An experimental research on the machinability of a high temperature titanium alloy BTi-6431S in turning process

Yanfeng Gao^{1,*}, Yongbo Wu^{1,2}, Jianhua Xiao¹, and Dong Lu^{1,2}

¹ School of Aeronautic Manufacturing Engineering, Nanchang Hangkong University, Nanchang, Jiangxi 330063, PR China

² Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, PR China

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Abstract. Titanium alloys are extensively applied in the aircraft manufacturing due to their excellent mechanical and physical properties. At present, the $\alpha + \beta$ alloy Ti6Al4V is the most commonly used titanium alloy in the industry. However, the highest temperature that it can be used only up to 300 °C. BTi-6431S is one of the latest developed high temperature titanium alloys, which belongs to the near- α alloy group and has considerably high tensile strength at 650 °C. This paper investigates the machinability of BTi-6431S in the terms of cutting forces, chip formation and tool wear. The experiments are carried out in a range of cutting parameters and the results had been investigated and analyzed. The investigation shows that: (1) the specific cutting forces in the machining of BTi-6431S alloy are higher than in the machining of Ti6Al4V alloy; (2) the regular saw-tooth chips more easily formed and the shear bands are narrower in the machining of BTi-6431S; (3) SEM and EDS observations of the worn tools indicate that more cobalt elements diffuse into the workpiece from tool inserts during machining of BTi-6431S alloy, which significantly aggravates tool wear rate. The experimental results indicate that the machinability of BTi-6431S near alpha titanium alloy is significantly lower than Ti-6Al-4V alloy.

Keywords: High temperature titanium alloy / machinability / cutting forces / chip formation / tool wear

1 Introduction

Titanium alloys have been widely used in the manufacturing of aircraft fuselages and gas turbines due to their excellent mechanical and physical properties such as high strength-to-weight ratio and strong corrosion resistance [1]. It is reported that titanium alloys account for approximately 11% of the fuselage structure weight of the Boeing 777, and about 15% of the Boeing 787 [2]. Compare to commercial aircrafts, the using of titanium alloys is considerably higher in military fighter aircrafts. For example, in the fourth generation jet fighter F-22 the weight proportion of titanium alloys is about 41% [3]. Moreover, titanium alloys have a more widely range of application in the automotive, chemical and medical industries.

Based on the different crystal structures, titanium alloys are classified usually into three categories (α , $\alpha + \beta$, and β alloys). The most commonly used titanium alloy in the aircraft manufacturing process is Ti6Al4V, which belongs to the $\alpha + \beta$ alloy group and accounts for more than 50% of total titanium alloy production [4]. However, Ti6Al4V can be used only in the environment that the

temperature below 300 °C [5]. In order to endure the higher temperature for the gas turbine components application, new alloys are being developed. One of the latest developed alloys is the BTi-6431S, which belongs to the near- α alloy group and has minimum tensile strength values of above 645 at 650 °C [6]. This high thermal tensile strength makes BTi-6431S a promising material for gas turbine structures.

There are many publications studied the machinability of Ti6Al4V alloy and β group alloys such as Ti555.3 and Ti1023 [7–10]. These studies show that β group alloys are more difficult to machine than Ti6Al4V alloy due to their high strength and toughness. However, few literature studied the machinability of near- α group titanium alloys. In this paper, a study of the machinability of a kind of near- α titanium alloy BTi-6431S compared with the most common titanium alloy Ti6Al4V is carried out and present experimental data for tool wear in turning process.

2 Experimental setup

2.1 Material properties

BTi-6431S titanium alloy consists of α -stabilizers Al and neutral elements Sn and Zr, and some β -stabilizers Mo, Nb and W, as well as Si. This alloy has high strength and

* e-mail: gaoyf@nchu.edu.cn

Table 1. Chemical composition and mechanical properties of BTi-6431S and Ti6Al4V alloys.

