JMEPEG (2012) 21:253–256
DOI: 10.1007/s11665-011-9830-6

1059-9495/$19.00

Flow Stress-Strain Rate Behavior of Ti-3Al-2.5V Alloy at Low Temperatures in the Superplastic Range

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(Submitted April 20, 2010; in revised form July 12, 2010)

Flow stress-strain rate behavior of Ti-3Al-2.5V, an α + β titanium alloy was studied at 750 and 800 °C by using the method of crosshead speed cycling. The alloy was found to exhibit superplasticity at these temperatures on the basis of complete flow stress, strain rate and strain rate sensitivity data. Strain-induced softening was observed in the alloy to a small extent at 750 °C and was thought to be related to the grain refinement occurring in both α- and β-phases during the initial stages of deformation. However, at 800 °C the effect was seen only under increasing strain-rate conditions. Flow stress versus strain rate curves generally exhibited only region II which corresponded to low- and intermediate-strain rates and region III corresponding to high-strain rates.

Keywords strain softening/hardening, superplasticity, titanium alloy

1. Introduction

In previous work on α + β titanium alloys both strain hardening and softening behaviors have been reported during high-temperature deformation tests. Arieli et al. (Ref 1) reported strain hardening in Ti-6Al-4V alloy at 900 °C at the slowest strain rate and associated it with grain growth. Ghosh and Hamilton (Ref 2) also reported a similar effect in Ti-6Al-4V at 927 °C. Prada et al. (Ref 3) investigated a nickel modified Ti-6Al-4V alloy and again reported strain hardening again occurring at elevated temperatures and low-strain rates. Gurwitz (Ref 4) studied the deformation behavior of Ti-6Al-4V in the temperature range of 750-850 °C and observed strain softening at 750 °C at higher strain rates. He attributed this behavior to grain refinement in both α- and β-phases, increase in the apparent volume fraction of β-phase and overaging process. More recently strain hardening has been reported by the same author in Ti-6Al-4V and a modified alloy Ti-3Al-4V at higher temperatures in the superplastic range (Ref 5, 6). In both alloys, the observed behavior was associated with grain growth in α- and β-phases. High-temperature deformation behavior of another modified alloy Ti-3Al-2.5V was also studied (Ref 7) and the alloy was found to exhibit strain hardening in the temperature range of 830-910 °C. In the present work, the study of deformation behavior of this alloy Ti-3Al-2.5V was extended to low temperatures in the superplastic range, i.e., 750 and 800 °C, on the basis of complete flow stress, strain rate, and strain rate sensitivity data.

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2. Experimental Techniques

The tensile test pieces were machined from the bar material. Crosshead speed cycling tests were conducted under both increasing and decreasing strain rate conditions in an Instron Universal Testing Machine with a Mays three zone furnace. A Windsor WHME three zone controller was used to control the test temperature within ±2 °C. The temperature was also monitored by the use of thermocouple probes inserted into the specimen grips. Also, argon was passed through the furnace continuously during the test to provide an inert atmosphere. The data were expressed as ln σ (flow stress) versus ln $\dot{\varepsilon}$ (strain rate) and *m* (strain rate sensitivity) versus ln $\dot{\varepsilon}$ plots. After testing the specimens were sectioned longitudinally over the undeformed grip and gage length sections. After polishing and etching, the specimens were examined in Cam Scan scanning electron microscope. An etching solution of 2% HF and 2% HNO_3 (by volume) in distilled water was used for the specimens (Ref 7).

3. Results and Discussion

Crosshead speed cycling tests were conducted at 750 and 800 °C under both increasing and decreasing strain rate conditions. The strain rate range used was between 4×10^{-5} and 3×10^{-3}/s. Complete ln σ versus ln $\dot{\varepsilon}$ and *m* versus ln $\dot{\varepsilon}$ data for the alloy at 750 °C are shown in Fig. 1 for increasing strain rates (up) cycles and Fig. 2 for decreasing strain rates (down) cycles. These plots show a decrease in flow stresses with increasing strain which indicate that the alloy exhibits strain softening at this temperature. There is a small decrease in *m* values with increasing strain during later stages of deformation (cycles 3 and 4) but these remain almost unchanged during the first and second cycles. Strain rate sensitivity values are found to be at maximum (0.5) at lower strain rates and decrease with increasing strain rates. Data obtained from the test carried out at 800 °C is presented up to a maximum of five cycles in Fig. 3 for up cycles and Fig. 4 for down cycles. Figure 3 which

