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Grain boundary sliding at low temperatures

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Abstract. Grain boundary sliding plays a key role on the high temperature deformation of fine grained materials. This mechanism is related to a high strain rate sensitivity of approximately 0.5 and usually gives rise to high superplastic elongations. The rate controlling equation for the mechanism of grain boundary sliding has shown good agreement with experimental data for multiple materials, with different grain sizes and tested at different strain rates. However, the predictive ability of the rate controlling equation seems to deteriorate at low temperatures. Although there are experimental evidences of high strain-rate sensitivities in ultrafine grained materials tested at low temperatures, this parameter does not reach values near 0.5 and also there seems to be disagreement in stress level in many conditions. The present overview evaluates the occurrence of grain boundary sliding in ultrafine grained materials at low temperatures considering an adapted rate controlling equation which display good agreement with experimental data. A gradual transition from grain refinement softening at high temperature to grain refinement hardening at low temperatures and a gradual increase in strain rate sensitivity with increasing temperature are observed.

Introduction

The occurrence of grain boundary sliding as a deformation mechanism at high homologous temperatures is now well established. This mechanism is observed in materials with fine grains, typically less than 10 µm, at temperatures typically above half of the material melting point. There is also a strain rate range, or stress range, in which this mechanism is rate controlling. The rate controlling equations for high temperature creep mechanisms are usually in the format in eq. 1 [1]

$$\dot{\varepsilon} = \frac{ADGb}{kT}\left(\frac{\sigma}{G}\right)^{n}\left(\frac{b}{d}\right)^{p} \tag{1}$$

in which $\dot{\varepsilon}$ is the effective strain rate, A is a dimensionless constant, D is the diffusion coefficient, G is the shear modulus, b is the Burgers vector, k is the Boltzmann constant, T is the absolute temperature for creep, σ is the effective stress, n is the stress exponent and p the inverse of the grain size exponent. Different creep mechanisms have different parameters *A, D, n* and *p* and so each is rate controlling at specific conditions of stress, temperature and grain size. A common way to visualize the rate controlling mechanism for the different conditions is through deformation mechanism maps and an example is given in Fig. 1 for the AZ31 magnesium alloy tested at different temperatures [2]. Thus, the range for each of the deformation mechanisms is delineated and experimental data from the literature [2-13] is also shown. A different color is used for each deformation mechanism and the same color is used to indicate the deformation mechanism reported in each experiment. It is apparent there is a good correlation between the theoretical deformation mechanism maps and the experimental data. Thus, the high temperature deformation of metallic materials is fairly well predicted in terms of creep mechanisms.

