THE GROWTH OF INTERGRANULAR CAVITIES DURING CREEP OF AN ALPHA BRASS

L-E. Svensson and G.L. Dunlop

Department of Physics, Chalmers University of Technology,
412 96 Göteborg, Sweden

ABSTRACT

Measurements have been made of the growth rates of intergranular creep cavities in alpha brass. The results are in good agreement with the predictions of models for cavity growth controlled by grain boundary diffusion. Except for deviations at both high and low stresses, similar agreement was also obtained when the time to fracture was considered.

KEYWORDS

Intergranular cavities, growth rates, grain boundary diffusion, creep, fracture.

INTRODUCTION

There are at least six possible modes by which intergranular creep cavities may grow while under the influence of stress and temperature. These growth modes, which have been fully discussed in a recent review (Svensson and Dunlop, 1980), are:

(i) grain boundary diffusion control;
(ii) continuum plastic hole growth;
(iii) deformation enhanced diffusional growth;
(iv) non-equilibrium growth with surface diffusion control;
(v) finger-like growth;
(vi) constrained growth.

It seems that cavity growth, rather than the other stages of nucleation, interlinkage etc, may often be the most important stage in determining creep fracture life. Therefore, it is important to be able to predict which mode of growth will occur and what the rate of growth will be. Analytical expressions have been arrived at for the various growth models but as yet only limited experimental evidence has been obtained which can be used to support these expressions. One major problem is that the creep fracture process involves not only cavity growth but also nucleation, interlinkage, crack propagation and final fracture. Thus, it is not possible to unequivocally associate the time-to-fracture with cavity growth or, for that matter, with any of the other stages.

One interesting way of avoiding this problem is to carry out experiments where a fixed number of cavities are either introduced prior to the beginning of the creep test or are nucleated rapidly in the very early stages of creep. Several experiments of this type have been carried out recently (Goods and Nix, 1978; Nieh and Nix, 1979; Dyson and Rodgers, 1977; Pavinich and Raj, 1977; Raj, 1978). However in all of these investigations the parameter which was measured was the time-to-fracture and, although this did not include any effects due to nucleation, there must have been some influence from the latter stages of the fracture process. In the light of these difficulties of interpretation it was decided to carry out similar experiments but with the exception that the growth rate was measured using detailed metallography and not inferred from times-to-fracture.

EXPERIMENTAL

The experimental material was a commercial alpha brass (76.5% Cu, 21.3% Zn, 2.2% Al) containing an excess of hydrogen. Small H_2 or H_2O bubbles of average radius $\bar{r}=0.3$ μm and spacing $\bar{\lambda}=6$ μm formed at the grain boundaries during annealing for 18 h at 700 K. These voids then subsequently grew during creep at the same temperature.

Unaxial creep tests were conducted in air at 700 K with stresses ranging between 5 and 63 MPa. Interrupted tests were conducted at stresses of 5.4, 15 and 43 MPa. Specimens from these tests were sectioned longitudinally, mechanically polished, lightly etched and subsequently examined by scanning electron microscopy. In order to provide good statistics, the sizes (radius in the boundary plane, r) of approximately 100 cavities were measured in each specimen.

RESULTS AND DISCUSSION

Creep curves for the three stresses at which interrupted tests were conducted are shown in Fig. 1. The specimens in which cavity sizes were measured are also indicated in this diagram.

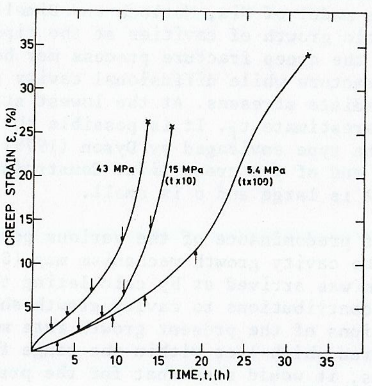
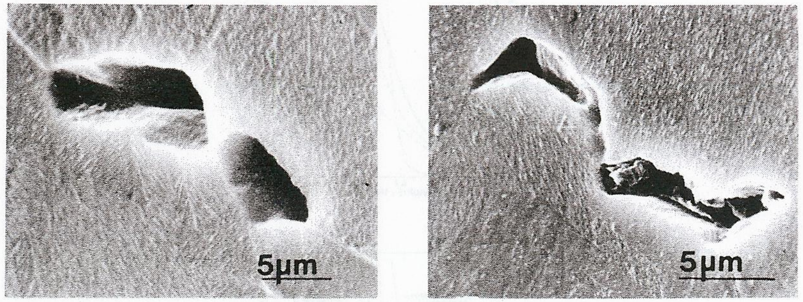


