An evaluation of available data for strain-enhanced grain growth during superplastic flow

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Several investigators in recent years have reported superplastic flow accompanied by grain growth [1–6]. In all cases the measured grain growth rate greatly exceeds that which occurs in the absence of deformation. This phenomenon, which we call "strain-enhanced grain growth" is the subject of the present paper. It has been observed in a wide range of superplastic materials including a solid-solution Sn–Bi alloy [1], a particle strengthened copper alloy [2], and several alloys with micro-duplex structures [3–6]. It is generally observed that the amount of grain growth in a tensile specimen after superplastic deformation increases with strain. It may also (but not always) depend on the strain rate applied.

This process is important for several reasons. First, the flow stress during superplastic deformation increases with grain size. Thus, strain-enhanced grain growth produces an effective strain hardening. This in turn increases the stability of flow, an important factor in assessing the sheet forming properties of a material. In addition, the superplastic regime is limited by grain size. Thus if sufficient grain growth occurs at a given strain rate, the material will lose its superplastic properties, and thus its formability.

Much of the previous work on this phenomenon has attempted to relate the grain growth increment during a test Δd, to the strain and strain-rate or time. For example, Cáceres and Wilkinson [2] show that data for a copper alloy fit a relation of the form

$$\Delta d_\epsilon = k_\epsilon \epsilon \dot{\epsilon} - p \qquad (1)$$

where $p = 0.25$ under the conditions studied. Here Δd_ϵ is the strain-enhanced portion of the grain growth only, i.e. the grain growth increase left after the grain growth produced by static annealing for the same time is subtracted. An alternative relationship, produced by Ghosh and Hamilton [5] for a titanium alloy uses time as a variable. They find

$$\Delta d_t = k_t t^q \dot{\epsilon}^{-p} \qquad (2)$$

These expressions, while they can be used to produce an empirical constitutive law for a single material, are of limited use. In this paper, we report some new experimental results. We then use these data, along with data from the literature to show that, by plotting the results in a different way than has generally been done, a more general relationship between grain growth and deformation is found.

The rate of grain growth during deformation has been measured for two superplastic alloys – a single phase copper alloy, Coronze 638, and the Zn–Al eutectoid.

Some of the Coronze data have been reported elsewhere [2], along with details on the materials and test procedures used. However, these tests have since been extended to lower strain rates, to better assess the limiting grain growth behaviour of the alloy. Most tests were run using a constant elongation rate, at 550° C. However, the lowest strain rates were achieved using a constant load creep tester. Here the load was adjusted periodically to ensure a nearly constant elongation rate. The material tested had an initial grain size (mean linear intercept) of 1.3 μm.

The results of this work are shown in Fig. 1. We find no measurable grain growth during static annealing for all times of interest. Thus both Δd and Δd_ϵ are equal. To within the accuracy of measurement, grain size increases linearly with strain. Moreover, the amount of grain growth per unit strain increases with decreasing strain rate

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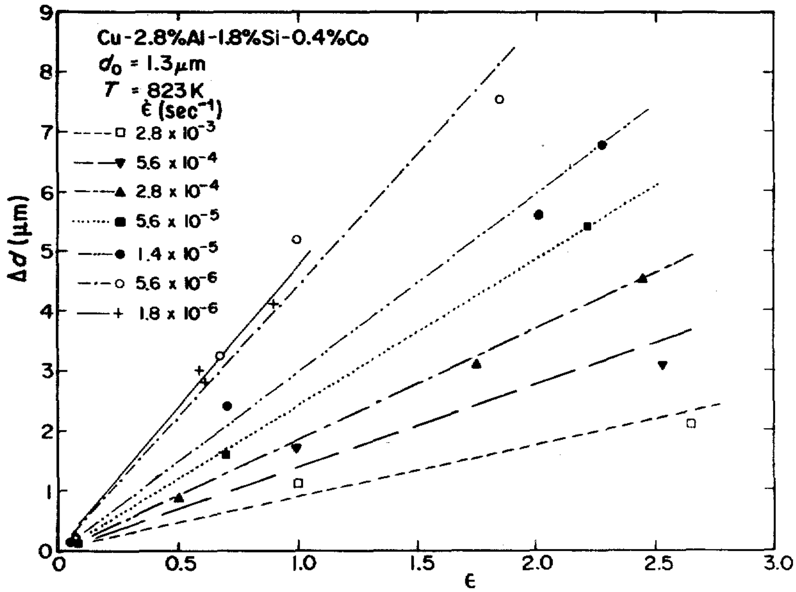

Figure 1 The increase in grain size Δd, plotted as a function of strain for different strain rates, for Coronze 638.

until, at the lowest strain rates, strain rate independent behaviour begins to emerge.

