



# Experimental study on chip deformation of Ti-6Al-4V titanium alloy in cryogenic cutting

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## Abstract

This paper first develops a cryogenic cutting system with adjustable jet temperature (− 196–20 °C), and then carries out a series of dry cutting and cryogenic turning experiments for titanium alloy. Metallographic microscope is used to observe the chip morphology of titanium alloy and the geometric characteristic parameters of the chip are measured using a Digimizer image measurement software. The influence of cutting speed and cooling conditions on the chip morphology, chip height ratio, and serrated pitch has been analyzed. The experimental results reveal that the cutting speed and cooling conditions play significant roles on the chip morphology and serrated characteristics of titanium alloy. During the cryogenic cutting process, with the increase of cutting speed, the chip height ratio and serrated pitch of titanium alloy chip increase. It has been found that under the condition of cryogenic cutting, the lower jet temperature, the more obvious serrated characteristic of titanium alloy chip. It is also found that the fibrous adiabatic shear band exists in the shear zone; the chip height ratio and serrated pitch remarkably increase.

**Keywords** Titanium alloy · Cryogenic cutting · Chip morphology · Chip height ratio · Serrated pitch

## 1 Introduction

The rapid tool wear, the poor machined surface quality and machining accuracy, the low processing efficiency, and the pollution of cutting environment are all the difficult problems in cutting of difficult-to-machine materials such as titanium alloy and high temperature alloy. How to reduce the tool wear; improve the machining efficiency, surface quality, and processing precision; improve the air quality of cutting environment; and achieve the green cleaner production model have been the research focus in machining field.

Nowadays, the problem of energy shortage and environmental pollution is becoming more and more serious, which

forces the countries all over the world to implement sustainable development strategies. In order to achieve the goal of green and high efficient machining of difficult-to-cut materials, researchers have put forward some green cutting technologies, such as minimal quantity lubrication (MQL) [1, 2], high-pressure coolant (HPC) [3, 4], electrostatic solid lubrication (ESL) [5, 6], and cryogenic cutting(CC) [7–9]. Cryogenic cutting has always been seen as one of the effective methods to realize green, high efficiency and high-quality processing of difficult-to-cut materials. At present, the research of cryogenic cutting is mainly focused on cryogenic cutting mechanism, cutting temperature, cutting force, tool wear, and machined surface quality. Bordin et al. [10] conducted a series of cryogenic turning experiments for Ti-6Al-4V titanium alloy using liquid nitrogen as the cooling medium. The results indicated that the cryogenic cutting showed better performances than dry and wet cutting by reducing the tool wear and improving the surface integrity and the chip breakability. Shokrani et al. [11] investigated the influence of cutting parameters and cooling conditions on surface roughness, surface integrity, and microhardness of titanium alloy in end milling operations. It was found that cryogenic cooling could reduce the surface roughness by 39 and 31% when compared to dry and flood cooling methods, respectively. Furthermore, cryogenic

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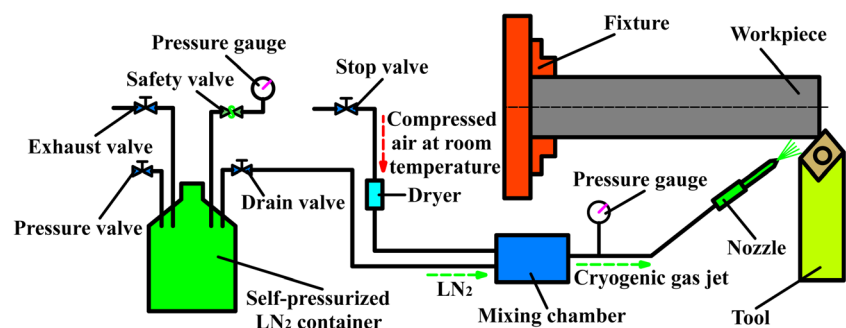
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**Table 1** The main physical properties of titanium alloy

