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A Study on Compression Test on Ti-6Al-4V in Various Strain Rates and Various Temperature

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Abstract: The study investigates the plastic deformation of titanium alloy under moderate strain rates and warm temperature condition. The compression tests are carried out at constant strain rates of 0.01, 0.1, and 1 s-1 to the reductions of 30, 50 and 70% in height at temperatures of 25,100,200,300,400 and 500°C. The flow stress data are analyzed in terms of strain rate and temperature sensitivities. The flow stress decreases with the increase of temperature, but its variation with strain rate is low. Micro structural characteristics of Ti-6Al-4V solid material after compressive plastic deformation were studied in the temperature range 25-500 °C and at strain rates of 0.01, 0.1 and 1.0 s−1. The fracture of the material occurs at a reduction in height of 70% and shows shear banding when compressed uniaxially at strain rates above 0.01s -1 up to a temperature of 500oC

Key words: Titanium, Compression, Microstructure, Plastic deformation, Temperature.

I. INTRODUCTION

The Ti–6Al–4V alloy is commonly used in the aerospace industries, nuclear engineering, civil industries, chemical industries and medically implanted materials for its significant strength-to-weight ratio, resistance to corrosion and high temperature creep [1]. The high cost of titanium alloy components may limit their use to applications for which lower-cost alloys, such as aluminium and stainless steels. The relatively high cost is often the result of the intristic raw material cost of metal, fabricating costs and the metal removal costs incurred in obtaining the desired final shape. Another important characteristic of titanium- base materials is the reversible transformation of the crystal structure from alpha (α, hexagonal close-packed) structure to beta (β, body-centered cubic) structure when the temperatures exceed certain level. This allotropic behavior, which depends on the type and amount of alloy contents, allows complex variations in microstructure and more diverse strengthening opportunities than those of other nonferrous alloys such as copper or aluminum. The most widely used titanium alloy is the Ti-6Al-4V alpha-beta alloy. This alloy is well understood and is also very tolerant on variations in fabrication operations, despite its relatively poor room-temperature shaping and forming characteristics compared to steel and aluminium. Alloy Ti-6Al-4V, which has limited section size hardenability, is most commonly used in the annealed condition.

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The mechanical properties of Ti–6Al–4V alloy are sensitive to both temperature and strain rate and the effect of temperature on flow stress is greater than that of strain rate [2]. Aging at 593^{0}C results in an increase in yield strength and a decrease in ductility at both room temperature and 593^{0}C [3].

However, in the current titanium-alloy compression test, the emphasis in most of the research is placed on the high temperature range [4]. There is a lack of experimental research to study its deformation behavior below cold-compression conditions, i.e. below 700°C [5-6]. Therefore, if a complete compression test data can be obtained and combined with macroscopic and microscopic research, it will be of great help to understand the compression characteristics of Ti-6AI-4V and will be beneficial to actual processing applications [7].

The main purpose of this study is to present the general nature of the influence of strain, strain rate and temperature on the compressive deformation behavior and characteristics of Ti-6Al-4V.

II. EXPERIMENTAL METHOD

A. Preparation of the material and the specimen

The material used in this study is commercial Ti-6AI-4V alloy bar of 7.7 mm diameter. The chemical composition of the as-received bar in wt% is 6.1 A1, 4.0 V, 0.2 Fe, 0.014 C, 0.008 N, 0.0057 H, and 0.15 O. The compression specimen is of cylindrical geometry, 6 mm in diameter and 9 mm in height, cut and machined from the rod in such a way that the compression axis is along the rolling direction. After polishing the specimens down with 1200 grit emery paper, the surface of both ends is sprayed with lubricants of two different kinds: molybdenum-disulfide is used for lubrication at the temperatures of 300 and 500°C and Teflon film at temperatures below 300°C.

B. Mechanical tests

The mechanical tests are carried out at constant strain rates of 0.01, 0.1, and 1 s^{-1} to the reductions of 30, 50 and 70% in height at temperatures of 25,100,200,300,400 and 500°C. Tests are performed in a FIE Servo Hydraulic system machine correlated with an isothermal heating furnace. The specimen is mounted and compressed between highly polished tungsten-carbide flat dies, the surfaces of the dies being parallel to within 0.005 mm. No evidence of specimen shearing resulting from misalignment was observed in any of the experiments conducted in this investigation.

