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ORIGINAL ARTICLE

Effects of cutting conditions on the milling process of titanium alloy Ti6Al4V

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Abstract Titanium alloy is a difficult-to-cut material, widely used due to its excellent material and mechanical properties. In this paper, the cutting mechanisms of titanium alloy Ti6Al4V under up-milling and down-milling with different cutting conditions have been theoretically and experimentally discussed. The milling processes were simulated by an orthogonal cutting finite element model. And a series of milling experiments were carried out to verify the simulated results. Significantly, it elaborates the prominent differences of cutting mechanisms of titanium alloy between up-milling and down-milling.

Keywords Titanium alloy · Milling force · Cutting temperature · Up-milling · Down-milling

1 Introduction

Titanium alloys are widely used in sports, aviation, and biomedical industries due to high strength, excellent fracture resistance, and corrosion resistance [1, 2]. Nevertheless, almost all titanium alloys are difficult to cut. Their low thermal-conductivity and high chemical activity can lead to low surface integrity, high temperature, and fast tool wear in their machining process [3, 4]. Many scholars have done a lot work to reveal their cutting mechanisms and enhance their machinability and efficiency [5, 6].

Ti6Al4V is the most common titanium alloy material in the aviation fields. Its machining process is a very complicated process with high-strain, high-temperature, and high-strain ratio. A lot of research work has been conducted to study material removal mechanisms of Ti6Al4V [7–10]. And milling is a complex process widely used in machining of Ti6Al4V. Some researchers experimentally investigated the milling process of titanium [8, 10–14]. In recent years, as a new method, the finite element method draws more and more attention [15–19]. It is a powerful tool to study the complex milling mechanisms [20–23]. However, the different cutting mechanisms of Ti6Al4V under up-milling and down-milling are not understood fully.

In this study, the two milling processes under up-milling and down-milling have been simulated by an orthogonal cutting finite element model. In addition, the effects of cutting conditions on milling forces have been investigated by a series of milling simulation and experiments. Further, the differences between the two milling processes have been discussed.

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2 Experimental setup

In this study, a series of milling tests of Ti6Al4V under up-milling and down-milling with different cutting conditions were carried out on the machine Fidia HS664RT. The Kistler 9257B dynamometer was employed to sense milling forces Fx (along the step direction), Fy (along the feed direction), and Fz (along the axial direction). In the milling processes, a TiAlN-coated carbide tool was employed. The detailed cutting parameters are listed in Table 1.

Table 1 Cutting parameters used in milling tests

Tool material	TiAlN-coated carbide
Tool diameter	10 mm
Tool rake angle	0°
Tool clearance angle	5°
Helix angle	25°
Milling depth	1, 2, 3, 4, and 5 mm
Milling width	0.5, 1, 1.5, 2, and 2.5 mm
Cutting speed	150~450 m/min
Feeding speed	1~10 m/min
Cutting environment	Dry cutting
Ambient temperature	20 °C

3 Finite element model

In simulation, an orthogonal cutting finite element model for up-milling and down-milling processes of titanium alloy Ti6Al4V was established using the finite element software ABAQUS 6.12. To improve simulation efficiency and precision, the workpiece was meshed. The part in the cutting region was further refined and the left not, as shown in Fig. 1. It totally has 56400 elements, which type is CPE4RT. The workpiece is 25-mm long × 10-mm wide. The initial temperature was set to ambient temperature 20 °C. The tool was meshed with 4156 elements, which type is also CPE4RT. Since the tool is harder than the workpiece, the tool is simulated as a rigid body. The cutting conditions are listed in Table 1. The whole simulation took about 40 h.

In the simulation, the Johnson-Cook material law [24] was adopted. Also, the damage criterion presented by Johnson and Cook [25] was employed. It takes into account the influence of strain, strain rate, and temperature. With this criterion, the material fracture or damage is initiated when the equivalent plastic strain reaches to a criteria value. Contact action between chip and tool's rake surface plays an important role in a metal milling process. In a contact area, one is a sliding region and the other is a sticking region. The sliding region obeys the Coulomb friction law. In the sticking region, the shear stress is equal to the critical frictional stress. It can be described by the modified Coulomb friction model [26]. In the simulation, the conductive heat transfer between chip and tool is described in [27]. The detailed parameters for Ti6Al4V in this simulation are referred to our prior work [28].