Density (Kg/m <sup>3</sup> )	Hardness (HB)	Melting point (°C)	Thermal conductivity (W/(m K))	Elastic modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Poisson ratio	Elongation (%)
4430	195	1668	7.955	110	960~1270	820	0.342	≥ 8

cooling led to a significant increase in the microhardness of machined surface, but a decrease in the depth of hardened layer. Schoop et al. [12] explored the influence of rake angle, cutting speed and pre-cooling temperature on surface roughness and tool wear in cryogenic machining of porous tungsten using a polycrystalline diamond tool. It was noticed that the surface roughness increased with the decrease of rake angle. When the cutting speed was 250 m/min, the tool wear value reached the minimum value. Manimaran et al. [13] used a Al<sub>2</sub>O<sub>3</sub> grinding wheel to grind AISI 316 stainless steel, and analyzed the effect of grinding depth; workpiece feed rate; and cooling conditions on grinding force, grinding temperature, and surface roughness. It was reported that cryogenic cooling could significantly reduce the grinding temperature between workpiece and grinding wheel, result in up to 37 and 13% lower grinding force compared to dry and wet cooling. The surface roughness under cryogenic cooling could be reduced by 59 and 32% compared to dry and wet cooling. Dinesh et al. [14] studied the influence of cutting speed, feed rate, and cooling conditions on cutting temperature, cutting force, surface roughness, and microhardness of machined surface in cryogenic machining of ZK60 magnesium alloy using liquid nitrogen as coolants. It was observed that compared with dry cutting, the cutting temperature can be reduced by 60%, and the microhardness of machined surface can be increased by 40%, and the surface roughness can be reduced by 25–40%. The main reason for the reduction in surface roughness value was that the use of liquid nitrogen as the cooling medium could form steady lubricating films between the contact surfaces. Khan et al. [15] compared some of the key machinability aspects in turning of commercially pure titanium with untreated and cryogenically treated carbide tools in a dry cutting environment. In the current study, they focused on tool wear, chip compression ratio, friction coefficient, and chip

morphology using both untreated and cryo-treated inserts. It was reported that cryo-treated tools resulted a significant improvement in wear resistance of carbide tools. In addition, cryogenically treated carbide tools exhibited an appreciable decrease in chip compression ratio and friction coefficient when compared to that of untreated inserts. Musfirah et al. [16] carried a series of experimental investigations to evaluate the effectiveness of cryogenic milling Inconel 718. The results revealed that the cryogenic cooling is more effective than dry cutting for reducing tool wear, lowering cutting force, improving surface roughness, and eliminating contamination of the machined part. Furthermore, compared with dry cutting, the utilization of cryogenic cooling reduced the cutting force to 23% and improved the surface roughness to a maximum of 88%. This can be attributed to the capacity of cryogenic machining to provide better cooling and lubrication through the reduction of heat generation at the cutting zone. Schoop et al. [17] used polycrystalline diamond tools to machine Ti-6Al4-V alloy under three different cooling/lubricating environments: cryogenic cooling, hybrid cooling/lubrication (cryogenic cooling and minimum quantity lubrication), and conventional flood cooling. In this study, it was observed that the use of hybrid cooling/lubrication approach resulted in better surface integrity, lower cutting force. However, the tool wear under conventional flood cooling was more than four–five times higher compared to both the cryogenic and hybrid conditions. Furthermore, it was reported that cryogenic high speed machining with PCD tools may be a suitable alternative to grinding and polishing. Özbek et al. [18] investigated the influence of cryogenic treatment on tool wear of uncoated tungsten carbide inserts in the turning of AISI 316 stainless steel. It was found that the treated inserts showed a better performance than the untreated ones of up to 34 and 53% in terms of flank wear and crater wear, respectively.

**Fig. 1** Schematic diagram of cryogenic cutting system

**Table 2** Turning test parameters

Cutting speed $v/(m/min)$	Feed rate $f/(mm/r)$	Depth of cut $a_p/(mm)$	Spindle speed $n/(r/min)$
60	0.1	1.0	191
90	0.1	1.0	286
120	0.1	1.0	382

Additionally, cryogenic treatment significantly improved the microhardness and wear resistance of tungsten carbide inserts compared to untreated tungsten carbide inserts.

