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High speed milling titanium alloy

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Ti 합금의 고속가공시 밀링특성에 관한 연구

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Abstract

The paper will present chip formation mechanism and surface integrity generation mechanism based on the systematical experimental tests. Some basic factors such as the end milling cutter tooth number, cutting forces, cutting temperature, cutting vibration, the chip status, the surface roughness, the hardness distribution and the metallographic texture of the machined surface layer are involved. The chip formation mechanism is typical thermal plastic shear localization at high cutting speed with less number of shear ribbons and bigger shear angle than that at low speed, which means lack of chip deformation. The high cutting speed with much more cutting teeth will be beneficial to the reduction of cutting forces, enlarge machining stability region, depression of temperature increment, auti-fatigability as well as surface roughness. The burrs always exist both at low cutting speed and at high cutting speed. So the deburr process should be arranged for milling titanium alloy in any case.

Key Words : Titanium Alloy, High Speed Milling, Cutting Mechanism, Surface Integrity

1. Introduction

Titanium alloys show excellent thermal, mechanical and chemical properties, which meet the practical needs in the area of astronautic, aeronautic and navigational industries. However the very poor machinability becomes the main obstacle for their further application. The available high speed cutting technology exhibits the good prospect for obtaining satisfied surface integrity and good chip

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formation control. The previous studies revealed the main problems in cutting this kind of materials, such as severe cutting tool wear induced by adhesive and diffuse action between the tool and the work-piece, low material removal rate, thermoplastic shear instability, oscillations of the cutting forces, high cutting temperature and poor surface integrity[1,2]. However, the comparative studies on the cutting mechanism and the dynamic characteristics as well as surface integrity during high speed milling titanium alloy with different cutting tooth number should also be necessary. The analysis of cutting tooth number plays an important part in the design of cutting tool and control of machining process. This paper presents the results of a series of experimental researches on chip formation, cutting force coefficients, cutting temperature distribution, machining stability lobe, surface layer residual stress distribution, the surface roughness, the hardness distribution as well as metallographic texture of the machined surface with regard to the cutting tooth number influence in the process of high speed cutting titanium alloy.

2. Experimental setup and procedure

All the cutting tests have been carried out through the high speed machining center DMU70V as seen in Fig.1. Titanium alloy TC4 was used as the work materials and the commercial carbide tools of K10 grade were used. The solid end milling cutters of 30 mm in diameter with different cutting tooth number ranging from 2 to 4 were used in the down dry milling process, with the axial cutting depth ranging from 0.5 mm to 10 mm, radial cutting depth ranging from 0.5 mm to 5 mm and feed rate per tooth ranging from 0.02 mm to 0.1 mm. The spindle speed ranges from 2500 rpm to 12000 rpm. The main cutting force and thrust force signals were picked up by KISTLER piezoelectric dynamometer measuring system and further analyzed by special software.

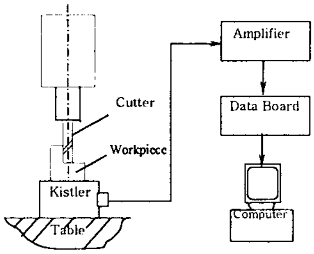


Fig. 1 Schematic of setup for cutting forces measurement

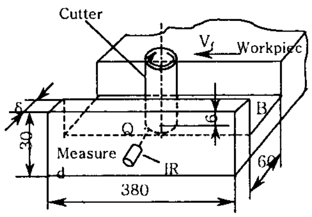


Fig.2 Measuring setup of the cutting temperature.

The cutting force coefficients could be obtained through response surface method based on a series of experiments. The cutting temperature distribution could be available through the special combination of temperature detection technique and heat conduction inverse calculation method. The thermal infrared imager and artificial thermocouple were applied to measuring cutting temperature. Fig.2 shows the experimental setup. The cutting tool began to cut in from point A and cut out from point B with constant cutting speed. At the same time the temperature distribution were recorded by infrared thermometer placed on the other side of finished surface. The B&K vibration sensors were used to detect the dynamic characteristics signals of the cutting process for the purpose of machining stability investigation.

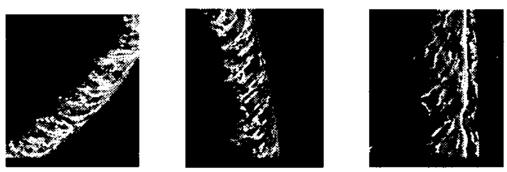
3. Results and discussions

3.1 The Chip Formation

A series of cutting tests have been conducted with different cutters of different cutting tooth number and different cutting speed. As seen in Fig3.A, B and C, with the increase of the cutting speed and

A B C

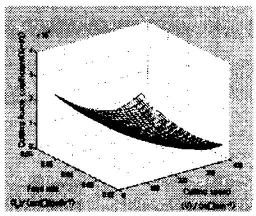
Fig. 3 Chip distortion with different cutting speed and different tooth number. A: Cutting speed is 62m/min and tooth number is 2; B: Cutting speed is 380m/min and tooth number is 2; C: Cutting speed is 380m/min and tooth number is 4.