4 Results and discussion

4.1 Simulation of up-milling and down-milling

The FEM simulation of Ti6Al4V cutting under up-milling and down-milling with the cutting conditions (milling depth of 3 mm, cutting width of 2 mm, spindle speed of 6000 rev/min, and feed speed of 2 m/min) was carried out by the finite element software ABAQUS 6.12. Because of the complexity of the milling process, the analysis step was set to be "Dynamic, temp-disp, explicit." The chip formation and cutting state in the simulation of the up-milling and down-milling processes for titanium alloy Ti6Al4V are shown in the Fig. 2. It shows that the stress under down-milling is larger than that under up-milling.

The temperature distribution between chip and tool in the up-milling and down-milling processes of titanium alloy Ti6Al4V at different cutting stages is shown in Fig. 3. It shows that the temperature on the tool tip under down-milling is larger than that under up-milling.

4.2 Effect of cutting parameters on cutting forces

Milling forces were detected during the milling process under up-milling with different cutting conditions. Figure 4 shows the effects of cutting speeds on milling forces. All of milling forces increase as cutting speed increases. Significantly, when the cutting speed exceeds 350 m/min, the milling forces begin to decrease. It proves that the milling forces will decrease when the cutting speed is over a special value in the cutting process of titanium alloy Ti6Al4V.

Figure 5 presents the milling forces under different feeds per tooth. It shows that all of milling forces increase with the increase of feed per tooth. In addition, the milling forces Fx and Fz increase a little while Fy increases significantly.

Figures 6 and 7 show the milling forces under different cutting depths and cutting widths, respectively. They demonstrate that all of milling forces increase with the increase of

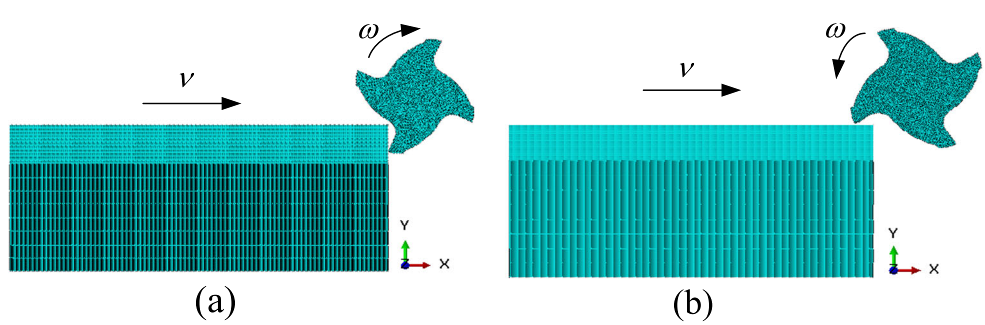

Fig. 1 Finite element model for milling of Ti6Al4V under **a** up-milling and **b** down-milling

