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Cavitation during the superplastic deformation of an α/β brass

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Cavitation during superplastic tensile flow has been studied in an α/β brass using metallography and precision density measurements. Cavities nucleated primarily at triple points and were sometimes associated with small second phase particles. The level of cavitation increased as strain, strain rate and grain size were increased and as the temperature was decreased. The influence of these variables can be interpreted in terms of their effects on cavity nucleation and/or cavity growth rates.

1. Introduction

The range of materials which can exhibit superplastic flow is increasing, and there is continuing interest in commercial superplastic forming techniques. The principal advantage of superplastic forming is related to the large plastic strains that may be achieved using relatively low stresses. Disadvantages are associated with the slow strain rates involved, the necessity of maintaining a relatively fine grain size during deformation, and the ability to control the deformation temperature within closely defined limits. A further problem which might inhibit commercial exploitation of some materials is the occurrence of cavitation during superplastic flow. Cavitation causes a decrease in the amount of deformation attainable [1, 2] and may have a deleterious effect on ambient temperature properties of superplastically deformed material [3–5].

Previous work in the authors' laboratory has been concerned with the superplastic deformation behaviour of microduplex steels, and it was clear that cavitation in these alloys was markedly influenced by the presence of large (5 to 10 μm), Ti(C,N) inclusions [6]. The present work was initiated on a relatively simple microduplex material, α/β brass, in an attempt to study the ways in which strain, strain rate, temperature and grain size influenced the level of cavitation in a system free from gross inclusions. Previous work by Sagat *et al.* [7] had shown that a fine-grained Cu–40% Zn alloy exhibited maximum superplasticity at 600° C with a tensile strain rate of approximately 10^{-5} sec^{-1}, and that during deformation cavitation had occurred.

2. Experimental

The α/β brass, containing nominally 40 wt % Zn was supplied by Imperial Metal Industries Ltd., as a 13 mm diameter bar. This had been extruded at 773 K to produce a microduplex α/β structure, with a grain size of $< 3\,\mu$m (measured as a mean linear intercept (m.l.i.)). A detailed spectrographic analysis indicated that no single impurity element was present in a quantity greater than 0.001 wt %.

Superplastic deformation was carried out in air by tensile straining of screw-headed specimens, of gauge length 10 mm and gauge diameter 3.8 mm, in a furnace attached to an Instron machine. Metallographic studies were made using optical and scanning electron microscopy. A number of specimens were deformed at constant cross-head velocities to pre-determined strains. The volume of cavities in the gauge length, produced by deformation, was measured by hydrostatic weighing in ethyl iodide using a corresponding gauge head as a standard.

3. Results

3.1. Mechanical behaviour

The strain rate sensitivity, m, was determined as a function of deformation temperature (Fig. 1),

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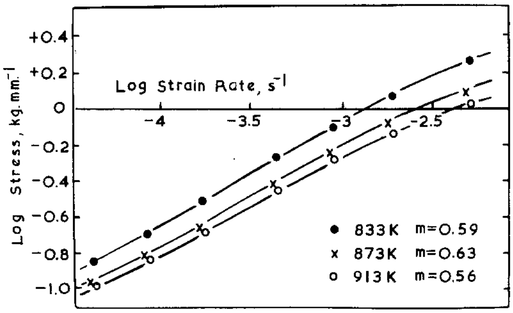


Figure 1 Logarithmic plot of flow stress/strain rate for α/β brass in the range 833 to 913 K. Initial m.l.i. 11.3 μm.

and grain size (Fig. 2), using the method proposed by Backofen *et al.* [8]. Although the as-received grain size was $< 3\,\mu$m, rapid grain growth during the initial temperature stabilization process produced much larger values prior to testing. Constant cross-head velocity tests to failure produced elongations up to 410% under optimum conditions of temperature and strain rate.

