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HOT DEFORMATION BEHAVIOUR OF Ti-6Al-4V IN DIFFERENT STRAIN RATES

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Abstract:-- The effect of process variables on flow response and microstructure evolution during hot working of Ti-6Al-4V with the lamellar microstructure was established using isothermal hot compression tests. Testing was conducted on material at strain rates of 0.01,0.1&1 S^{-1}, test temperature between 950^0C to 1020^0C and true strain of 20%-40%. All of the flow curves exhibited a peak stress followed by flow softening. The strain rate sensitivity of the flow stress decreases with strain at 950^0C, but increases with strain at 1000^0C and 1020^0C. At 950^0C temperature the globularization of β phase occur but at 1000^0C and 1020^0C globularization of β phase and globularization occur mainly near the colony boundaries and grain boundaries. Microstructure measured in different deformation condition and increase with deformation temperature and decreasing strain rate.

Key Words: Microstructure, compression, temperature, globularization, deformation.

I. Introduction:

Titanium alloys are widely used in structural application for their excellent properties such as high strength to weight ratio, low density and good corrosion resistance. Two phase (α+β) titanium alloys are most widely used because of mechanical and microstructural properties which can be obtained by thermo mechanical processing and heat treatment [1, 2, 3,]. Ti-6Al-4V is mainly used as compressor discs and blades in gas turbine engines with good tensile strength, fatigue resistance and creep performance at a temperature of up to 600^0C [4].

The properties of Ti alloys are strongly dependent on the microstructure so mechanical properties can be optimized by controlling microstructure at different stages of thermo mechanical processing. Two broad classes of titanium microstructure can be identified. The first is the lamellar structure which arises from heat treatment above the β transus in the single phase β region followed by subsequent cooling into the α+β phase filed. The morphology of the α phase in the lamellar structure can be modified to a globular or equiaxed morphology by hot working in the α+β phase field. The relative volume fractions, size and distribution of the lamellar and globular morphologies of the α phase strongly affect properties such as strength, fatigue and creep [1, 2].

This paper examines the effect of strain rate and temperature on the flow stress of the alpha phase in the Ti-6Al-4V alloy, and is based on exhaustive work carried out by Semiatin and co workers and others [5-9] on the processing of α + β titanium alloys. It provides a brief background on the physical metallurgy of titanium alloys and describes earlier work on the processing of α+β alloys. The experimental procedures are then described followed by the results and discussion

A. Classification of Titanium Alloys

Titanium shows an allotropic transformation from the low temperature α (hcp) phase to the high temperature β (bcc) phase at 882^0C. The temperature at which β to α transformation occurs is called the β transus and depends on the amount and type of alloying element added. Alloying elements generally classified in to three categories. α–stabilizer, β–stabilizer and neutral alloying elements [1, 2, 3].

1. α –stabilizers

The α–stabilizers include substitutional as well as interstitial alloying elements. The substitutional α stabilizers are Al, Ga, Ge, and interstitial α stabilizers are O, N, and C. Among the substitutional alloying element Al is the most widely used because it has large solubility in both α and β phase and also reduces the density of the alloy. In Ti-alloys, Al addition restricted up to 5-6 wt% because with increasing the Al content. Some other substitutional alloying elements are Ga, Ge and rare earth elements but their solubilities are much lower than Al and O [1]. O, N and C all are strong α-stabilizer. These alloying elements tend to increase the strength but decrease the ductility of Ti alloys [1].

2. β–stabilizers

β–stabilizers are generally transition metals and divided into two categories β-isomorphous and β–eutectoid. β–isomorphous stabilizers have complete solid solubility with β Ti. β isomorphous elements used in titanium alloys are V, Mo, and Nb. Sufficient concentrations of these elements make it possible to stabilize the β phase to room temperature. Ta and W are rarely used because of density considerations [1, 2]. The high diffusivity of hydrogen led to a special process of microstructure refinement, which uses hydrogen as a temporary alloying element. Cr is restricted up to 5 wt% because above this composition it forms the intermetallic compound TiCr2 which is not desirable. Similarly, Fe is restricted to 5.5 wt%. Si is a common addition to titanium alloys for high temperature applications and improves creep resistance [1].

