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ULTRAFINE GRAINED (UFG) AND NANOCRYSTALLINESTRUCTURE IN Ti-6Al-4V THROUGH MACHINING

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Abstract

Titanium alloys are well known for their high strength and corrosion resistance that makes them useful in wide variety of applications. They are also well known as difficult to machine materials. A finer grain size increases the strength of the material and provides the potential for superplastic deformation at moderate temperatures and high strain rates. One of the recently established approaches for grain refinement in metals and alloys is through severe plastic deformation. In the present work, an effort has been made to study the grain refinement during orthogonal machining of commercial Ti-6Al-4V alloy by varying the machining parameters. Grain refinement in to nanometre regime was observed under certain conditions of machining.

***Keywords**: Ti-6Al-4V alloy, Ultrafine Grain (UFG) Structure, Orthogonal Machining, Rake angle*

1. Introduction

Titanium alloys are well known as difficult-to-machine material. The deformation mechanisms of these alloys are very complex and completely different to that of conventional metals. Ti-6Al-4V is the workhorse of the titanium industry. It is a two phase (α+β) titanium alloy, with aluminium as the alpha stabilizer and vanadium as the beta stabilizer. Moreover, it has high potential for further strengthening by tailoring the microstructure and grain refinement. Severe plastic deformation (SPD) is one of the recent method for obtaining grain refinement, wherein, the metals and alloys are deformed to very high plastic strains to confer significant benefits to the material, including microstructural refinement and enhanced mechanical and physical properties (Lowe &Valiev,

2004), (Valiev et al., 2000). Some of the popular severe plastic deformation (SPD) processes are equal channel angular pressing (ECAP), accumulative roll bonding (ARB), high pressure torsion (HPT), repetitive corrugation etc. However, all of these processes require multiple passes so as to impose large plastic strains by the cumulative application of deformation(Shankar et al., 2005). Further, all these processes are limited to smaller strain rates and as such, have uncertain deformation parameters. This makes the processing of moderate-to-high strength alloys such as titanium alloys quite tedious(Shankar et al., 2005). Orthogonal machining under plane strain condition is an attractive route for creating very large plastic strains in a single stage of deformation, which can simultaneously overcome the limitations of the SPD (Swaminathan et al., 2005).

In plane strain (2-D) machining, the tool cutting edge is perpendicular to the cutting velocity and the width of cut is large compared to the undeformed chip thickness. Chip formation occurs by concentrated shear in a small, distinct deformation zone, known as shear plane. As the tool is forced into the material, the chip is formed by shear deformation along shear plane oriented at an angle φ (shear angle) with the surface of the workpiece. During cutting, the cutting edge of the tool is positioned at a certain distance below the original work surface. This corresponds to the chip thickness prior to chip formation, t_o. As the chip is formed along the shear plane, its thickness increases to t_c. The ratio of t_o/t_c, called chip thickness ratio t_c, is always less than 1 and the shear strain depends exclusively on the shear angle (φ) and the tool rake angle(α). A schematic representation of plane strain machining is shown in Figure 1.

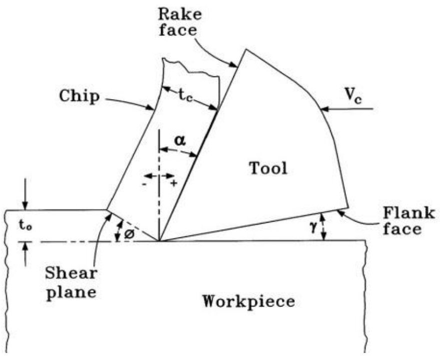

Figure 1. Schematic representation of plane strain machining

From the measured deformed chip thickness (t_c) and undeformed chip thickness (t_o) and the shear plane angle (φ), the shear strain values (γ) imposed in the chip can be estimated:

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$$\tan\varphi = \frac{\frac{ao}{ac}Cos\ \alpha}{1-\frac{ao}{ac}Sin\ \alpha} \quad (1)$$

Shear strain, $\gamma = \frac{Cos\ \alpha}{Sin\ \varphi\ Cos\ (\varphi-\alpha)}$ (2)

In the present work, large strain deformation machining of Ti-6Al-4V is studied in detail, employing various machining parameters to get optimum grain refinement.

2. Experimental

Machining Chips were produced by plane strain machining of Ti-6Al-4V by conducting experiments under controlled plain strain conditions with a range of rake angles and machining speeds. The depth of cut was kept significantly smaller than the workpiece width to realize a plane strain condition in the primary deformation zone. Feed rate was kept at 0.0046mm/rev, while the rake angle was varied from -14° to -60° and the depth of cut was kept constant at 10 µm. The machining velocity was kept at extremely low value to avoid the influence of temperature.