A similar set of tests were performed on a Zn–Al alloy at 200° C. This material has a nominal composition of Zn–22%Al–0.5% Cu, and had been thermomechanically treated to achieve an initial grain size of 1.2 μm. A detailed description of this work is reported elsewhere [8], but the results which are relevant here are given in Fig. 2. As with the copper alloy, considerable grain growth is observed, and the grain size depends linearly on strain. The grain growth per unit strain becomes independent of strain rate at low rates.

Fig. 3 shows the data for the copper alloy plotted in terms of grain size increment per unit strain as a function of strain rate. The datum shown as an open circle is the result of tests performed since this work was first published [2]. Without this extra point, it is reasonable to draw a straight line through the data and produce the empirical grain growth relation given as Equation 1. With the additional point, this is no longer possible. Instead the grain growth per unit strain seems to approach a limiting value at low strain rate. This illustrates the obvious disadvantage of employing empirical relations based on limited data. They are strictly valid only over the range of conditions for which the data was collected.

This trend is observed more celarly if we plot, as in Fig. 4, the grain growth increment per unit strain as a function of strain rate for a range of materials – the two reported above, plus three others for which the necessary data* is available in the literature [1, 4, 5]. The test conditions for each material are listed in Table I. It is important to realize that this figure shows Δd_ϵ, the strain-

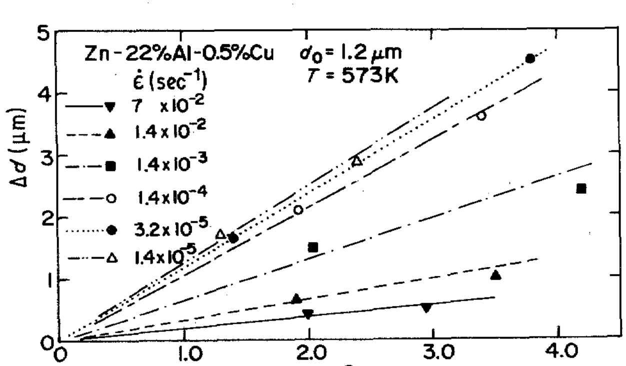

Figure 2 The increase in grain size Δd, plotted as a function of strain for different strain rates, for Zn–22% Al.

*This is done by replotting the data provided in the literature, as Δd_ϵ against ϵ, as in Fig. 1. The slope for a linear fit to these data for a given $\dot{\epsilon}$ is then used to produce the curves shown in Fig. 4.

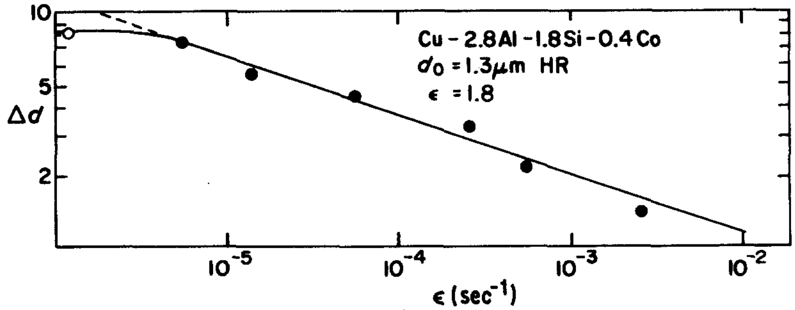

Figure 3 The increase in grain size per unit strain ($\partial d/\partial \epsilon$) for Coronze 638, plotted as a function of strain rate. The open circle represents recent data.

enhanced portion of the grain growth only. Inclusion of the static annealing portion of the grain growth Δd_a, obscures the trend of the data at low strain rates†. It is clear from this figure that while the strain-enhanced grain growth per unit strain $\partial d_\epsilon/\partial \epsilon$, is strain-rate dependent at higher strain rates, if tests are carried out to low enough strain rates, an upper limit is approached. This is most clearly evident in Clark and Alden's [1] data for the Sn–Bi alloy which cover the largest range of strain rate (5 orders of magnitude).