3. Neutral Elements

Sn, Zr and Hf are considered neutral elements because they lower the α/β transformation temperature only slightly and then increase the transformation temperature again at higher concentrations. Zr and Hf both exhibit the same β to α allotropic phase transformation, and are isomorphous with both phases of titanium

B. Objectives

As stated earlier, Ti-6Al-4V is mainly used as compressor discs and blades in gas turbine engines with good tensile strength, fatigue resistance and creep performance at a temperature of up to 600^0C [5]. The Ti-6Al-4V alloy is currently being evaluated by DRDO for application in gas turbine engines. This paper studies the effect of strain rate and temperature on the flow stress of the alpha phase in the Ti-6Al-4V alloy. The work is divided into 2 major parts

a. To determine the flow behavior of Ti-6Al-4V at strain rates of 0.01, 0.1, and $1S^{-1}$and temperatures of 950^0C, 1000^0C, and 1020^0C.

b. To examine the microstructural changes occurring prior to deformation and after deformation at these temperatures

II. Experimental Procedure

A. Preparation of The Material and The Specimen

The material used in this study is commercial Ti-6AI-4V alloy bar of 6 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 borosilicate glass is used for lubrication.

B. Compression Tests

Compression tests were carried out in a FIE Servo Hydraulic system machine correlated with an isothermal heating furnace. Cylindrical samples of 9 mm height and 6 mm diameter (L/D=1.5) were machined for compression tests. The specimens had parallel faces with concentric grooves of 0.3 mm wide and 0.3 mm depth machined on the parallel faces to retain a lubricant. A 1mm 45^0 chamfer was given at the edges of the faces. A 0.4mm diameter hole to 3-4 mm depth at half the height of the specimen is drilled for insertion of a thermocouple. A borosilicate glass is used as a lubricant on surface of sample. This also acted as a protective coating. The processing temperature is achieved by high temperature split isothermal heat furnace. Furnace temperature control is achieved by using a dimmer stat which is used to vary the voltage being supplied to heating elements. Temperature control was within range of ± 2^0C. Tests were carried out isothermally at 950^0C, 1000^0C and 1020^0C for three different strain rates at 0.01, 0.1 and $1S^{-1}$ to true strain levels of 0.2 and 0.4 (Table I). Samples were inserted in the furnace and after the furnace temperature was attained, they were soaked for 15 min before compression. Following the completion of the test, the furnace was opened as quickly as possible and the sample quenched into water. There was however some delay in this process, so that the as deformed microstructure could not be strictly retained. The microstructures developed after the compression tests were examined on surfaces of longitudinally sectioned samples at the sample diameter and at half the sample height after compression.

TABLE I Strain rates and temperatures used in the compression tests of this study

Temperature^{0}C	Strain Rate S^{-1}		
950	0.01	0.1	1
1000	0.01	0.1	1
1020	0.01	0.1	1

C. Metallographic observations

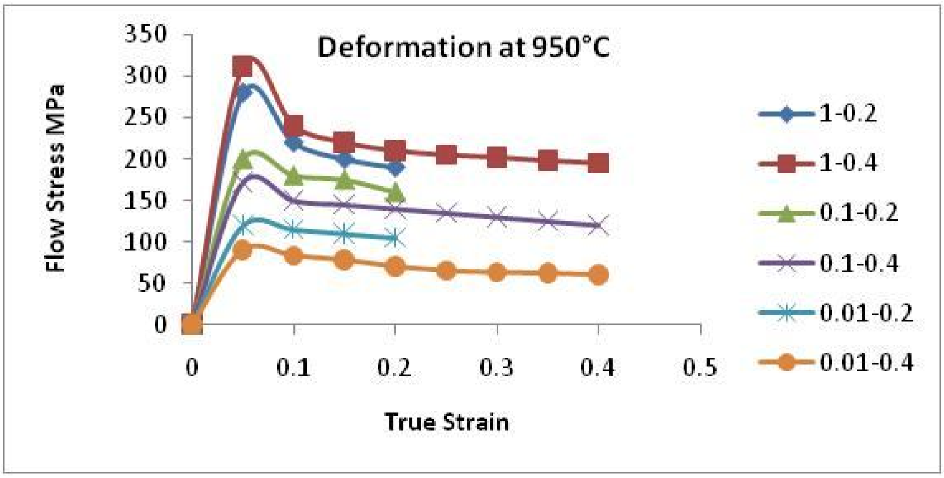
The deformed specimen to study the development of the plastic flow patterns and cracking during deformation, compression tests were run to various reductions in height. After compression testing, the specimens were immediately quenched in water and the deformed specimens were sectioned vertically and 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 climax vision image analysis software.

