breakup by high speed impact at high cutting speeds and the resistance to high temperature of cutting tools are the limitation of high speed machining of titanium alloys, which makes the development of cutting tool technology the essential factor. Moreover, chips formation mechanisms of titanium will be developed by the analysis of shear angle and fracture characteristics in our future work.

### Acknowledgements

This work was financially supported by the National Natural Science Foundation (No. 51375373) and the Fundamental Research Funds for the Central Universities.

### References