Fig. 1. Creep curves for the three applied stresses at which cavity size measurements were made. The arrows mark the points at which tests were interrupted. Note the reduced time scale for 5.4 and 15 MPa.

It was observed that at the lower stresses of 5.4 and 15 MPa the cavities had an equiaxed shaped, although somewhat elongated in the plane of the grain boundary. The half apex angle was $\psi \sim 50^{\circ}$ (Fig. 2(a)). At the high stress of 43 MPa (Fig. 2(b)) the cavities were more crack-like in nature with sharp apices ($\psi \sim 35^{\circ}$) and had a high length to breadth aspect ratio.



(a) (b)

Fig. 2. Intergranular creep cavities on polished sections after 6% strain. Stress axis vertical (a) σ=5.4 MPa; (b) σ=43 MPa.

Most of the mathematical expressions for the different possible modes of cavity growth express the growth rate in terms of the rate of volume increase, dV/dt, rather than in terms of the rate of radius increase, dr/dt. Thus, it is most convenient to present the size measurements in terms of dV/dt. This is done using the following expression for a lens shaped cavity due to Chuang et.al. (1979):

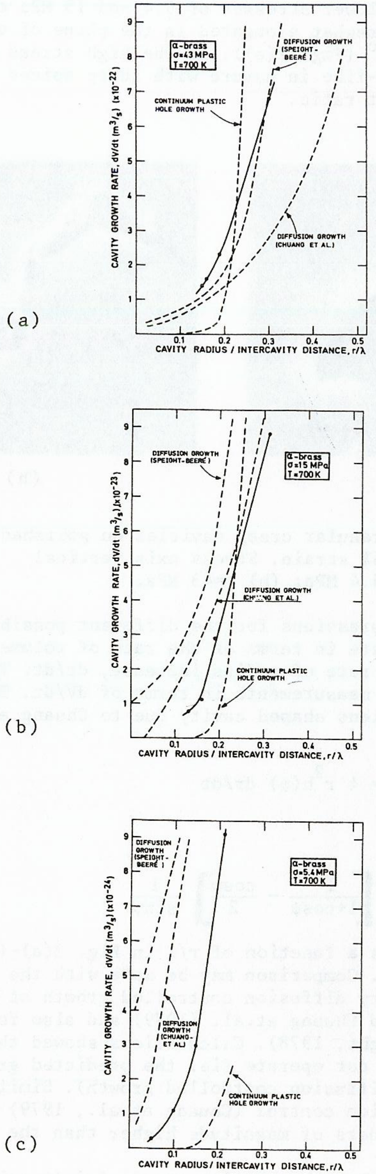
$$dV/dt = 4\, r^2 h(\psi)\, dr/dt$$

where

$$h(\psi) = \left[\frac{1}{1+\cos\psi} - \frac{\cos\psi}{2}\right] \frac{1}{\sin\psi}$$

The results are presented as a function of r/λ in Fig. 3(a)-(c). The ratio r/λ increased with creep strain. Comparison may be made with the predictions of the models for the grain boundary diffusion controlled growth of cavities due to Speight and Beeré (1975) and Chuang et.al. (1979) and also for continuum plastic hole growth (Beeré and Speight, 1978). Calculations showed that the constrained growth model (Dyson) should not operate (ie. the predicted growth rates were considerably higher than for diffusion controlled growth). Similarly the model for growth under surface diffusion control (Chuang et.al., 1979) predicted growth rates which were several orders of magnitude higher than the observed.