In addition, some researchers have carried out several research works on the chip morphology under various machining parameters, cooling and lubrication conditions. Bermingham et al. [19] performed an experimental study of the influences of cryogenic and high pressure emulsion cooling techniques on tool life and chip morphology in turning of Ti-6Al-4V titanium alloy. It was pointed out that high pressure coolant provided better tool life and better chip breaking performance than cryogenic cooling. Zhu et al. [20] systematically investigated the relationships between tool wear, chip morphology, and cutting vibration in milling of titanium alloy. It was reported that cutting vibration increased the instability between tool and chip interfaces, which led to the increase of tool wear and chip segment degree. Sui et al. [21] explored the variation regular of serrated chip morphologies and the relationship between chip macro morphologies and tool flank wear in milling of titanium alloys. The results revealed that the occurrence of tool flank wear could have an influence on serrated chips morphologies and surface color during the cutting process. Zhao et al. [22] studied the influence of various cutting speeds and feed rates on chip morphology. The experimental results showed that the height-to-thickness ratio of saw-tooth chips increased with the increase of cutting speeds and feed rates. Li et al. [23] conducted an investigation of chip morphologies in high-speed dry milling of Ti-6Al-4V titanium alloy under various cutting conditions. It was reported that the degree of chip serration was more obvious with the increase of cutting speed, feed rate, and depth of cut. Bermingham et al. [24] presented an investigation on chip morphology, cutting force, and tool life in cryogenic machining of Ti-6Al-4V titanium alloy. It was found that less deformation and heat was generated during chip formation at a combination of low feed rate/high depth of cut compared to high feed rate/low depth of cut.

The studies mentioned above show that cryogenic cutting offers better machining performance as compared to dry and

wet cutting. However, there are few researches on chip deformation of difficult-to-cut materials in cryogenic cutting. Furthermore, the research of chip deformation is very important for analyzing cutting force, cutting temperature, tool wear, and surface quality. Therefore, an attempt has been made in this paper to investigate the influence of cutting speed and cooling conditions on chip deformation of Ti-6Al-4V titanium alloy in cryogenic cutting.

## 2 Experimental details

### 2.1 Experimental materials

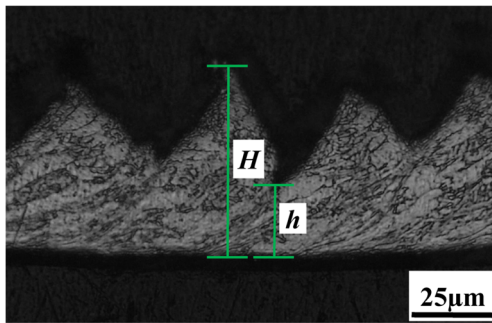
The workpiece used was a titanium alloy bar of TC4 with a diameter of 100 mm and a length of 350 mm. Titanium alloy is widely used in the field of aerospace, energy, and biomedical industries due to its superior mechanical properties such as high strength, light weight, and high corrosion resistance [9]. TC4 is a typical  $\alpha + \beta$  type two-phase alloy, the main component is 90% Ti + 6% Al + 4% V, and the main physical properties are shown in Table 1.

### 2.2 Experimental setup

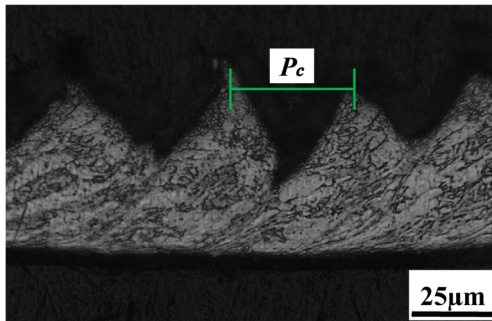
All cutting experiments were carried out on a C630 lathe with a maximum speed of 850 r/min. KORLOY tungsten carbide insert with PVD coating was employed for cutting tests. The model of cutting insert is MGMN300-M PC9030 and the shape of cutting insert is square. The width of cutting edge is 3 mm, the nose radius of cutting insert is 0.4 mm, and the relief angle of cutting insert is 7°. In order to study the influence of different jet temperatures on the chip formation under the condition of cryogenic cutting, a cryogenic cutting system was constructed, as shown in Fig. 1. The system mainly consists of self-pressurized liquid nitrogen container, lathe, cutting tool, workpiece, fixture, and nozzle. Firstly, the self-pressurized liquid nitrogen supply system provides liquid nitrogen (LN<sub>2</sub>) with a certain pressure ( $\leq 0.1$  MPa), and then