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After being heated to the preset temperature, the specimens are deformed between the fiat dies, which move in response to a programmed constant ram speed of the metal forming testing machine. All the specimens were deformed to true strain of about 0.6 & water quenched from the test temperature. The deformed specimens are shown in (Fig. l). The load-stroke data obtained from the compression tests are converted into true stress-true strain curves, using standard equations for true-stress and true-strain calculations. To study the effect of flow stress strain rate on flow strain stress rate sensitivity is calculated is given by the formula

$$M= ln(\sigma_1/\sigma_2) / ln(\varepsilon_1/\varepsilon_2)$$

Strain rate sensitivity calculated for different temp stress and strain rate range are given in table 1.

C. Metallographic observations

The deformed specimen to study the development of the plastic flow patterns and cracking during deformation, compression tests were run to various reductions in height. After compression testing, the specimens were immediately quenched in water and the deformed specimens were sectioned vertically and microstructural examination was conducted using standard metallographic techniques. The etchant was the standard Keller's reagent. The microstrctural analysis was carried out using with VERSAMET optical microscope and clemax vision image analysis software.

III. RESULTS AND DISCUSSION

A. Isothermal compression characteristics of the specimens

Typical true stress-true strain curves recorded at a temperature of 25°C and at different strain rates in the range of 0.01 to 1 s^{-1} are shown in (Fig. 2) whilst (Fig. 3) shows the true stress-true strain curves in the same strain rate range at 500°C. As observed from these figures, the flow stress decreases with the increase of temperature, but its variation with strain rate is low [8]. At room temperature the flow stress is found about 1020 MPa for specimens deformed at a strain rate of 1s^{-1}, while at 500°C, under the same strain rate level, it decreases to 760 MPa. The general features of the curves are similar to those at temperatures of 100^{0}C and 300°C [9]. It is also evident that the rate of work hardening at room temperature in the initial stages of deformation is greater than that at 500°C, and is slightly dependent on the strain rate.

The stress-strain behavior resulting from uniaxial compression tests at temperatures of 25, 100, 300 and 500°C at the strain rates of 0.01, 0.1 and 1 s^{-1} are presented in (Figs. 4, 5 and 6). In comparing these curves the most obvious difference is the pronounced influence of the test temperature. The flow stress obtained at 25°C is greater when compared with those obtained for the other three higher temperatures. In tests at a strain rate of 1 s^{-1} and at room temperature, (Fig. 4), the material exhibits a slight drop in flow stress indicating thermal softening behavior, when the true strain is greater than 0.2.

However, for the rest of the temperatures, the stress strain curves show steady state flow without any peak stress. The flow stress at 300^{o}C & 500^{0}C remains substantially constant from a true strain of 0.1 to about 0.6. When the material is tested at the strain rate of 0.1 s^{-1} (Fig. 5), the stress strain behavior is different from that when deformed at 1 s^{-1}. For this strain rate, after reaching the yield strength, the flow stress for all temperatures increases with strain following different work hardening rates, except for 500°C where steady-state flow was observed. With regard to the specimens tested at a strain rate of 0.01 s^{-1} (Fig. 6), for a given temperature all the flow stresses are increased directly with the increase of strain, but a small rate of work hardening appeared when the temperature was greater than 500°C. From the aforementioned stress-strain characteristics, it can be concluded that the work-hardening effect is pronounced at temperatures below 500°C under the three tested strain rates and that the rate of work hardening decreases markedly with increase of temperature and strain rate (Fig 7). A similar result was obtained by Seetharaman et al. [10] in their tests on Ti-6AI-4V alloy deformed within the same strain rate range but at higher temperature.

The specimens were compressed to a reduction in height of 10, 30, and 50 % under each tested strain rate and temperature condition, in order to study the workability of the Ti-6AI-4V alloy. The results indicate that when the reduction in height is smaller than or equal to 30%, the deformation of the material is very uniform, neither cracks nor ruptures appearing in the specimen. However, with increasing reduction in height up to 50%, although they generate an evidential failure feature is shown in (Fig 10).