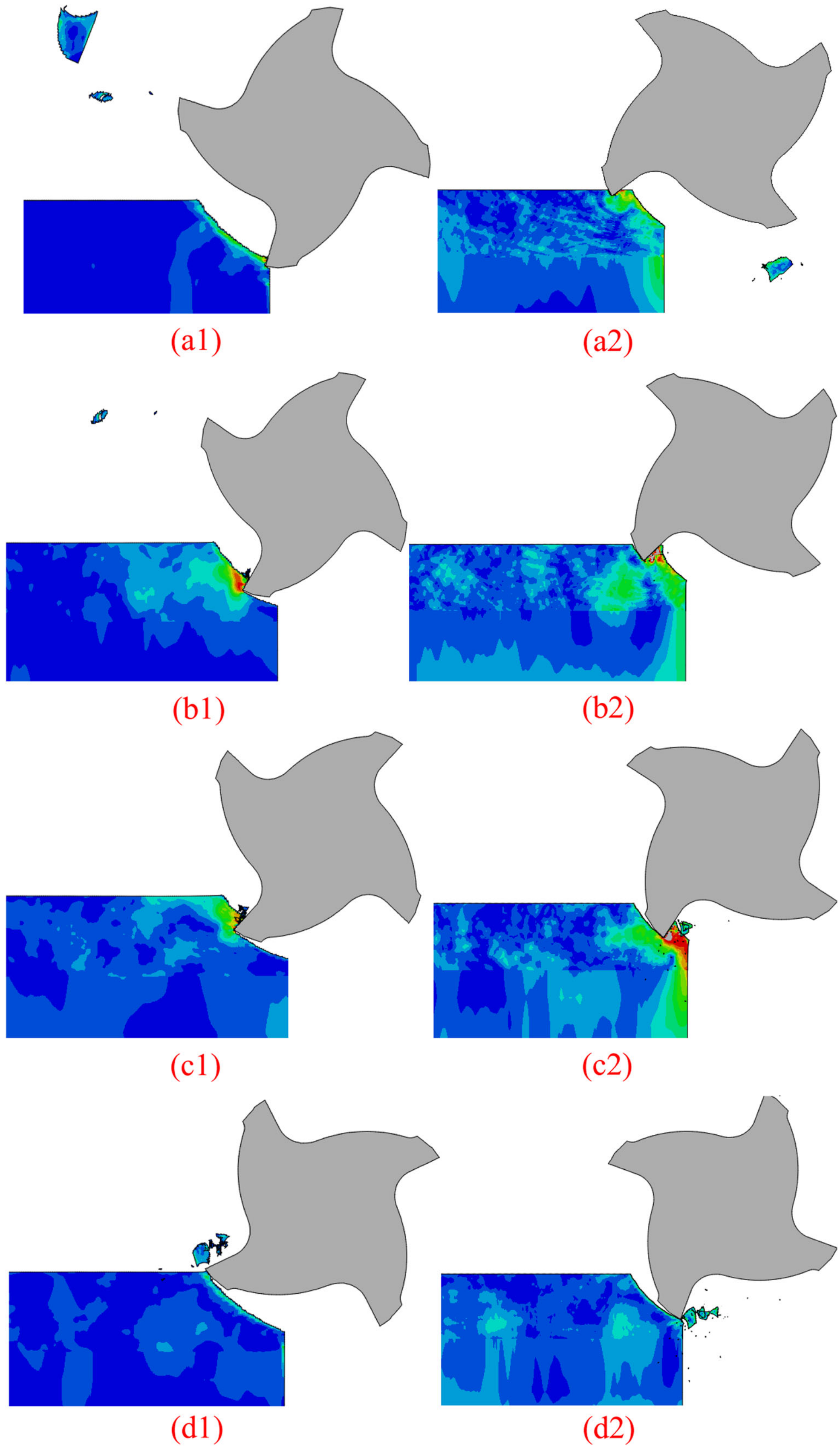

Fig. 2 The cutting process of titanium alloy under *1* up-milling and *2* down-milling: **a** cut in, **b** steady state, **c** steady state, and **d** cut out

