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Effect of β phase fraction in titanium alloys on chip segmentation in their orthogonal machining

Shashikant Joshi, Pravin Pawar, Asim Tewari, Suhas S. Joshi *

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

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ABSTRACT

β phase fraction in titanium alloys changes their shear band forming tendency, which in turn influences chip segmentation during machining. To investigate this aspect further, orthogonal turning experiments to obtain chip roots were performed on three titanium alloys, with increasing β phase fraction, viz. α, $\alpha + \beta$ and β rich alloys. Besides microstructure of chip roots, three segment deformation parameters, viz. shear plane length, segment strain and included angle were used as responses. An increase in β phase fraction increases fracture part in a segment formation. Consequently, chip segment formation shows thermal softening leading to shear band formation in α alloys, whereas occurrence of fracture over longer length in the $\alpha + \beta$ and β rich alloys. A higher β phase fraction increases shear plane length, segment strain but decreases the segment included angle. Finally, chip segmentation frequency has been correlated to the frequency of variation in cutting forces.

Introduction

Titanium and its alloys are widely used in aerospace, chemical, marine, and surgical applications because of high strength-to-weight ratio which is maintained at elevated temperatures, good corrosion resistance and inertness to human body. However, titanium alloys are 'difficult-to-machine' due to their poor thermal conductivity, reactivity with tool materials, low modulus of elasticity and their ability to maintain strength at high temperatures. These properties of titanium alloys cause several kinds of damages on machined surfaces and cutting tools. Thus, it is not only difficult to attain good surface quality and integrity, but also the cost of machining and subsequent salvage of components increases. Therefore, intensive research has been undertaken all over the world to improve their machinability and consequently to reduce the cost of their machining.

Depending upon the β phase fraction at room temperature, titanium alloys are broadly classified as α, $\alpha + \beta$ and β alloys. α alloy has the smallest fraction of β phase and β alloy has the largest β phase fraction. The composition of α- and β-phases in titanium alloys, change their mechanical and microstructural properties. α titanium alloys have excellent resistance to high temperature due to presence of a single phase. $\alpha + \beta$ titanium alloys are heat treatable due to the presence of two phases and have excellent combination of strength and ductility. β rich alloys have higher heat treatability, deep hardening potential, fatigue resistance, and ductility due to higher contents of β phase. However, the response of these materials to the machining operations in terms of their tendency to form shear bands and mechanisms of segment formation are very different. In this paper, an influence of β phase fraction on the machinability of titanium alloy is considered for the study.

Extensive research has been carried out to study the influence of processing parameters on the mechanism of chip segment formation during machining of $\alpha + \beta$ titanium alloys (Ti6Al4V). Zhen-Bin and Komanduri [1] observed the mechanism of segment formation by catastrophic thermoplastic shear. The catastrophic thermoplastic instability causes a decrease in the flow stresses due to thermal softening in a narrow zone called shear band, leading to the formation of segmented chips. On the other hand, the formation of saw tooth chips even at extremely low cutting speeds, and visualization of cracks at the free surface of the chips provide a strong evidence of periodic fracture as being the root cause of segmented chips formation. Therefore, Vyas and Shaw (1999) attributed the formation of chip segments to periodic cracks. Bayoumi and Xie [2] considered a combined effect of cutting speed and feed rate to evaluate quantity of heat required to form the segmented chips. The heat generated with a critical cutting load of 0.004 m^2/min (cutting speed × feed = 0.004) was considered sufficient to form segmented chips during machining.

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* Corresponding author. Tel.: +91 22 25767527; fax: +91 22 2672 6875.
E-mail address: ssjoshi@iitb.ac.in (S.S. Joshi).

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Also, they found that at higher cutting speeds, chip segmentation frequency decreases. However, at higher feed rate, chip segmentation frequency increases. Armendia et al. [3] compared chip morphology of Ti6Al4V and TIMETAL, which have similar mechanical properties but different microstructures. They observed that higher cutting speed and feed rate increases spacing between chip segments, in the case of both titanium alloys. Also, they measured segment angle on the chip segment, which is the shear angle passing through the shear zone. This is measured on the chip segment and found to decrease from 60° to 45°, with an increase in the cutting speed from 1200 to 4800 m/min. Gentel et al. [4] observed that at very high cutting speeds above 4800 m/min, the segments become triangular in shape and are formed by propagation of crack along the chip thickness. Also, they observed a transition in the chip morphology from serrated to discontinuous at a higher cutting speeds of 4400 m/min. Sutter and List [5] observed a change in the chip segment formation mechanism, from thermal softening to fracturing along shear plane at cutting speeds above 2700 m/min. In another study, Sun et al. [6] correlated chip segmentation frequency to the fluctuations in cutting forces during machining. The chip segmentation frequency matched well with the frequency of variation in the cutting forces during machining operation. In addition, they attributed an increase in the cutting forces at a lower cutting speed of 600 m/min to work hardening of the material. On the other hand, a decrease in the cutting forces above 600 m/min was attributed to thermal softening caused by high work-tool interface temperature.

