Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

FACTORS AFFECTING CAVITATION DURING SUPERPLASTIC FLOW

N. Ridley* and D. W. Livesey*

INTRODUCTION

During superplastic deformation in tension some alloys thin down very gradually to a fine point at fracture while others show fracture surfaces of substantial cross sectional area. The former behaviour is typical of alloys which do not cavitate during superplastic flow and this type of failure has recently been studied in detail by Sagat and Taplin [1]. The latter mode of failure occurs in alloys which cavitate and an essentially brittle type of fracture results from the growth and interlinkage of cavities.

Alloys of copper [2-5] and iron [6-10] are particularly prone to cavitation and the present paper outlines aspects of cavity nulceation during superplastic flow and identifies the factors which affect the overall level of cavitation in some of these alloys, before extensive interlinkage of cavities, leading to final fracture, occurs. The results of successful attempts to induce cavitation in alloys based on the non-cavitating Pb-Sn eutectic are also presented.

EXPERIMENTAL

Tensile specimens of round or rectangular section, and of 10 mm gauge length, were superplastically strained at constant cross-head velocities in an Instron machine. High temperature tests were carried out in a furnace attached to the machine, with copper alloys being deformed in air and the steels, in vacuum. Binary and ternary alloys based on the Pb-Sn eutectic were tested at room temperature in air. Metallographic studies were made using optical and scanning microscopy, and the overall level of cavitation was obtained from density measurements made by hydrostatic weighing in ethyl iodide.

CAVITATION IN COPPER ALLOYS

α/β brasses

Cavitation has been studied in high purity α/β brasses as a function of strain, strain rate, grain size, temperature and composition.

The brasses all had as-received grain sizes of <5 μ (where grain size is defined as 1.4 times the average interphase spacing) although during testing marked grain growth tended to occur. In a Cu-40% Zn alloy the level of cavitation, which could be as high as 10% by volume, was observed to increase as the strain, strain rate and grain size were increased and as the

---

*Joint Department of Metallurgy, The University, Grosvenor Street, Manchester M1 7HS.

temperature was decreased. The effects of grain size and strain rate on the level of cavitation for constant elongation at 873K are shown in Figure 1. Nucleation of cavities occurred most frequently on α/β boundaries, with $\beta/\alpha/\beta$ triple points often being involved, while growth appeared to occur along boundaries between like phases. Scanning electron microscopy showed that some cavities contained unidentified particles of sub-micron dimensions, although other cavities were not associated with particles.

The cavitation behaviour of 60-40 brass at 873K was compared with that of alloys of composition Cu-41% Zn, and Cu-42% Zn. It can be seen in Figure 2 that the level of cavitation varies markedly with composition, although the three alloys had similar maximum strain rate sensitivities and showed similar elongations to fracture at a constant cross-head velocity of 0.02 mm/sec (Table 1). The cross-sectional area of the fracture face decreased as the zinc content was increased, with the 42% Zn alloy showing substantial necking.

α/β Cu-37% Zn-15% Ni

The as-received alloy was a commercial nickel-silver with a microduplex structure consisting of α grains (or sub-grains) of 2-3 μm diameter, containing about 10% volume of grain boundary β particles of diameter ~ 1 μm. The alloy showed extensive cavitation during testing (Figure 3). For constant strains, the level of cavitation was almost independent of strain rate. Metallographic examination showed that cavities nucleated at α/β interfaces (Figure 4) with growth occuring along α/α boundaries.

CAVITATION IN STEELS

Cavitation has been studied in low alloy and high alloy steels containing titanium additions [7-9,11]. The volume of cavities which was appreciably less (2-3% maximum) than that often encountered in copper alloys increased with increasing strain, but was relatively independent of strain rate and grain size for a given elongation. A correlation between the volume of Ti(C,N) in a high alloy α/γ steel, the level of cavitation and the elongation to fracture, has been observed, and metallographic studies of fracture faces have confirmed the important role that relatively large Ti(C,N) cuboids (~ 5 μm) play in cavity nucleation [11].

BINARY AND TERNARY ALLOYS BASED ON Pb-Sn EUTECTIC

The effect of relatively hard particles on superplastic flow in a Pb-Sn alloy of eutectic composition has been examined. Initially a careful metallographic and density study was carried out to see if the binary alloy cavitated during superplastic deformation at room temperature. A range of microstructural conditions was examined including a fine grained microduplex structure (grain size 2-3 μm), a coarse equiaxed structure (grain size ~ 30 μm) and an as-cast and cold worked structure. The tensile elongations obtained varied from 2000% to 60%, but in no case did cavitation occur.