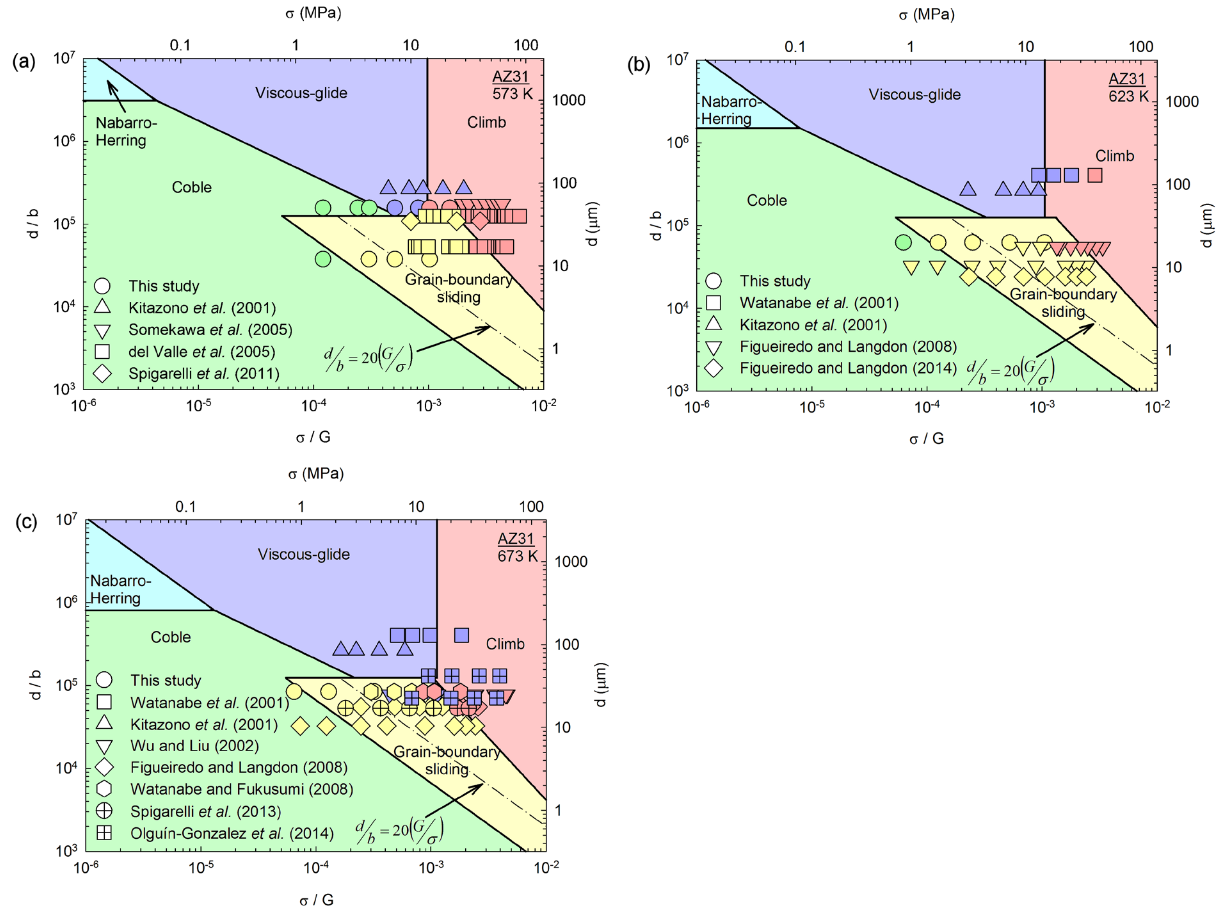

Figure 1 – Deformation mechanism maps for high temperature creep of a Mg alloy AZ31 [2].

The occurrence of grain boundary sliding (GBS) in fine grained materials at temperatures above half the melting point is well established. However, there has been great interest in the development of ultrafine and nanocrystalline materials [14] and in the evaluation of the occurrence of GBS at lower temperatures. Early studies showed that some features of GBS were observed at lower temperatures in these materials such as grain boundary offsets after deformation and increased strain rate sensitivity. However, the experimental data of flow stress and strain rate do not agree with the predictions from the rate equation for high temperature GBS. A recent paper [15] showed that a simplification considered in the model for high temperature GBS is not valid for lower temperature deformation and a modified version of the rate equation was suggested. The present overview evaluates this modified model and show that the mechanism of grain boundary sliding agrees with experimental data for lower temperature deformation of many metallic materials.

The model for grain boundary sliding and data for room temperature strength

The model [15] considers that grain boundary sliding takes place by the movement of dislocations in the vicinity of grain boundaries. These dislocations pile up at triple junctions increasing the stress and trigger dislocation motion in the neighboring grains. These dislocations then pile up at the opposite boundaries where they undergo climbing assisted by the high stresses. The equation for the deformation rate is available elsewhere [15] and an equation for the flow stress is given below [15].

$$\sigma \approx \sqrt{\frac{3GkT}{2d_s b^2} ln\left(\frac{\dot{\varepsilon} d_s{}^3}{10\delta D_{gb}} + 1\right)} \tag{2}$$

where d_s is the spatial grain size and δ is the grain boundary width which is usually considered as $2b$. It was shown that the predictions of this model agrees with experimental data for multiple materials tested at different temperatures and strain rates [15]. For instance, Fig. 2 shows a good agreement between the flow stress determined in experiments at room temperature and the predictions from eq. 2 for 27 different materials processed by high-pressure torsion [16].

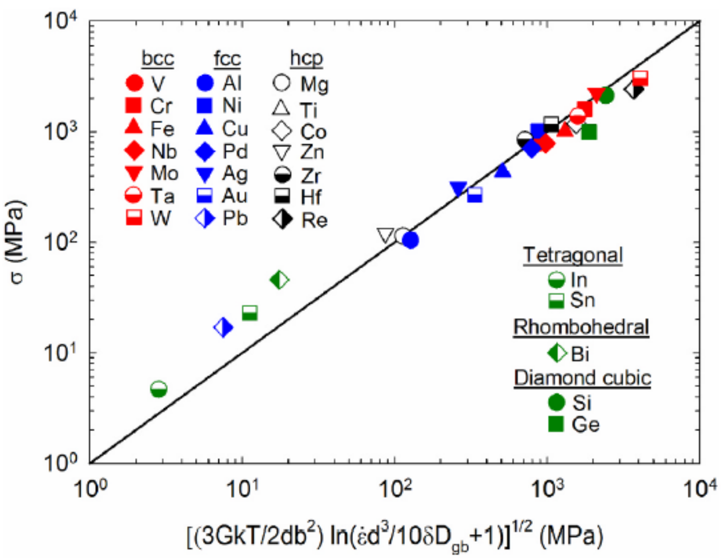

Figure 2 – Flow stress determined in experiments at room temperature plotted as a function of the flow stress predicted by the model of grain boundary sliding for 27 different materials [16].