3.2. Microstructural observations

Metallographic examination of deformed specimens revealed that extensive cavitation had occurred under all test conditions. Fig. 3 shows a polished unetched longitudinal section of a specimen strained to 150% at a constant cross-head velocity of 1.67×10^{-2} mm sec^{-1} at 873 K. The cavities were relatively equiaxed, generally rounded, and evenly distributed across the specimen diameter.

Detailed examination of a large number of microsections revealed the association of cavities with phase and grain boundaries. It was difficult to determine the exact nucleation sites as the

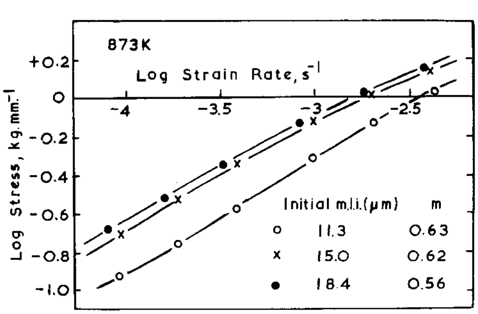


Figure 2 Logarithmic plot of flow stress/strain rate at 873 K for α/β brass with m.l.i. in the range 11.3 to 18.4 μm.

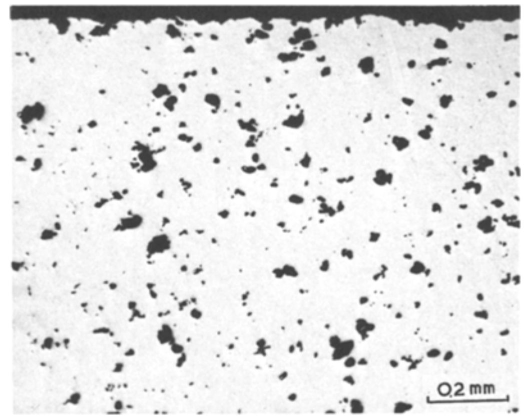


Figure 3 Cavities in a polished, unetched, longitudinal section of α/β brass. Strained to 150% elongation at 1.67×10^{-2} mm sec^{-1} at 873 K.

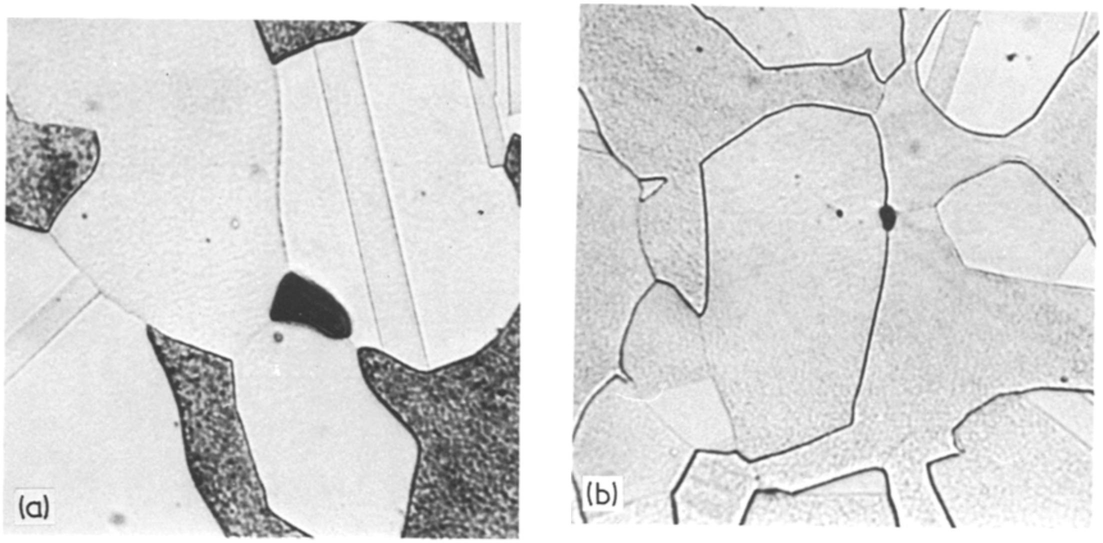
cavities had undergone growth before becoming optically visible and also cavities could have nucleated at sites above or below the plane of section. However, Fig. 4 shows (a) a cavity at an $\alpha/\alpha/\alpha$ triple point, (b) a cavity at an $\alpha/\beta/\beta$ boundary, (c) the growth of a cavity along an α/α boundary, and the separation of two β grains by a cavity. A significant proportion of cavities appear to "bridge" adjacent β grains, suggesting that the adjacent β grains were once joined.

