Communications

Superplastic Behavior of a Zn-22 Pct Al-0.5 Pct Cu Alloy

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The Zn-22 pct Al eutectoid alloy is a popular superplastic material, due to its low forming temperature, high strain rate sensitivity, and very high tensile elongation. However, because of its low melting temperature the material is prone to creep at room temperature. In an attempt to improve the room temperature properties of this material, the addition of small amounts of copper has been tried. Alloy additions of up to 1 pct have led to a 300 pct increase in room temperature yield strength and a decrease in creep rate of more than two orders of magnitude.[1] These additions, moreover, seem to have relatively little effect on the superplastic properties of the material, at least as regards flow stress and strain rate sensitivity.

The superplastic properties of the simple binary eutectoid alloy have been extensively investigated by Langdon *et al.*[2-6] They find only limited amounts of deformation-induced grain growth, both in commercial material and in a high purity alloy.[4,5] Thus the material exhibits relatively sharp necks and low tensile elongations at low strain rates (region I superplastic behavior). In contrast, Nuttal and Nicholson[7] reported a grain size increase by a factor of 2 after a strain of only 1.8, at a strain rate of 10^{-3} s^{-1}, albeit at a relatively high temperature (250 °C). The appearance of cavitation has been reported, even in material made from high purity elements, although in this case the level of cavitation is considerably reduced.[4,5]

The present study was initiated to investigate in more detail the effect of copper additions to a commercial Zn-Al alloy on the superplastic properties. In particular, we have examined the deformation-induced grain growth behavior in this alloy. The differences which we find between this alloy and the Cu-free alloy can be related to differences in neck development and tensile elongations, as outlined below.

Material for testing was obtained from Cominco, Ltd. in the form of a 2.5 mm thickness sheet, and in a condition suitable for superplastic forming. Tensile specimens were cut from the sheet with the tensile axis parallel to the rolling direction. The specimens had a gauge length of 6 mm and a width of 4 mm. Each specimen was annealed for 1 hour at 553 K (80 K above the test temperature) to give a grain size of 1.2 μm (as measured by mean linear intercept).

All tensile tests were conducted in air using an Instron machine operating at constant crosshead speed. At the lowest strain rate, however, the elongation rate was doubled every 150 pct elongation. The test temperature was 473 K. Temperature was maintained to within ± 2 K both along the gauge length and throughout the test.

After failure, specimens were sectioned parallel to the tensile direction and polished to a 0.3 μm Al_2O_3 finish. Nital etching was used to reveal grain structure. The mean linear intercept grain size (actually average phase size) was measured. No measurements of grain aspect ratio or of individual phase size were obtained.

Figure 1 shows the true flow stress as a function of the nominal strain rate, taken at a constant strain of about 0.3. This curve exhibits typical superplastic sigmoidal behavior. The strain rate sensitivity, m, has a peak value of 0.55 at intermediate strain rates, falling to about 0.21 at the lowest strain rate. Figure 2 shows the elongation to fracture, again as a function of the nominal strain rate. There is a broad maximum in the elongation, the center of which occurs at roughly the same strain rate as that at which the peak in strain sensitivity is found. It is also clear from the figure that the fracture elongation falls more rapidly with increasing strain rate than with decreasing strain rate. This is consistent with observations of the samples after testing. Deformation in the lower strain rate regime is very uniform—only diffuse necks are found. In contrast, samples tested at high strain rates exhibit sharp necks.

Measurements of strain-enhanced grain growth in this alloy have been briefly reported previously.[8] The results are discussed in detail here. We find that very little grain growth occurs during stress-free annealing or in the shoulder of the specimen while very considerable grain growth occurs under the influence of deformation. The results of quantitative measurements of grain size are shown in Figure 3. As

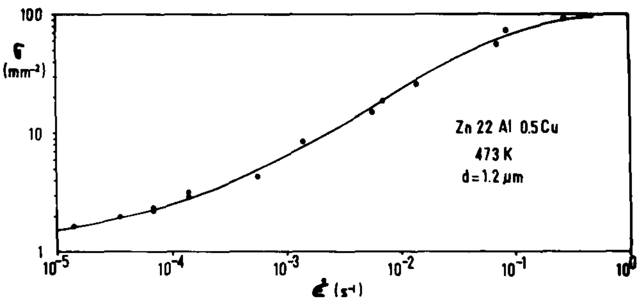

Fig. 1—The stress-strain rate curve, showing typical sigmoidal behavior, measured after a strain of about 0.3.