What is not clear from this figure is what governs the shape of the curve at high strain rates. This is better determined by plotting the grain growth rate (per unit time) against strain rate, as in Fig. 5. It appears, although the evidence is far from conclusive, that the growth rate approaches an upper limit at high strain rates, in much the same way that a lower limit, the static annealing grain growth rate, is approached at low strain rates. These limits are clearly material dependent. They are also, no doubt, sensitive to temperature.

The horizontal regions of Fig. 4 translate into linear regions of unit slope in Fig. 5. The extent of this linear region depends on the rate of static grain growth. However, it appears for all materials. Furthermore, the grain growth rates in this regime all lie within a restricted range of a little over an order of magnitude. Considering the wide range of materials and testing conditions, this is remarkable.

We can improve this correlation even further if we normalize $\dot{d}$ by the initial grain size d_0, as in Fig. 6. The linear regime now lies within a narrow band which is adequately described by the equation

$$\dot{d} = \lambda d_0 \dot{\epsilon} \tag{3}$$

where $\lambda \approx 1$.

The overall shape of the curves in Fig. 6 can be described by an equation of the form

$$\dot{d} = \dot{d}_a + \frac{\lambda d_0 \dot{\epsilon} \dot{d}_u}{\lambda d_0 \dot{\epsilon} + \dot{d}_u} \tag{4}$$

Here $\dot{d}_a$ and $\dot{d}_u$ are the upper and lower limiting grain growth rates respectively. The meaning of $\dot{d}_a$

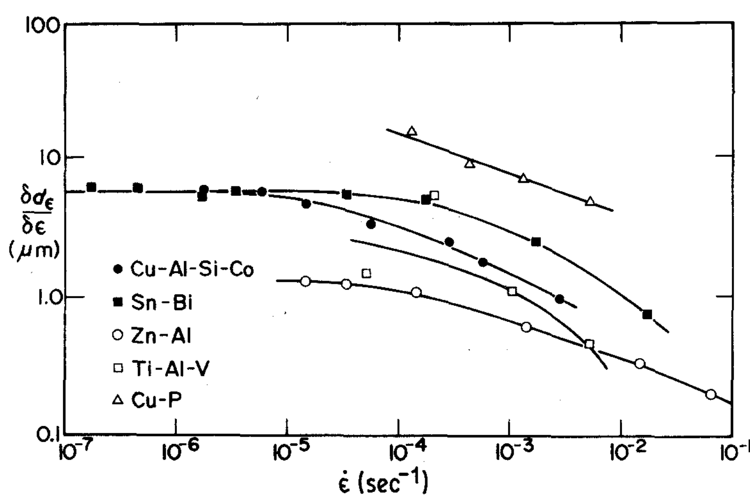

Figure 4 The strain-enhanced grain size increase ($\partial d_\epsilon/\partial \epsilon$), plotted against strain rate, for a variety of materials.

†Of course, this assumed that the two processes are separable, i.e. $\Delta d = \Delta d_a + \Delta d_\epsilon$, which may not be strictly valid in all cases.

TABLE I

Material	Temperature (K)	Initial grain-size (μm)	Material type	References
Cu–2.8% Al–1.8% Si.4% Co	823	1.3	Single phase	Present work
Sn–1% Bi	300	1.8	Single phase	[1]
Zn–22% Al–0.5% Cu	573	1.2	Microduplex	Present work
Cu–7% P	823	8.6	Microduplex	[4]
Ti–6% Al–4% V	1200	6.4	Microduplex	[7]

is clear – it is the grain growth rate found in the absence of deformation. The meaning of $\dot{d}_u$ is less clear. We do not know whether it exists for all materials, whether it is temperature dependent, etc. However, a limit does appear to exist for at least two of the materials studied (Sn–Bi, and Ti–Al–V). Since both of these materials are tested at relatively low homologous temperature ($T/T_M \sim 0.6$, using T_M for the primary element), it may be that $\dot{d}_u$ represents an upper limit on the grain boundary migration rate which increases with temperature. This concept needs to be studied experimentally.

