Study of thermally activated dislocation motion in AJ51 and AE42 magnesium alloys

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Abstract. Stress relaxation tests along stress-strain curves of two magnesium alloys AJ51 and AE42 are used for determining the activation volume at different test temperatures. The applied stress has been separated into its effective stress and internal stress components. The variations of the activation volumes with the effective stress are examined.

1. Introduction
Improvement of mechanical properties of Mg-Al based alloys has attracted many studies. Third alloying elements are used to improve the properties of the alloys. Among the alloying elements, rare earth elements, Ca, and Sr are promising additions. They also improve high temperature properties of the alloys. However, only a few studies have been reported where dislocation mechanisms during deformation of Mg alloys were clarified.

It is widely accepted [1] that the resolved shear stress necessary for dislocation motion in the slip plane can be divided into two components. In polycrystals, the resolved shear stress is related to the applied stress, \( \sigma \). The same is valid for the components. Then:

\[
\sigma = \sigma_i + \sigma^*,
\]

(1)

where \( \sigma_i \) is the (internal) athermal contribution to the stress, resulting from long-range internal stresses impeding the plastic flow. The effective shear stress \( \sigma^* \) acts on dislocations during their thermally activated motion when they overcome short range obstacles. The plastic strain rate \( \dot{\varepsilon} \) for a single thermally activated process can be expressed as:

\[
\dot{\varepsilon} = \dot{\varepsilon}_0 \exp \left[ - \frac{\Delta G(\sigma^*)}{kT} \right],
\]

(2)

Here \( \dot{\varepsilon}_0 \) is a pre-exponential factor, \( T \) is the absolute temperature and \( k \) is the Boltzmann constant. \( \Delta G(\sigma^*) \) is the change in the Gibbs free enthalpy depending on the effective stress \( \sigma^* = \sigma - \sigma_i \) and the simple form is

\[
\Delta G(\sigma^*) = \Delta G_0 - V \sigma^* = \Delta G_0 - V(\sigma- \sigma_i).
\]

(3)

Here \( \Delta G_0 \) is the Gibbs free enthalpy necessary for overcoming a short-range obstacle without the applied effective stress and \( V = bdL \) is the activation volume where \( d \) is the obstacle width and \( L \) is the
mean length of dislocation segments between obstacles. It should be mentioned that L may depend on the stress acting on dislocation segments. The stress relaxation technique has been demonstrated to be a useful method for estimating the activation volume. In a stress relaxation (SR) test, the specimen is deformed to a certain stress \( \sigma_0 \) and then the testing machine is stopped and the stress is allowed to relax. The stress decreases with time \( t \). The specimen can be again reloaded to a higher stress (load) and the SR test may be repeated. The stress decrease with time during the SR can be described by the well known Feltham equation [3]:

\[
\Delta \sigma(t) = \sigma(0) - \sigma(t) = \alpha \ln(\beta t + 1),
\]

where \( \sigma(0) \equiv \sigma_0 \) is the stress at the beginning of the SR at time \( t = 0 \), \( \beta \) is a constant and

\[
\alpha = \frac{kT}{V}.
\]

The aim of this work is to use the SR tests during plastic deformation of AJ51 and AE42 magnesium alloys at different temperatures in order to obtain the values of the activation volume and to identify thermally activated process(-es) responsible for the plastic deformation.

2. Experimental procedure

Magnesium alloys AJ51 (Mg-5Al-0.6Sr) and AE42 (Mg-4Al-2Nd) were used. Samples for tensile tests of a cylindrical form with a diameter of 5 mm and a gauge length of 25 mm were deformed in an INSTRON 5882 machine at a constant cross head speed giving an initial strain rate of 6.7x10^{-5}s^{-1} over a wide temperature range of 23 to 300 °C. Duration of the SR was 300 s. Components of the applied stress \( (\sigma_i, \sigma^*) \) were estimated using Li’s method [4, 5]. The SR curves were fitted to the power law function in the form:

\[
\sigma - \sigma_i = \left[ a(m-1)(t + t_0)^{-m} \right] \frac{1}{m},
\]

where \( a, t_0 \) and \( m \) are fitting parameters. This relation was derived based on dislocation dynamics (a power low between dislocation velocity and stress) assuming both the internal stress and the density of mobile dislocations are constant during the SR test.

