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Dynamic Strain Ageing in Alpha Titanium

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The influence of temperature on the yield stress, the maximum stress, the strain rate sensitivity, the activation volume, and yielding effects after stress relaxations in alpha titanium is studied. The role of solute atoms (most probably interstitial oxygen) in dynamic strain ageing is discussed.

1. Introduction

The deformation behaviour of alpha titanium is strongly influenced by temperature, T, and content of intersticial solutes, above all 0, N and H [1, 2]. At low temperatures ($T < 0.3\ Tm$, Tm being the melting point), the flow stress decreases strongly with increasing temperature; at intermediate temperatures it is practicaly independent of temperature (so called plateau region appears) and at higher temperatures (usually $T < 0.4\ Tm$) it again descreases with temperature. In order to identify the occurence of the thermally activated processes during deformation one of three parameters:
a) strain rate sensitivity

$$\beta = \frac{\partial \sigma}{\partial \ln \dot{\varepsilon}}. \tag{1}$$

b) activation volume

$$v = kT \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma}, \tag{2}$$

and
c) stress sensitivity parameter

$$n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma} \tag{3}$$

should be estimated. In eqs. (1) to (3) σ is the flow stress, $\dot{\varepsilon}$ is the strain rate, and k

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is the Boltzmann constant. Yin et al [2] have observed a non-monotonous temperature dependence of the activation volume of alpha titanium. It has been found [3] that the variation of n with temperature is also non-monotonous.

The aim of this paper is to investigate the influence of temperature on the flow stress and the occurence of the strain ageing phenomena in alpha titanium.

2. Experimental procedure

The investigations were carried out on alpha titanium containing 0.15 % O. Tensile tests were performed on an Instron testing machine (Type TT-CL 1195) at an initial strain rate of order 10^{-4} s^{-1} at temperatures between 295 and 900 K. The tests at temperatures above 400 K were carried out in a purified argon atmosphere. The values of the activation volume and the stress sensitivity parameter were estimated from the stress relaxation experiments. The stress relaxation were allowed to occure for about 300 s. Since after stress relaxations at intermediate temperatures yielding effects were observed samples of titanium containing 0.05wt% O were used in order to supress the influence of impurities.

3. Experimental results

A serie of the true stress- true strain curves showing the effect of temperatures is presented in Fig. 1. It can be seen that the flow stress descreasing with increasing temperature except at 753 K where the flow stress is higher than that at 653 K. It is also seen that some phenomena which are connected with strain ageing appear.

Figure 2 shows the temperature dependence of the yield stress σ_{00} (defined as the

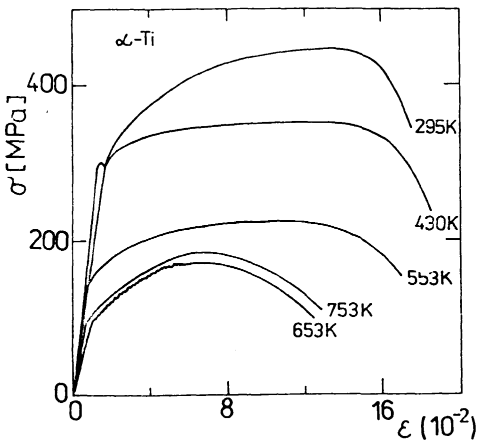

Fig. 1. True stress- true strain curves.

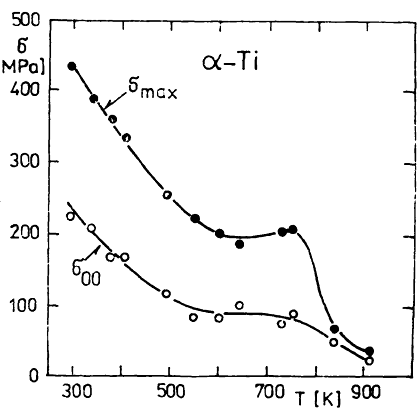

Fig. 2 Temperature dependence of the yield stress and the maximum stress

first deviation from Hooke's line) and the maximum stress σ_{max}. It is seen that the yield stress decreases with increasing temperature below about 500 K. In the intermediate temperature range from about 500 to 750 K the yield stress is athermal and then it descreases again with increasing temperature. The temperature dependence of the maximum stress exhibits a hump at about 750 K (corresponding to the end of the plateau region in the σ_{00} vs T plot).

Figure 3 shows the temperature dependence of the activation volume. A local maximum at about 650 K is observed. It can be seen three distinct regions in the temperature dependences of the activation volume. At intermediate temperatures the variation of the activation volume with temperature is non-monotonous; this temperature region is corresponding to that where the yield stress is independent of temperature. A similar temperature variation of strain rate sensitivity η at 1 %

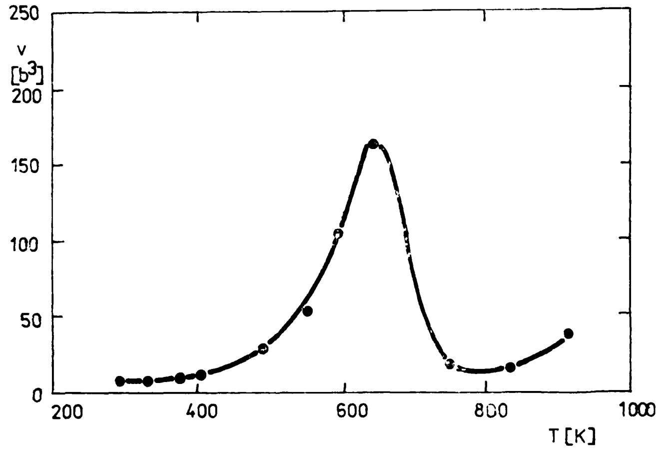

Fig. 3. Temperature dependence of the activation volume.

