JOURNAL OF MATERIALS SCIENCE 5 (1970) 839-842

The Activation Areas for Grain Boundary Sliding

N. BALASUBRAMANIAN*, J. C. M. LI*
Henry Krumb School of Mines, Columbia University, NY, USA

The activation areas for grain boundary sliding in Al, Pb, Sn, Zn, and Cu are compared with those for creep in the same materials. It is found that the activation area-stress relation for grain boundary sliding is similar to that for creep. This observation is consistent with a dislocation or ledge mechanism of grain boundary sliding.

1. Introduction

The phenomenon of grain boundary sliding was reviewed recently by Stevens [1]. From the temperature dependence of sliding rate it seems that it is a thermally activated process involving the diffusion of vacancies. However, the stress dependence of sliding rate is not so simple. Internal friction studies show that at very low stresses, the sliding rate is proportional to stress. But macroscopic displacement studies on bicrystals show that at high stresses, the sliding rate varies non-linearly with stress, similar to the stress dependence of creep rate. It seems that the activation area for grain boundary sliding may be comparable to that for creep [2]. An attempt will be made in this paper to make such comparisons in the hope of shedding some light on the mechanism of grain boundary sliding.

2. Definition of Activation Areas

The activation area for creep deformation has been defined before [2]:

$$A^* = \frac{kT}{\mathbf{b}}\left(\frac{\partial ln\dot{\epsilon}}{\partial\tau^*}\right)_T \qquad (1)$$

where $\dot{\epsilon}$ is the steady state creep rate, τ^* is the effective shear stress, T is the temperature, k is the Boltzman constant and **b** is the magnitude of Burgers vector of the moving dislocation. The quantity $A^*\mathbf{b}$ is the same as "activation volume" [3] misleadingly used in low temperature deformation studies. To avoid the confusion with the activation volume derived from the pressure dependence of creep rate [4], the term activation area was introduced. All activation parameters must be evaluated at constant structure. Hence the constancy of mobile dislocation density has to be assumed in all calculations of activation parameters although the total dislocation density may depend appreciably on stress, temperature or pressure.

If grain boundary sliding takes place by the motion of a line defect (dislocation, ledges, steps, etc.) which can be helped by the external shear stress to overcome the activation barriers, an activation area can be defined also:

$$A^* = \frac{kT}{\mathbf{b}}\left(\frac{\partial ln v}{\partial\tau^*}\right)_T \qquad (2)$$

where v is grain boundary sliding rate, and τ^* is the effective shear stress applied over the grain boundary area. The physical meaning of activation area can be understood as in the case of creep [2] and will not be repeated here. Equations 1 and 2 are strictly true when the quantity $(\mathbf{b}\tau^* A^*/kT)$ is greater than about 2 and require correction [2] in other cases.

3. Activation Areas for Grain Boundary Sliding

Data on the stress dependence of macroscopic sliding rate are used to calculate the activation areas according to equation 2 and to compare with the activation areas for creep according to equation 1. Data on internal stress are not available at this time to calculate the effective stress (applied stress minus internal stress). As discussed previously [2] a correction for internal stress would lower the activation area curves but will not affect the correlation to be presented.

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*Now at Materials Research Center, Allied Chemical Corporation, Morristown, NJ ,USA.

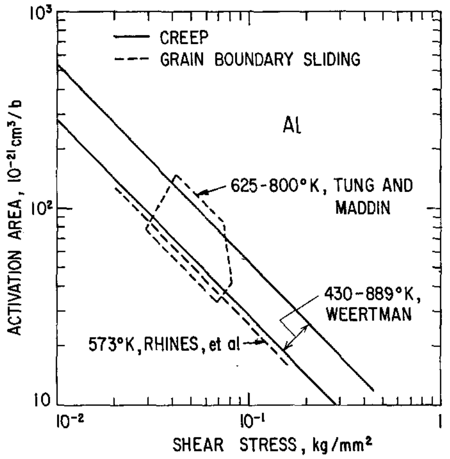

Figure 1 Activation area for grain boundary sliding and for creep in aluminium.

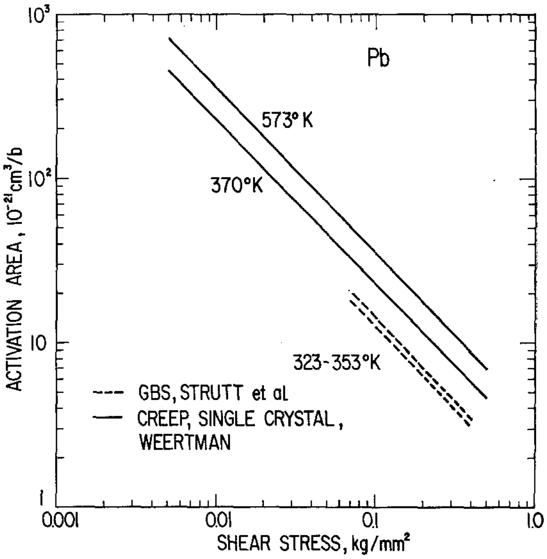

Figure 2 Activation area for grain boundary sliding and for creep in lead.