An alternative formulation to Equation 4, which also describes the shape of the curves in Fig. 5 is

$$\dot{d} = \dot{d}_a + \lambda d_0 \dot{\epsilon}$$

where

$$\lambda = \lambda(\dot{\epsilon})$$

such that $\lambda \approx 1$ at low strain rates, but decreases with increasing strain rate above a certain value. It may for example be tied to the decrease in strain-rate sensitivity of the flow stress at high

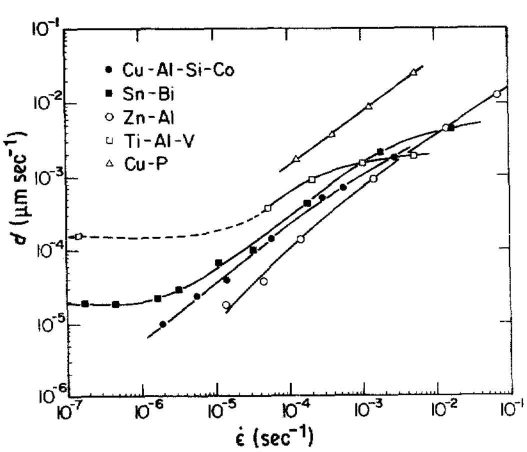

Figure 5 Grain growth rate $\dot{d}$, plotted against strain rate, for a variety of materials.

strain rates. This however, does not appear to be the correct explanation. For example, the peak in strain-rate sensitivity occurs at about the same strain rate (2×10^{-4} sec^{-1}) for both the Coronze and Sn–Bi alloys. However, the deviation from linear behaviour occurs at very different strain rates (see Fig. 4). Moreover, in all materials, this deviation occurs at strain rates below that at which the strain-rate sensitivity is a maximum.

It can be concluded:

1. Strain-enhanced grain growth during superplastic flow is a widespread phenomenon, being found in both single-phase (solid solution and particle strengthened) alloys, and in microduplex alloys.

2. When the grain growth rate (per unit time) is plotted against strain rate, three regimes appear:

(a) At low strain rates, strain-enhanced grain growth is swamped by the normal grain growth process.

(b) At intermediate strain rates, a linear relation of the form

$$\dot{d} = \lambda d_0 \dot{\epsilon}$$

is found, where $\lambda \approx 1$, for all materials and conditions studied.

(c) At higher strain rates, but still within the superplastic regime, a deviation form this linear behaviour is found. This may represent an approach to an upper limiting grain growth rate $\dot{d}_u$, or it may represent a strain rate dependence for the parameter λ.

3. Depending on which of the postulates (2c) one prefers, the data may be represented either by an equation of the form

$$\dot{d} = \dot{d}_a + \frac{\lambda d_0 \dot{\epsilon} \dot{d}_u}{\lambda d_0 \dot{\epsilon} + \dot{d}_u}$$

or one of the form

$$\dot{d} = \dot{d}_a + \lambda d_0 \dot{\epsilon}$$

where $\lambda = \lambda(\epsilon)$.

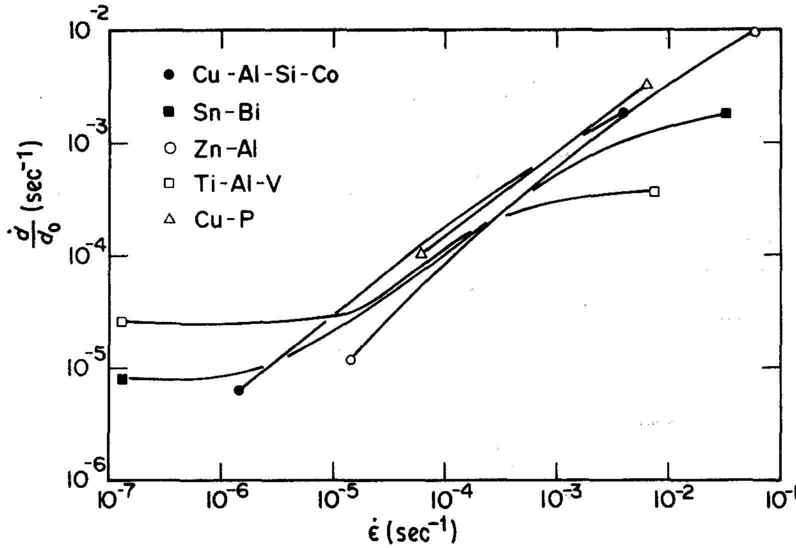

Figure 6 Grain growth rate $\dot{d}$, normalized by the initial grain size d_0, and plotted against strain rate, for various materials. For clarity, the individual data points are not included. The symbols at the ends of each curve are intended only to denote the material to which it corresponds.

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