The model of grain boundary sliding only predicts the contribution of the grain size to the flow stress and other strengthening mechanisms such as solid solution hardening must be incorporated in order to evaluate the overall strength of materials. Thus, the contribution of other strengthening mechanisms might be introduced by the incorporation of a parameter σ_0 in addition to the right side of eq. 2. Also, many studies evaluate the grain size using the mean linear intercept length method and this affects the prediction of the GBS model. Thus, eq. 3 shows the prediction of the flow stress considering a threshold stress, σ_0, and the mean linear intercept grain size, d_l.

$$\sigma = \sigma_0 + \sqrt{\frac{\sqrt{3}GkT}{2d_l b^2} ln\left(\frac{\dot{\varepsilon} d_l{}^3}{2\delta D_{gb}} + 1\right)} \tag{3}$$

It has been shown that the model of GBS might predict a Hall-Petch relationship between the flow stress and the grain size at low temperatures and a good agreement has been reported with experimental data for multiple materials and a broad range of grain sizes [15, 17-21]. The transition between the high temperature and low temperature behavior is examined next.

Transition between high- and low-temperature behavior

A recent review [21] evaluated the relationship between the grain size and the flow stress for different temperature ranges considering the grain boundary sliding (GBS) model. A Hall-Petch relationship is predicted at low temperatures and superplasticity is predicted at high temperatures for fine grained materials. Low temperature is considered as $T<0.3T_M$ and high temperature is

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considered as T>0.5T_M where T_M is the melting temperature of the material. Moderate temperatures are considered as the range 0.3 T_M<T<0.5 T_M and a gradual transition is predicted in the moderate temperature range. Figure 3 shows representative curves of the prediction of the GBS model for the relationship between flow stress and strain rate for two grain sizes at the different temperature ranges [21]. The behavior of an ultrafine grained material is depicted by the dashed lines and d_1 while the behavior of a fine grained material is depicted by continuous lines and d_2. The ultrafine grained material display higher flow stress than the fine grained counterpart at low temperatures and the opposite is observed at high temperature. At moderate temperatures the ultrafine grained material might display higher strength at high strain rates and lower strength at low strain rates. The slope of the curve of the ultrafine grained material is larger than the slope of the fine grained counterpart.

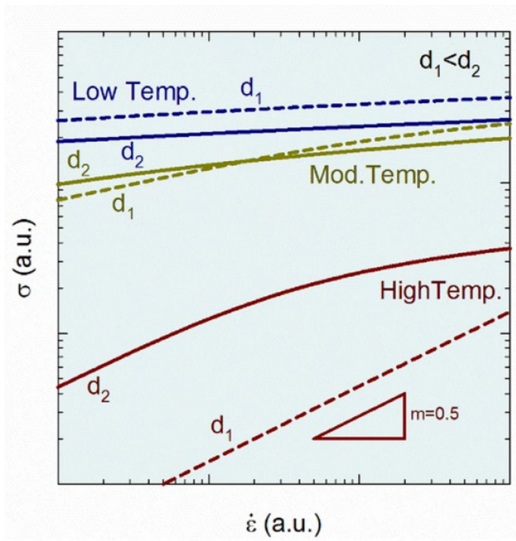

Figure 3 – General trends for the relationship between flow stress and strain rate for materials with different grain sizes and tested at different temperature ranges [21].

The strain rate sensitivity is estimated by the slope in the plots of flow stress vs strain rate. Thus, the predictions of the GBS model depicted in Fig. 3 suggests that the strain rate sensitivity of ultrafine grained materials increases with increasing temperature. This effect has been reported in the literature for multiple materials and Fig. 4 shows experimental data [22-24] of strain rate sensitivity of a CrMnFeCoNi multi component alloy tested at different temperatures. The predictions from the GBS model are also shown. The experimental data shows an increase in the strain rate sensitivity values with increasing temperature in agreement with the predictions from the model.