**Table 3** Cooling and lubrication conditions

Experimental conditions	Description
Dry cutting	Room temperature ( $T$ ) 20 °C
Cryogenic cutting	Jet temperature ( $T$ ) - 40, - 80, - 120, - 160, and - 196 °C



**Fig. 2** The schematic diagrams of measurement of chip height ratio



**Fig. 3** The schematic diagrams of measurement of serrated pitch

liquid nitrogen is mixed with dry compressed air at room temperature in mixing chamber. Thus, liquid nitrogen will be instantaneously vaporized to form a cryogenic gas jet. The temperature and flow rate of cryogenic gas jet can be adjusted by adjusting the flow rate and proportion of liquid nitrogen to compressed air. When the compressed air supply is

stopped, the nozzle directly sprays liquid nitrogen ( $-196\text{ }^{\circ}\text{C}$ ) to the cutting zone.

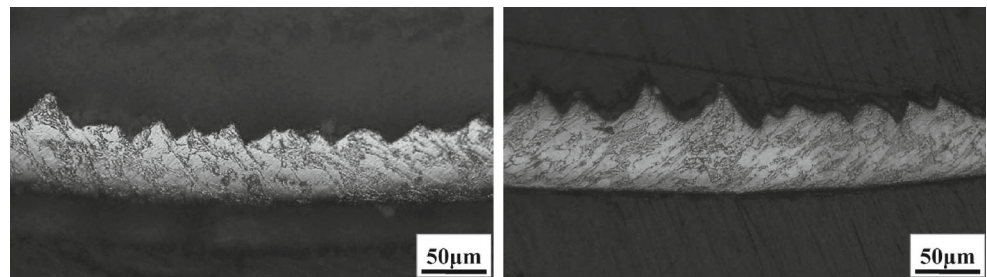
The cutting parameters, the cooling and lubrication conditions used in the experiments are given in Tables 2 and 3, respectively.

The chips generated under different cutting parameters and cooling conditions were collected, and then the chips were inlaid using epoxy resins. The chips were ground and polished by sandpapers and a polishing machine, and then the samples of chips were placed in the corrosive solution. Metallographic etchants are 10% HF + 5% HNO<sub>3</sub> + 85% H<sub>2</sub>O. The chip morphology of titanium alloy was observed using a metallographic microscope. The geometric characteristic parameters of the chip were measured using a Digim�er image measurement software. The schematic diagrams of measurement of chip height ratio and serrated pitch are shown in Figs. 2 and 3, respectively. The degree of chip deformation can be characterized by chip height ratio ( $G_s$ ) and chip height ratio is calculated as:

$$G_s = \frac{H-h}{H} \quad (1)$$

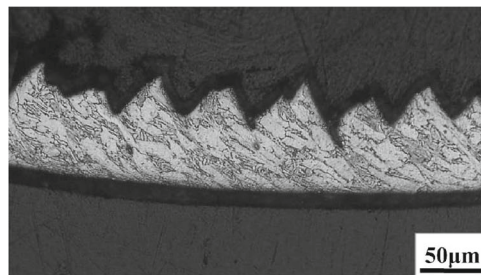
where  $G_s$  is chip height ratio,  $H$  is the height from the bottom of chip to the peak of serrated chip, and  $h$  is the height from the bottom of chip to the lowest valley of serrated chip. The serrated pitch ( $P_c$ ) can be obtained by measuring the distance between the addenda of two adjacent teeth in the chip. Each of the geometric characteristic parameters of the chip was measured three times and the average values of  $G_s$  and  $P_c$  were used for analysis.