Titanium alloy	Chemical composition %								Transus bate °C
	Al	Mo	V	Sn	Zr	Nb	W	Si	
Ti6Al4V	6	–	4	–	–	–	–	–	995
BTi-6431S	6.0–7.2	1.0–3.2	–	2.5–3.5	2.5–3.5	1.0–3.2	0.3–1.5	0.10.5	1010±20
<i>Titanium alloy</i>	<i>Density (kg/m³)</i>	<i>Young's Modulus</i> GPa	<i>Yield strength</i> MPa	<i>Tensile strength</i> 20 °C MPa		<i>Tensile strength</i> 400 °C Mpa			
Ti6Al4V	4430	110	900	1000		550			
BTi-6431S	4530	121	1160	1210		850

(a) Ti6Al4V

(b) BTi-6431S

Fig. 1. Microstructure of the two titanium alloys [11].

superior creep resistance at the temperature of 650–700 °C. The chemical composition and mechanical properties for BTi-6431S and Ti6Al4V alloy are shown in Table 1.

From Table 1 it is observed that the strengths of the BTi-6431S alloy are higher than Ti6Al4V alloy, especially in the high temperature environment. The optical microstructure of the two titanium alloys after etching with Kroll's reagent are shown in Figure 1. There are major quantities of the primary alpha phase both in the two titanium alloys, but the structure of alpha phase in BTi-6431S show the stripped shapes other than lamellar shapes in Ti6Al4V alloy, which makes BTi-6431S more compact than Ti6Al4V alloy.

2.2 Experimental parameters

The experimental setup is shown in Figure 2. A CKA6150 computerized numerical control (CNC) lathe was used to perform machining trials under dry conditions. To eliminate the errors of the diameter of the Ti alloy bars, the workpiece firstly was finish machined. A coated with TiAlN tungsten carbide insert (TPGH080204R-FS) supplied by Mitsubishi company was used in this study. The rake angle of the cutting tool insert is 0°, and relief angle is 11°. The insert has a chip breaker in each cutting edge to bend and break the chips produced during the process of turning. A Kistler9257B dynamometer was used to measure the feeding force, thrust force and the main cutting force.

Some experimental trials were performed in this study to compare the machinability of Ti6Al4V and BTi-6431S titanium alloys. These trials investigated the machining process over a wide range of cutting speeds from 45 m/min to 90 m/min with a constant feed rate of 0.2 mm/rev. The cutting parameters in experimental trials are given in Table 2.

3 Results

In order to compare the machinability of Ti6Al4V and BTi-6431S alloys the cutting force, chip morphology and tool wear were measured and analyzed in this study.

3.1 Cutting force

The specific cutting force is not influenced by the volume of the materials to be removed in one cutting path, so it is used to compare the forces in turning of Ti6Al4V and BTi-6431S alloys. The changes of the specific cutting force (F_c) and the specific feed force (F_d) with the cutting speed (v_c) are shown in Figure 3.

It is observed from Figure 3 that the specific cutting force (F_c) and the specific feed force (F_d) of near alpha BTi-6431S alloy are higher than Ti6Al4V alloy. With the increase of cutting speed, the specific cutting force and the feed force of the two titanium alloys decrease accordingly. However, the cutting force and feed force of Ti6Al4V alloy

Fig. 2. The experimental setup.

Table 2. The parameters in the cutting experiments.

Materials	Ti6Al4V, BTi-6431S
Cutting tool	TPGH080204R-FS (Mitsubishi)
Depth of cut (mm)	0.2
Feed rate (mm rev ⁻¹)	0.2
Cutting speed (m min ⁻¹)	45,60,75,90

(a) Specific cutting force versus cutting speed

(b) Specific feed force versus cutting speed

Fig. 3. Specific cutting forces and feed forces of BTi-6431S and Ti6Al4V alloy.

Fig. 4. The chips morphology of Ti6Al4V and BTi-6431S.

decrease more quickly. It is because with the increase of cutting speed the temperatures in the cutting area rise, which soften the material and reduce the flow stresses. Rahman had report [12] the same changing trends of cutting forces when cutting speed more than 50 m min⁻¹ during conventional turning of Ti1023 alloy. And because

BTi-6431S alloy has considerably high tensile strength at high temperatures, so the specific cutting force and feed force of it decrease slowly with the increase of cutting speed. The higher forces generated during the process of cutting BTi-6431S alloy show that this titanium alloy is more difficult to machine than Ti6Al4V alloy.

Fig. 5. Magnified images of the chips.

Fig. 6. The shear angle θ , chip compression ratio r_c and the serrated degree G_c under different cutting speed.

3.2 Chip morphology

3.2.1 The micro-morphology of chips

The cross sections of the chips for the two titanium alloys produced during different turning process are shown in Figure 4.