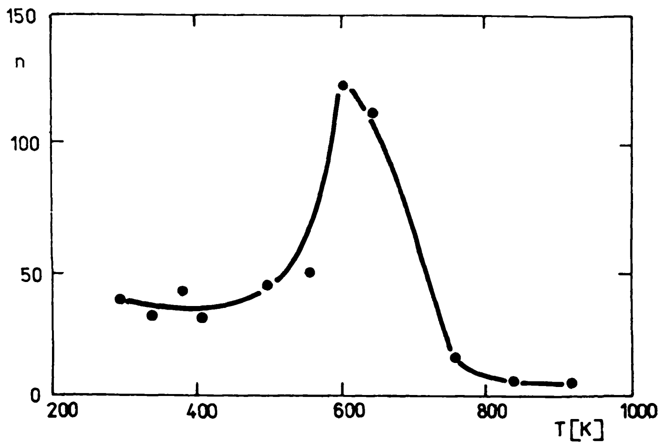

Fig. 4. Temperature dependence of the stress sensitivity parametr

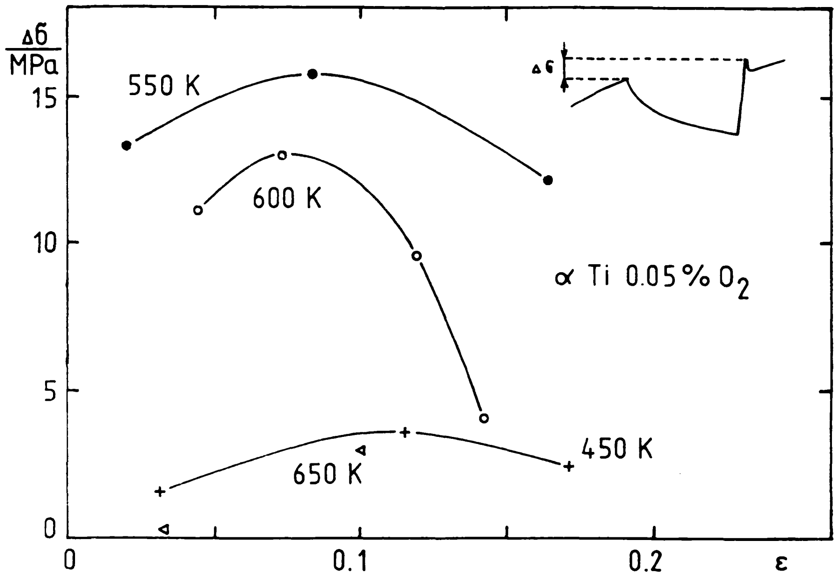

Fig. 5. Strain dependence of σ

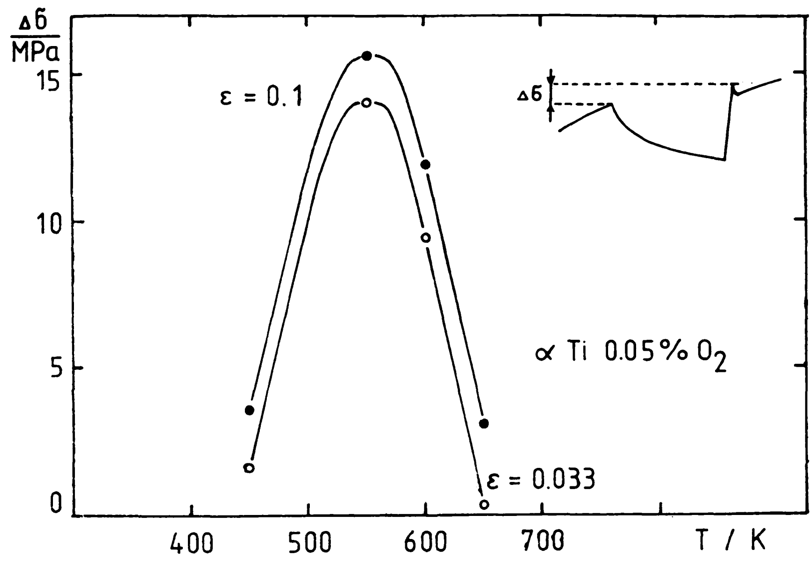

Fig. 6. Temperature dependence of $\Delta\sigma$.

strain has been observed on Ti-50A (0.5 at%O_{eg}) alloy by Yin et al. [1]. The temperature variation of the stress sensitivity parameter n (Fig. 4) is also non-monotonous. The dependence exhibits a local maximum, which should be expected comparring eq. (2) and eq. (3).