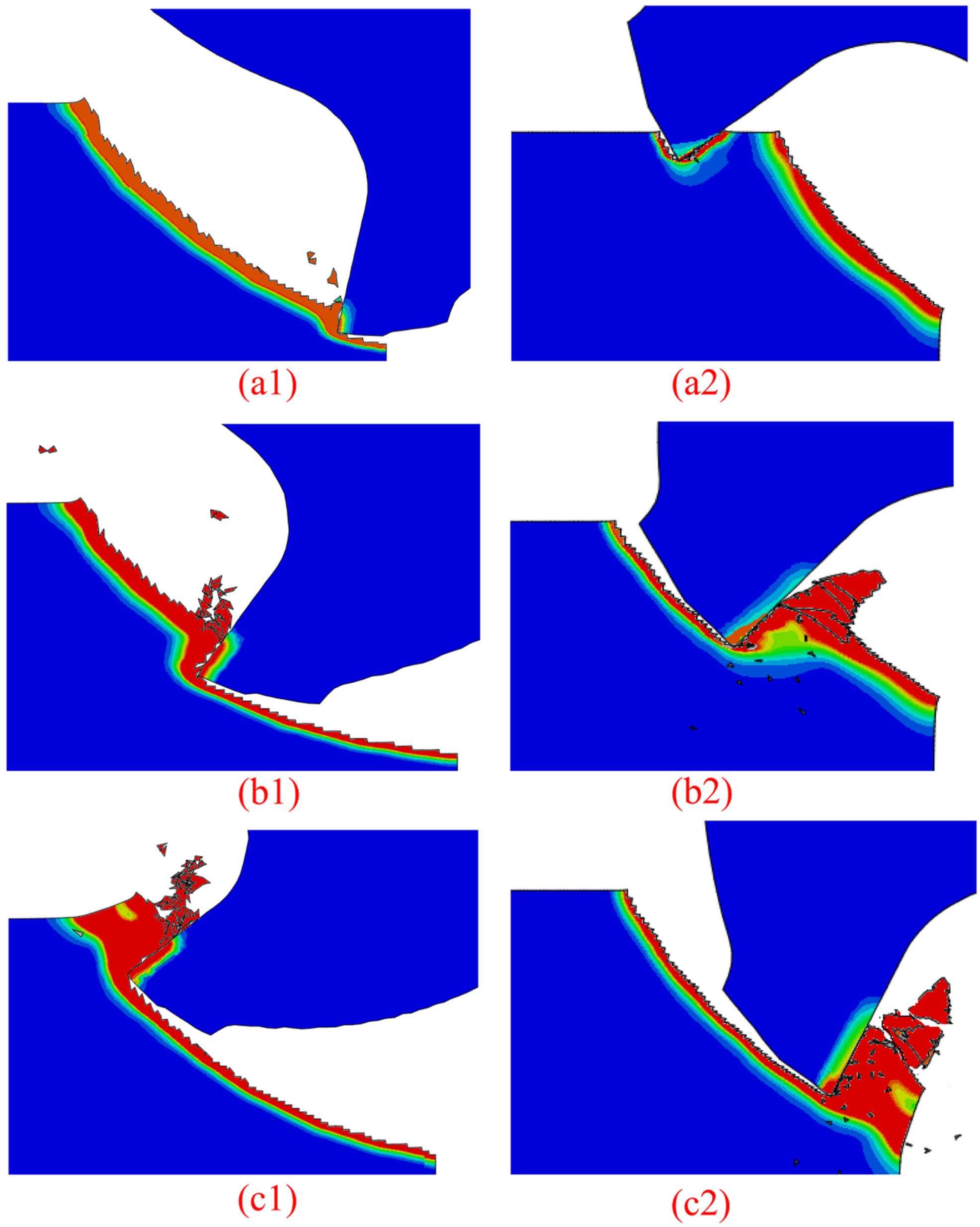

Fig. 3 Temperature distribution between tool and chip under *1* up-milling and *2* down-milling: **a** cut in, **b** steady state, and **c** cut out