The absence of appreciable dezincification, to within approximately one grain diameter of the specimen surface, was indicated by optical metallography, and confirmed by electron probe microanalysis.

Despite the high purity of the brass some inclusions were noted in the microstructure (Fig. 4a). To determine the role that these particles were playing in cavity nucleation, several specimens were pre-cavitated by tensile straining at elevated temperature, and then broken in tension at room temperature. Examination of the fracture surfaces using scanning electron microscopy showed that some of the cavities were associated with inclusions (Fig. 5).

3.3. Density studies

In an initial investigation of the cavitation behaviour of the alloy, a series of specimens were strained at 873 K to pre-determined strains, at various strain rates within the superplastic regime. Density results showed that the volume of cavities increased with increasing strain and with increasing strain rate (Fig. 6).



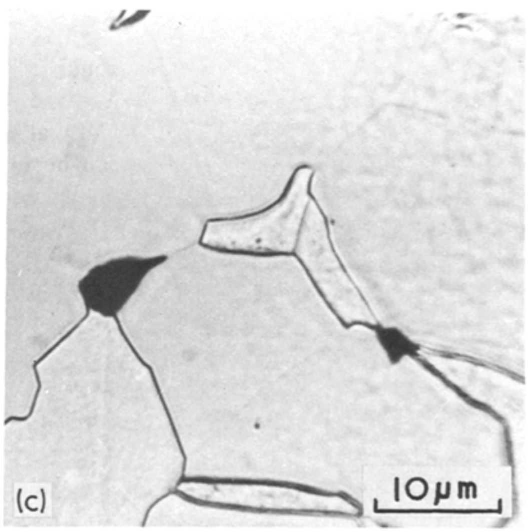


Figure 4 (a) Cavity at $\alpha/\alpha/\alpha$ triple point. (b) Cavity at $\alpha/\beta/\beta$ boundary. (c) Cavity growing along α/α boundary and separation of two β grains by a cavity.

A more systematic survey was then carried out, in which two series of specimens were deformed to a constant strain (150% elongation) at a temperature of 873 K. In the first series each specimen was allowed to remain at the test temperature for a different period of time prior to deformation, so as to produce a range of initial grain sizes. This type of test was performed at three different initial strain rates within the superplastic range. The volume of voids and area under the true stress–true strain curve, are plotted as a function of the average grain size (m.l.i.) during the test for the three different initial strain rates, in Fig. 7. The area under the true stress–true strain curve (in arbitrary units) provides a measure of the stress level, which varies with strain, during the test. The overall level of cavitation is essentially a summation of a series of incremental volume changes, each associated with a unique condition of stress, grain size etc.

In the second series of tests, specimens were allowed to equilibrate at the test temperature for a fixed time, so producing a constant initial grain size. Specimens were then strained to 150% at various strain rates within the superplastic regime. This type of test was carried out on specimens having initial grain sizes (m.l.i.) of 11.3 or 15.0 μm. The volume of cavities, area under the true stress–true strain curve, and

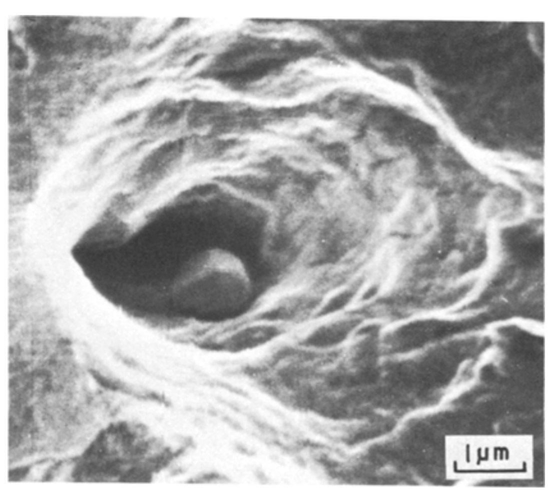


Figure 5 Particle associated with a cavity formed during superplastic deformation.