In the stress relaxation experiments at intermediate temperatures, the flow stress after reloading σ_1 is higher than the stress at the beginning of stress relaxation σ_0, i. e. the material harden on ageing. In the present experiments the measure that has been used is $\Delta\sigma = \sigma_1 - \sigma_0$. This stress increment depends on strain, temperature and oxygen content and we will present the results obtained on alpha titanium with 0.05 % O. Figure 5 shows the effect of strain on the value of $\Delta\sigma$ for Ti-0.05 % O obtained at various temperatures. Using the data in Fig. 5 the temperature dependence of $\Delta\sigma$ has been constructed and it is presented in Fig. 6. This phenomenon we can call a post-relaxation effect. It is seen that the post-relaxation effect has its maximum at about 550 K.

4. Discussion

From the experimental results mentioned above one can conclude that dynamic strain ageing should be considered. The following features may be taken into account as an evidence for the accurence of dynamic strain ageing:

1) a plateau in the temperature dependence of the yield stress (Fig. 2);

2) a hump in the maximum stress versus temperature curve (Fig. 2);

3) serration in the stress-strain curves (Fig. 1);

4) a non-monotonous temperature dependence of the activation volume and the stress sensitivity parameter (Figs. 3 and 4);

5) a stress increase after stress relaxation in the intermediate temperature region (Figs. 5 and 6).

In order to explain the temperature dependence of the activation volume in Ti-50A obtained by Yin et al. [1, 2] Hong [4] has assumed that the flow stress is the sum of the stress due to dynamic strain ageing σ_a and the stress of the basic rate controlling mechanism, σ_d. According to Hong [4] σ_a depends on temperature as

$$\sigma_a = \sigma_{a0} \exp\left[-(T - T_1)^2/B\right] \tag{4}$$

where σ_{a0}, T_1 and B are constants. The apparent activation volume (measured in experiment) can be obtained from the following equation

$$v = kT \frac{\partial \ln \dot{\varepsilon}}{\partial(\sigma_d + \sigma_a)} \tag{5}$$

Using expression (4) we become

$$v = \frac{v_D}{1 + K v_D} \tag{6}$$

where $K = (1/kT)(\partial\sigma_a/\partial \ln \dot{\varepsilon})$, v_D is the activation volume without dynamic strain ageing. Since K depends on temperature equation (5) indicates that the strain rate sensitivity parameter and hence the activation volume can change with temperature in the dynamic strain ageing region. The maximum value of v is observed in the temperature region where $K < 0$. However, Hong [4] has not presented the origin of the stress component σ_a.

Dynamic strain ageing is the phenomenon of interactions between moving dislocations and diffusing solute atoms. The oldest model for dynamic strain ageing is that proposed by Cottrell and coworkers [5, 6]. According to this theory the number of solute atoms reaching unit length of the dislocation line in time t is given by

$$n = n_0 \, (ADt/kT)^{2/3} \tag{7}$$

where n_0 is the number of solute atoms in unit volume, D is the diffusion coeficient for the impurities and A is a constant (depending on the interaction between a solute atom and the dislocation).

We can assume that during stress relaxation at intermediate temperatures solute atoms diffuse to dislocations. Dislocations are pinned by these solute atoms [7, 8]. Therefore an increase in the stress ins needed to move dislocations after reloading, i.e. the flow stress at the start of deformation after stress relaxation is higher. It is reasonably to assume that $\Delta\sigma$ is proportional to the number of solute atoms on the dislocation line. Then $\Delta\sigma$ may be written as

$$\Delta\sigma = A_1(Dt/kT)^{2/3} \tag{8}$$

where A_1 is a constant. Since D is increasing with temperature $\Delta\sigma$ could go through a maximum with increasing temperature, which is observed. During deformation vacancies are formed. Their concentration depends on temperature and strain. Vacancies generated during deformation can enhance diffusion which should be taken into account. On the other hand, Dlouhý, Lukáč and Trojanová [9] have shown that changes in the internal stress and the density of moving dislocations with the time of stress relaxation can cause the stress increment after reloading. The stress increment is a complex function of the stress relaxation time [9]. It is reasonable to assume that solute atoms diffussing to dislocations can influence both the density of moving dislocations and the internal stress.

It should be mentioned that Mulford and Kocks [10] have pointed out some objections to theories using the model proposed by Cottrell [6] in explaining the dynamic strain ageing phenomena. In model of Balík and Lukáč [7, 8, 11] it is shown that at intermediate temperatures solute mobility makes a negative contribution to the total strain rate sensitivity. That is to say that they have considered that the flow stress has two contributions: $\sigma = \sigma_d + \sigma_f$, and that the friction stress σ_f due to solute mobility is a complex function of solute concentration and the dislocation velocity which is dependent on the activation energy for overcoming obstacles by dislocation, the activation energy for positive and reverse jumps of solutes and temperature.

In any cases it seems likely that the dynamic strain ageing phenomena in titanium are associated with moving oxygen atoms.

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