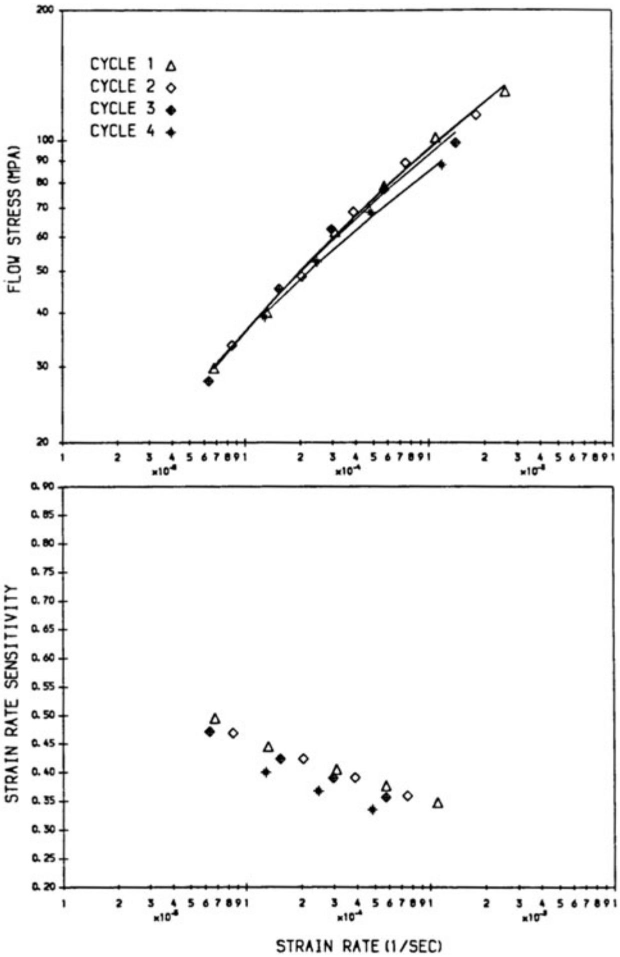

Fig. 1 ln σ vs. ln $\dot{\varepsilon}$ and *m* vs. ln $\dot{\varepsilon}$ plots for Ti-3Al-2.5V at 750 °C. Only the increasing strain rate part of each cycle is plotted

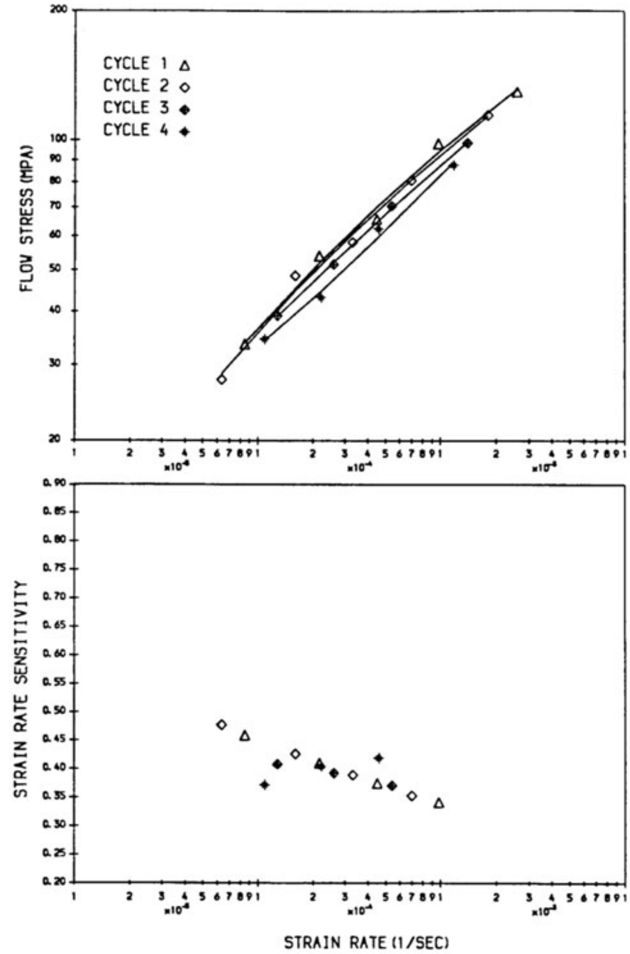

Fig. 2 ln σ vs. ln $\dot{\varepsilon}$ and *m* vs. ln $\dot{\varepsilon}$ plots for Ti-3Al-2.5V at 750 °C. Only the decreasing strain rate part of each cycle is plotted