**Fig. 4** The influence of cutting speed on chip deformation ( $T = -80\text{ }^{\circ}\text{C}$ )



(a)  $v = 60\text{m/min}$

(b)  $v = 90\text{m/min}$



(c)  $v = 120\text{m/min}$

### 3 Results and discussion

#### 3.1 Influence of cutting speed on chip deformation

The metallographic micrographs of the chips obtained using different cutting speeds are shown in Fig. 4. As can be seen from Fig. 4, when the cutting speed is low, a certain shape of serrated chips has been produced, but the distribution of serrated chips is not regular. The height of the saw-tooth is relatively small and there is a great difference between the heights of each saw-tooth. When the cutting speed increases to 120 m/min, the serrated characteristics of the chips are obvious, and the distribution of serrated chips is more regular. It can also be seen that the adiabatic shear bands produced by shear slip. The formation of serrated chips and shear bands was observed during the machining of titanium alloy, which complies with the finding of other studies [25, 26]. The reason for the formation of serrated chips and shear bands in the machining of titanium alloy is that the thermal softening effect of titanium alloy is greater than that of the strain hardening effect and strain rate strengthening effect [9].

#### 3.2 Influence of cutting speed on chip height ratio and serrated pitch

Figures 5 and 6 depict the influence of cutting speed on chip height ratio and serrated pitch of titanium alloy. As shown in Figs. 5 and 6, the chip height ratio and serrated pitch increased with the increase of cutting speed. This indicates that the contact length between each serrated chip decreases gradually and the deformation of adiabatic shear band becomes more and more obvious. This can be attributed to the fact that the connection area between the chips decreases due to the cracking of adiabatic shear band. When the cutting speed increases from 60 to 120 m/min, the chip height ratio and serrated pitch increases by 45.93 and 34.68%, respectively. This finding is in good agreement with the results reported by Li and Zhao et al. [23]. They also pointed out that the higher

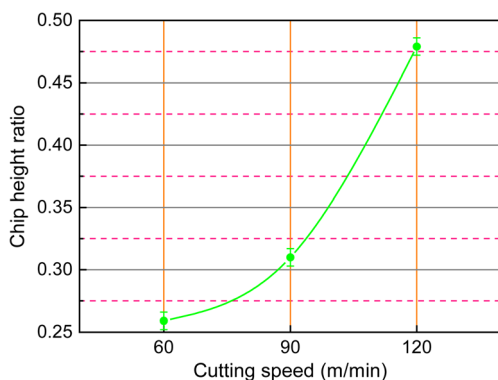


Fig. 5 The influence of cutting speed on chip height ratio ( $T = -80\text{ }^{\circ}\text{C}$ )

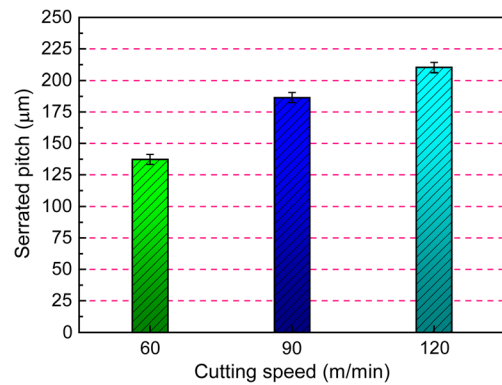


Fig. 6 The influence of cutting speed on serrated pitch ( $T = -80\text{ }^{\circ}\text{C}$ )

chip height ratio at higher cutting speeds could reduce the energy required to deform the chip and consequently a decrease in cutting force. Besides, the formation of serrated chips and higher chip height ratio were beneficial to the chip breaking.

