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Deformation Behaviour of Ti-8Ta-3Nb During Hot Forging

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Ti-8Ta-3Nb, as a new biomaterial, was prepared by cast and swaging process. Their deformation behavior of Ti-8Ta-3Nb alloy has been characterized on the basis of its flow stress variation obtained from the true strain rate compression testing in the temperature of 700-900℃ and strain rate of $0.001-10\ \mathrm{s}^{-1}$. At the strain rates lower than $0.1\ \mathrm{s}^{-1}$ and the all temperature ranges which consist of two phase $\alpha+\beta$ as well as single β phase fields, the flow curves show a small degree of flow softening behavior. In contrast, the shapes of the flow curves at other strain rates indicate unstable behavior. The shapes of the flow curves were similar in both as-cast and swaged specimen as well as in both $\alpha+\beta$ phase and β phase. The flow stress data did not obey the kinetic rate equation over the entire regime of testing but a good fit has been obtained in the intermediate range of temperatures (750-850℃). In this range, a stress exponent value of about 7.7 in as-cast specimens and about 6.2 in swaged specimens with an apparent activation energy of about 300 kJ/mol and about 206 kJ/mol respectively have been evaluated.

Key Words : Deformation, Forging, Stress, Strain Rate

1. Introduction

Ti alloys are usually used in the space and chemical industries due to an excellent specific strength, corrosion resistance, biocompatibility and fracture characteristics.

Ti-8Ta-3Nb is developed as a candidate material for applications in the human body. Compared with conventional Ti alloys it offers an improved high biocompatibility.

For successful application of Ti alloy, it is necessary to develop suitable and economical processing techniques to produce the material with the desired shape without losing the low cost advantage. (Sundar et al., 2003)

Hot forging operations are advantageous in that the temperature is uniform and deformation tends to be homogeneous. For any forging operation, there is a limit to achievable deformation before failure is likely to occur. This forging limit depends, in addition to the shape change and process conditions, on the formability of the material, i.e. the material's ability to deform without failure. To increase the achievable deformation for a particular process and to be able to model the process, it is essential to know the flow behavior of the material which is determined by

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process factors, such as true strain (ε), strain rate ($\dot{\varepsilon}$), deformation temperature (T), and material factors, such as flow stress (σ), strain rate sensitivity (m), and deformation activation energy (Q) (Huang et al., 1996).

The objective of present work is to examine the forging flow behavior and then determine the deformation characteristics for different forging conditions during hot forging of Ti-8Ta-3Nb in order to provide some fundamental data for engineering processing.

2. Experimental

The Ti-8Ta-3Nb alloy was melted three times using and made into small rods using a non-consumed electrode. The as-cast specimens were made through the consumable VAR process. Remelting was carried out in a furnace filled with Ar, to make uniform alloys with the electrode. Then cylindrical rods were made. The chemical composition of the alloy in wt.% was as follows : Ta-7.23, Nb-3.22, Ti-balance. The homogenizing treatment was carried out at 1050℃ for 24 hours.

The cylindrical specimens of length 8.25 mm, and diameter 5.5 mm, were machined from a Ti-8Ta-3Nb alloy on which the homogenizing treatment was carried out. The Ti-8Ta-3Nb underwent two primary processes. The first, the swaging process, was at 950℃ followed by a homogenizing treatment whereby same sized specimens were made, similar to the as-cast specimens.

The temperature of the specimen during compression tests was monitored with the aid of a thermocouple spot-welded on the surface at the height of the specimen. This thermocouple was also used to measure the adiabatic temperature rise in the specimen during deformation. A computer controlled servohydraulic testing machine (Thermecmastor_Z) was used for hot compression tests.

The machine was equipped with an exponentially decaying cross head speed, enabling constant true strain rates in the range $0.001-10\ s^{-1}$ to be imposed on the specimen. Isothermal tests were conducted by surrounding the specimen, platens and pushrods with a resistance furnace with a temperature control of ±2℃. The adiabatic temperature rise was also measured on the specimen using the spot-welded thermocouple and a recorder.

The tests were conducted over a temperature range of 650-900℃, at intervals of 50℃ and in the strain rate range of $0.001-10\ s^{-1}$. In each test, the specimen was compressed to about half its original height and the stress-strain data were recorded.