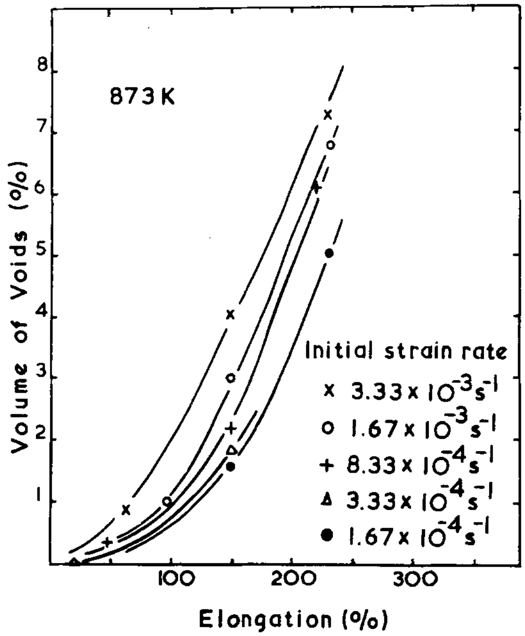


Figure 6 Volume of cavities as a function of strain for various initial strain rates at 873 K.

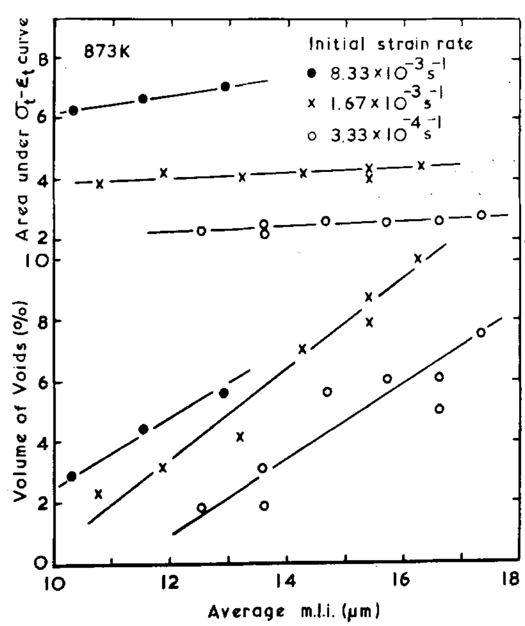


Figure 7 Volume of cavities and area under the $\sigma_t - \epsilon_t$ curve as a function of average m.l.i. for specimens elongated 150%.

the average grain size, are plotted as a function of the log of the average strain rate in Fig. 8.

The effect of temperature on the level of cavitation was measured by deforming a number of specimens to 150% elongation at a velocity of 1.66×10^{-2} mm $\sec^{-1}$, at temperatures in the range 833 to 913 K. The variation in temperature