All the above studies show that the influence of processing parameters on the chip morphology of Ti6Al4V has been well studied. However, there is very little knowledge of the influence of β phase fraction of titanium alloys, on the mechanism of chip segment formation during machining. β phase fraction changes the frequency of segmentation which introduces vibrations in tool-work system during machining. This paper therefore focuses on the influence of β phase fraction in titanium alloys on their mechanism of chip segment formation and the corresponding variation in the frequency of chip segmentation.

Accordingly, orthogonal turning experiments were performed using a chip freezing device. SEM analysis of chips and chip roots was carried out to understand the mechanism of chip segment formation during machining of the three titanium alloys with different microstructures. The details of this work are presented in the following sections.

Experimental details

Theme of the experiment

The theme of the experiments involved understanding the influence of β phase fraction on machinability of the three titanium alloys viz. α, $\alpha + \beta$,$\beta rich(\alpha + \beta)$. β phase fraction in the alloys depends upon the % of β stabilizing element like W, V, Mo. With an increase in the percentage β stabilizing alloying elements, the proportion of β phase in the titanium alloy at room temperature increases. On the other hand, with an increase in the α stabilizing element like Al, Sn, O, etc., the proportion of α phase at room temperature increases. Theβ phase has BCC crystal structure and has more number of slip systems available for deformation. On the other hand, α phase has HCP crystal structure and has less number of slip systems available for deformation. Therefore, β phase is ductile and easier to process thermo mechanically than α phase. To study the influence of β phase fraction, three titanium alloys with increasing β phase fraction, viz. α, $\alpha + \beta$, and β rich ($\alpha + \beta$) alloy were considered for the study. Fig. 1 shows the phase diagram of titanium alloys considered for this analysis.

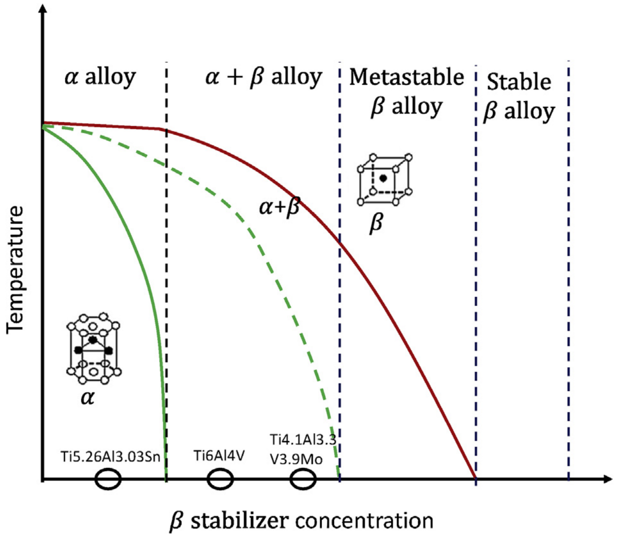

Fig. 1. β isomorphous phase diagram showing approximate position of analyzed titanium alloys.

The scheme of experiment is presented in Fig. 2. The experimentation involved performing orthogonal turning on all the three alloys and obtaining partially deformed chip roots using a quick-stop device. Another part of the experiments involved measurement of cutting forces using dynamometers. The experiments were performed by changing cutting speeds and the parameters such as chip segment forming mechanism, segment deformation, frequency of chip segmentation and cutting forces. These have been used to analyze machinability of the three titanium alloys. The influence of β phase fraction on the machinability of the three titanium alloys was mainly evaluated. This analysis was also used to determine the processing parameters that help improve the machinability of the three titanium alloys.

Experimental specifications

The experimental specifications which include detailed specifications of workpiece materials, machine tool, processing parameters, dynamometer, thermal camera and cutting tool are presented in Fig. 3a. Fig. 3b shows a schematic of the quick-stop or chip freezing device used for the experiments.

Table 1 gives the mechanical properties of the three titanium alloys. Hardness of the three titanium alloys was determined by nano-indentation. It may be noted that the strength of β rich alloy is the highest and that of the α alloy is the lowest.

Microstructure of the three alloys is as shown in Fig. 4a–c. The microstructure consists primarily of α and β grains; white grains being α-phase, which are surrounded by black β-phase. Both α and $\alpha + \beta$ alloys have coarse equi-axed grain microstructure, see Fig. 4a and b. On the other hand, the microstructure of β rich alloy is lamellar with very fine grains formation, see Fig. 4c. Online measurement of temperature was carried out using thermal camera, model Therma CAM P640. At the same time, online cutting forces were measured using Kistler dynamometer (Model 9257).

Experimental set up and procedure

All the machining experiments were conducted at room temperature without any external lubrication or coolant (in dry condition). Some of the orthogonal turning experiments were performed using a quick-stop or chip freezing device. The device stops cutting action instantaneously leaving a chip segment