Microhardness measurements of the machining chips were done after mounting the specimen in a polymer mount and polishing with 2µmDiamond paste, using a Shimadzu Microhardness tester. A force of 490.3 mNand a dwell time of 15 minutes were used for measuring the hardness values. A minimum of 10 measurements was performed to obtain an average value and the standard deviation. The standard deviation was found to be less than 5% for all samples. A typical mounted chip and microhardness indentation on the chip specimen is shown in Figure 2.

The microstructure of the specimen was studied by mounting the specimen in a polymer resin. The mounted samples were initially ground with silicon carbide papers of 400, 800 and 1200 grit, and finally polished using 2µm and 1µm diamond paste on a polishing disk to get mirror finish. The samples were etched with a mixture of 2mL HF, 5mL HNO_3, and 93mL H_2O. The microstructures of the original bulk specimen was observed using Scanning Electron Microscope (SEM). The microstructure of the machining chips were studied using optical microscopy, field emission scanning electron microscopy (FESEM) and atomic force microscopy (AFM).

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3. Results and Discussion

The chemical composition of the material is presented in Table 1.
Using Equation (1) and (2) the minimum shear strain imposed on the machining chips for various rake angles under consideration were calculated. The variation of minimum shear strain with rake angle is presented in Table 2.

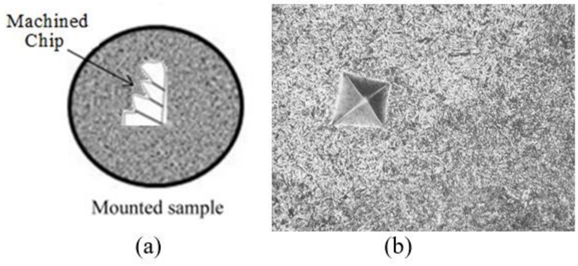

Figure 2. Typical (a) mounted chip and (b) microhardness indentation on the chip specimen

Table 1. Chemical Composition of Ti-6Al-4V

Element	Ti	Al	V	Fe	C	H	O	N
Wt%	Balance	5.96	3.69	0.13	0.08	0.02	0.08	0.05

Table 2. Variation of Minimum shear strain with rake angle

Rake Angle (deg)	Min. Shear Strain
-14	2.58
-35	3.84
-45	4.83
-60	7.46

Table 3. Variation of Microhardness with rake angle

Rake Angle (deg)	Microhardness (HV)
-14	301
-35	358
-45	386
-60	432

The average bulk hardness of Ti-6Al-4V was found to be ~301 HV while the chip hardness was found to increase substantially with decrease in rake angle. The variation of microhardness with rake angle is presented in Table 3. The formation of submicronic and nanocrystalline structure in the machining chip of Ti-6Al-4V alloy appears to significantly enhance (by 1.5 times) the microhardness of that in the as-received state. Since hardness of a materials is a measure of the ease in with which plastic strain can occur, restricting the mobility of dislocations translates to a harder and more resistant material, which requires higher mechanical forces to initiate plastic strain. During severe plastic deformation, a network of dislocations is generated through dislocation pile-ups that ensues the condensing of the dislocation structure into very fine, lower dislocation density crystallites or in other words, ultrafine or nano-crystalline materials. Since yield strength of a material is inversely proportional to the square root of grain size, a significant strengthening occurs in nanostructured materials obtained through SPD.

The microstructure of the bulk specimen is presented in Figure 3. The bulk specimen exhibited a bimodal microstructure, typical of (α+β) Titanium alloy, consisting of primary α-grains and fine lamellar α colonies within relatively small β-grains. The average grain size was found to be around 10-20μm.The primary α-phase is mainly featured by its equiaxial structure. The optical micrograph of a single chip specimen is presented in Figure 4(a) and the SEM micrograph of the chips embedded in the polymer mount is presented in Figure 4(b). The SEM and FESEM micrographs of the chips obtained for various conditions are shown in Figure 5 (a-d).