B. Strain-rate Sensitivity

The variation of flow stress with strain rate can be seen more clearly in (Fig. 7), where the flow stress at a true strain of 0.3 is plotted as a function of the logarithm of the strain rate for all tested temperatures. The curves in (Fig. 7) show a slight linear increase of flow stress from 0.01 s^{-1} up to about 1 s^{-1}. These results are in reasonable agreement with other published works for Ti alloy and other metals, and imply that the deformation mechanism associated with the isothermal compression test is a thermally activated process. It should be pointed out that, although the flow stress increases with strain rate in the presently tested ranges, the rate of increase is so small that the effect of strain rate on the flow stress is very limited.

Table 1. Strain rate sensitivity values calculated for different temperatures, strains and strain rate ranges.

Strain Rate	Strain		
	ε=0.1	ε=0.2	ε=0.3
25^0 C			
0.01-0.1	0.006	-0.009	-0.19
0.1-1.0	0.016	0.019	0.014
100^{0}C			
0.01-0.1	-0.001	-0.001	-0.005
0.1-1.0	0.028	0.019	0.010
300^{0}C			
0.01-0.1	-0.015	-0.013	-0.014
0.1-1.0	0.004	0.021	0.024
500^{0}C			
0.01-0.1	0.027	0.027	0.024
0.1-1.0	0.019	0.012	0.007

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These results show that the strain-rate sensitivity depends quite strongly on the strain, strain rate and temperature. Two different variations of strain-rate sensitivity with strain can be observed. In the strain-rate range between 0.01 and 1 s^{-1}, for four tested temperatures (Fig 2-3), all the values of m decrease nonlinearly as the strain increases, indicating that a thermal softening behavior occurs when the material is strained further to a large value. However, in the strain rate range between 0.01 and 1 s^{-1}, the value of strain-rate sensitivity is a weak function of strain and the tendency of variation of the strain-rate sensitivity with strain is not seen clearly. Further, at temperatures below 300°C, for a given strain, the strain-rate sensitivity increases with increase of the strain-rate range, but a contrary result is observed at a temperature of 500°C, implying that there is significant competition between the rate of thermal softening and the rate of work hardening. At a temperature of 500°C, under the presently-explored strain-rate ranges, the rate of thermal softening due to the increase of temperature is more pronounced than that of work hardening produced by the augmentation of the strain rates.

C. Metallographic observations

The deformation features were observed near to the center of the specimens sectioned along the compression axis, subsequent to the different height reductions of 30, 50 and 70%. In the case of 30% reduction in height under the three tested strain rates at temperatures of 30ºC, 100ºC and 300°C and 500°C, all of the deformation is very uniform. The flow lines on the cross-section are parallel to the specimen axis indicating homogeneous deformation behavior (Fig 8), which corresponds to a specimen deformed at 30°C and 1 s^{-1} (Fig 11 a).However, at the test temperature of 500°C, for all of the three tested strain rates, the specimens have barreled largely and non-uniform deformation is particularly evident from the 'bending' of the aligned flow lines on the cross-section (Fig 9). In addition, the shear bands can also be observed when the regions of intense deformation are presented. These shear bands originate along the slip lines of classical plasticity theory [11], the orthogonal net of the two directions of maximum shear stress and maximum shear strain. Since shear bands are internal defects that can be observed only after deformation is completed and since no other phenomenon can be positively identified with shear band initiation (Fig 11 b), it is not surprising that shear bands noted in metallographic sections have initiated at 30% height reduction and the higher temperature of 500°C (Fig 11 c).