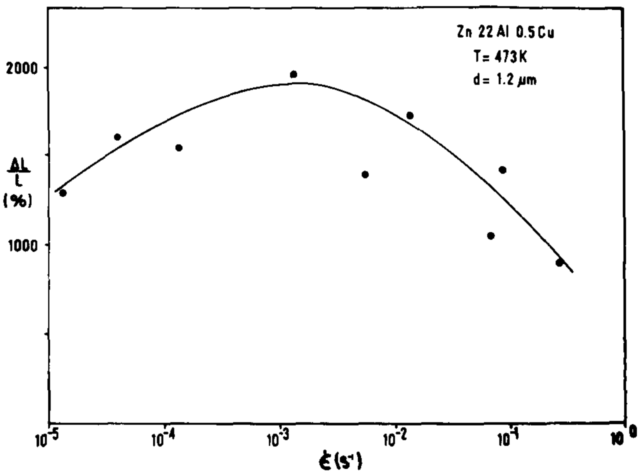

Fig. 2—The percent elongation to fracture as a function of the nominal strain rate.

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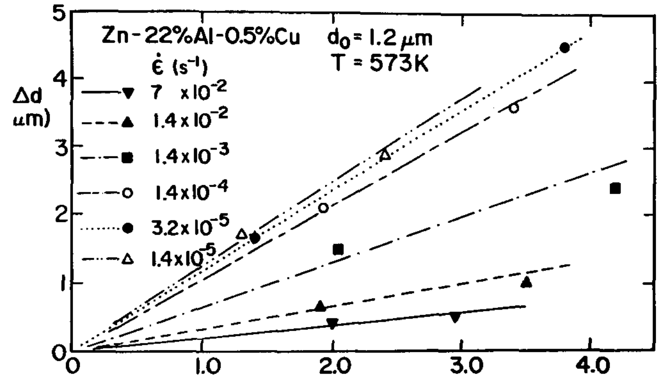

Fig. 3 — Grain size increment as a function of true strain for samples tested at different nominal strain rates.

generally observed, the amount of grain growth per unit strain is largest at the smallest strain rates, even though the actual grain growth rate per unit time increases with increasing strain rate.

A comparison of our results with those of Mohamed *et al.* (1977) on Cu-free Zn-22 pct Al suggests that there is very little effect of copper addition on the flow stress of this material under superplastic testing conditions. This is consistent with the results of Naziri and Pearce.[1] However, the other properties which we have measured, related to grain growth and the fracture process, are considerably different between the two materials. While we have no clear understanding of the mechanism by which Cu influences the behavior of the material, we are able to suggest how the various property changes are interrelated. In particular, we feel that the primary role of the Cu addition is to influence the grain growth behavior — both normal stress-free grain growth and strain-enhanced grain growth — and that other property changes follow directly from that.

The fracture behavior of the two alloys differs considerably. Figure 4 contrasts the elongation to failure which we have measured with that measured by Mohamed *et al.*[3] on the Cu-free alloy. The Cu-containing alloy shows a much weaker dependence of elongation on strain rate. At intermediate strain rates the elongations are considerably higher in the Cu-free alloy, while at low strain rates they are lower in the Cu-free alloy. In addition we see very diffuse necking in the Cu-containing alloy at low strain rate, while Mohamed *et al.*[3] report sharp necks in the Cu-free material.