gives the data for the increasing strain-rate conditions, show a decrease in flow stress with increasing strain, i.e., strain softening, but the data shown in Fig. 4 for decreasing strain rate conditions does not show any such effect. Again *m* values are high (0.63) at lower strain rates and gradually decrease with increasing strain rate except during first down cycle and second up cycle, where "flattening" of the curve at lower strain rates has resulted in low *m* values.

The micrograph corresponding to the as-received specimen is shown in Fig. 5 which shows a banded microstructure. The microstructures which represent the undeformed (grip) and deformed (gage length) sections of the specimen tested at 800 °C are shown in Fig. 6 and 7, respectively. The microstructure shows some banding in the undeformed region of the specimen which transforms to an equiaxed grain structure after deformation. Similar features were observed in the microstructures corresponding to the specimen tested at 750 °C. Grain growth is also seen in the microstructure corresponding to the deformed specimens but this did not lead to any strain hardening in alloy. However, in the previous work of the author on the same alloy in the temperature range of 830-910 °C, the grain growth was observed in the entire temperature range and led to strain hardening and subsequently degradation of superplastic properties. On the basis of microstructural features observed in this work, it is considered that both grain refinement and coarsening processes occur at these temperatures, grain refinement in the initial stages of deformation and grain growth during the later stages. It may therefore be stated that the effect of changes in microstructure. i.e., grain refinement and coarsening on flow stress-strain rate behavior, depends on as to which of the two processes is dominant at a given temperature, resulting in either strain softening or hardening.

In an earlier work of the same author (Ref 8), the alloy was found to exhibit superplastic behavior on the basis of high-strain rate sensitivity values determined only from first increasing strain rate cycles. These cycles were considered more appropriate to determine strain rate sensitivity values due to possible effects of increasing strain on these values during the subsequent cycles. However, in present work, complete flow stress versus strain rate data was studied, i.e., four increasing and four decreasing strain rate cycles at 750 °C and five increasing and five decreasing strain rate cycles at 800 °C, instead of only first increasing strain rate cycles. The *m* values greater than 0.4 were generally observed from the entire flow stress-strain rate data, suggesting that the effects of increasing strain observed at these temperatures did not affect the superplastic properties of the alloy.

The flow stress-strain rate data also show that the ln σ versus ln $\dot{\varepsilon}$ curves are not sigmoidal in shape in most of the cases. Therefore, only region II corresponding to intermediate- and low-strain rates and region III corresponding to high-strain