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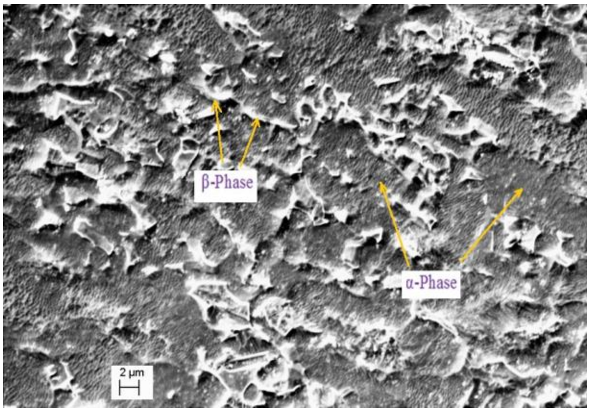
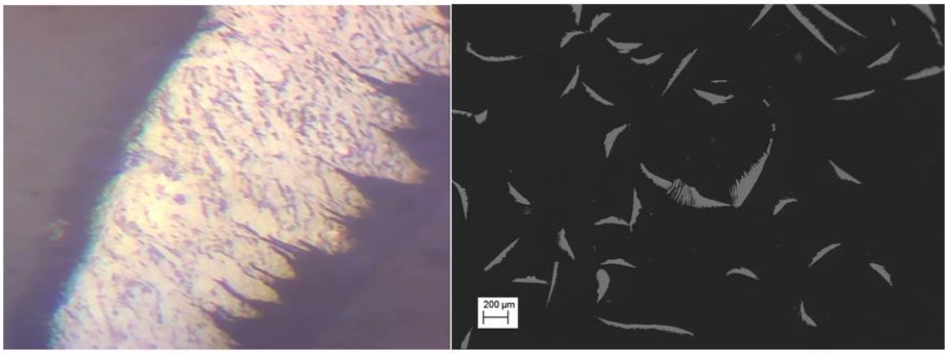


Figure 3.SEM micrograph of the bulk specimen

The micrographs demonstrates that as we move from the bulk specimen to the machining chips the grain size gradually decreases from microns to nanometer regime(Zhou et al., 2016). The bulk specimen exhibits an average grain size of 20microns while the machined chips with rake angle of -60 has grains in the range of 20-90nm. We can say that imposition of large shear strains entails progressive refinement of the microstructure.



(a) (b)

Figure 4. (a) Optical micrograph of a single chip specimen (b) SEM micrograph of the mounted chips

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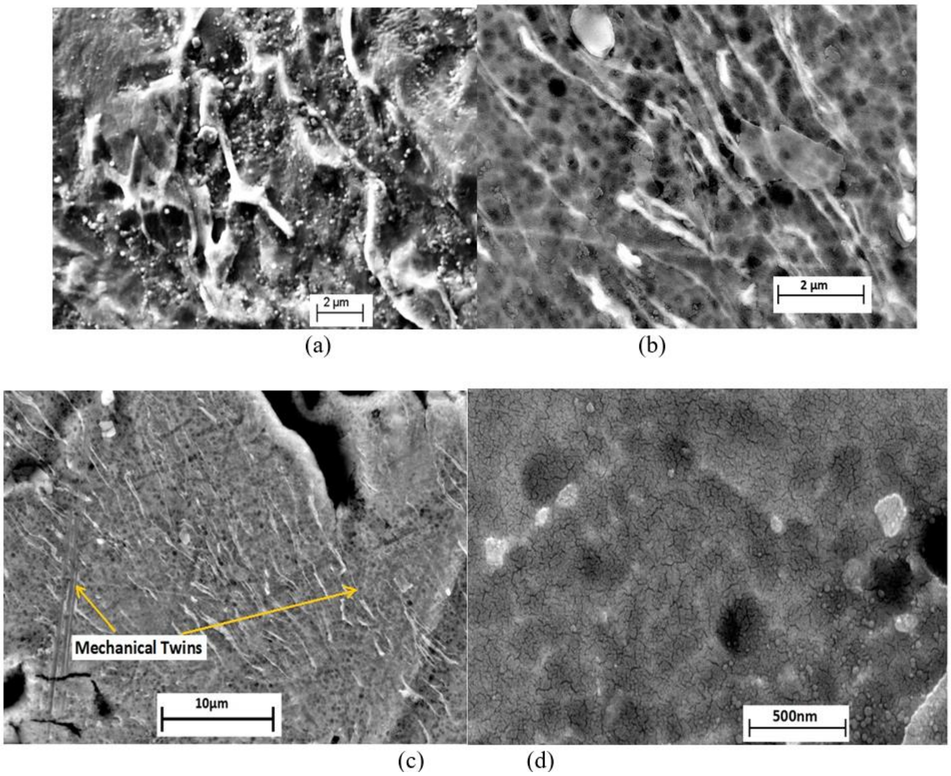

Figure 5. SEM Micrograph of machining chips at different rake angles

The β -phase of the Ti-6Al-4V alloy has a body-centered cubic (BCC) crystal structure has high stacking fault energy and more slip systems, so dislocation multiplication is easily achieved in this phase. The α-phase of the Ti-6Al-4V alloy has a hexagonal close-packed (HCP) crystal structure, and only four independent slip systems are available in the phase. Therefore, HCP metals usually need other deformations, such as twinning, to accommodate the plastic deformation. FESEM image in Figure 5(c) shows the high-density twin lamellae with a thickness of sub-micrometric size, were formed during large strain deformation in the α-phase. The dislocations pile up at the twin boundaries and divide the twins into finer blocks though twin and dislocation intersections, leading to formation of grains with nanometric sizes.