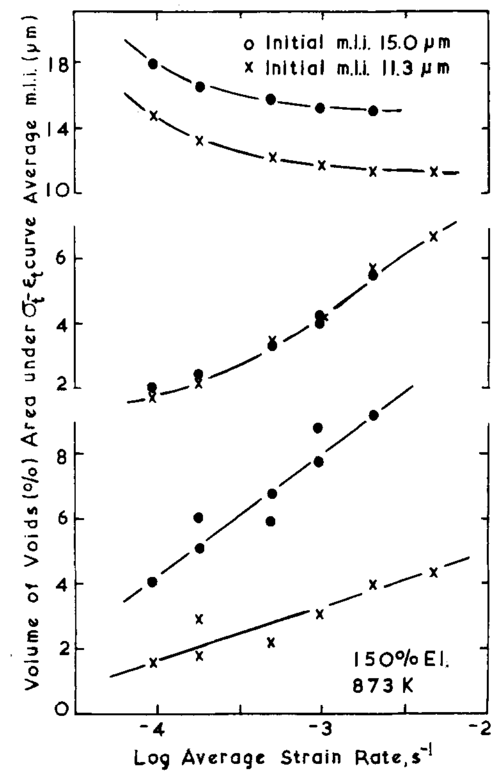


Figure 8 Volume of cavities, area under $\sigma_t - \epsilon_t$ curve and average m.l.i. as a function of average strain rate.

was restricted in order to ensure that the measurements were made over regions of comparable "m" values. The results, presented in Fig. 9, show the volume of cavities and the area under the true stress–true strain curve, as a function of the deformation temperature. Grain size (m.l.i.) measurements were only made at the completion of tests and the final values are included in Fig. 9.

4. Discussion

Examination of Figs. 1 and 2 shows that: (i) it is possible to obtain high "m" values, even at grain sizes greater than those normally associated with superplastic behaviour, i.e. m.l.i. of 14 to 21 μm, and (ii) a decrease in grain size or an increase in temperature moves the log stress–log strain rate curves to lower stress values, a result generally consistent with the observations of other workers [6, 9].

The large number of individual cavities present (Fig. 3) is indicative of the slow rate of cavity interlinkage, and this may be attributed to the high "m" value of the material. Detailed examination of the alloy has shown that cavities appear to be nucleated at grain and interphase boundaries,

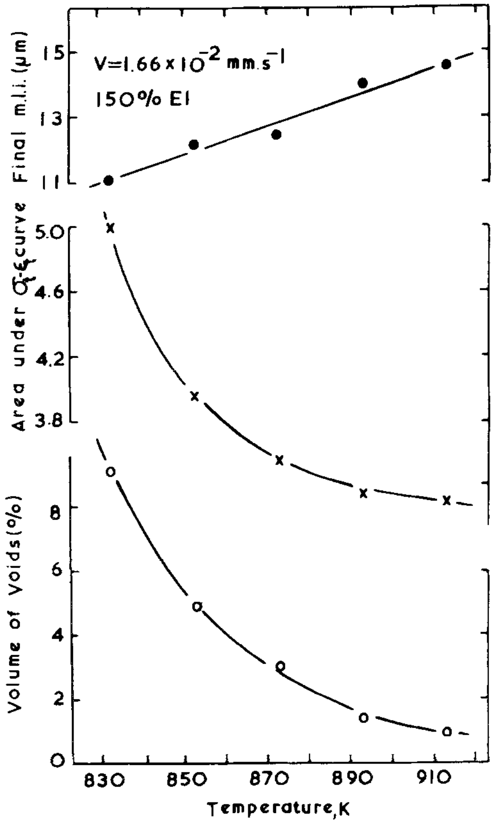


Figure 9 Volume of cavities, area under σ_t–ϵ_t curve and final m.l.i. as a function of deformation temperature.

particularly triple points. Subsequent cavity growth is more frequently observed along boundaries between like phases, than along boundaries between unlike phases. Fleck *et al.* [10], in work on a copper base alloy, have reported that twin/grain boundary intersections can provide favourable sites for cavity nucleation during superplastic deformation but this was not apparent in the present work.

Scanning electron microscopy of the room temperature fracture surfaces of pre-cavitated specimens shows that small particles present in the alloy are often associated with cavities. Similar observations have recently been reported by Sagat and Taplin [11] working with an α/β brass containing 3% Fe. While it was clear that the large number of iron-rich particles in the latter alloy provided sites for cavity nucleation, the type of particles in the present alloy is unknown. It is probable that the particles are oxides or sulphides.