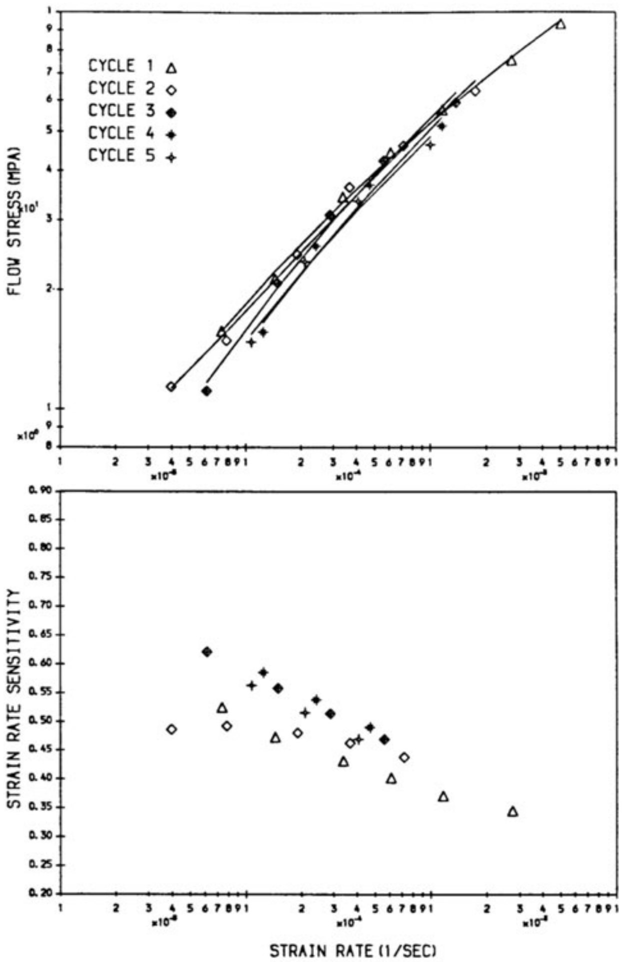

Fig. 3 ln σ vs. ln $\dot{\varepsilon}$ and m vs. ln $\dot{\varepsilon}$ plots for Ti-3Al-2.5V at 800 °C. Only the increasing strain rate part of each cycle is plotted

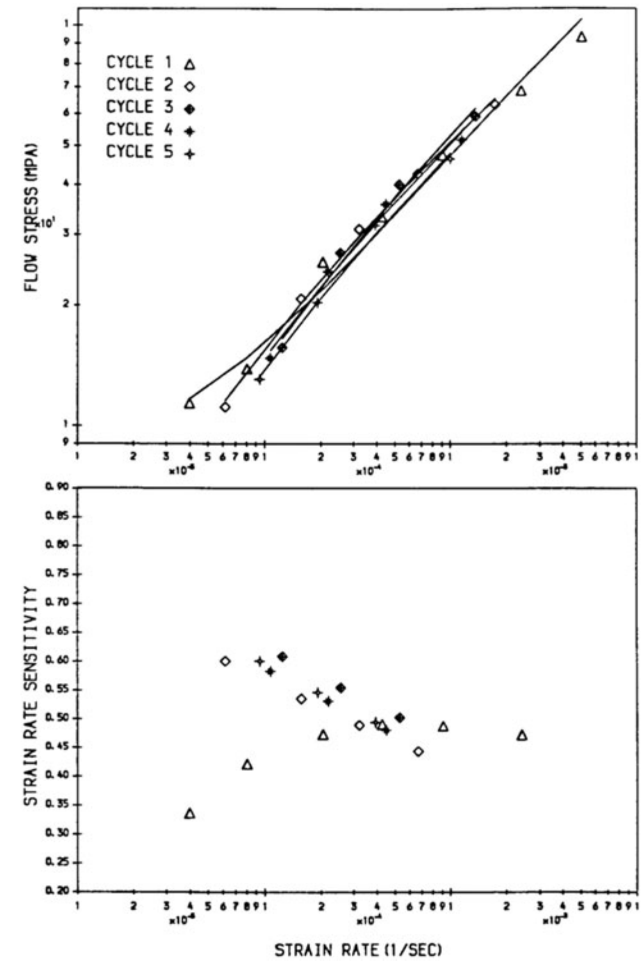

Fig. 4 ln σ vs. ln $\dot{\varepsilon}$ and m vs. ln $\dot{\varepsilon}$ plots for Ti-3Al-2.5V at 800 °C. Only the decreasing strain rate part of each cycle is plotted

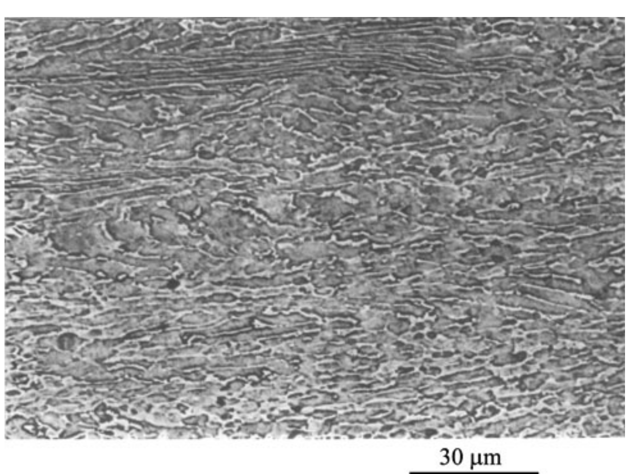

Fig. 5 Microstructure of as-received Ti-3Al-2.5V alloy (bar) longitudinal section