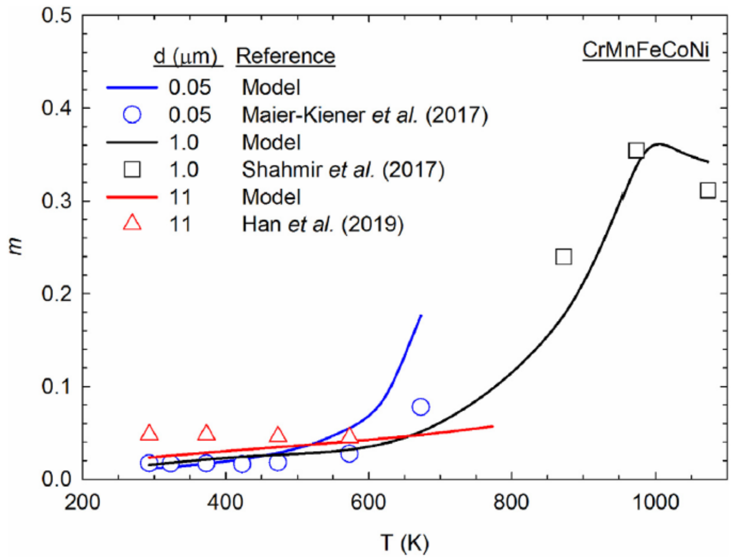

Figure 4 – Strain rate sensitivity of CrMnFeCoNi alloy at different temperatures [20]

The gradual transition between low temperature behavior, with low strain rate sensitivity, and high temperature behavior, with high strain rate sensitivity, is also confirmed by experimental data from ultrafine grained Al-Mg alloys tested at different temperatures. Figure 5 shows the predictions from the model of grain boundary sliding for the relationship between flow stress and strain rate for temperatures of 298 K, 403 K, 523 K and 673 K. It is important to note that the threshold stress is considered as a thermally activated process in the prediction depicted in Fig. 5 [21]. Experimental data from the literature is also shown for comparison and display good agreement with the predictions. Thus, a gradual increase in slope in the relationship between flow stress and strain rate is observed with increasing temperature. This analysis confirms that the model of grain boundary sliding [15] display good agreement with experimental data and predicts a gradual increase in strain rate sensitivity of fine grained material with increasing temperature.

Summary and conclusions

Grain boundary sliding is an established deformation mechanism for high temperature deformation of fine grained materials. A recent paper [15] showed that the rate controlling equation for the mechanism of grain boundary sliding can be adapted to account for the higher stresses of low temperature deformation.

The present overview shows that the adapted equation for grain boundary sliding predicts a gradual transition from the typical behavior observed at high temperature in fine grained materials to a Hall-Petch type of behavior at low temperatures.

The transition from low temperature to high temperature changes the relationship between flow stress and grain size in a way that grain refinement hardening is observed at low temperatures and grain refinement softening at high temperatures.

A gradual increase in strain rate sensitivity with increasing temperature is predicted and confirmed by experiments in ultrafine grained materials.

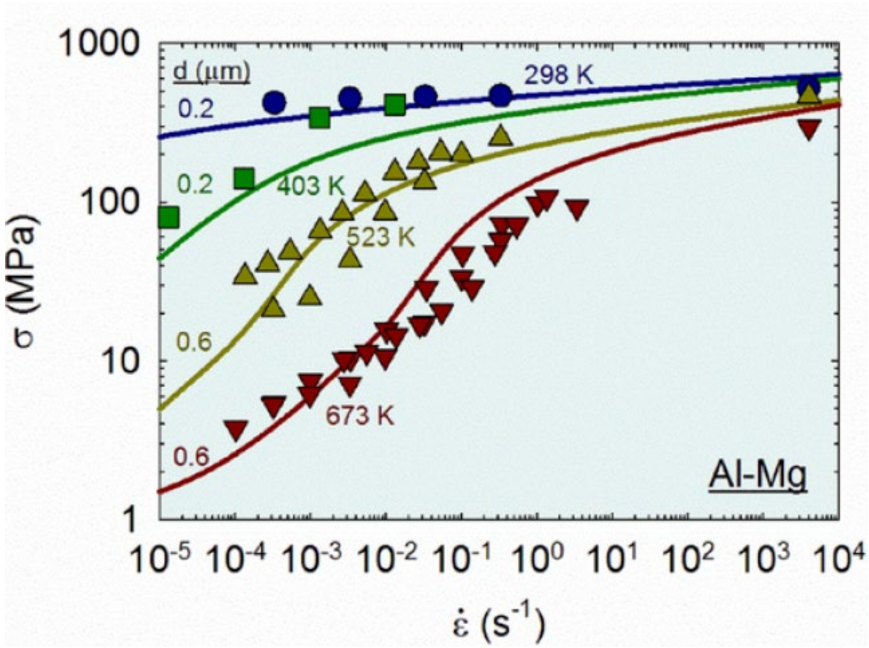

Figure 5 – Experimental data and model prediction of flow stress of ultrafine Al-Mg alloys tested at different temperatures plotted as a function of the strain rate [21].

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