Abstract

Microstructure of titanium alloys has great influence on the manufacturing processes. In the current investigation the effect of change in volume fraction of alpha and transformed beta phase in the bimodal titanium alloy Ti6Al4V was discussed in relation with the mechanical and machining performance. The quenching process in STA (solution treatment and annealing) heat treatment was delayed by 30, 50 and 70 sec to get different microstructural morphology in each heat treated specimen. Face turning experiments with dry and high pressure coolant environment were performed on the solution treated samples. A detailed chip mechanism and microstructural analysis was performed to investigate the role of quench delay and subsequent change in phase volume fraction on thermal softening and frictional phenomenon in machining. The specimen treated with quench delay of 50 sec exhibited poor machinability because of thermal and frictional shock generated at the cutting zone.

1. Introduction

Titanium alloys such as Ti6Al4V are extensively used in the aerospace industry for structural as well as engine components such as fan blades, disks, shafts, etc. due to their superior properties such as excellent strength-to-weight ratio, strong corrosion resistance and ability to retain high strength at elevated temperatures. However, titanium still possesses some undesirable properties in particular, low thermal conductivity, high strength, high hardness, high chemical reactivity, etc. which results into more friction and cutting heat leading to poor machinability[1-5]. Titanium alloy Ti6Al4V is the most popular alloy among the titanium alloys; it contains alpha and beta phases in the percentage volume fraction with reference to the heat treatment followed. This volume fraction further determines the deformation behavior and mechanical properties of this alloy under both quasi-static and dynamic loading conditions [2]. Both α and β phases are relatively soft but α – β interface is an effective stoppage to dislocation and crack propagation [2, 4]. It has been reported by various researchers that the machinability of titanium alloys is strongly affected by the heat...
treatment process and subsequent microstructure produced [2, 5-7, 9]. A detailed research was found on mechanical and machining aspects of globular, bimodal and fully-lamellar microstructures of titanium alloy Ti6Al4V [6-7]. Titanium alloys with coarse grain microstructure such as beta annealed input condition leads to high shear stresses and correspondingly higher cutting forces and are more difficult to cut than the finer grain structure [2, 5]. It was also reported that main cutting force during machining of titanium alloy Ti6Al4V with globular phase morphology is lower than that of bi-modal and fully lamellar phase morphologies at cutting speed lower than 100m/min [2, 5-7]. The Widmanstätten microstructure showed more inhomogeneous deformation with presence of large lamellae even at the lowest feed rate [2, 9]. However, the effect of change in volume fraction of alpha and beta phase of heat treated titanium alloy Ti6Al4V on the machinability aspect has not been investigated. Therefore, the objective of current research is to investigate the effect of change in phase fraction on mechanical and machining behavior for titanium alloy Ti6Al4V. For this purpose, samples of Ti6Al4V were subjected to solution treatment and annealing (STA) process with introducing various quench delays. These quench delays used resembles the actual transfer time used in aerospace industries to transfer the heated parts from heating furnace to quench tank. The machinability aspect was investigated using face turning experiments in terms of frictional and thermal softening phenomenon using detailed parameters of chip mechanism and chip microstructure.

<table>
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<th>Nomenclature</th>
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<td>QD</td>
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2. Experimental details

2.1. Heat treatment

The raw input for titanium alloy Ti6Al4V with chemical composition as per AMS 4928 was procured in the form of round specimen (Ø70 mm) in annealed condition. The beta transition temperature for the material was assumed to be 995°C. As shown in Fig.1, the as-received micro sample (transverse direction) shows equiaxed grains of α-phase with β-phase. The β-phase settles along the grain boundaries of equiaxed α-phase. Annealing relieves residual stresses in the material and influence grain recrystallization and growth [4].

As shown in Fig.2, the samples were solution treated at 967°C and hold for 1 hour. A Batch of three samples each subjected to water quenching with quench delays of 30, 50 and 70 sec respectively. These samples were further annealed at 730 °C for 2 hours and then cooled in air. A box type laboratory scale muffle furnace of make Therelek
was used for the heat treatment process. The uniformity achieved inside the furnace was +/- 3 °C. It was a temperature
temperature controlled furnace heated by electric coils and could achieve a maximum of 1200 °C and having facility of varying
the heating rate up to max. 12 °C/min. A small sample was sliced from each heat treated specimen for optical analysis.
The sample was initially hot mounted using Citopress-10 mounting device with Poly-Fast resin. The mounted sample
was polished using an automatic polishing device Tegramin-30. The mounted and polished sample was etched using
Kroll’s reagent for the period of 10 seconds. The etched sample was analyzed using optical microscope of make Zeiss
with Axio-Imager Z.2m. The micrographs were further analyzed for phase distributions using the software Axio-
Vision. Vickers hardness tests were performed using Clemex make microhardness tester on the heat treated samples
using 500 g load. Tensile tests were performed at constant crosshead speed with an initial strain rate of 0.005 min-1.
Fig. 3 a-c shows the optical micrographs of quench delayed samples and Fig. 4d-f shows corresponding investigation
of volume fraction of alpha and transformed beta phase. From microstructures shown below, it is seen that quench
delays provides remarkable effect on the phase composition in titanium alloy Ti6Al4V.