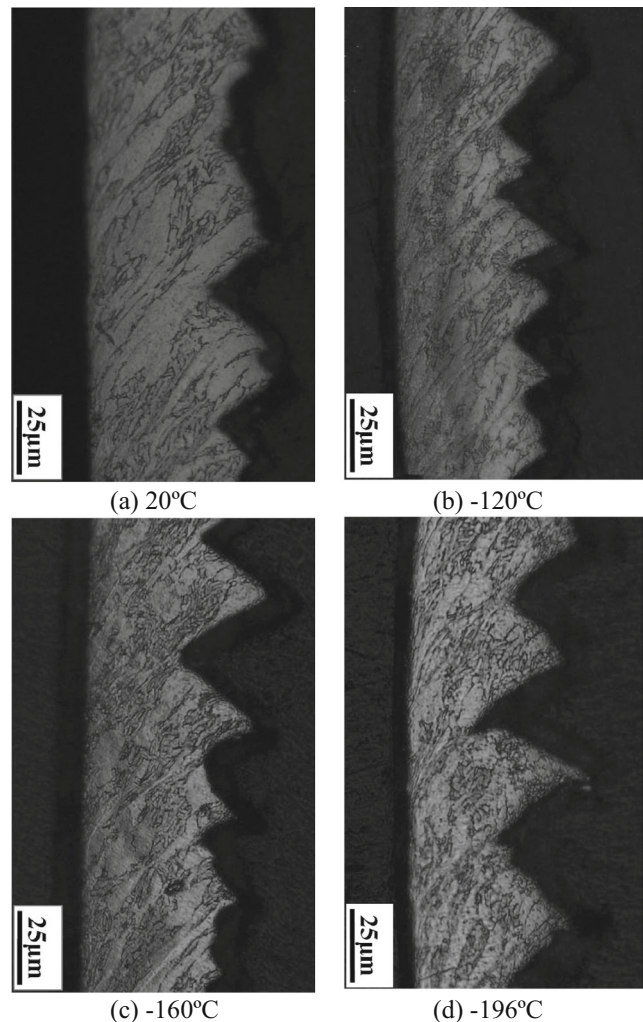


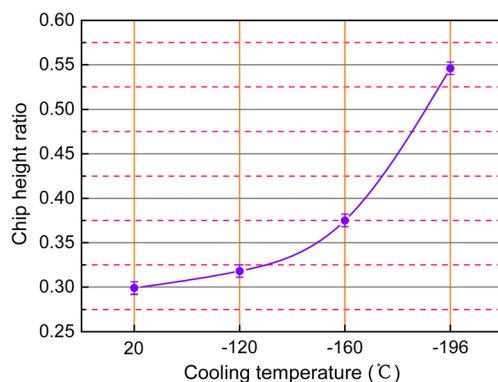
Fig. 7 The influence of jet temperature on chip deformation ( $v = 90\text{ m/min}$ )

### 3.3 Influence of jet temperature on chip deformation

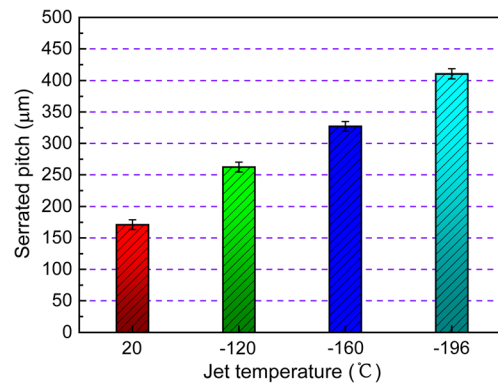
Figure 7 shows the influence of jet temperature on chip formation of titanium alloy. As shown in Fig. 7, the morphology of the cross section of the chip is serrated under the condition of dry cutting and cryogenic cutting. There are obvious adiabatic shear bands in the main deformation zone of serrated chip. Compared with the surrounding tissues, the grains of shear zone are obviously elongated and fibrous. This behavior is in good agreement with the findings reported by Aramcharoen et al. [27]. This is due to the fact that the shear deformation is highly concentrated in a relatively narrow area, the heat generated by the plastic deformation of material causes local temperature rise, which leads to the thermal softening of material. When the thermal softening effect is dominant, the material will occur in shear instability and the adiabatic shear band is formed. Furthermore, it is also clearly indicated that temperature plays an important role in chip deformation of titanium alloy [27].