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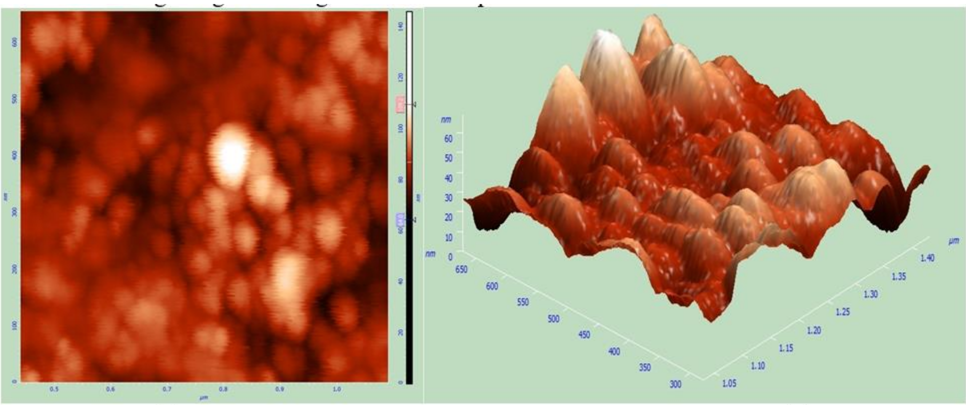
Figure 6represents the atomic force micrographs of metallographically prepared specimens. Figure 6(a) is a typical AFM 2D image of the machined chip microstructure of the machining chips of Ti-6Al-4V alloy. The grain size varies between 30 - 80 nm which is in agreement with the FESEM analysis. The 3D image (Figure 6(b)) shows the average height and roughness of the chip surface.



(a) (b)

Figure 6(a) AFM 2D image of the machined chip microstructure of the machining chips (b) average height and roughness of the chip surface

The grain size of machining chips obtained from FESEM and AFM analysis supports the results obtained by the present co-authors (Rebello et al., 2014) through Small Angle Neutron Scattering (SANS) studies for machining chips of brass and commercial grade steel, which is presented in Figure 7.

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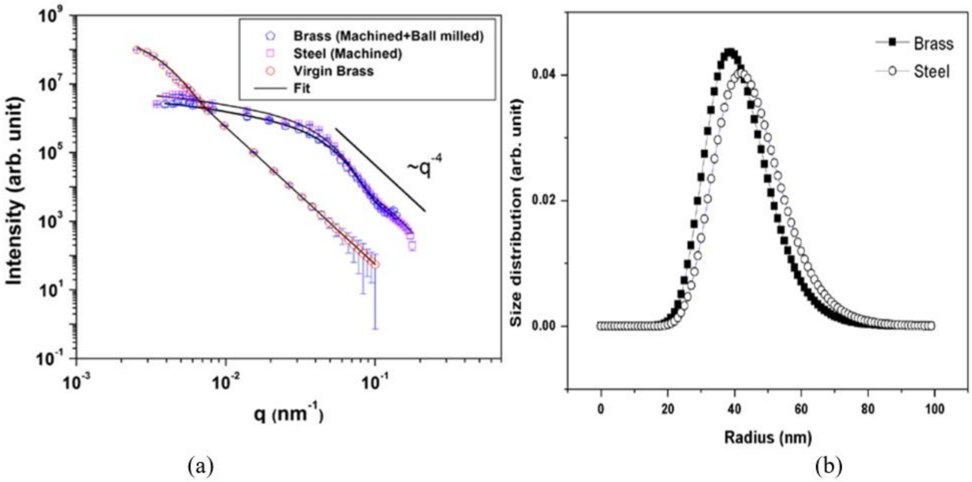

Figure 7. (a) Small angle neutron scattering profiles and (b)particle size distribution for Brass and steel machining chips (Rebello et al., 2014)

4. Conclusions

High strength and microhardness can be obtained in Ti-6Al-4V alloy processed through large strain deformation machining. A decrease in rake angle transpires a large increase in dislocation density and the associated hardness value. The most significant increase in microhardness is recognized for -60° rake angle. Large strain deformation machining with proper selection of machining parameters can be a cost-effective method for producing severe plastic deformation in a single stage as opposed to other SPD methods.

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