As shown in Fig. 3, solution treatment and annealing (STA) heat treatment resulted into bimodal distribution of
interconnected equiaxed primary α grains (bright) and lamellar α+ β colonies (transformed β) (dark) [2,4-5]. A careful
investigation of volume fraction of phases was carried out from these micrographs by using an image analyzer tool
and the results are shown in Fig. 4 and Table I. An increase in quench delay from 30 sec to 70 sec, resulted into higher
volume fraction of primary alpha (red) and reduced percentage of transformed beta (green).

![Fig. 3 Optical micrographs of heat treated (solution treated and annealed) titanium alloy Ti6Al4V with quench delay of (a) 30 sec (b) 50 sec (c) 70 sec (100 X)](image)

![Fig. 4 Phase mapping of solution treated and annealed titanium alloy Ti6Al4V with quench delay of (d) 30 sec (e) 50 sec (f) 70 sec (100X).](image)

<table>
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<tr>
<th>Quench delay (sec)</th>
<th>Primary α (%)</th>
<th>Transformed β (%)</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>Hardness (HRc)</th>
</tr>
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<tr>
<td>30</td>
<td>30</td>
<td>70</td>
<td>1073</td>
<td>1034</td>
<td>37.2</td>
</tr>
<tr>
<td>50</td>
<td>49</td>
<td>51</td>
<td>1006</td>
<td>998</td>
<td>35.6</td>
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<td>70</td>
<td>67</td>
<td>33</td>
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<td>950</td>
<td>32.5</td>
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The effect of increase in volume fraction of alpha on the mechanical properties was clearly visible as shown in Table 1 where a gradual diminution in strength and hardness was recorded with the increase in quench delay from 30 sec to 70 sec. Direct quenching in water from 967 °C resulted into formation of a martensitic structure. This martensite structure is of hexagonal α' type with acicular morphology in different orientations. The α'-martensite further transforms during tempering heat treatment and decomposes to equilibrium α and β. This transformation to α is in the form of fine precipitate that is nucleated heterogeneously at martensite plate boundaries or at internal structures such as twins [4]. An increase in the quench delay before quenching offered an extra time to precipitate equilibrium α instead of α'-martensite which further resulted into percentage increase for alpha phase and percentage decrease for transformed beta phase in the bimodal microstructure of titanium alloy Ti6Al4V.

2.2. Machining

Titanium alloy Ti6Al4V quench delayed samples of 30 sec, 50 sec and 70 sec were used as an input for face turning operation performed using DMG Turn Mill center – CTX beta 1250 TC as shown in Figure 5. All the turning experiments were performed at room temperature using dry cooling environment as well as using high pressure coolant of 50 bar. Total 6 sets of experiments were performed with first 3 nos. of experiments QD 30-DRY, QD 50-DRY and QD 70-DRY using dry cutting environment followed with remaining 3 nos. of experiments QD 30-HP coolant, QD 50-HP coolant and QD 70-HP coolant with high pressure coolant application. A constant cutting speed of 90 min/min, feed rate of 0.3 mm/rev and depth of cut of 1 mm was used for all the experimentations.

Face turning operation was performed using carbide insert CNMG 120408-NFT WSM20- Walter make. As shown in Fig. 6, for high pressure coolant assisted experiments, a constant coolant pressure of 50 bar was directed at the chip tool interface near the rake face of the tool. Cutting chips collected after each cutting trial were polished and etched for detailed optical and scanning electron microscopy to reveal the chip mechanism and chip microstructure during machining.

3. Results and Discussion

3.1. Effect on chip thickness and shear angle

In this quantitative analysis of chip mechanism, as shown in Fig.7a-c, chip thickness, shear angle, shear band spacing, shear strain in shear band, shear displacement in shear band, etc. were discussed and their significance was correlated with the machinability of different alpha and beta phase volume fraction in titanium alloy Ti6Al4V. The generation of thicker, uneven chips is not favorable for high quality machining as these chips affects the tool cutting area, resulting in non-uniform friction and generating high cutting temperature, high cutting forces and rapid tool wear, etc. [10-11]. Higher shear angle represents less deformation along the shear plane which contributes to less cutting forces. More amount of shear deformation along the shear plane resulting from normal stresses will represent
more crack formation at the shear zone. An increased spacing between shear bands will represent less amount of cutting temperature and subsequently less shear band formation. The value of shear strain in the shear band is essential to understand the extent of shear localization [9-11].

