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Severe Plastic Deformation of Ti-6Al-4V Alloys through Machining

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Abstract: -- **In the recent years, severe plastic deformation (SPD) has been increasingly used as a material processing method for producing nanostructured materials. However, most of the SPD processes are time consuming and require repetitive routes to obtain the envisaged nanostructure. Severe plastic deformation through large strain deformation machining is a unique method that produces nanostructured materials in a single step. In the present work, large strain deformation machining of a titanium alloy, Ti-6Al-4V, is studied by employing various machining parameters.**

Index Terms **- Large strain deformation, Machining, Ti-6Al-4V alloy, Severe Plastic Deformation, Ultrafine grain.**

I. INTRODUCTION

Titanium and its alloys are renowned for their high strength to weight ratio and outstanding corrosion resistance, which has led to their wide and diversified range of applications that demand high levels of reliable performance in engineering industry. Ti-6Al-4V is the workhorse of the titanium industry. It is a two phase (α+β) titanium alloy, with aluminum as the alpha stabilizer and vanadium as the beta stabilizer. Owing to its potential for further strengthening through tailoring the microstructure, many investigations have been done on heat treatment and thermomechanical methods to obtain refinement in microstructures and their effect on the mechanical properties of the alloy[1]-[3]. The most common method of obtaining grain refinement is through activation of recrystallization by severe plastic deformation (SPD), with a consequent decrease in the average diameter of the grains. The driving force for recrystallization is the energy stored in the network of dislocations that is generated during severe plastic deformation. A fraction of the plastic work associated with such deformation is stored in the dislocation network formed through 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.

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. 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 becomes quite tedious. Alternately, machining is considered as one of the most effective SPD method, since it offers better deformation parameters and the maximum amount of shear equivalent plastic strain can go up to 15, with an average grain refinement into the nanometer range[4]. In this paper, an experimental study of localized shearing and chip formation is carried out during orthogonal machining of Ti-6Al-4V alloy, employing different machining parameters, with grain refinement within 100nm being the primary objective of the

II. PLANE STRAIN MACHINING

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, to. As the chip is formed along the shear plane, its thickness increases to tc. The ratio of to/tc is called chip thickness ratio rc, 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 Fig.1

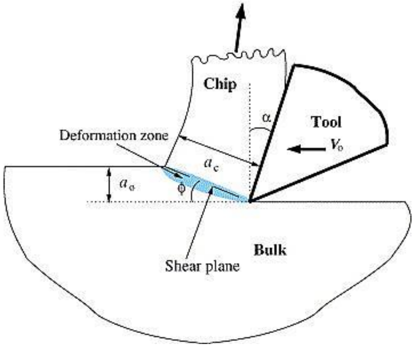


Figure 1. Schematic representation of plane strain machining

The shear angle (φ) can be obtained from the following relation:

$$\tan\phi = \frac{\frac{a_o}{a_c}\cos\alpha}{1-\frac{a_o}{a_c}\sin\alpha} \qquad (1)$$

The shear strain (γ) imposed in the deformation zone is approximately given by

$$\gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)} \qquad (2)$$

III. EXPERIMENTAL

A. Machining

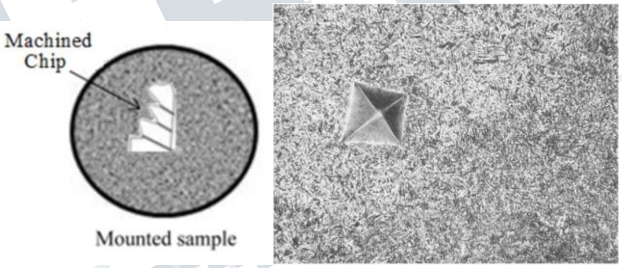
The experiments were conducted using a commercial Ti-6Al-4V alloy rod of 26 mm diameter using ceramic tools. The depth of cut was kept significantly smaller than the workpiece width to realize a plane strain condition in the primary deformation zone. Chips were produced by plane strain machining of Ti-6Al-4V with carbide tools under controlled plain strain conditions with a range of rake angles and machining speeds. Feed rate was kept between 0.0046 to 0.045mm/rev, rake angle was varied from -15 to -65 degree with a depth of cut ranging from 10 to 100 µm. The machining velocity was kept at 15 to 20mm/sec to avoid the influence of temperature.

B. Hardness Test

Hardness tests were conducted on the chips obtained from different machining conditions, using a Shimadzu Microhardness tester. The chip samples were put in a polymer mount and polished down to 1 micron using Diamond paste before being tested for hardness. A force of 490.3 mN and a dwell time of 15 minutes was used for measuring the hardness values. A minimum of 10 measurements were taken to find 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.

C. Microstructure

Samples for microstructural analysis were mounted in polymer resin. The samples were initially ground with silicon carbide papers of 400, 800 and 1200 grit, and finally polished using 2 micron and 1micron diamond paste on a polishing disk to get mirror finish. The samples were etched with a mixture of 2mL HF, 5mL HNO3, and 93mL H2O.The microstructures of the original bulk specimen was observed using Carl-Ziess Scanning Electron Microscope (SEM). The microstructure of the machining chips were studied using optical microscopy, field emission scanning electron microscopy and atomic force microscopy.



(a) *(b)*

Figure 2. A typical (a) mounted chip and (b) microhardness indentation on the chip

IV. RESULTS AND DISCUSSION

The chemical composition of the alloy is presented in Table 1.