Hard particles ($\sim 6\%$ volume) of the intermetallic phase based on Cu_6Sn_5 (Microhardness V.P.N. = 290 compared with V.P.N. of Pb = 2, and Sn = 3) were introduced into the alloy by making an addition of 4 wt.% copper. The average size of the Cu_6Sn_5 particles was ~ 2 μm. Although the flow stress levels were raised by a factor of about 2, measurements of strain rate sensitivity were consistent with superplasticity over a wide range of strain rates. Tensile specimens pulled to failure at various constant velocities all showed brittle superplastic fractures.

Density measurements and metallography confirmed that cavitation had occurred during superplastic flow, and that cavities had nucleated at intermetallic phase-matrix interfaces. Cavitation was observed to increase with increasing strain and increasing strain rate (Figure 5). Preliminary measurements on the effect of antimony additions, leading to the formation of SnSb (V.P.N.$\sim$ 52), also resulted in cavitation (Figures 5 and 6) but to a lesser extent than for the alloy containing copper.

DISCUSSION

The observation made on steels, copper-base-alloys and on Pb-Sn-based alloys show the important role that "second phase" particles play in cavity nucleation. Nucleation occurs primarily by decohesion of the particle/matrix interface due to stress concentrations resulting from grain boundary sliding. The ease of nucleation will depend upon the magnitude of stress concentration, which will be affected by the size and hardness of the inclusion, and on the strength of the particle/matrix interface.

For α/γ stainless steels there is a correlation between cavitation and the volume fraction of Ti(C,N) and it is unlikely that the threshold stress for cavity nucleation in the alloys would be reached if Ti(C,N), or other hard grain boundary particles such as $M_{23}C_6$ [12], was absent.

For the Pb-Sn alloys there is clear evidence that in the absence of hard Cu_6Sn_5 particles the system does not cavitate, and preliminary results for further Pb-Sn based alloys show a correlation between the level of cavitation and the hardness of the nucleating phase. The copper addition performs two functions which aid nucleation. That is, the general flow stress level is raised and particles which act as sites for cavity nucleation are introduced into the microstructure. However, it is improbable that cavity nucleation would occur in the absence of the hard particles, since it is possible to raise the flow stress level in the binary alloy, by changing the microstructure, without getting cavitation.

Cavitation in α/β brasses is not entirely nucleated by inclusions, and it appears that nucleation can occur at triple points and other grain boundary sites [3]. It is probable that void nucleation is affected by the presence of trace impurities which are well known to influence grain boundary cohesion in copper base alloys. The much higher level of cavitation observed in copper alloys, compared with steels, may also be related to trace impurities. In recent work in the authors' laboratory on two different batches of high purity 60-40 brass, marked differences in cavitation behaviour were observed in what were otherwise structurally identical materials.

In addition to the Pb-Sn eutectic alloy, other systems which do not appear to cavitate include Zn-Al eutectoid and α/β titanium alloys. In these systems stable microduplex structures, which deform superplastically at low flow stresses, may be readily attained, and the alloys are usually free from grain boundary particles which would aid cavity nucleation. In titanium alloys, impurities such as nitrogen and oxygen, which if present in other systems could give rise to deleterious inclusions, are effectively removed by being taken into solution.

Although cavities nucleate by grain boundary sliding, it is uncertain whether they continue to grow by sliding, or whether a vacancy mechanism is involved. The cavitation behaviour of the steels containing Ti(C,N) and the α/β nickel silver alloy showed marked similarities, in that the level of cavitation increased with strain, but remained relatively constant with increasing strain rate for a constant strain. These observations are consistent with the growth of a relatively constant number of voids by grain boundary sliding. That is, for the range of strain rates examined the threshold stress for cavity nucleation at the large Ti(C,N) particles or at β particles is readily exceeded. On the other hand, the higher stresses associated with increasing strain rates could nucleate an increased number of cavities which are able to grow by a vacancy mechanism for a time which is inversely proportional to the strain rate. Hence, the experimental observations would represent a balance between relatively few cavities undergoing substantial growth and many cavities undergoing little growth. However, in the absence of quantitative nucleation and growth measurements it is not possible to distinguish alternative mechanisms.

The cavitation behaviour of the α/β brasses was different from that of the α/γ steels and the nickel-silver alloy. The fractors which led to higher volume fractions of cavities i.e. increasing strain rate, increasing grain size, decreasing temperature, were also associated with higher flow stresses. At lower stress levels cavity nucleation on inclusions is likely to be of significance whereas, at higher flow stresses cavity nucleation at grain boundary ledges, triple points and twin intersections could become of more significance. The increased number of cavities nucleated at higher stresses would lead to the increased volume of voids observed, whether the voids grow by sliding or by a vacancy mechanism.