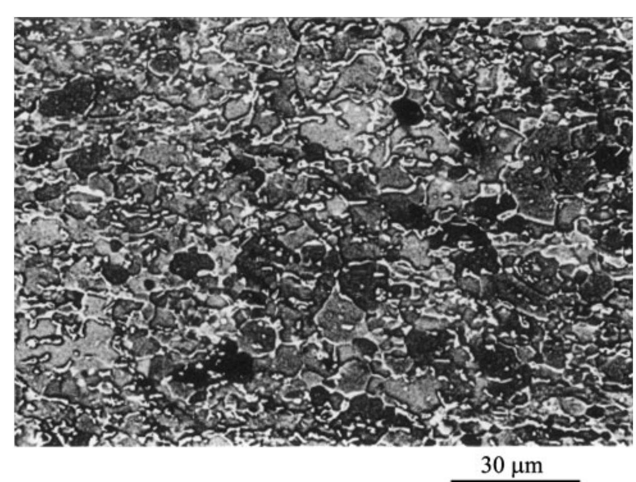

Fig. 6 Post test microstructure of Ti-3Al-2.5V specimen tested at 800 °C. Grip, longitudinal section

rates are generally observed. However, it is relevant to mention here that the very low-crosshead speeds were not used in present work which might be the reason for the absence of region I in most cases. However, it may be seen from Fig. 2, 3, and 4 that at some stages of deformation, curves decrease in slopes at lower strain rates resulting in the appearance of region I. Region I may be seen during first and second cycles at strain rates lower than 7×10^{-5}/s. Identifying region II and III from fourth and fifth cycles was not considered appropriate because of a very short-strain rate range used. Occurrence of region I was reported by Arieli et al. (Ref 1) and Ghosh and Hamilton (Ref 2) in Ti-6Al-4V alloy, but it was attributed to grain growth,

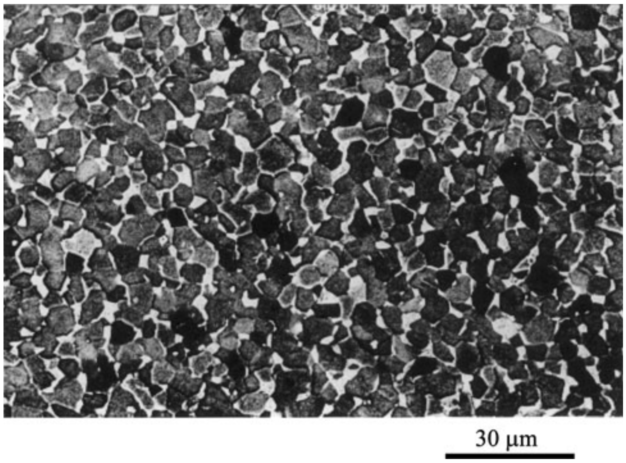

Fig. 7 Post test microstructure of Ti-3Al-2.5V specimens tested at 800 °C. Gage length, longitudinal section

but in these cases flow stress-strain rate data were plotted by using a number of separate specimens. Observation of region I would not be expected in the present work because repeated strain rate cycling with a single specimen was used. Arieli et al. (Ref 1) reported all three region I, II, and III in Ti-6Al-4V alloy, but the strain rate range used was broader than that used in present work. The author also reported a clear transition from one region to the other but this was not the case in present work carried out on Ti-3Al-2.5V alloy. Transition between region II and III was not very clear due to a very small difference in strain rate sensitivity values in most cases, and on that basis the beginning of region III was considered to occur at strain rates greater than 1×10^{-3}/s.

4. Conclusions

Following conclusions may be drawn from the above work.

1. The alloy generally exhibited high-strain rate sensitivity values (>0.4) corresponding to the entire flow stress-strain rate data obtained from tests carried out at 750 and 800 °C and are therefore indicative of superplasticity in this alloy at these temperature.
2. Strain-induced softening in the alloy was observed at 750 °C.
3. Strain-induced softening in the alloy was also observed at 800 °C but only under increasing strain-rate conditions.
4. The observed strain-induced softening may be related to the grain refinement in both α- and β-phases.
5. In general, only region II corresponding to low- and intermediate-strain rates and region III corresponding to high-strain rates were observed. However, in some cases region I was also observed at strain rates lower than 7×10^{-5}/s.

Acknowledgments

The author wishes to thank Dr. C. Hammond, under whose supervision the work was carried out at Institute for Materials Research, University of Leeds, UK.

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