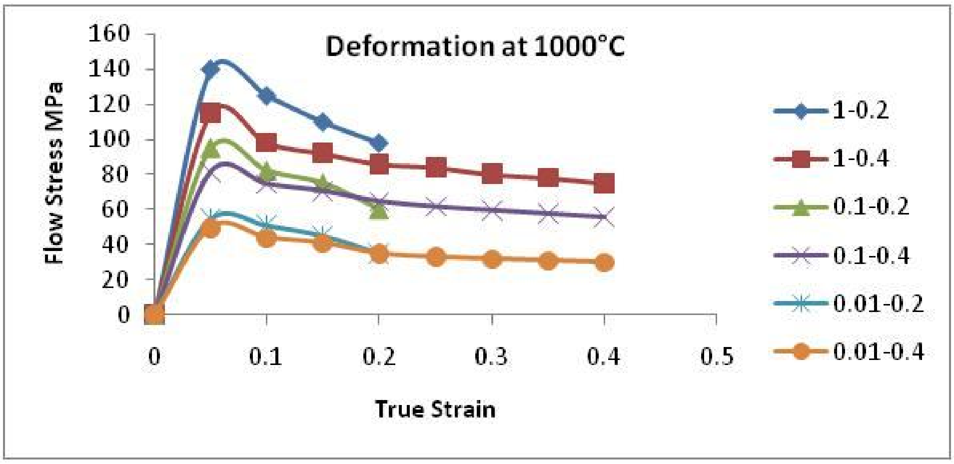
III. Results & Discussion

The results are described in two sections: the first section describes the flow curves that were obtained from the compression tests, the second shows the effect of temperature, strain rate and strain on the deformed microstructures.

A. Flow Behavior

The flow curves for Ti-6AI-4V at different temperature and strain rate are shown in Fig. 1 respectively. All the curves exhibited a peak flow stress followed by softening to a near steady state value. The flow curves showed poor reproducibility, that is, the curves for tests of samples deformed to 0.2 true strain and 0.4 true strain at the same temperature and strain rate differ quite substantially with respect to flow stress values. A variety of reasons may contribute to these differences: the parallelism of samples and alignment with the compressive axis of the platen, or intrinsic differences due to large prior β grain size effects. The serrations observed in the tests at 1020ºC and 950ºC at the lower strain rates appears to arise from noise affects in the data collection system since they do not reproduce in the second test to higher strain under the same conditions. A yield drop phenomena appears to present at higher strain rates at 1020ºC. The peak flow stress decreases with temperature and strain rate but occurs at similar true strain values for all conditions of strain rate and temperature. The curves as plotted are not corrected for adiabatic heating effects because the output of the thermocouple embedded in the sample was not recorded.





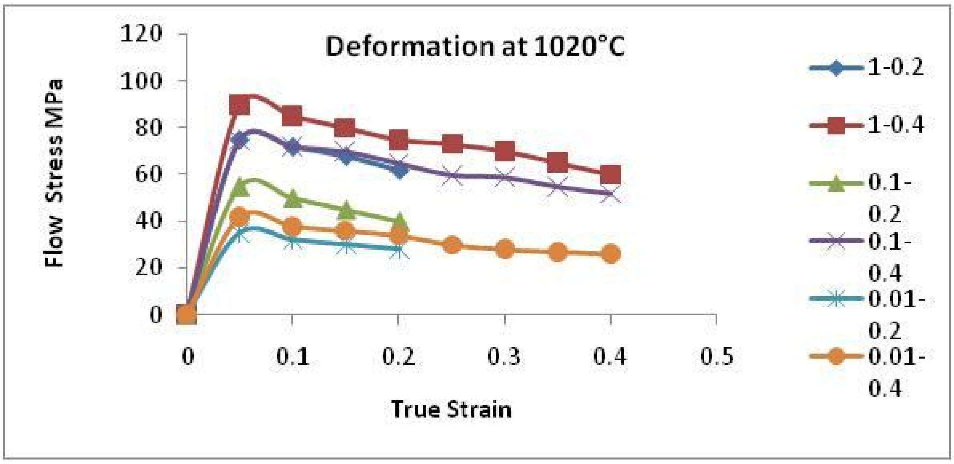


Fig. 1 Variation of flow stress with strain at different strain rates and temperatures