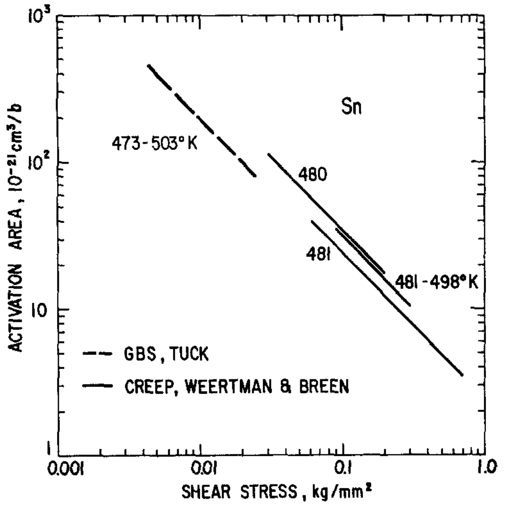

Figure 3 Activation area for grain boundary sliding and for creep in tin.

3.1. Aluminium

The stress dependence of the initial sliding rate at 625 to 800° K for grain boundary misorientations of 20° to 85° (pure tilt around ⟨110⟩) was measured by Tung and Maddin [5]. Activation areas calculated from their results are shown in fig. 1, together with those from the results of Rhines *et al.* [6] on a random high-angle boundary at 573° K based on the stress dependence of an average sliding rate in a displacement of 25 μm. Activation areas for creep are calculated from the data of Weertman [7] in the stress range of the grain boundary sliding experiments. It is seen that the activation area for creep and for grain boundary sliding are quite similar.

3.2. Lead

Strutt *et al* [8] investigated bicrystals of pure lead with a tilt boundary of 60° around ⟨111⟩ and other axes in the stress range of 0.07 to 0.42 kg/mm^2 at 323 to 353° K. As in the case of creep, the steady state sliding rate was found to depend non-linearly on stress. Creep data for lead were obtained by Weertman [9] covering the same stress range, but at 370 to 573° K. The activation areas for both grain boundary sliding and creep are shown in fig. 2, and it is seen that they are comparable. The difference may arise from the stress dependence of microstructure as suggested by Strutt *et al.* [8].

3.3. Tin

Tuck [10] studied grain boundary sliding in bicrystals of tin containing a symmetric tilt boundary of misfit angle 84° around ⟨110⟩. Boundary sliding occurred initially at a constant rate. The stress dependence of the initial rate was reported in the stress range 0.0038 to 0.025 kg/mm^2 at temperatures of 473 to 503° K (melting point 505° K). The activation areas are shown in fig. 3, together with those for creep from the data of Weertman and Breen [11] in a different stress range. It is seen that the activation area-stress relation for grain boundary sliding is similar to that for creep.

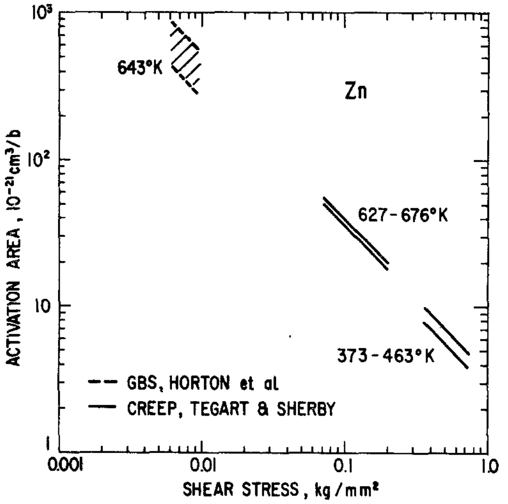

Figure 4 Activation area for grain boundary sliding and for creep in zinc.