The results on the three brasses (Table 1) are in accordance with the view that the α/β ratio controls ductility, with maximum elongations being observed when equal proportions of the phases are present (2,4,13), although the effect was not very marked under the test conditions used. The flow stress level decreased with increasing proportion of β phase in the alloy, and this is reflected by the decreasing level of cavitation in the alloys, and in the cross-sectional areas of their fracture surfaces.

CONCLUSIONS

1. Cavitation occurs during superplastic tensile straining of α/β brasses, α/β Cu-Zn-Ni alloy, and steels containing titanium.

2. In brasses, cavities nucleate at grain boundary particles and at triple points.

3. In the α/β Cu-Zn-Ni alloy cavities nucleate at β particles located in grain boundaries, while in steels nucleation occurs primarily at large Ti(C,N) cuboids.

4. Lead-tin eutectic alloy does not cavitate during superplastic deformation.

5. The introduction of relatively hard particles into a microduplex Pb-Sn eutectic alloy results in cavity nucleation at the particle/matrix interface during superplastic deformation.

6. In steels containing Ti(C,N) and in α/β Cu-Zn-Ni alloy, the level of cavitation is relatively independent of strain rate, for a given elongation.

7. In α/β brass the level of cavitation for a given elongation decreases as the strain rate and grain size are decreased and as the temperature and zinc content are increased.

REFERENCES

1. SAGAT, S. and TAPLIN, D.M.R., Metal Science, <u>10</u>, 1976, 94.
2. SAGAT, S., BLENKINSOP, P. and TAPLIN, D.M.R., J. Inst. Metals, <u>100</u>, 1972, 268.
3. SAGAT, S. and TAPLIN, D.M.R., Acta Met., <u>24</u>, 1976, 307.
4. DUNLOP, G.L. and TAPLIN, D.M.R., J. Mat. Science, <u>7</u>, 1972, 316.
5. SCHELLENG, R.D. and REYNOLDS, G.H., Met. Trans., <u>3</u>, 1973, 2199.
6. MORRISON, W.B., Trans. A.S.M., <u>61</u>, 1968, 523.
7. SMITH, C.I. and RIDLEY, N., Metals Technology, <u>1</u>, 1974, 191.
8. HUMPHRIES, C.W. and RIDLEY, N., J. Mat. Sci., <u>9</u>, 1974, 1429.
9. SMITH, C.I., NORGATE, B. and RIDLEY, N., Metal Science, <u>10</u>, 1976, 182.
10. SCHADLER, H.W., Trans. A.I.M.E., <u>242</u>, 1968, 1281.
11. RIDLEY, N. and HUMPHRIES, C.W., Proc. Conf. on 'Grain Boundaries', Institution of Metallurgists, 1976.
12. NAZIRI, H., High Voltage Electron Microscopy, Third International Conference Proceedings, Academic Press, London, 1974.
13. TAPLIN, D.M.R. and CHANDRA, T., J. Mat. Sci., <u>10</u>, 1975, 1642.

Table 1 Characterisation of superplastic α/β brasses

Nominal Composition	Volume Fraction of β phase at 600°C	Elongation to fracture v = 0.2 mm/sec	Maximum m
Cu-40% Zn	32%	370	0.58
Cu-41% Zn	62%	390	0.63
Cu-42% Zn	85%	338	0.58