Then further deformation to a reduction of 50% in height with room temperature, the deformation features are similar to those of 30% reduction at 500°C, (Fig 8, 9, 10). But the intense deformation is more marked. At room temperature and at 0.1 $s^{-1}$the deformation within the shear band is more intense than outside, hence the cracks are initiated and propagated along a conical zone of intense shear. In contrast, there is no crack on the cross-sections obtained for other temperatures. These results indicated that the workability of Ti-6Al-4V alloy increases with the temperature. At a strain rate of 0.01s $^{-1}$, it is interesting to note that at the same temperature and reduction in height, the growth of the crack and the extent of rupture tend to reduce as the strain rate is increased. This showed that Ti-6AI-4V alloy exhibits a better fracture resistance for loading at greater strain rates. Finally, when increasing the reduction in height up to 70%, all the specimens cracked catastrophically, except for the specimen deformed at 25°C (Fig 8) in which cracking was absent.

IV. CONCLUSION

This study has conducted an experimental investigation in to the effects of the strain rate on the impact response and micro structural examination of Ti-6AI-4V alloy at strain rates ranging from 0.01s $^{-1}$, 0.1s $^{-1}$, 1s $^{-1}$ and temperature in the range of 30ºC to 500ºC. The deformation characteristics of Ti-6AI-4V alloy by means of the compression test have been determined over a practical range of temperature and strain rates. The experimental results have shown that the flow stress increases with increasing strain rate, but decreases with increasing temperatures. More over the strain rate is increases; the strain rate sensitivity also increases. The fracture of the material occurs at a reduction in height of 70% and shows shear banding when compressed uniaxially at strain rates above 0.01s $^{-1}$ up to a temperature of 500ºC..The metallographic observations show that, under 30% reduction in height, the specimens deformed in a homogeneous manner, except for 500ºC.

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Fig.1 Different forms of the compression test results

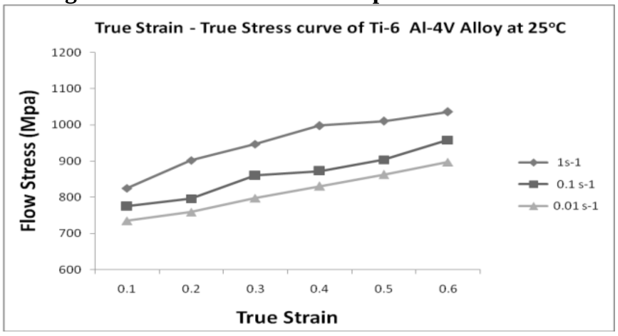

Fig.2 True strain – true stress curves of Ti-6Al-4V alloy at 25⁰C

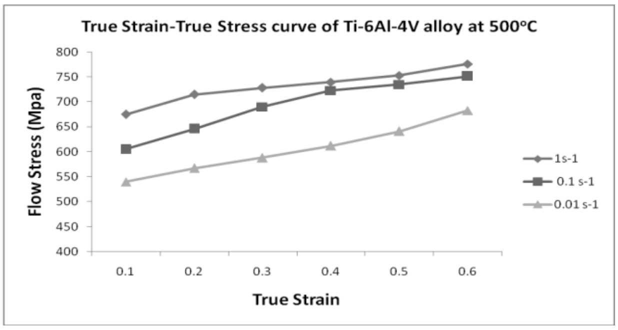

Fig.3 True strain – true stress curves of Ti-6Al-4V alloy at 500⁰C

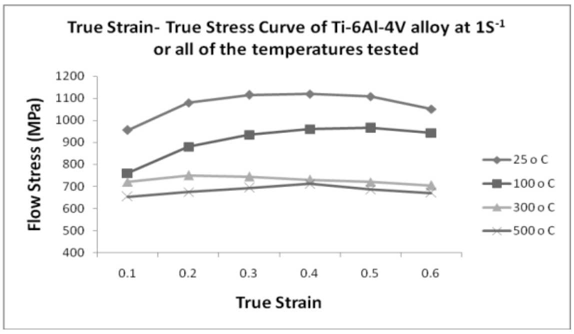

Fig.4 True strain – true stress curves of Ti-6Al-4V alloy at $1S^{-1}$ for all the temperatures tested