From Fig. 3 it can be seen that the results are in fairly good agreement with both models for grain boundary diffusion controlled growth. Better agreement can hardly be expected, when the inaccuracies of diffusion data are considered. It is doubtful if continuum plastic hole growth made any strong contribution to the growth, since if it did the cavities would have tended to be elongated in the direction of the stress axis.



(a)

(b)

(c)

Fig. 3. Cavity growth rates, dV/dt expressed as a function of the ratio r/λ. (a) σ = 43 MPa; (b) σ = 15 MPa; (c) σ = 5.4 MPa.

The times to fracture for stresses between 5 and 63 MPa are plotted in Fig. 4. For stresses between 10 and 30 MPa the experimental values for t_f follow fairly well those predicted by the models for simple grain boundary diffusion controlled growth although the stress sensitivity of the time-to-fracture, n_f, is greater than predicted. It can be seen from Fig. 4 that, even at high stresses, cavity growth by power law creep deformation predicts such large values of t_f that this mode of growth is expected to have virtually no effect on the experimental t_f.

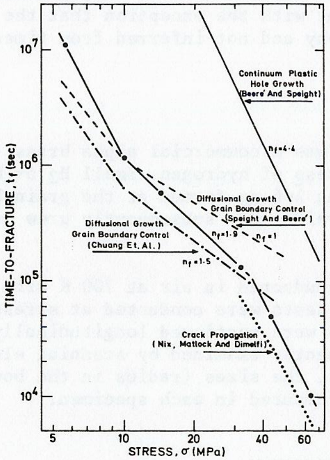


Fig. 4. Time-to-fracture as a function of applied stress.

The change in slope in the simple diffusional growth curves at 10 MPa is due to a slightly larger λ at the lower stresses. At high stresses the results deviate markedly from the predictions of the simple diffusional growth models but here they follow closely the model of Nix, Matlock and Dimelfi (1977), for creep fracture based on the plastic growth of cavities at the tips of grain boundary cracks. Thus, at high stresses the creep fracture process may be dominated by the crack propagation stage of fracture while diffusional cavity growth dominates the fracture process at intermediate stresses. At the lowest stress of 5.4 MPa the diffusion growth models underestimate t_f. It is possible that this is due to constraint on cavity growth, of the type envisaged by Dyson (1976), taking place at large values of r/λ near the end of the creep life. Constrained growth is likely to become important when r/λ is large and σ is small.

The predicted ranges of predominance of the various possible cavity growth mechanisms are plotted in the cavity growth mechanism map (Svensson and Dunlop, 1980b) in Fig. 5. This diagram was arrived at by calculating the stress and the values of r/λ at which equal contributions to cavity growth should be made by adjoining mechanisms. The conditions of the present growth rate measurements are indicated by the cross-hatched area which lies within the range for grain boundary diffusion controlled growth. Thus, it would seem that for the present material, theory and experiment are in good agreement.

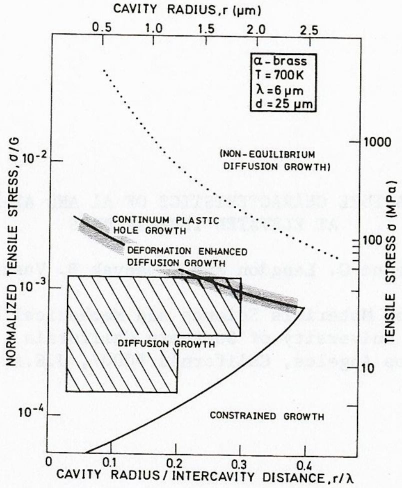


Fig. 5. Cavity growth mechanism map for α-brass with axes of normalised stress and r/λ. The relevant region for the growth rate measurements is indicated by the cross-hatched area.

CONCLUSIONS

1. The growth rates of intergranular creep cavities in alpha brass were found to be in reasonable agreement with the predictions of models for growth controlled by grain boundary diffusion.

2. Except for deviations at high and low stresses, a similar agreement was also obtained when the time-to-fracture was considered.

3. The results are in accordance with the predictions of a cavity growth mechanism map.

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