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

Element	Ti	Al	V	Fe	C	H	O	N
Wt%	Balance	5.96	3.69	0.134	0.08	0.02	0.08	0.05

Using equation (1), the minimum shear strain imposed on the machining chips for various rake angles under consideration is calculated. The variation of minimum shear strain with rake angle is shown in Figure 3.

The average microhardness of the bulk Ti-6Al-4V specimen was found to be around 300-320HV while that of all the machining chips were much higher compared to bulk material. Thevariation of microhardness of the chip specimen as a function of rake angle is presented in Figure 4. This illustrates the fact that the severe deformation of the chips resulted in increase of hardness values.

The microstructure of the bulk specimen exhibits a bimodal microstructure consisting of primary α-grains and fine lamellar α colonies within relatively small β-grains of 10-20µm (Figure 4).The primary α-phase is mainly featured by its equiaxed morphology. The SEM and FESEM micrographs of the chips obtained for various conditions are shown in Figure 6 (a-f).The micrographs demonstrates that as we move from the bulk specimen to the machining chips the grain size gradually decreases from microns to nanometers regime5. 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.

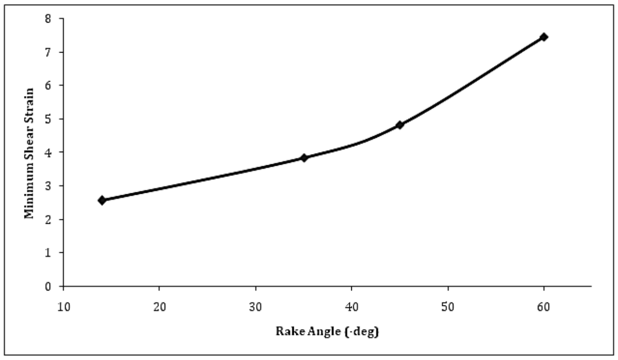


Figure 3. Variation of Minimum Shear Strain with rake angle

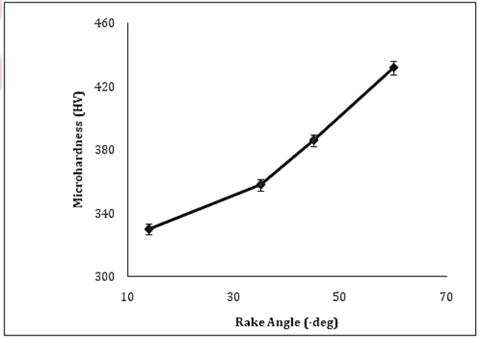


Figure 4. Variation of microhardness with rake angle

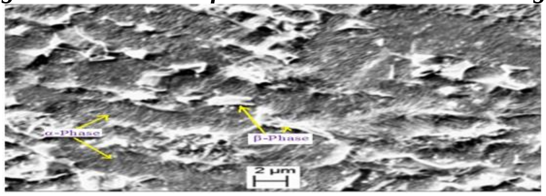
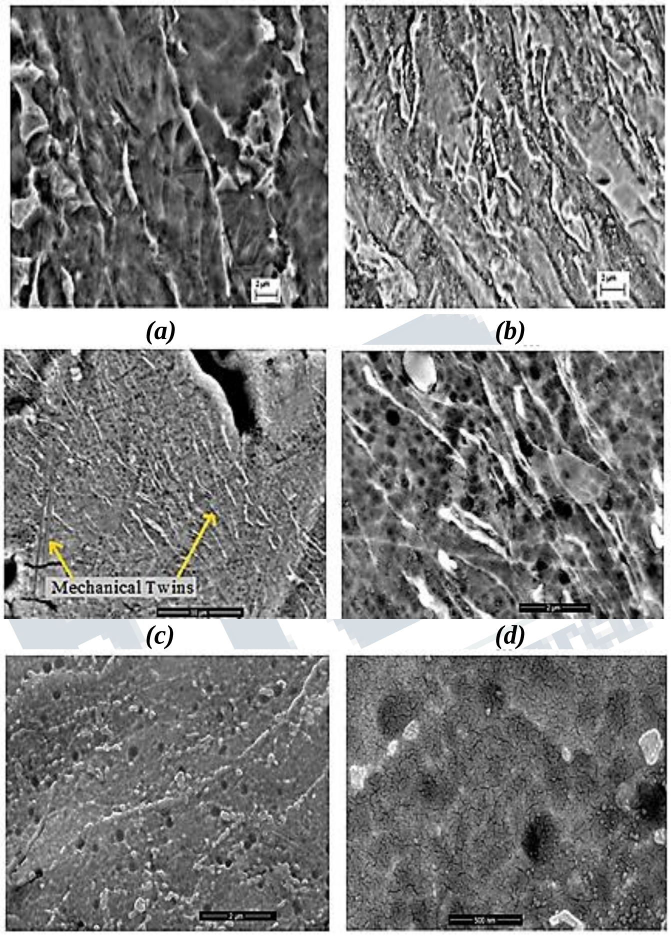


Figure 5 SEM micrograph of the bulk specimen



(a) (b)

(c) (d)

Figure 6. SEM Micrographs of machining chips at (a) α = -14° (b) α = -35° (c) α = -45°@ lower magnification (d) α = -45°@ higher magnification (e) α = -60°@lower magnification (f) α = -60°@ higher magnification

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 6c shows the high-density twin lamellae with a thickness of submicronic 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.

V. CONCLUSIONS

A wide range of microstructures can be obtained by varying the orthogonal machining parameters, with a grain refinement into nanometer range. This can be attributed to dislocation pile-up and deformation twins formed as a consequence of large strain deformation during machining. A decrease in rake angle transpires a large increase dislocation density and the associated hardness value. Plane strain 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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