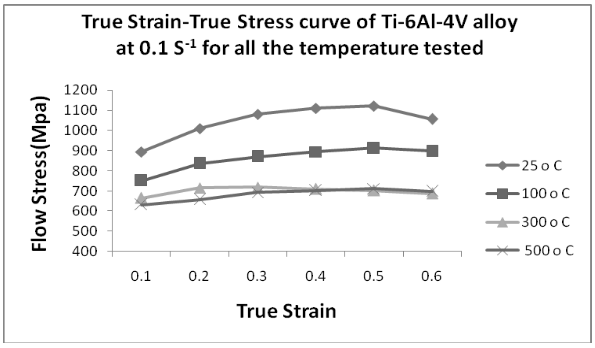

Fig.5 True strain – true stress curves of Ti-6Al-4V alloy at $0.1S^{-1}$ for all the temperatures tested

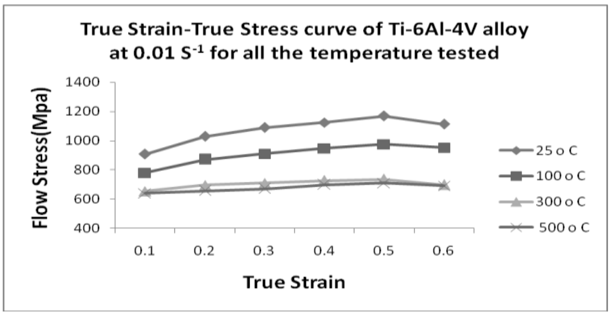

Fig.6 True strain – true stress curves of Ti-6Al-4V alloy at $0.01S^{-1}$ for all the temperatures tested

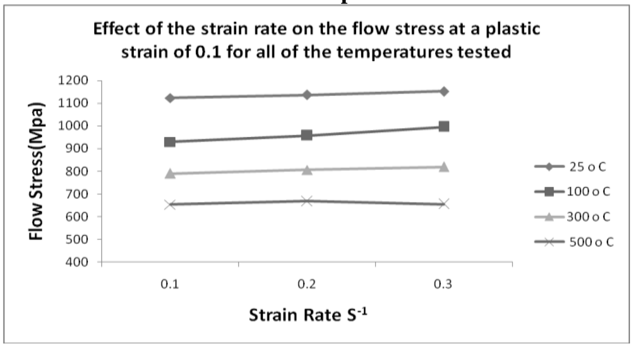

Fig.7 Effect of the strain rate on the flow stress at a plastic train 0f 0.1 for all of the temperatures tested

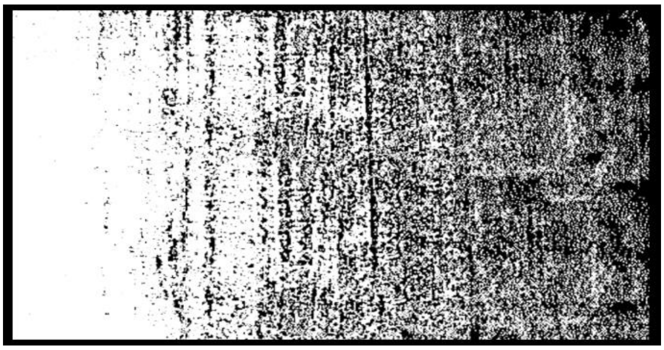

Fig.8. A metallographic cross section taken for the Ti-6Al-4V alloy deformed at 25⁰C and 1 S^{-1} to a reduction in height of 30%

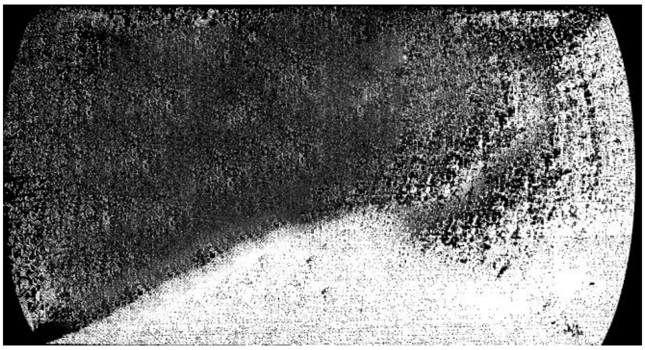

Fig.9. A metallographic cross section taken for the Ti-6Al-4V alloy deformed at 500⁰C and $0.1S^{-1}$ to a reduction in height of 30%