As shown in Fig. 8, the effect of change in quench delay and the subsequent phase composition was clearly seen on the chip thickness. The impact of change in phase composition was more critical during dry machining. The adhesion of titanium may have resulted to an increased friction between chip and the tool rake face which ultimately produced thicker chip [3]. With the use of high pressure coolant machining approach, the adhesion and subsequent formation of BUE on the tool surface was reduced. This was mainly because of reduction in contact time between tool and chip [3]. However, with both the machining approach an increase in quench delay from QD 30 to QD 70 resulted in higher chip thickness. In particular, compared to quench delayed samples with QD 30 and QD 70, the specimen with QD 50 showed highest chip thickness. This shows that as explained in Table 1, phase composition of 51% transformed beta and 49% primary alpha has resulted into more amount of friction at the interface. This may be because of the frictional shock created during machining of ductile primary alpha phase with the higher strength transformed beta phase.

The shear plane angle increases with reduction in friction at the tool-chip interface [2]. As shown in Fig. 9 and Fig. 10a-b, with the increase in alpha percentage against the transformed beta in the bimodal microstructure of titanium alloy Ti6Al4V, the shear angle was found to be drastically reduced for QD 50 with alpha 49% and transformed beta 51%. This shows that during machining of QD 50, the cutting tool may have experienced alternate work hardening and thermal softening characteristics of alpha and transformed beta counteracting on each other resulting to BUE and excessive grain deformations which further contributed to an increased cutting force. However, with the use of high pressure coolant machining approach the intensity of frictional cutting was relived to some extent, this may be because of adequate lubrication provided at the cutting interface.
3.2. Effect on shear deformation

As shown in Fig. 11, Fig. 12, Fig. 13, and Fig. 14a-f, alternate dual phases with high strength of transformed beta and ductile primary alpha affects the shear deformation process in machining. As explained in Fig. 11 and Fig. 12, for QD 50 with the lesser amount of difference between volume fraction of transformed beta and primary alpha, none of the phase acts as a dominant phase fraction in titanium alloy Ti6Al4V. During machining process this will promote excess friction and thermal softening behavior resulting to an increased shear band formation with great amount strain in the shear band but reduced crack formations at the shear plane. The shear strain in the shear band was measured by [11]:

\[ Y = \text{shear displacement} / \text{shear band width} \]
As shown in Fig. 13 and Fig. 14b-d-f, during dry machining, an increase in the primary alpha content reduces the crack formations at shear zone of the chip. As shown in Fig. 14d, for QD 50 - DRY, the absence of crack formations shows that the higher amount friction between tool and chip resulted to an excessive plastic deformation. This can be revealed from the gradual increase in shear strain measured in shear band for QD 50 – DRY. However, this excess shear strain measured at the shear band has not contributed to crack formations but delayed cracking [5]. The formation of very thin and multiple or twins shear bands for the chips of QD 50-DRY can also explain the thermal softening phenomenon during dry machining [5, 10-11]. However, as shown in Fig. 14 a-c-e, high pressure coolant machining has resulted in increased crack formations along the shear plane.

![Fig. 13 Crack formations at the shear plane](image)

![Fig. 14(a-f) Shear deformation during Dry and HP coolant machining](image)

**Conclusions**

The current investigation showed that the wrong industrial practices of delayed quenching because of the transfer time associated with furnace and quench tank makes significant effect on the volume fraction alpha and beta percentage during solution treatment and annealing of titanium alloy Ti6Al4V. An increase in the quench delay promotes the precipitation of alpha rather than the formation of α’ martensite. After annealing process, this will contribute to more amount of alpha phase than that of transformed beta. The increase in alpha content with an increase in quench delay from 30 sec to 70 sec leads to reduction in mechanical strength and hardness of solution treated
titanium alloy Ti6Al4V. During machining process, this effect of change in volume fraction was clearly visible on the chip mechanism and microstructural aspect. For QD 50 - DRY, reduction in difference between the volume percentage of alpha and beta phases resulted to an alternate hard and soft cutting which generated thermal and frictional shock at the cutting face leading to higher chip thickness, less shear angle, less crack formation, increased shear band formations, etc. to impair the machinability. Use of high pressure coolant generates adequate lubrication at the cutting interface to reduce the overall effect of phase change on machinability of titanium alloy Ti6Al4V.

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References