It is can be investigated from Figure 4 that the chips of Ti6Al4V and BTi-6431S alloys show different morphologies under different cutting speeds. The chip of Ti6Al4V alloy shows a nearly continuous shape at the cutting speed of 45 m min^{-1} . With the increase of cutting speed, the chip gradually displays a saw-tooth characteristic. However, the chips of BTi-6431S alloy show the typical saw-tooth appearances at different cutting speeds. With the increase of cutting speed the chips show more regular saw-tooth appearances. It is always believed that the thermoplastic instability, frequently referred to as adiabatic shear, was the main mechanism to produce the saw-tooth chips. The occurrence of the adiabatic shear is an unstable process and harmful to the machining process. In the continuous chips there are usually no adiabatic shearing bands exist, but in the saw-tooth chips the adiabatic shearing bands usually exist. To further observe the shear bands in the chips, the magnified images of these chips are shown in Figure 5.

From Figure 5 it is observed that the chip of Ti6Al4V alloy shows distinct adiabatic shearing bands only the cutting speed up to 90 m min^{-1} . On the contrary, the chips of the BTi-6431S alloy show the regular saw-tooth shapes and have narrow adiabatic shearing bands at every cutting speed. These adiabatic shearing bands produce significant fluctuations in the cutting forces and make the cutting process unstable. Therefore the forming of saw-tooth chips easily resulting in the chattering of machine tool and the quickly wear of cutting tool.

3.2.2 The geometry of chips

To further study the characteristics of the chip morphologies of the two titanium alloys at different cutting speeds, some geometrical parameters are measured and analyzed. As shown in Figure 5, d is the pitch of teeth; l is the width of the teeth in the chip free surface; h_t is the total height of the teeth; h_b is the root height of the teeth; θ is the angle of the shear band. Even in the same chip, if the positions of the chip cross section to be observed are different, some absolutely geometrical parameters such as d , l , h_t and h_b are different. However, some relative geometrical parameters are not changes with the positions of the chip cross section, such as the shear band angle θ , the chip compression ratio, and the serrated degree of the chips. These parameters represent the machinability of the two titanium alloys with the changing of the cutting conditions, so they are measured and analyzed through digital image processing method in this study, and the results were shown in Figure 6. To acquire a credible result, under each kind of turning parameters, 100 teeth were measured and the average values were taken as the final result.

Here, the chip compression ratio r_c and the serrated degree G_c of the chips are defined as:

$$r_c = \frac{d}{l}, \quad G_c = \frac{h_t - h_b}{h_t}. \quad (1)$$

It is observed from Figure 6 that the shear band angle θ decrease with the increasing of cutting speed for the two titanium alloys. The compression ratio r_c and the serrated degree G_c increase with the increasing of cutting speed. These parameters for BTi-6431S alloy always higher than those for Ti6Al4V alloy. This phenomenon manifest that

(a) BTi-6431S; $V_c=45\text{m/min}$; (b) Ti6Al4V; $V_c=45\text{m/min}$

Fig. 7. The average flank wears of cutting BTi-6431S and Ti6Al4V titanium alloys.

Fig. 8. The average flank wears with the volume of removed material ($v = 45\text{ m/min}$, $f = 0.2\text{ mm/r}$, $ap = 0.2\text{ mm}$).

the near alpha BTi-6431S alloy is more easily form saw-tooth shape chips, which would made it is harder than Ti6Al4V alloy to be machined.

3.3 Tool wear analysis

3.3.1 Flank wear

Flank wear occurs on the tool flank as a result of friction between the machined surface of the workpiece and the tool flank. The flank faces of cutting tool for the two titanium alloys with the cutting speed of 45 m/min are shown in Figure 7a. Figure 7 is flank wear of the tool for cutting BTi-6431S alloy after removed material volume of 7.94 cm^3 , and Figure 7b is flank wear of the tool for cutting Ti6Al4V alloy after removed material volume of 8.98 cm^3 .

ISO 3685 standard specifies that the end of tool life occurs once the average flank wear exceeds 0.2 mm or the maximum flanks wear exceeds 0.6 mm whichever occurs sooner [11]. It is observed from Figure 7 that with the same cutting speed the average flank wear exceed 0.2 mm of BTi-6431S alloy after remove material volume of 7.94 cm^3 , meanwhile the average flank wear is 0.13 mm of Ti6Al4V alloy under the same removed material volume. The average flank wear with the increasing of removed material volume is shown in Figure 8.