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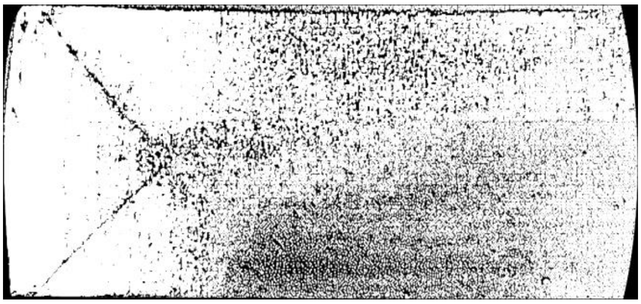

Fig.10. A metallographic cross section taken for the Ti-6Al-4V alloy deformed at room temperature and $0.1S^{-1}$ to a reduction in height of 50%

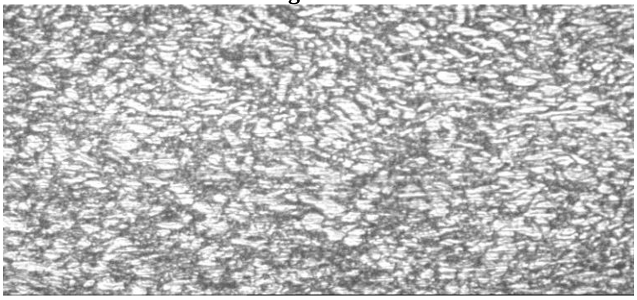

Fig.11(a). Microstructures of the samples compressed at 30°C

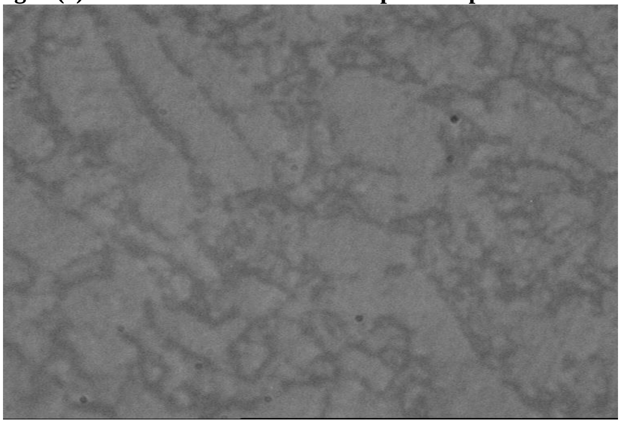

Fig.11(b). Microstructures of the samples compressed at 500^{0}C

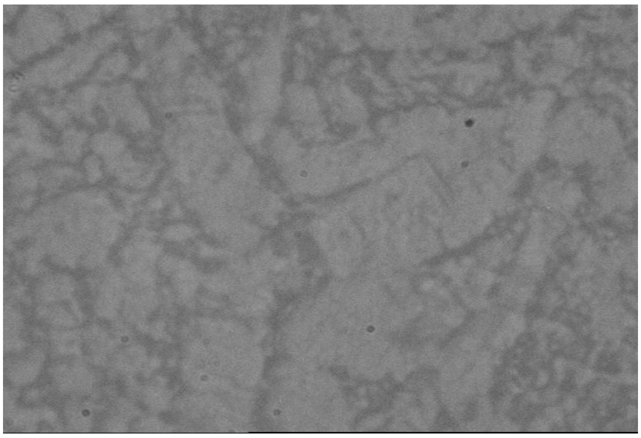

Fig.11(c). Microstructures of the samples compressed at 500^{0}C

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Mr. M. Arulsevan working as an Assistant Professor in the Department of Manufacturing Engineering, Annamalai University. Completed M.E Manufacturing Engineering, Annamalai University. Area of interest is Mechanical behavior of Metals & Metal forming. One Article communicated to International Journal of Advanced Manufacturing Technology and applied for one mini research project. More than 15 research papers were presented in national and international conferences. Participates More than 25 numbers of national symposium and workshops.

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