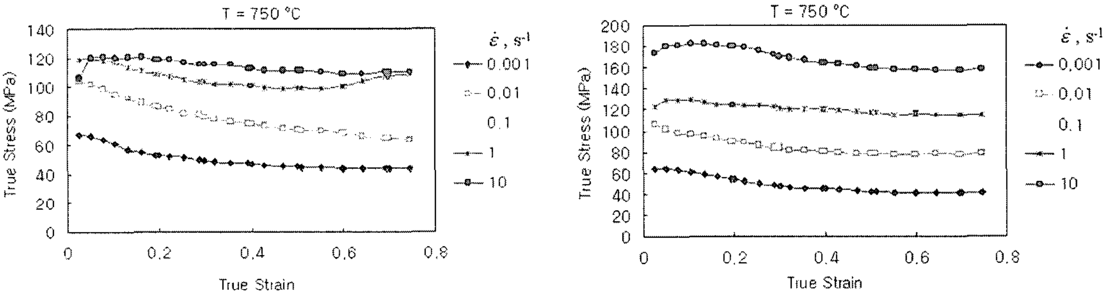
3. Results and Discussion

Figure 1 shows the true stress-strain curves at forging temperatures and strain rates. In general, the stress increases rapidly with increasing strain to reach a maximum stress value. At the strain rate lower than $0.1\ s^{-1}$ and at all temperature range consisting of two phase $\alpha+\beta$ (<880℃, (Lee et al., 2004)) as well as single β phase fields (>880℃, (Lee et al., 2004)), the flow curves show a small degree of flow-softening behavior. In contrast, the shapes of the flow curves at other strain rates indicate unstable behavior. The limited amount of flow softening in most test conditions may indicate that the hot deformation of Ti alloy is led mainly by dynamic recovery and not by dynamic recrystallization (Park et al., 2002). The limited amount of flow softening at slow strain rates can be attributed to the occurrence of dynamic spheroidization of the α grains or dynamic recovery. The variation of flow stress is less significant at low strain rates, which means that it is beneficial to process the alloy under these conditions.

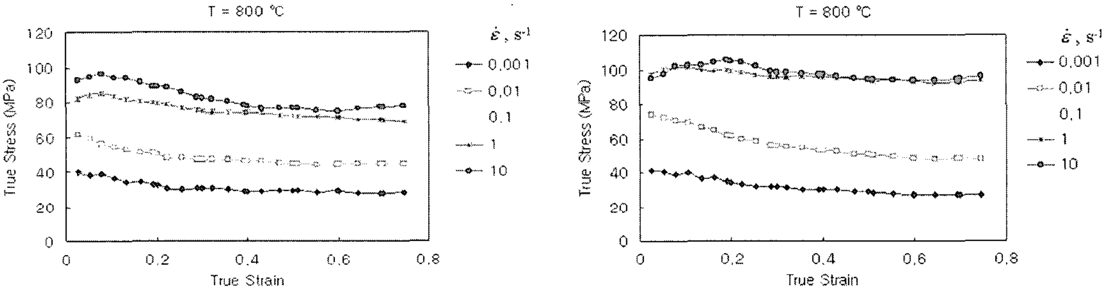
At strain rate higher than $0.01\ s^{-1}$ in the $\alpha-\beta$ range, the flow stress is similar in comparison with that of other strain rates, while in the β phase the flow stress is clearly higher according to increasing strain rate. At strain rate higher than $0.01\ s^{-1}$ in the $\alpha+\beta$ phase and β phase fields, the flow stress of the swaged specimen is higher than that of the as-cast specimen. At other strain rates, the flow stress is similar in both as-cast and swaged specimen.

The shapes of the flow curves are similar in both as-cast and swaged specimen as well as in both $\alpha+\beta$ phase and β phase.