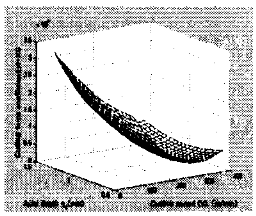
A B C

Fig. 4 The cross section of the chips corresponding to Fig. 3. A, B and C respectively.

the cutting tooth number, the chip distortion decreased. From the aforementioned pictures, we conclude that it is advisable to use the cutter with more cutting edges in the high speed cutting process to reduce the cutting forces that are beneficial to the force-induced work-piece deformation control. Fig.4 A, B and C indicate the cross section of the chips corresponding to Fig3.A, B and C respectively. Although all the chip formation show the typical segmental state, the extensive researches reveal that there are much more clear demarcated ribbons with smaller shear angle at the low cutting speed and with less tooth number, which means that the chips experienced large enough deformation, whereas at the high cutting speed with more cutting edges, the number of shear ribbons decreases and the shear angle increases, that means lack of sufficient chip deformation. The so-called thermoplastic shear instability of chip formation in high speed cutting is likely to be the result of high local warming in the field of shear plane. On the other hand, there is little plastic deformation inside the segments of the chip.



A



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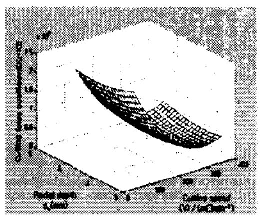


C

Fig. 5 The relationship between the cutting parameters and the cutting force coefficient.

3.2 Cutting Force Coefficient

The cutting force coefficient is always regarded as the constant in most of previous papers related to the milling force model setup. Considering that the high speed milling mechanism maybe much different from that of conventional case, this paper concerns much about the cutting speed, axial depth, radial depth and feed rate per tooth for the setup of the cutting force coefficient model. The response surface method (RSM) has been used to successfully establish a quadratic polynomial equation. Fig.5.A, B, and C describe the relationship between the cutting parameters and the cutting force coefficient. These figures show that during high speed milling titanium alloy, from viewpoint of reducing cutting force, there exists a optimal value of cutting speed corresponds to the minimum cutting force under the certain machining condition. The optimal cutting speed in the paper rates 250 m/min.

3.3 Cutting Temperature

During high speed milling titanium alloy, the cutting temperature maybe the main cause to result in the very short tool life and poor surface integrity. In order to get the cutting temperature of tool-work interface precisely, the infrared pyrometer was used to detect the temperature distribution on the surface. And the inverse heat conduct method was used to estimate the heat flux. The calculated temperature values were compared with that measured by the artificial thermocouple.

A series of experiments have been conducted to obtain the surface temperature of work-piece by the aid of infrared thermometer and the dynamic characteristics of cutting temperature in high-speed milling titanium alloy are studied according to the various cutting speed. Based on the measured temperature values, the average heat flux flowing into the work-piece and the temperature on interface can be inversely calculated using heat transfer inverse model[3]. The interesting phenomenon was found that with the increase of cutting speed and the cutting tooth number, the heat flux flowing into the work-piece kept up constant level and the steep increasing of heat flux was not found with the milling process ongoing. Therefore in high speed milling difficult-to-cut material, as long as the cutter can withstand the cutting forces, the high cutting speed and more cutting tooth number would be recommendable. The fact should not be neglected that the milling process is a kind of intermittent machining, and the cutting edges are heated up and cooled down periodically. The cutting time is quite short to raise the cutting temperature and the cooling time is pretty long to cool down the cutting edges.

3.4 Stability Lobe

Stability analysis for high-speed milling is much more complicated due to the rotation of the cutting tool and the interrupted nature of the cutting process. The forces during milling are not only time varying but also periodic. Both time domain simulation and frequency domain predictions are the common ways to stability analysis[4]. The prediction of stability lobes is based on the frequency response functions of the systems structural dynamics and successfully avoids the drawback of the time domain simulations. Based on the fundamental physics of the high speed milling process in this paper, the stability analysis of the dynamic milling system led to analytical relations between the chatter frequency, largely determined by the spindle speed, and the chatter limit which was expressed in terms of cutting depth. Fig.6.A and B depict the generated stability lobe diagrams with the variant of the cutting tooth number and the cutting speed. The diagrams show that the stable zone will enlarge with the increase of the spindle speed, and further with the cutting tooth number increase. It means that in the process of high speed milling, much more cutting tooth number is advisable.

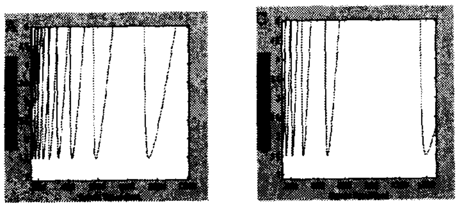
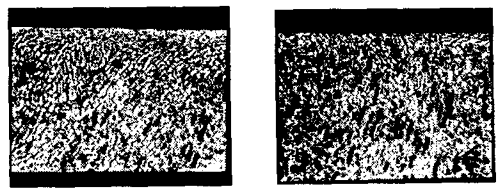


Fig. 6 Frequency domain prediction of stability lobe with the variant of the cutting tooth number and the cutting speed in milling titanium alloy. A: The tooth number is 2; B: The tooth number is 4.

