Effect of anisotropy on mechanical properties of Ti-6Al-4V in superplastic region

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Abstract: This paper presents an experimental investigation on the flow stress behaviour of Ti-6Al-4V alloy at elevated temperatures and very low strain rate. Though Ti-6Al-4V alloy is very hard to deform at room temperature, having only about 16% elongation, it exhibits superplasticity at elevated temperatures. To investigate this, the tensile tests were conducted from 700°C to 900°C temperatures at an interval of 50°C and at a very low strain rate 0.0001/s along three different directions: rolling direction, 45° to rolling direction and transverse direction. The experimental study shows more than 50% elongation in all the cases and particularly more than 250% elongation at 0.0001/s strain rate and at 750°C to 900°C temperature in all directions, which is an indication of superplasticity in the material. This is also corroborated by the microstructural study of the fractured specimens.

1. Introduction

Titanium is the fourth most copious metal found in the earth’s crust after iron, magnesium and aluminium [1]. Among titanium alloys, Ti-6Al-4V is very significant as it contributes 50% of overall production and is considered as the workhorse alloy of the titanium industry. Ti-6Al-4V alloy possess diverse fields of applications like aerospace, biomedical, automotive, marine etc. Ti-6Al-4V alloy contains splendid properties like low density, high strength, corrosion and erosion resistance, but its application is limited to 400°C due to oxidation phenomena. Ti-6Al-4V alloy is one of the polycrystalline material which can undergo large tensile deformations prior to fracture and if elongations are exceeded by 200%, then it is an indication of super plasticity [2]. Salischev et al. [3] developed a Ti-6Al-4V alloy sheet with grain size of 0.3μm and examined it for superplastic properties. Patankar et al. [4] investigated super plastic nature of Ti-6Al-4V alloy with very fine grains (300nm) and reported it can be used in the commercial applications. Vanderhasten et al. [5] examined deformation mechanism of Ti-6Al-4V alloy during tensile test and reported mechanism results by using microstructure, EBSD and mechanical properties. Rayudu et al. [6] studied super plastic forming of Ti-6Al-4V by manufacturing a complex shaped square part used in the aerospace applications. Kumar et al. [7] reported the effect of temperature on tensile behaviour of Ti-6Al-4V alloy and showed results in the form of engineering stress – strain graphs. Xiao et al. [8] conducted uniaxial tensile tests on Ti-6A-4V alloy sheet at different temperatures and strain rates until 25% elongation and results reveal that the initial grain size was same in case of tested condition also. Kotkunde et al. [9] investigated metallurgical behaviour of Ti-6Al-4V alloy at high temperatures and developed constitutive models to understand the flow behaviour. Fan et al. [10] reviewed the effect and relationship of microstructure on mechanical and fatigue properties of thin-section Ti-6Al-4V alloy sheets. In this paper, effect of anisotropy on mechanical properties of Ti-6Al-4V alloy has been studied. The results were discussed in terms of flow stress - strain graphs, microstructure and fractography.
2. Material and experimental details
Ti-6Al-4V alloy sheet of 1.3 mm thickness was received as per ASTM grade 5 standard in annealed condition according to the chemical composition given in the Table 1 and same was used for conducting tensile test experiments.

Table 1. Chemical composition of Ti-6Al-4V alloy sheet (%weight)

| Element | Mass Fraction |
|---------|--------------|
| Al      | 5.980        |
| Ti      | 4.070        |
| V       | 0.225        |
| Fe      | 0.027        |
| C       | 0.120        |
| O       | Bal.         |

The tensile test specimens were machined out of the raw material sheet by using wire-cut electro-discharge machining process for high accuracy and finish. The specimens were prepared as per ASTM E8/E8M-11 sub-size standard along three different directions: rolling direction (0°), 45° to rolling direction and transverse direction (90°) as shown in Figure 1 (a) and (b). The specimens were coated with delta glaze to avoid oxidation effect at elevated temperatures. Tensile tests were carried out at different temperatures ranging from 700°C to 900°C at an interval of 50°C and at a very low strain rate 0.0001/s in all the three directions using a 50kN BISS make Electra servo - electric hot forming universal testing machine. Microstructure of tensile test specimens was studied by using optical metallurgical microscope following etching by Krolls reagent (HF + HNO₃ + H₂O). For fractography studies on broken tensile test specimens a high resolution scanning electron microscope (SEM) Carl Zeiss machine (Model EVO -18 special edition) was used.