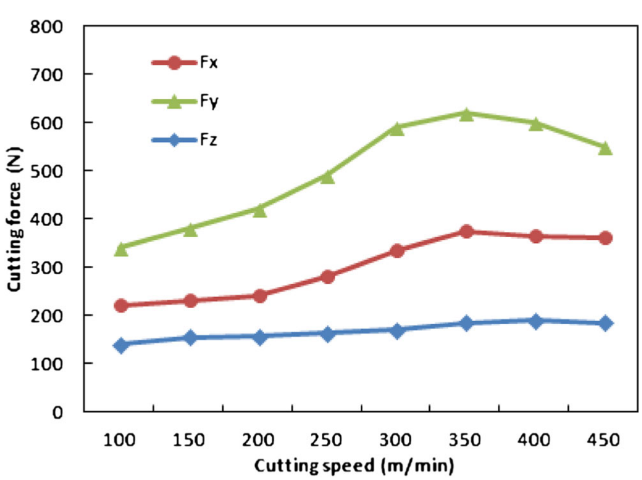

Fig. 4 Milling forces with various cutting speeds

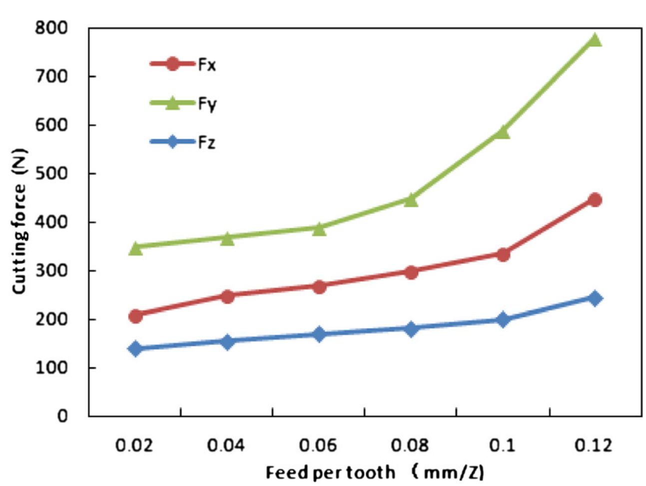

Fig. 5 Milling forces with different feeds per tooth

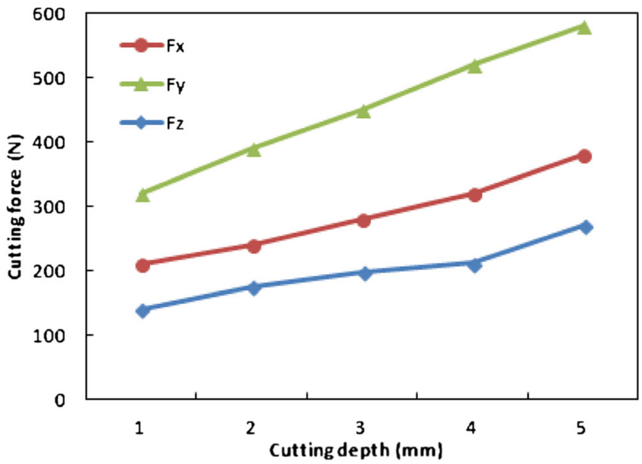

Fig. 6 Milling forces with different cutting depths

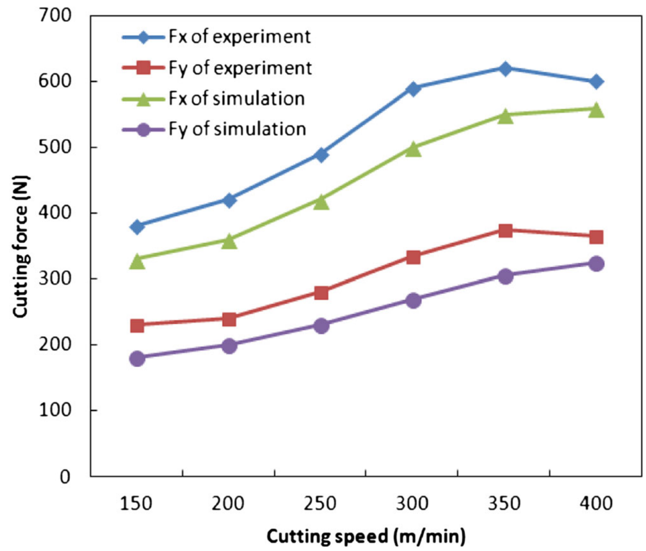

Fig. 8 Comparisons of milling forces in the simulation and experiments

cutting depth and cutting width. However, the milling forces Fx and Fz increase a little while Fy increases significantly. It is obvious that the cutting depth has more significant effects on milling forces than the cutting width.

Figure 8 shows the milling forces under up-milling between simulation and experiments. It can be seen that the milling forces in simulation have a good agreement with that in experiments.

5 Conclusions

In this study, a series of milling experiments and simulation under up-milling and down-milling were performed to investigate cutting mechanisms of Ti6Al4V alloy. The influences of cutting conditions on milling forces were investigated in detail. In view of the above results, milling forces increase significantly with the increase of feed per tooth and cutting depth. In order to optimize a milling process, feed per tooth and cutting depth should be considered firstly. In addition, the cutting speed has an important effect on milling forces, and there exists a given value of speed at which the forces reach their maximum, and beyond that value, the milling forces are decreased. Finally, the orthogonal cutting finite element model has been established to simulate the up-milling and down-milling processes of Ti6Al4V. The affected zone of temperature and stress on tool tip and workpiece under down-milling is larger than that under up-milling.

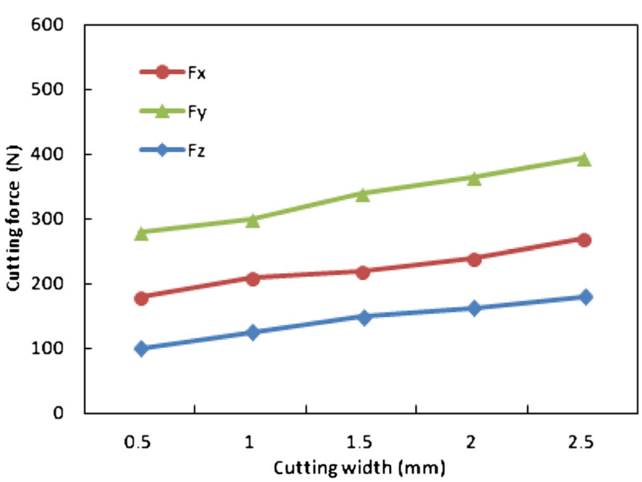

Fig. 7 Milling forces with different cutting widths

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