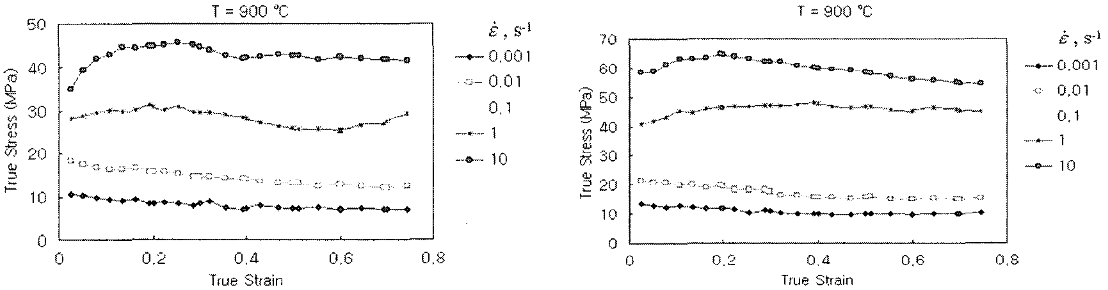
The variation of flow stress corresponding to a strain of 0.5, as a function of temperature at different strain rates is shown in Fig. 2. The flow stress in the α-β temperature region decreases largely with an increase in temperature, however,



(a) As-cast specimen (b) Swaged specimen

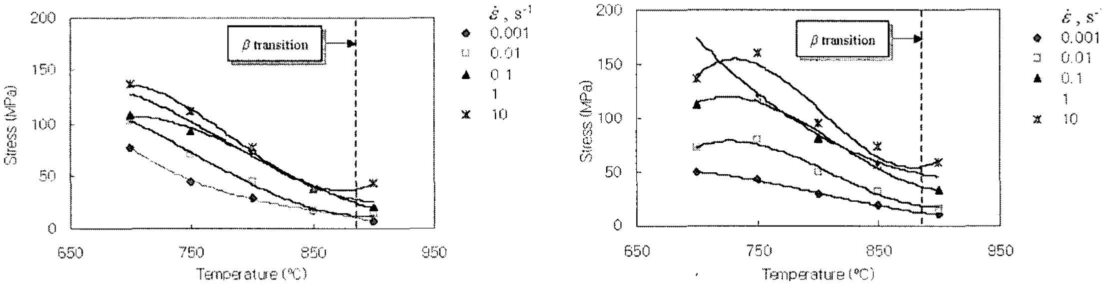


(c) As-cast specimen (d) Swaged specimen



(e) As-cast specimen (f) Swaged specimen

Fig. 1 True stress-strain curves of Ti-8Ta-3Nb at different temperatures and strain rates.



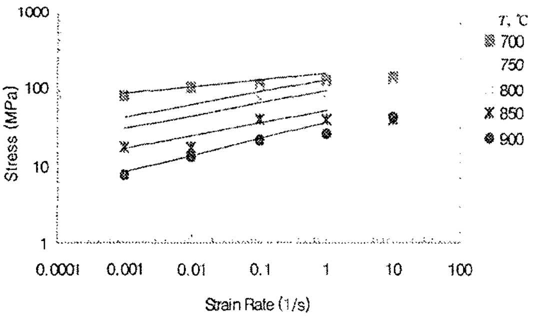
(a) As-cast specimen (b) Swaged specimen

Fig. 2 Variation of flow stress of Ti-8Ta-3Nb at a strain 0.5, with temperature at different strain rates the flow stress shows little difference with an increase in temperature above the β transition temperature. The shapes of the flow curves at strain rates in both as-cast and swaged specimen show a similar trend, but the interval of the flow stress with strain rates in the swaged specimen is wider than that of the as-cast specimen. The above trends indicate that deformation is thermally activated.

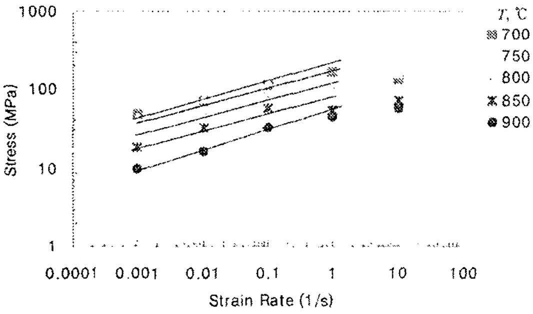
In hot working of materials, the dependency of steady-state flow stress on temperature and strain rate of testing is generally expressed in the form of a kinetic rate equation :