Figure 1. (a) Dimensions of the tensile test specimen (in mm) (b) Directions of specimens

3. Results and discussion

3.1 Tensile Behaviour
True stress – true strain curves were plotted in 0°, 45° and 90° directions for temperature range of 700°C - 900°C at an interval of 50°C and at a very low strain rate of 0.0001/s as shown in Figure 2 (a), (b) and (c). Due to anisotropy, difference in curve orientation and true stress (MPa) were observed. At 700°C, true stress is highest in 0° direction as shown in Figure 2 (a) and lowest in 45° direction as shown in Figure 2(b). As the temperature increases, true stress decreases drastically from 700°C – 750°C, then it slowdowns and varies in every direction. Particularly from 750°C temperature onwards, serrations in the flow stress increases due to strain hardening and strain softening phenomena leading to the process of superplastic deformation.
Figure 2. True stress - true strain curves in different directions (a) 0°, (b) 45° and (c) 90° and at different temperatures

Yield strength vs. temperature curves were plotted as shown in Figure 3 (a). It shows variations in the yield strength (0.2% offset) due to anisotropy. At 700°C yield strength (MPa) is highest in 0° direction and lowest in 45° direction. As the temperature increases yield strength decreases.

Ultimate tensile strength (UTS) vs. temperature curves were plotted as shown in Figure 3 (b). Effect of anisotropy can be observed as there is variation in the tensile strength. At 700°C tensile strength (MPa) was highest in 0° and lowest in 90° direction. As the temperature increases ultimate tensile strength decreases.

Elongation vs. temperature curves were plotted as shown in Figure 3(c), it depicts at 700°C elongation is highest in 90° direction and lowest in 45° direction and it is less than 200%, but from 750°C temperature onwards elongation increases more than 250% indicating the superplastic behaviour of the Ti-6Al-4V alloy.

Strength coefficient ($K$) vs. temperature curves were plotted as shown in Figure 3(d), at 700°C strength coefficient is highest in 0° direction and lowest in 90° direction. As the temperature increases, strength coefficient decreases.
3.2 Microstructural analysis

Microstructure of tensile test specimens within gauge length along the surface was studied as per ASTM E 407 standard by using optical metallurgical microscope as shown in Figure 4 (a) and (b). Result reveals a microstructure consisting of alpha grains with intergranular beta in the matrix. Grain size of tensile test specimen performed at room temperature was 11 $\mu$m, which increases to 16 $\mu$m for tensile test specimen at elevated temperature, i.e., from ASTM NO 10 to ASTM NO 9, indicating an increase in the elongation (%) and decrease in yield strength and ultimate tensile strength (MPa).

3.3 Fractography study

A high resolution Scanning Electron Microscope (SEM) was used for examining fractured surfaces of tensile test specimens. Result reveals ductile fracture at elevated temperatures. It can be observed from the fractographs that dimple morphology is predominant at all the tested conditions. In addition dimple size increases from room temperature to elevated temperatures as shown in Figure 5 and 6. Behaviour of Ti-6Al-4V alloy at room temperature is brittle as percentage of elongation was less than 16% and at elevated temperatures, significant increase in the percentage of elongation occurs due to ductility. Inclusions can be observed at elevated temperatures. Due to more shallow dimples, initial elongation is more in $90^\circ$ direction and less in $45^\circ$ direction.
4. Conclusion

The following conclusions can be drawn from this work:
1) True stress decreases with increase in the temperature, particularly from 750°C temperature onwards serrations increases leading to the process of superplastic deformation.
2) Yield strength and ultimate tensile strength clearly show the variation due to anisotropy and they decrease as the temperature increases.
3) Variation in elongation can be noticed, due to anisotropy and it increases with the temperature, specifically from 750°C temperature onwards, elongation continuously increases more than 250% indicating the superplastic nature of Ti-6Al-4V alloy.
4) Microstructure reveals increase in grain size with increase in the temperature due to which strength decreases.
5) Ductile fracture was observed at elevated temperatures. Initial elongation was more in 90° direction due to more micro voids and less in 45° direction. Fractured specimen shows dimple size increasing with increase in the temperature.

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