The strain rate sensitivity of flow stress as function of temperature and strain is shown in Fig. 2. The strain rate sensitivity decreases with strain at the deformation temperature of 950ºC, but increases with strain at higher temperatures. The values for strain rate sensitivity at 1000ºC lie between those at 1020ºC and 950ºC.

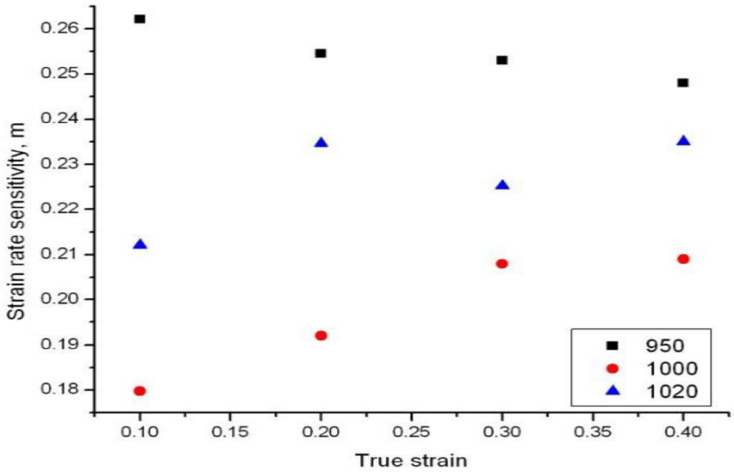


Fig. 2 Strain rate sensitivity as a function of temperature and strain

The flow softening behavior has been examined by comparing the difference in peak stress with the stress at 0.4 true strain (approximating the steady state stress). The flow softening values are very similar at all conditions of deformation, except at the lowest strain rate at 1000^0C and 1020^0C where it increases.

B. Microstructure after deformation

Titanium alloys may exhibit different types of microstructure (lamellar, acicular, globular) according to their thermomechanical history. In-service properties are very much dependent on the microstructure type. Therefore, controlling microstructure after thermomechanical processing is an outmost important industrial issue, especially in high technology fields such as aeronautics. The involved mechanisms result from a combination of recrystallization and phase transformation processes.

The typical microstructures of the isothermally compressed Ti6Al4V alloy at a strain rate of 0.01/s are shown in Figure.

The Ti6Al4V compressed at the temperature range of 950^0C to 1020^0C , revealed elongated and partially martensitic structured grains in the direction perpendicular to the compression stress. At 1020^0C no dynamic globularization process occurred during compression (Fig. 3).

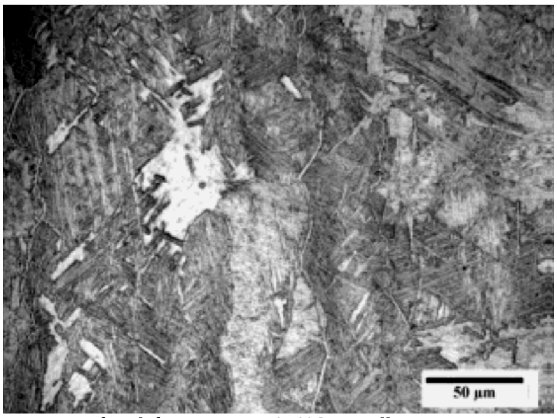


Fig. 3 Microstructure after deformation at 1020ºC partially martensitic structured grains

However, compressing the Ti6Al4V alloy at the temperature 950^{0}C to 1020^{0}C typically to three differently structured zones.

The first zone is (Fig. 4) which has a partial martensitic structure with α-phase grain boundaries. The microstructure in this zone is similar to that obtained in Fig. 3.