3. Results and discussion

A part of the AE42 true stress-true strain curve at 25 °C (points indicate the stresses at which the SR tests were performed) is shown in figure 1. The internal stress and effective stress are shown as functions of strain. It is obvious that the internal stress \( \sigma_i \) forms the substantial contribution to the applied stress \( \sigma_{ap} \). Analogous dependences obtained at elevated temperatures show that the internal stress decreases with increasing temperature. Similar results were also obtained in the case of some Mg-Al-Ca and Mg-Al-Sr alloys [6, 7].

The apparent activation volumes (in b^3) estimated for AJ51 samples deformed in tension and compression at various temperatures are shown in figure 2 as a function of the effective stress \( \sigma^* \). From figure 2 it can be seen that all values of \( V/b^3 \) lie at one line, “master curve”, done by the equation:

\[
V = kT \frac{\partial \ln \dot{\varepsilon} / \dot{\varepsilon}_0}{\partial \sigma^*} = \frac{\Delta G_0 pq}{\sigma_0^*} \left[ 1 - \left( \frac{\sigma^*}{\sigma_0^*} \right)^{\gamma-1} \right] \left( \frac{\sigma^*}{\sigma_0^*} \right)^{\gamma-1},
\]

where \( p \) and \( q \) are phenomenological parameters reflecting the shape of a resistance profile and \( \sigma_0^* \) is the effective stress at 0 K. The fit of the experimental values of equation (6) gives for the activation enthalpy \( \Delta G_0 = 0.95 \pm 0.05 \) eV for the AJ51 alloy. It should be mentioned that in the case of other Mg-Al-Sr alloys, all values of the apparent activation volume lie on the master curve [6, 7].
Figure 1. A part of the true stress true strain curve. Points at the curve indicate the points at which the SR tests were performed.

Figure 2. Plot of the apparent activation volume against $\sigma^*$ estimated for four deformation temperatures in tension (T) and compression (C) for the AJ51 alloy [7]. The apparent activation volumes for AE42 estimated at three temperatures are plotted against the thermal stress in figure 3. It can be seen that three different curves were obtained in this case. Equation (6) is not fulfilled in the case of the AE42 alloy. This is probably due to strain ageing at intermediate temperatures. Strain ageing phenomena (serrated yielding, post-relaxation effect,) were also observed in some Mg alloys containing rare earth [8]. The values of an increase in the flow stress $\Delta \sigma$ after the SR test observed at different strains are plotted against temperature in figure 4. It can be seen that the maximum of the ageing effect is at a temperature of 150 °C. $\Delta \sigma$ is zero at temperatures lower than 50 °C and higher than 250 °C. In an alloy, the flow stress may be considered as a sum of two contributions:

$$\sigma = \sigma_f + \sigma_d$$

with $\sigma_f$ relating to a friction imposed by the solutes-dislocation interaction and $\sigma_d$ relating to the dislocation-dislocation interaction [9, 10]. Hong [11, 12] have shown that irrespective of the mechanisms of dynamic strain ageing, the frictional stress $\sigma_f$ could be approximately described by the following equation:

$$\sigma_f = \alpha_2 \sqrt{G b \delta \varepsilon \exp\left(-\frac{(T - T_0)^2}{B}\right)}$$

The apparent activation volumes for AE42 estimated at three temperatures are plotted against the effective stress, estimated for three temperatures.

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where $\alpha_2$ is a constant, $\delta$ is the atomic size misfit parameter, $G$ is the shear modulus, $c$ is the solute concentration and $B$ is the width of the statistical normal distribution about the temperature $T_0$ where the maximum of the solute–dislocation interaction force occurs. This temperature was found, in the case of AE42 alloy, to be in the vicinity of 150 °C. At this temperature the interaction of mobile solute atoms with moving dislocations may reach its maximum value. The isolated solute atoms are not significant obstacles for the thermally activated dislocation motion at higher temperatures. They may diffuse to the stacking fault and influence double cross slip from basal to non-basal planes.

The values of the activation volume and the activation enthalpy may help to identify thermally activated processes considering some of the common short–range barriers to dislocation motion. The values and the observed stress dependence of the activation volume indicate that the double cross slip (and formation of jogs) may be the rate-controlling mechanism.

4. Conclusions

Stress relaxation tests are used to estimate the activation volume and to determine the internal stress and effective stress. In the case of the AJ51 alloy, the activation volume is a function of the effective stress independent of temperature because the microstructure is constant in the temperature range studied. Dynamic strain ageing influenced the deformation behaviour of AE42 magnesium alloy; the variation of the activation volume with the effective stress is different for different temperatures.

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