In a given alloy system, the formation of cavities during high temperature deformation may be dependent on strain, strain rate, stress, time, temperature and grain size. Many of these parameters are interdependent, and their effect on cavitation is difficult to interpret, e.g. the stress level and strain rate diminish as a function of strain in constant cross-head velocity tests, grain growth will depend on time and temperature, and the stress level is affected by the strain rate and grain size.

Fig. 6 shows the effect of strain and strain rate on the volume of cavities in the Cu–40% Zn alloy, although in these initial experiments no effort was made to assess the superimposed effects of changes in stress and grain size. The longer deformation times associated with the slower strain rates promote grain growth, and, as will be shown later, increase the level of cavitation. The curves therefore tend to be "bunched", and they exaggerate the extent of cavitation at low strain rates. However, it can be reasonably assumed that whatever the mechanisms for cavity nucleation and growth, the volume of cavities will increase with increasing strain; this is confirmed in Fig. 6.

The results of an attempt to identify more specifically the variables responsible for cavitation are presented in Figs. 9 and 10. Whilst maintaining constant values of strain and temperature, the effect of grain size, Fig. 7, and strain rate, Fig. 8 was measured. The variation in the other parameters was also recorded.

It is particularly interesting to note in Fig. 7 that for each of the initial strain rates involved, the average stress level, as described by the area under the stress–strain curve, is essentially constant. Since temperature, strain, average strain rate, and hence time are also constant, it is clear that the effect of grain size can be isolated, and that the level of cavitation decreases as the grain size decreases. An estimate of the grain size below which the level of cavitation is zero, or very small, for each initial strain rate, may be obtained by extrapolation of the data in Fig. 7.

It is not possible to isolate the effect of strain rate in the same way, as the stress level increases as the strain rate increases. Nevertheless it is quite clear from Figs. 7 and 8 that a high level of cavitation can be avoided by having a small grain size and a slow strain rate. However, from a practical point of view the latter requirement tends to be incompatible with the first because of the long deformation times available for grain growth.

The effect of temperature on the level of cavitation is shown in Fig. 9. Despite an increase in grain size with increasing temperature the level of cavitation is reduced considerably over the temperature range studied. However, the effect of temperature is difficult to separate from the effect of stress which also decreases with increasing deformation temperature.

It is well established that during superplastic deformation, grain boundary sliding makes a substantial contribution to the deformation process. Local stress concentrations generated at triple points and other grain boundary sites, or at second phase particles, by the sliding process, are relieved by accommodation processes involving diffusion or dislocation movement. If the rate of grain boundary sliding exceeds the rate of accommodation, then the resulting stresses will lead to cavity nucleation.

In the present work quantitative measurements have shown that the overall volume of voids produced during superplastic tensile deformation of α/β brass increases as strain, strain rate, grain size are increased, and as the temperature is decreased. However, as no measurements of void nucleation and void growth rates were made it it not possible to establish whether the variables exert their influence primarily through their effect on nucleation or on growth.

Increasing strain rate and decreasing temperature are accompanied by increasing flow stress. If the external stress level reflects the magnitude of the stress concentrations which can develop in the material, then the threshold stress for cavity nucleation will be exceeded at more potential nucleation sites as the stress level rises, so increasing the cavity nucleation rate. If cavity growth is controlled by lack of diffusional accommodation, then increasing strain rate reduces the time available for diffusion, increasing grain size increases the length of diffusion path, and decreasing temperature leads to lower diffusivities.

5. Conclusions

(1) A high "m" value ($\sim$0.6), and tensile elongations of up to 400% have been obtained in the microduplex brass examined, at 600° C. The grain sizes involved (m.l.i. = 14 to 21 μm) were larger than those often associated with a good superplastic response.

(2) The formation of cavities was observed under all test conditions. The cavities appeared to be nucleated primarily at triple points and second phase particles. Subsequent cavity growth was more frequently observed along boundaries between like phases, than unlike phases.

(3) The level of cavitation increased as strain, strain rate, and grain size were increased and as temperature was decreased.

(4) The influence of the variables on the overall level of cavitation can be related to their effects on cavity nucleation and/or cavity growth rates.

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