$$\dot{\varepsilon}=A\sigma^{n}\exp[-Q/RT] \qquad (1)$$

where $\dot{\varepsilon}$ is the strain rate, A is a constant, σ is the flow stress, n is the stress exponent (constant), Q is the apparent activation energy, R is the gas constant and T is the temperature in Kelvin. In order to evaluate the stress exponent, the flow stress data obtained at a strain of 0.5 are plotted against the strain rate on a log-log scale at different temperatures (Fig. 3). The slope of the $\log(\sigma)-\log(\dot{\varepsilon})$ shows a tendency to increase with increasing temperature. The value of n, which is the inverse of the slope of the line, is dependent on temperature and is lower at higher temperatures. The value of n is about 14.6 in as-cast specimens and about 5.4 in swaged specimens at 700℃, 7.7 and 6.2 in the range 750-850℃, 5.6 and 4.3 at 900℃. In view of the dependence of n on T, the kinetic rate equation given by Eq. (1) is not obeyed in the entire temperature range of testing. In view of this limitation, it is necessary to apply the rate equation within narrow ranges of temperatures, as shown in Fig. 3.



(a) As-cast specimen

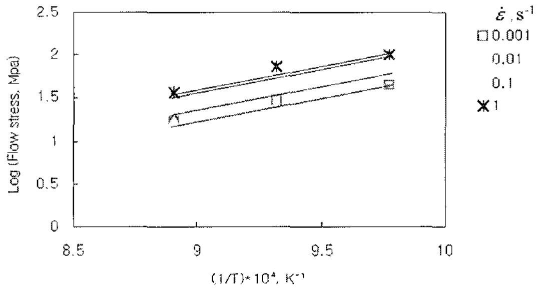


(b) Swaged specimen

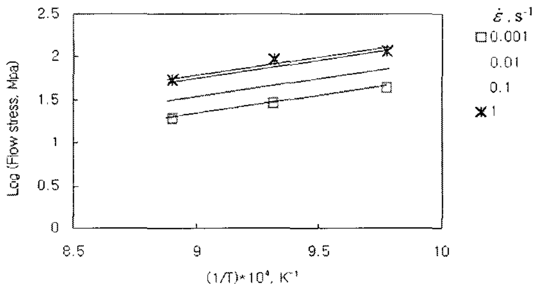
Fig. 3 Variation of flow stress of Ti-8Ta-3Nb at a strain of 0.5, with strain rate on a log-log scale at different temperatures

In both as-cast and swaged specimens, the value of n is higher in the $\alpha+\beta$ phase field than in the β phase field.

The Arrhenius plot obtained between $\log(\sigma)$ and $(1/T)$ at different strain rates is shown in Fig. 4. The plot shows a very good correlation existing at strain rates $(0.001-1\ \mathrm{s}^{-1})$ and temperatures (750-850℃). The estimated value for the apparent activation energy is about 300 kJ/



(a) As-cast specimen



(b) Swaged specimen

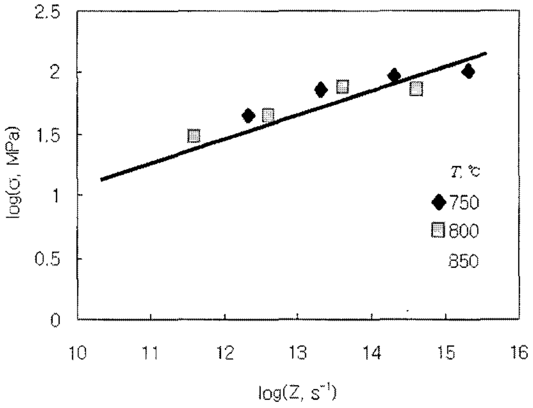
Fig. 4 Arrhenius plot showing the variation of log (σ) with $(1/T)$ for Ti-8Ta-3Nb mol in the as-cast and about 206 kJ/mol in the swaged specimens. This value is higher than that for the self-diffusion of α-Ti (150 kJ/mol) (Dyment and Libanati, 1968), ruling out the possibility of diffusion in α phase being the rate controlling process. This is reasonable because the value of Q for a pure metal is usually lower than that for alloys. Although the activation energy for self-diffusion of α-Ti and β-Ti (153 kJ/mol) (Walsoe de Reca and Libanati, 1968 ; Zener and Hollomon, 1994) is very close, that for $\alpha+\beta$ deformation of Ti can be very different (Liu and Baker, 1995). The value of the activation energy for $\alpha+\beta$ deformation of Ti-6Al-4V has been given as 356-711 kJ/mol (Bryant, 1975), considerably higher than the other reported value for self-diffusion in both α-Ti and β-Ti as well as Ti-8Ta-3Nb obtained in the present work.