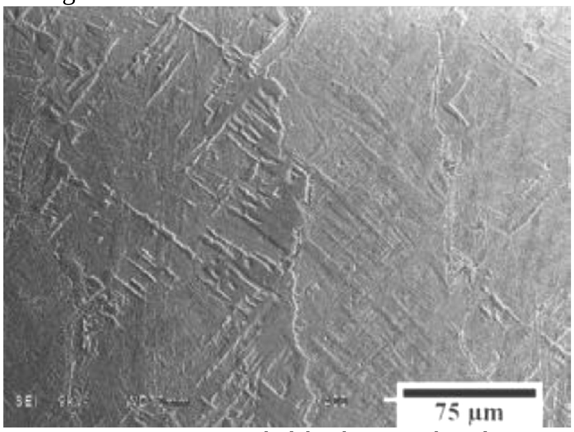


Fig. 4 Microstructure with alpha phase grain boundries

The second zone is (Fig. 5) contains acicular and globular α-phase morphology.

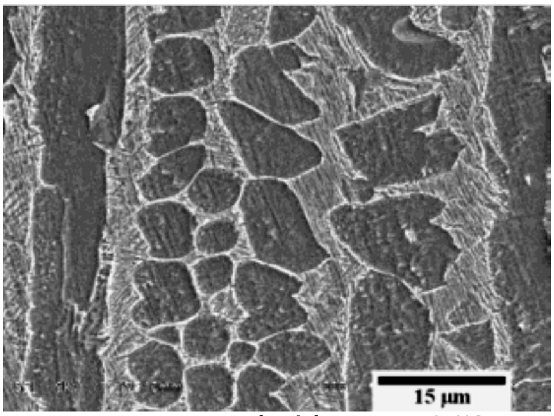


Fig. 5 Microstructure after deformation at 1020ºC.

And the last zone is (Fig. 6) relatively finer acicular and globular α-phase structure. At 950^{0}C and at a strain rate of 0.01/s, dynamic globularization is predominantly observed in (Fig. 5 and 6).

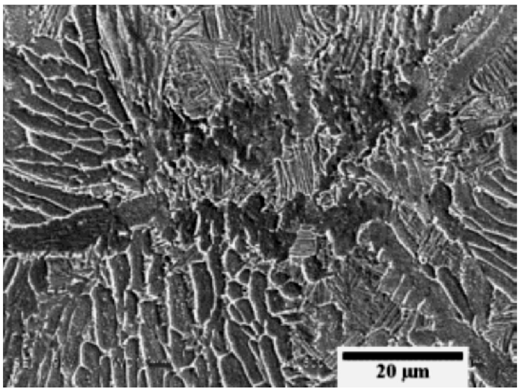


Fig. 6 Microstructure after deformation at 1020ºC.

IV. Discussion

This paper has examined the behaviour of the titanium alloy in high temperature compressive deformation. The flow stress behaviour at different temperatures and strain rates (Fig. 3) are similar to that observed in earlier work on alpha structure deformation at high temperatures [10-15]. The flow stress reaches a peak at very low strains and subsequently softens to a near steady state at higher strains. The softening behaviour is abrupt an unlike in other titanium alloys. The flow stress are nor very reproducible from sample to sample. The strain rate sensitivity of the flow stress (Fig. 4) decreases with strain at 950ºC, but increases with strain at 1000ºC and 1020ºC. The values of strain rate sensitivity are similar to that obtained in Ti-6Al-4V [15]. The difference in the strain dependence at lower temperatures suggests that there are processes occurring at higher temperatures that do not occur at 950ºC.

V. Conclusion

Isothermal hot compression tests were conducted on Ti-6Al-4V with a microstructure. Flow stress data and deformed microstructures were analyzed to establish the operative microstructural changes and to quantify dynamic changes.

- The flow stress reaches a peak at very low strains and subsequently softens to a near steady state at higher strains.
- Strain rate sensitivity of the flow stress decreases with strain at 950^0C, but increases with strain at 1000^0C and 1020^0C.

The Ti6Al4V compressed at the temperature range of 950^0C to 1020^0C , revealed elongated and partially martensitic structured grains in the direction perpendicular to the compression stress train.

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