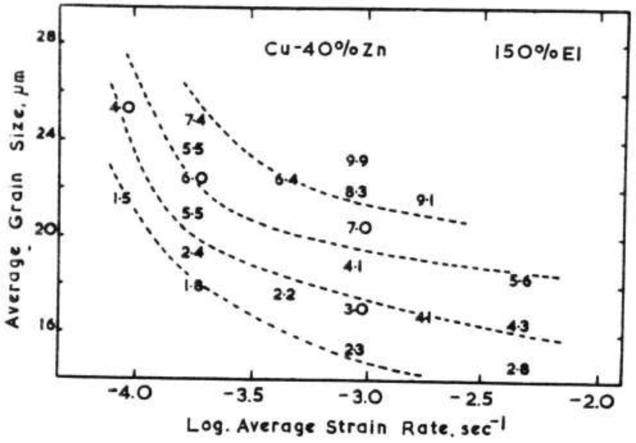

Figure 1 Variation of % void volume with grain size and strain rate

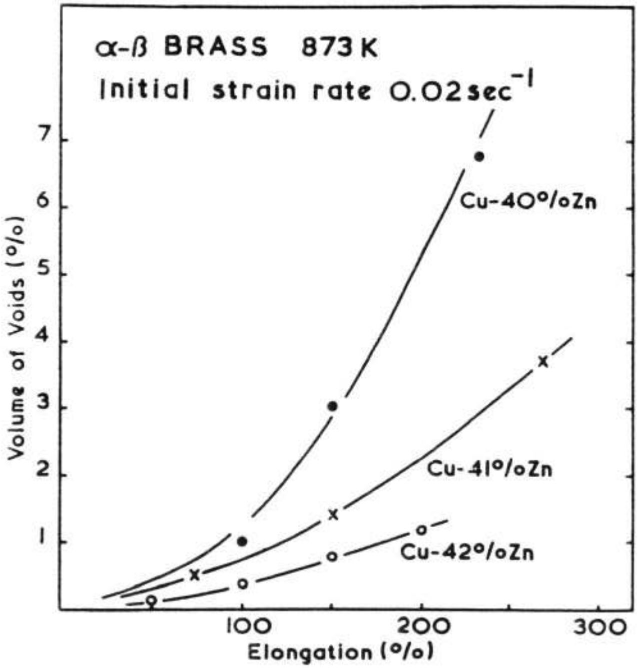

Figure 2 Void volume % in α/β brass as a function of elongation and composition.

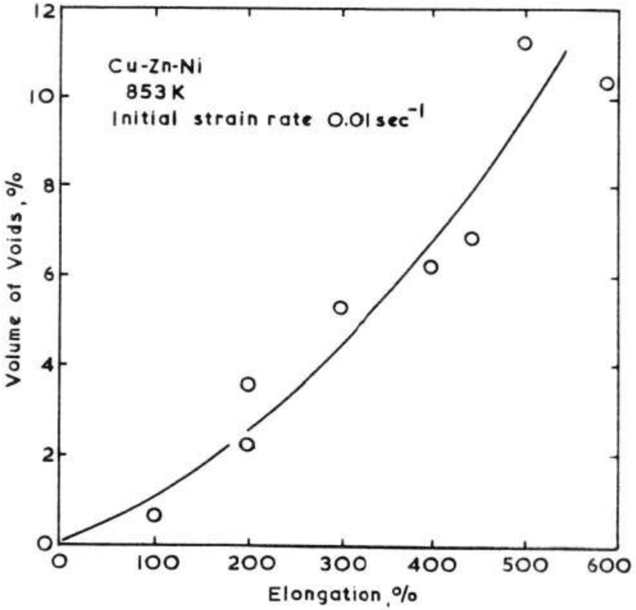

Figure 3 Variation of void volume % in α/β Cu-Zn-Ni with elongation

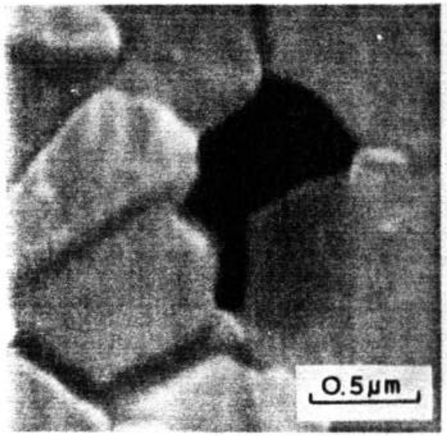

Figure 4 Cavitation at an α/β interface in Cu-Zn-Ni alloy

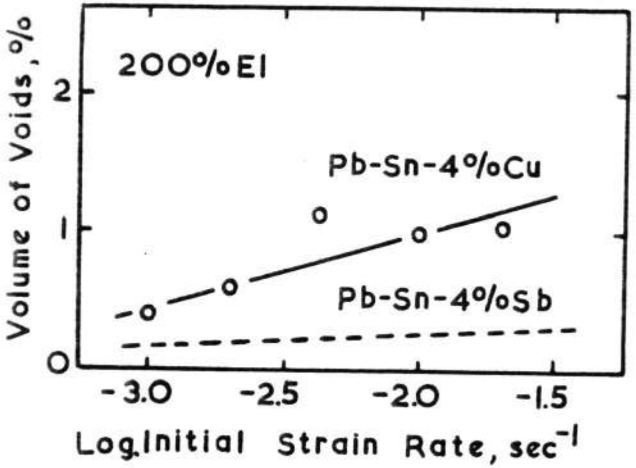

Figure 5 Effect of strain rate on void volume % in ternary lead alloys

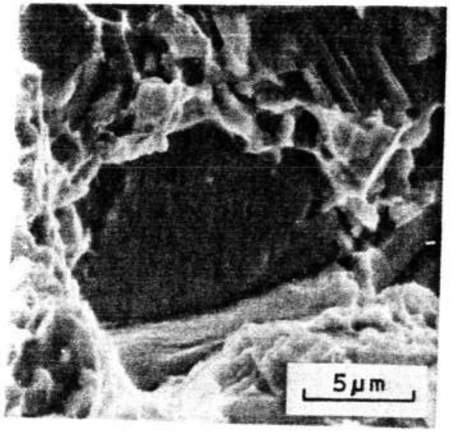

Figure 6 Cavitation at SbSn/matrix interface in Pb-Sn-4% Sb