When the deformation mechanism is dynamic recovery, the hot working activation energy is equal or close to those for creep and diffusion (Jonas et al., 1969 ; McQueen and Bourell, 1987). Also, the lower value of a activation energy is related to recovery and grain boundary sliding, while the higher value is resulting from fully dynamic recrystallization and grain growth. (Huang et al., 1996). Therefore, the activation energy for swaged specimens of Ti-8Ta-Nb close to the activation energy values for self-diffusion in titanium suggest that dynamic recovery is the main mechanism operating during the hot forging. The activation energy for as-cast specimens of Ti-8Ta-3Nb is close to those reported during hot working (Semiatin et al., 1992). This implies a dislocation-climb dominated deformation mechanism (Huang et al., 1996).

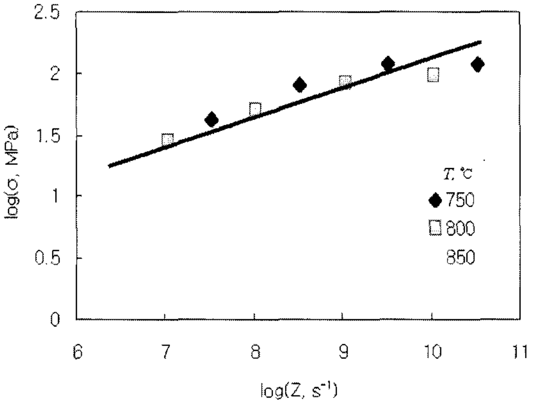
It should be noted, however, that the β volume fraction and α grain size are not constant with increasing temperature (Lee et al., 2004) and Eq. (1) does not include the influence of these factors on deformation kinetics. Continuing the analysis on the basis of the kinetic rate equation, the temperature compensated strain rate parameter, Z, given by :

$$Z = \dot{\varepsilon}\exp(Q/RT) \qquad (2)$$

is evaluated on the basis of the above apparent activation energy and plotted as a function of flow stress in Fig. 5.



(a) As-cast specimen



(b) Swaged specimen

Fig. 5 Variation of flow stress with Zener-Hollomon parameter (Z) in the $\alpha-\beta$ regime of Ti-8Ta-3Nb

The plot exhibits a good fit for the data and confirms that the kinetic rate equation is obeyed in the limited temperature and strain rate range being considered in both as-cast and swaged specimens.

4. Conclusions

The hot working behavior of as-cast and swaged specimens of Ti-8Ta-3Nb under hot forging in the temperature range 700-900℃ and strain rate range 0.001 — 10 s^{-1} has been evaluated by analyzing the variation of flow stress as a function of temperature, strain rate and strain.

At strain rates slower than 0.1 s^{-1} and at all temperatures, including two phase $\alpha+\beta$ as well as single phase β phase fields, the flow curves show a small degree of flow softening behavior. From this result, at slow strain rates dynamic spheroidization of the α grains or dynamic recovery can occur. The shapes of the flow curves are similar in both as-cast and swaged specimens, as well as in both the $\alpha+\beta$ phase and β phase.

Over the entire range of test parameters, the kinetic rate equation is not obeyed but over an intermediated temperature range of 750-850℃, the stress exponent has a value of about 7.7 in as-cast specimens and about 6.2 in swaged specimens. In both as-cast and swaged specimens, the value of n is higher in the $\alpha+\beta$ phase field than in the β phase field.

The apparent activation energy is about 300 kJ/mol in as-cast specimens and about 206 kJ/mol in swaged specimens. From these results, the activation energy for swaged suggest that dynamic recovery is the main mechanism operating during hot forging.

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