3.4. Zinc

Horton *et al* [12] tested bicrystals of zinc containing a tilt boundary around ⟨11$\bar{2}$0⟩ with misfit angles of 10 to 26°. Grain boundary sliding was observed in the absence of macroscopic transcrystalline slip. Stress sensitivity of the sliding rate was determined by "stress change" tests at 643° K in the stress range of 0.006 to 0.009 kg/mm^2. Impurities of 1 to 100 ppm did not seem to affect the stress sensitivity. The activation areas calculated from these results are shown in fig. 4 together with those for creep at higher stresses. The creep data are taken from Tegart and Sherby [13] (see also Tegart [14] and Flinn and Munson [15]). Although the stress ranges do not overlap, it seems that the activation area-stress relationship is similar in both grain boundary sliding and creep in Zn.

3.5. Copper

Harper [16] studied grain boundary sliding in copper bicrystals for both high- and low-angle boundaries. The applied stresses were so low that no detectable grain deformation occurred. The activation area is calculated from the data on a random grain boundary at 773° K and is shown in fig. 5. The activation areas for creep are calculated from data of Barrett and Sherby [17] and Feltham and Meakin [18] at much higher stresses. Here again, although the stress ranges do not overlap, it seems that the activation area-stress relationship may be the same for grain boundary sliding as for creep in Cu.

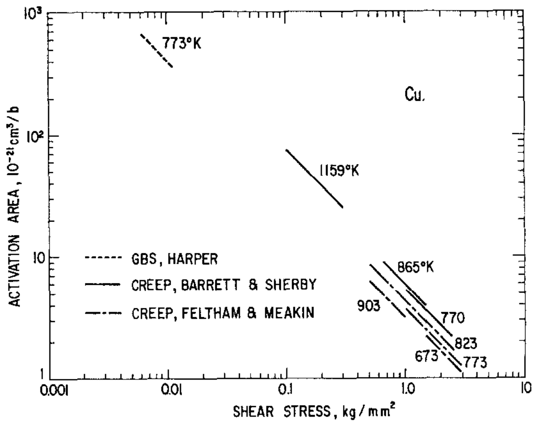

Figure 5 Activation area for grain boundary sliding and for creep in copper.

4. Discussion

The comparison just presented between the activation areas for grain boundary sliding and those for creep suggests that grain boundary sliding may take place by a dislocation mechanism or the motion of ledges and steps. Such mechanism or its equivalent has been proposed by many people [19-22]. The present comparison provides a quantitative support based on the concept of activation area.

Gifkins and Snowden [23] have recently proposed a mechanism for grain boundary sliding for stresses below 250 psi (0.18 kg/mm^2). This model considers protrusions in a grain boundary and the rate of grain boundary sliding equals the rate of movement of the protrusion. However, the protrusions are assumed to move by Nabarro-Herring creep, or in other words a linearity between stress and sliding rate is assumed as in internal friction studies. The present model on the other hand does not make such an assumption and it can explain the non-linear stress dependence of sliding rate in terms of a stress dependent activation area.

Bell and Langdon [24] reviewed recently the present status of our knowledge on grain boundary sliding. Among other things, they concluded that several possible mechanisms can occur and one of them may be important under certain conditions. The following mechanisms are consistent with the present correlation: (i) the motion of grain boundary dislocations by a climb-glide process, (ii) grain boundary sliding induced or controlled by deformation within the grain or by zone shear, and (iii) motion of line defects in the boundary hindered by impurities and small precipitates. On the other hand, mechanisms such as thermally activated block-shear of good-fit islands of a few atoms' diameter are not consistent with the present correlation. In these mechanisms the quantity A^* is of the order of a few $\mathbf{b}^2$ while the observed values are much higher as shown in figs. 1 to 5.

Sometimes the differences in sliding rates observed between bicrystals and polycrystals or the differences in activation energies are explained by suggesting different rate-controlling mechanisms. Such suggestions are open to question since the rate of grain boundary sliding may depend on the number of mobile units in the boundary; internal stresses may be different; and the activation energy may depend on the effective stress. All activation parameters should be compared under similar conditions before suggesting different mechanisms.

In addition to grain boundary sliding, the rate of grain boundary migration is also found to depend, non-linearly, on driving force [25]. The activation areas are again found to correlate with those for creep [26].

A suggestion was made for creep [27] in an attempt to explain the activation area-stress relation without invoking a stress dependence of microstructure. This was based on a jog-limited dislocation motion with a non-uniform distribution of jog spacings. A similar suggestion can be made here, namely, that the grain boundary sliding and migration are both controlled by the motion of dislocations (ledges or steps) with diffusion-limited barriers (jogs, impurities, or some misfit regions in the grain boundary) distributed along the dislocation.

Acknowledgement

This work was partially supported by Army Research Office, Durham, North Carolina, under contract DA-31-124-ARO (D)-382. The authors thank Professor M. Gensamer for his interest and advice.

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Received 11 February and accepted 30 May 1970