### 3.4 Influence of jet temperature on chip height ratio and serrated pitch

Figures 8 and 9 show the influence of jet temperature on chip height ratio and serrated pitch of titanium alloy. It can be seen from Figs. 8 and 9 that decreasing the jet temperature leads to a significant increase in chip height ratio and serrated pitch under the condition of cryogenic cutting. This indicates that the lower jet temperature, the shorter contact length between tool and chip during the machining of titanium alloy. This is beneficial to reduce tool wear and increase tool life. This is because the contact length between tool and chip is reduced under the condition of cryogenic cutting and thus reduces the frictional heat generated on the rake face; therefore, it can reduce tool wear. This finding is in good agreement with the results reported by Bermingham and Kirsch et al. [24]. Compared with dry cutting, under the condition of liquid



**Fig. 8** The influence of jet temperature on chip height ratio ( $v=90$  m/min)



**Fig. 9** The influence of jet temperature on serrated pitch ( $v=90$  m/min)

nitrogen cooling, the chip height ratio and serrated pitch increase by 45.24 and 58.30%, respectively.

## 4 Conclusions

The influence of turning parameters and cooling conditions on chip deformation is analyzed by the cryogenic cutting experiments of titanium alloy. Based on experimental results, the following conclusions can be obtained:

- (1) In terms of chip deformation of titanium alloy, increase in cutting speed results in an increase in the chip height ratio and serrated pitch. This is due to the strain and strain rate strengthening effect of titanium alloy and its poor thermal conductivity.
- (2) The jet temperature has an important influence on chip deformation of titanium alloy. It has been found that under the condition of cryogenic cutting, the lower jet temperature, the more obvious serrated characteristic of titanium alloy chip. Compared with dry cutting, the chip height ratio and serrated pitch increase by 45.24 and 58.30%, respectively.
- (3) Under the condition of cryogenic cutting of titanium alloy, the adiabatic shear band is easy to be formed by the shear slip of the material in the main deformation zone, and the formation of adiabatic shear band is beneficial to the chip breaking.

In further study, more experiments will be conducted under various conditions of cutting speeds, feed rates, depth of cuts, and jet temperatures to roundly explore and compare the influence of chip deformation on surface roughness and tool life.