The deformation-induced grain growth behavior of this alloy also contrasts with that of the Cu-free material. The largest grain growth increment observed by Mohamed *et al.*[3] was a factor of 2 increase at a low strain rate, while we find much larger grain size increases. Unfortunately, an exact comparison of the two sets of data is impossible since the true strains at the point where grain size is measured are not reported by Mohamed *et al.*[3] The data presented here for the Cu-containing alloy, however, have been shown to be consistent with grain growth data on other alloys, and to fit the predictions of a model for deformation-induced grain growth.[8,9] This model suggests that in micro-duplex materials, grain growth results from an enhanced coarsening of the second phase particles as they are brought into contact by grain switching during superplastic flow. If the rate of grain growth is able to keep up with the rate of particle coarsening, then the model predicts a grain growth rate per unit strain approximately equal to the current grain size, and independent of the strain rate. If, however, the rate of grain growth is unable to keep up with the rate of particle coarsening, and the grain size falls below the Zener limit, then the rate of grain growth will become strain-rate dependent. One ought to be able to confirm such a prediction experimentally by measuring the growth rate of the two phases separately. If the prediction is correct, then at the higher strain rates the phase size of the harder, nondeforming phase should increase more rapidly than that of the softer phase. This model suggests a possible explanation for the difference in grain growth between the two alloys. Even if the rate of grain growth far exceeds that observed in the absence of stress, the above prediction suggests that differences in the static grain growth rate should be reflected in the deformation-induced grain growth behavior. We have measured the rate of grain growth during stress-free annealing. We find that our results are in good agreement with those of Guimaraes and Victoria[10] on a high-purity Zn-Al eutectoid alloy. Mohamed *et al.*[4] observed a lower rate of static grain growth. This is consistent with the predictions of the model, and suggests that the influence of Cu on the strain-enhanced grain growth behavior is related to its influence on normal stress-free grain growth.

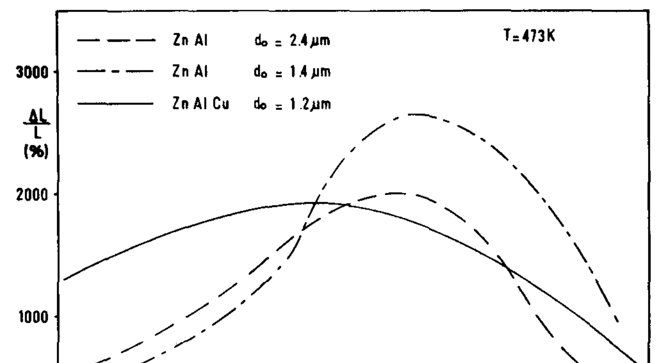

Fig. 4 — Elongation to failure data for the Cu-containing alloy tested in this work (solid line) is compared with data from the work of Mohamed *et al.*[3] for a Cu-free alloy (dashed lines).

To understand the effect of deformation-induced grain growth on the elongation to failure, we use a simple model proposed in earlier work.[11] It is based on the effect of grain size on flow stress during superplastic deformation. We can write a simplified constitutive equation for superplastic flow as

$$\sigma = K\dot{\varepsilon}^m d^{pm} \qquad [1]$$

where K and p are material constants. It is clear from this equation that if grain size varies in the specimen as a function of the local strain, then the flow stress will also vary locally and will be strain-dependent. Thus strain-induced grain growth leads to a form of strain hardening. The exact form of the strain hardening depends, at constant strain rate, on the dependence of grain size on local strain. This can be approximated by a power relationship of the form

$$d = d_0 + C\varepsilon^\alpha \qquad [2]$$

where C is a constant which depends on the strain rate as well as material parameters. Equations [1] and [2] can be combined to yield the strain-dependence of the strain hardening coefficient

$$\gamma = \frac{1}{\sigma}\frac{d\sigma}{d\varepsilon} = \frac{\alpha C p m \varepsilon^{\alpha-1}}{d_0 + C\varepsilon^{\alpha}} \qquad [3]$$

