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

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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(G_s) 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 G_s 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.

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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

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difficult-to-cut materials[9]. Gene et al.[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[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.

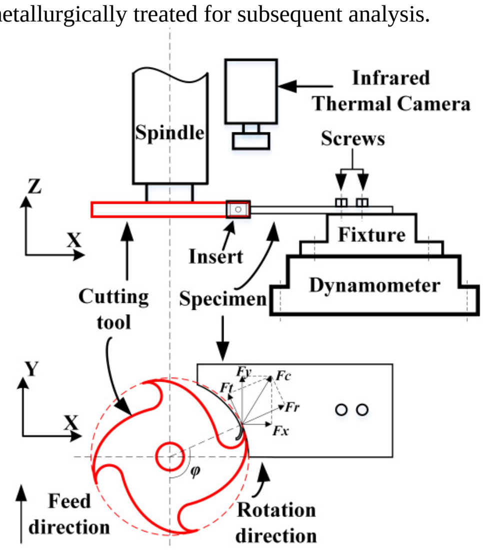

Fig.1. Schematic of experimental set-up

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[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.

Table 1. Cutting parameters

Cutting speed(m/min)	50, 80, 125, 250, 375, 500
Cutting depth per tooth(mm/z)	0.1
Feed rate(mm/min)	20, 32, 50, 100, 150, 200

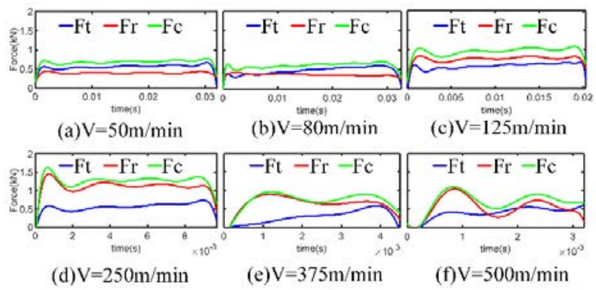

Fig.2. Variation of cutting forces at different cutting speeds

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[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