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## References

- Su Y, Gong L, Li B, Liu ZQ, Chen DD (2016) Performance evaluation of nanofluid MQL with vegetable-based oil and ester oil as base fluids in turning. *Int J Adv Manuf Technol* 83(9–12):2083–2089
- Wang YG, Li CH, Zhang YB, Yang M, Zhang XP, Zhang LQ, Dai JJ (2017) Experimental evaluation on tribological performance of the wheel/workpiece interface in minimum quantity lubrication grinding with different concentrations of  $Al_2O_3$ , nanofluids. *J Clean Prod* 142(4):3571–3583
- Mia M, Khan MA, Dhar NR (2017) High-pressure coolant on flank and rake surfaces of tool in turning of Ti-6Al-4V: investigations on surface roughness and tool wear. *Int J Adv Manuf Technol* 90(5–8):1825–1834
- Mia M, Khan MA, Dhar NR (2017) Performance prediction of high-pressure coolant assisted turning of Ti-6Al-4V. *Int J Adv Manuf Technol* 90:1433–1445
- Reddy NSK, Nouari M, Yang M (2010) Development of electrostatic solid lubrication system for improvement in machining process performance. *Int J Mach Tool Manu* 50(9):789–797
- Reddy NSK, Yang M (2010) Development of an electro static lubrication system for drilling of SCM 440 steel. *Proc Instit Mech Eng Part B: J Eng Manuf* 224(2):217–224
- Trabelsi S, Morel A, Germain G, Bouaziz Z (2017) Tool wear and cutting forces under cryogenic machining of titanium alloy (Ti17). *Int J Adv Manuf Technol* 91(5–8):1493–1505
- Lee I, Bajpai V, Moon S, Byun J, Lee Y, Park HW (2015) Tool life improvement in cryogenic cooled milling of the preheated Ti-6Al-4V. *Int J Adv Manuf Technol* 79(1–4):665–673
- Park KH, Suhaimi MA, Yang GD, Lee DY, Lee SW, Kwon P (2017) Milling of titanium alloy with cryogenic cooling and minimum quantity lubrication (MQL). *Int J Prec Eng Manuf* 18(1):5–14
- Bordin A, Sartori S, Bruschi S, Ghiotti A (2017) Experimental investigation on the feasibility of dry and cryogenic machining as sustainable strategies when turning Ti-6Al-4V produced by additive manufacturing. *J Clean Prod* 142(4):4142–4151
- Shokrani A, Dhokia V, Newman ST (2016) Investigation of the effects of cryogenic machining on surface integrity in CNC end milling of Ti-6Al-4V titanium alloy. *J Manuf Process* 21:172–179
- Schoop J, Ambrosy F, Zanger F, Schulzec V, Balkb TJ, Jawahira IS (2016) Cryogenic machining of porous tungsten for enhanced surface integrity. *J Mater Process Technol* 229:614–621
- Manimaran G, Kumar MP, Venkatasamy R (2014) Influence of cryogenic cooling on surface grinding of stainless steel 316. *Cryogenics* 59(1):76–83
- Dinesh S, Senthilkumar V, Asokan P, Arulkirubakaran D (2015) Effect of cryogenic cooling on machinability and surface quality of bio-degradable ZK60 Mg alloy. *Mater Des* 87:1030–1036
- Khan A, Maity K (2017) Comparative study of some machinability aspects in turning of pure titanium with untreated and cryogenically treated carbide inserts. *J Manuf Process* 28:272–284
- Musfirah AH, Ghani JA, Che Haron HC (2017) Tool wear and surface integrity of inconel 718 in dry and cryogenic coolant at high cutting speed. *Wear* 376–377:125–133
- Schoop J, Sales WF, Jawahir IS (2017) High speed cryogenic finish machining of Ti-6Al-4V, with polycrystalline diamond tools. *J Mater Process Technol* 250:1–8
- Özbek NA, Çiçek A, Gülesin M, Özbek O (2016) Effect of cutting conditions on wear performance of cryogenically treated tungsten carbide inserts in dry turning of stainless steel. *Tribol Int* 94:223–233
- Birmingham MJ, Palanisamy S, Kent D, Dargusch MS (2012) A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti-6Al-4V cutting. *J Mater Process Technol* 212(4):752–765
- Zhu ZJ, Sun J, Li JF, Huang PL (2016) Investigation on the influence of tool wear upon chip morphology in end milling titanium alloy Ti6Al4V. *Int J Adv Manuf Technol* 83(9–12):1477–1485
- Sui SC, Feng PF (2016) Investigation of serrated chip morphology change regular in the turning of titanium alloys. *Int J Adv Manuf Technol* 87(9–12):2665–2671
- Zhao YH, Sun J, Li JF (2015) Study on chip morphology and milling characteristics of laser cladding layer. *Int J Adv Manuf Technol* 77(5–8):783–796
- Li AH, Zhao J, Zhou YH, Chen XX, Wang D (2012) Experimental investigation on chip morphologies in high-speed dry milling of titanium alloy Ti-6Al-4V. *Int J Adv Manuf Technol* 62(9–12):933–942
- Birmingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. *Int J Mach Tool Manu* 51(6):500–511
- Palanisamy S, McDonald SD, Dargusch MS (2009) Effects of coolant pressure on chip formation while turning Ti6Al4V alloy. *Int J Mach Tool Manu* 49(9):739–743
- Shivpuri R, Hua J, Mittal P, Srivastava AK, Lahoti GD (2002) Microstructure-mechanics interactions in modeling chip segmentation during titanium machining. *CIRP Ann-Manuf Technol* 51(1):71–74
- Aramcharoen A (2016) Influence of cryogenic cooling on tool wear and chip formation in turning of titanium alloy. *Procedia CIRP* 46:83–86