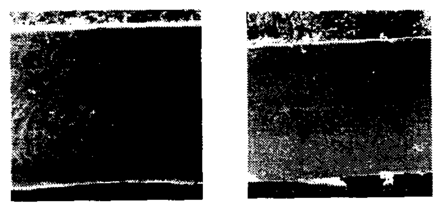
3.5 Surface Integrity

Due to the poor machinability of the titanium alloy, great concern has been taken to the surface integrity, especially to the surface residual stress distribution and metallographic texture, which resulted from the heat accumulated at the interface of the cutting tool and the machined surface. The surface integrity affects much to the practical performance and fatigue life of the parts usually used in aeronautics & astronautics field. This paper showed that with the increase of cutting speed, especially at very high spindle speed, the generated heat was contained in the chips and moved away from the tool-work interface quickly and therefore the heat affected sub-surface layer depth decreased. The X-ray measurement results of the residual stress also verified that the value of residual tensile stress and affected depth of the layer were smaller at cutting speed 380m/min than that at cutting speed 62m/min for titanium alloy. Fig.7 A and B show the metallographic texture of TC4 with the variant of cutting tooth number and cutting speed in milling titanium alloy. It is obvious that the crystals of the machined surface tensioned and experienced great distortion at the normal cutting speed, while at the high cutting speed, the affected surface layer depth looks like very shallow.



A B

Fig.7 The metallographic texture of TC4 with the variant of tooth number and speed in milling titanium alloy. A: 62m/min and tooth number 2; B: 380m/min and tooth number 4.



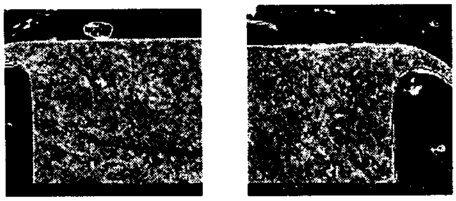
A B

Fig.8 The surface topography titanium alloy in case of 50 amplification. A: 62m/min and tooth number 2; B: 380m/min and tooth number 4.

With the increase of the cutting tooth number, the metallographic texture changes slightly. The surface topography of the machined titanium alloy at 380m/min looks like more smooth as seen in Fig.8B than that at 62 m/min as seen in Fig.8A.

In all cutting tests of titanium alloy, the SEM pictures showed that the burrs could never be avoided both at low cutting speed and at high cutting speed. Fig.9 A and B indicated the burr remained at speed of 380m/min and 62 m/min in case of 400 amplification respectively. So the deburring process should be arranged in any case.

Fig.10 showed the hardness distribution along the machined surface layer depth and revealed that with the increase of the cutting speed, the depth of the surface layer tended to be shallow and also revealed that with more cutting tooth number, the changed texture tended to be hardened. It is advisable that the high speed milling with more cutting edges be very useful for promoting surface quality of titanium alloy.



A B

Fig.9 SEM pictures of burrs remained in case of 400 amplification. (A)380m/min; (B) 62 m/min.

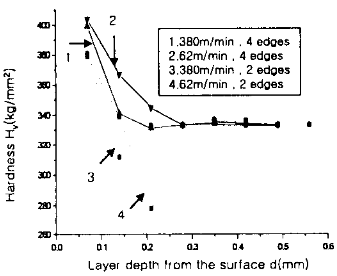


Fig .10 The hardness distribution along the machined surface layer depth.

4 Conclusions

1) The chip formation mechanism is typical thermal plastic shear localization at high cutting speed with less number of shear ribbons and bigger shear angle than that at low speed, that means lack of sufficient chip deformation.

2) The inverse heat conduction method can be used to estimate the heat flux flowing into work-piece and temperature distribution on the tool-work interface. Using infrared thermometer as a remote sensor can solve the problem of measuring temperature in high-speed milling.

3) There exists the critical cutting speed in high-speed milling titanium alloy. The value of this critical speed will be different in the different cutting conditions. The heat flux flowing into the work-piece increases with the spindle speed. While the cutting speed exceeding the critical speed, the increase of heat flux flowing into the work-piece will slow down.

4) The constant feed per tooth must be kept in high-speed milling to efficiently suppress the heat generation while obtaining high material removal rate, especially for machining difficult to-cut materials with thin wall construction.

5) The high cutting speed with more cutting edges will be beneficial to reduction of cutting forces, enlarge machining stability region, depression of temperature increment, anti-fatigability as well as surface roughness.

6) The burrs always exist both at low cutting speed and at high cutting speed. So the deburring process should be arranged for milling titanium alloy in any case.

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