Experimental observations indicate either that grain growth is linear in strain ($\alpha = 1$), or that the rate of grain growth decreases with increasing strain ($\alpha < 1$). In the first case, Eq. [3] reduces to

$$\gamma = \frac{Cpm}{d_0 + C\varepsilon} \qquad [4]$$

Using Eq. [4] we can determine the strain hardening coefficient as a function of strain from experimental data. This can then be used to understand the development of tensile instabilities during deformation. In previous work[10] we suggested that the rate of neck development could be characterized by an instability parameter I, where

$$I = \frac{1 - \gamma - m}{m} \qquad [5]$$

The larger the value of I, the faster necks will grow. A value of I equal to zero corresponds to $\gamma + m = 1$, which according to Hart[12] defines the onset of instability during tensile testing.

An evaluation of I for the Zn-Al-Cu alloy requires a knowledge of several parameters in Eq. [3]. We first assume on the basis of our data that grain growth is linear in strain. Thus $\alpha = 1$ and Eq. [4] can be used in place of Eq. [3]. The grain size dependence of the flow stress has not been measured for this alloy. However, since the flow stress behavior is much the same as in the Cu-free alloy, we can obtain an estimate using the data of Mohamed *et al.*[3] This gives a value for $p = 2.44$ under the conditions of interest here. Values of m and C are taken from our data. The results are plotted in Figure 5 for three different strain rates. At the highest and lowest strain rates the strain rate sensitivity was approximately equal ($m = 0.21$ at $1.4 \times 10^{-5}\ s^{-1}$, while $m = 0.20$ at $5 \times 10^{-2}\ s^{-1}$). However, the values of I are much lower at the lower strain rate due to the influence of

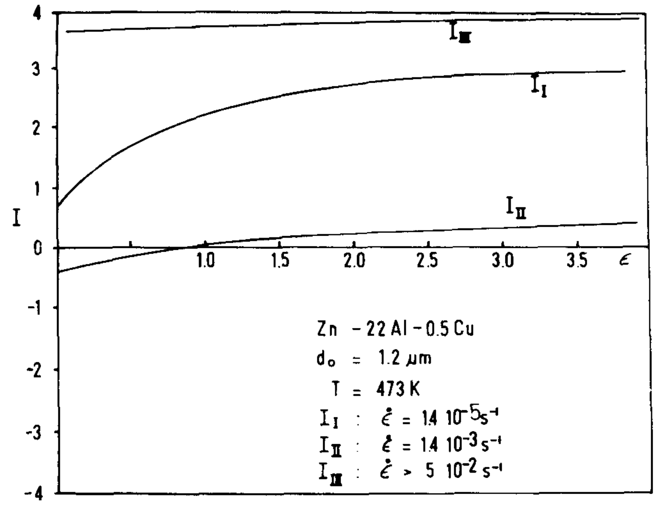

Fig. 5—The instability parameter, I, plotted as a function of strain for three different strain rates.

grain growth-induced hardening. The sharpness of the necks we observe rank in the same order as the values of I. This therefore provides qualitative evidence for the effect of grain growth on tensile instability. However, the absolute values of I are disturbing. I is considerably larger at the lowest strain rate than at the intermediate strain rate. This would suggest that necks should be considerably sharper at the lower strain rate. This is not the case. This may be the result of an inappropriate value for p, implied from work on the Cu-free alloy. More likely, it is due to strain rate changes during the test. During constant elongation rate testing, the true strain rate changes considerably especially after the commencement of necking. Therefore the value of m used in these calculations, which applies at small strains, is not applicable throughout the test. Instead, the material sees a range of m (and C) values. This is likely to smooth out the difference between region I and region II.

In summary, we find that a commercial Zn-Al eutectoid alloy containing 0.5 pct Cu shows a decrease in superplastic elongation (as compared to a Cu-free alloy) under optimum strain rate conditions. However, a considerable enhancement of elongation is found at lower strain rates. Strain-enhanced grain growth is much more pronounced in this alloy than in the Cu-free alloy. The difference in elongation between the two alloys at low strain rates can be understood qualitatively in terms of the strain hardening effect brought about by strain-enhanced grain growth.

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