It is observed from Figure 8 that the average flank wear VB_{avg} increases quickly with the material volume to be removed in the turning of BTi-6431S alloy. Compare to BTi-6431S alloy, the flank wear VB_{avg} is significantly lower and increases slowly with the increase of the material volume to be removed in the cutting of Ti6Al4V alloy. With these cutting parameters, during the turning of Ti6Al4V, a new cutting tool can remove about 17.8 cm^3 material. However, during the turning of BTi-6431S, a new cutting tool can only remove 5.3 cm^3 material.

3.3.2 The cutting edge analysis

Figures 9 and 10 show the SEM images of the worn tool edge of the two inserts used during the machining of BTi-6431S and Ti6Al4V at 75 m/min and the volume of removed material of 10.56 cm^3 and 22.17 cm^3 , respectively. EDS analysis was also carried out in order to investigate the adhesion and diffusion of the composition in the cutting tool and the workpiece material.

It is observed from Figures 9 and 10 that a big amount of adhered material exists on the each insert along the cutting edge. In the area of spectrum 1 in Figure 9, the elements of Ti, Al, C, and Sn are observed and the weight proportion of Ti is about 84%. These elements are the composition of the workpiece material BTi-6431S alloy, which means a serious adhesion occurring in this area. Similarly, a large amount of Ti6Al4V alloy material adheres in the area of spectrum 4 in Figure 10. For the areas of spectrum 2 and spectrum 5, an obviously feature is the significantly W element has been observed. The element of W is the main composition in the substrate of the cutting insert. Because the used cutting insert with a TiAlN coat, theoretically the elements of the coating should be observed and account for a very large proportion in these areas. However, a few of the elements of Ti, Al and N are observed in these areas, which show that there is a serious wear taking place. The elements that compose the coating layer Ti, Al and N are observed in the areas of spectrum 3 and spectrum 6. In these areas, no serious tool wear has taken place.

Comparing Figures 9 and 10, it is obviously observed that more titanium alloys adhere to the insert edges when cutting Ti6Al4V alloy. Hartung and Kramer [12] have

Fig. 9. SEM image and EDS analysis of worn tool edge for cutting BTi-6431S.

Fig. 10. SEM image and EDS analysis of worn tool edge for cutting Ti6Al4V.

found the presence of a built-up edge during machining of Ti6Al4V and suggested that the built-up layer considerably reduces the tool wear rate and limits the diffusion rate of the tool constituents. So it is maybe another reason to explain the more rapid tool worn in cutting of BTi-6431S alloy. The wear area in spectrum 2 is larger than the wear area in spectrum 5 when cutting Ti6Al4V alloy. Moreover, in these areas, the weight proportions of Co elements are

1.68% and 7.54% in cutting of BTi-6431S and Ti6Al4V alloys, respectively. Therefore, more Co elements diffuse into the workpiece from tool inserts during cutting of BTi-6431S titanium alloy. Generally, cobalt is a kind of binder in the tungsten carbide insert. The cobalt diffusion leads to the pulling out and removing of WC particles, which deleterious to the hardness and wear resistance of cutting tool.

4 Conclusions

- During turning process, the specific cutting forces and feed forces are significantly higher for cutting of near alpha BTi-6431S alloy. At the cutting speed of 45 m min^{-1} , the specific cutting force for BTi-6431S average increases about 18%, and the specific feed force increases about 6.4% compared to the cutting of Ti6Al4V alloy;
- for the Ti6Al4V alloy the regular saw-tooth chips only formed when the cutting speed increases to 90 m min^{-1} . On the contrary, the chips from the BTi-6431S have regular saw-tooth shape and narrow adiabatic shearing bands at every cutting speed from 45 m min^{-1} to 90 m min^{-1} ;
- the flank wear of inserts for cutting BTi-6431S alloy is more rapid than for the cutting of Ti6Al4V at the same cutting speed. SEM and EDS observations of the worn tools indicate that the adhesion of titanium material on the cutting insert edge and the diffusion of the tool constituents are the main mechanism to cause serious tool wear. For cutting Ti6Al4V alloy, more titanium material was adhered onto the insert edge, which is beneficial to reduce the tool wear speed. For cutting BTi-6431S near alpha titanium alloy, more Co elements diffuse into the workpiece from tool inserts which significantly aggravates tool wear rate.

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