CAVITY GROWTH DURING SUPERPLASTIC DEFORMATION IN 7475 ALUMINUM ALLOY

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ABSTRACT

Tensile specimens of the 7475 aluminium alloy were investigated in order to understand the mechanism of cavitation at different levels of strain. For this purpose a temperature and strain-rate pertinent to maximum level of cavitation were selected and the constant strain rate tests were interrupted at appropriate strain levels. This was supplemented with microstructural observations and density measurements. The percentage cavitation increases with strain in this alloy. The experimental result is assessed with respect to Stowell's model and plasticity-controlled hole growth.

KEY WORDS

Cavitation, superplastic deformation, density, Stowell's model, plasticity-controlled hole growth.

INTRODUCTION

Because of the substantial benefits shown for the superplastic forming (SPF) of the 7475 aluminium sheet aerospace components compared with the equivalent conventionally fabricated components, in terms of weight savings, cost savings and in some cases, more efficient operating design, this aluminium alloy was chosen for investigating the failure process during superplasticity. This alloy has the following chemical composition (in wt %)

Al	Zn	Mg	Cu	Cr	Si	Fe
Remainder	5.2-6.2	1.9-2.6	1.2-1.9	0.18-0.25	0.10 max	0.12 max

Mn	Ti	Others each	Other Total
0.16 max	0.06 max	0.05 max	0.15 max

The alloy was obtained from ALCOA Research Laboratory after it was thermomechanically processed for fine grain size (Paton and Hamilton, 1978; Hamilton et. al., 1980; Wert et. al., 1981). With the objective of achieving (1) a grain size of 18 μm (parallel to rolling direction) and (2) homogenization of the matrix, the as-received material was heat-treated at 530°C for 24 hours under vacuum and subsequently polished for metallographic examination.

EXPERIMENTAL

A) Mechanical Testing:
Tests for studying mechanical properties were conducted with the MTS Automated Testing Machine using a constant strain-rate control test program. Elevated temperature was controlled to an accuracy of ±1°C along the gage length of the sample in a Research Incorporated clamshell radiant furnace.

Since the flow stress is a function of testing temperature, rate of straining and imposed strain, it was neccessary to find conditions favorable for maximim cavitation. This was achieved in the following manner. Mechanical tests were performed with the 18 μm grain size specimens having a gage length of 25.4 mm, at temperatures between 437°C and 457°C at a pre-selected strain rate of 1×10^{-4} s^{-1}. These testing conditions assured the deformation of the specimens in the typical (region II) superplastic regime.

Since cavitation was found to be higher at 457°C, tests were conducted at strain-rates ranging from 1×10^{-5} to 5×10^{-3} s^{-1} generally to a strain level of 1.4. After a condition for maximum cavitation had been ascertained, tests were performed in order to study the level cavitation as a function of strain to fracture. Since the true strain to fracture was as high as 2.24, these tests were performed using a similar tensile specimen as mentioned before but with a shorter gage length of 7 mm, in order to keep the deforming specimen within the constant temperature zone of the furnace.

B) Density Measurements:
The percentage cavitation was determined by hydrostatic weighing in methyl iodide (density 2.28 gm/cc at 21°C) using Mettler H51 AR balance with a corresponding dummy specimen, which had undergone no deformation as a density standard.

C) Metallographic Studies
Metallographic studies were made using Phillips EM 400 transmission electron microscope operating at 100 kV. Thin foils were prepared by using an electrolytic polishing solution containing 25 parts nitric acid and 75 parts methanol under 20 V DC current for 30 sec.

For studying the cavity morphology, some of the deformed specimens were ion-beam milled in vacuum for 3 hours using Argon ions. These, together with the fractured specimens, were examined using a 510 Phillips Scanning Electron Microscope operating at 25 kV.

RESULTS

Fig. 1 shows the trend in the level of cavitation as a function of temperature. It is clear that percentage cavitation increases with decreasing test temperature. Fig. 2 depicts the scanning electron micrograph of the cavities in an ion-beam milled specimen that was tested at a temperature of 457°C and a strain-rate of 1×10^{-4} s^{-1} to a true strain of 1.4. The value of a true strain of 1.4 was determined by the constraints imposed by the limitation of the cross-head movement. Fig. 3 depicts the increase in cavitation with a decrease in strain-rate for specimens tested at strain-rates between 1×10^{-5} and 5×10^{-3} s^{-1} to a true strain level of 1.4 at 457°C. Fig. 4 is the optical micrograph of the specimen tested at a maximum strain rate of 5×10^{-3} s^{-1}. This micrograph shows the dense population of cavities as well as cavity coalescence in the vicinity of fracture. Fig. 5 is the scanning electron micrograph of specimen which was notched and fractured at room temperature after previously straining it to true strain of 1.4 at a temperature of 457°C and at a slow strain-rate of 1×10^{-5} s^{-1}. One observes the growth of cavities to very large size. Fig 6 depicts the increase in cavitation with strain to fracture, under optimal cavitating conditions. Fig. 7 (bright field) and 8 (dark field) are transmission electron micrographs at true strains of 0.5 and 2.24 respectively. Whereas the individual dislocations at low strain level can be easily distinguished, intense (and often unresolvable) dislocation tangles in the vicinity of cavity is typically representative of the microstructure at the highest strain level. Fig. 9 is a scanning electron micrograph of the fracture surface of the specimen tested to a true strain of 2.24 at a testing temperature of 457°C and strain rate of 1×10^{-4} s^{-1}. The fracture is intergranular, with evidence of shear interlinking of cavities by fracture of the ligaments between the cavities.

DISCUSSION

The value of Q, the apparent activation energy, was obtained using the relation, $Q = R\ [(\ln \dot{\varepsilon}_1/\dot{\varepsilon}_2)/(1/T_1 - 1/T_2)]$ where R is the universal gas constant, $\dot{\varepsilon}_1$, and $\dot{\varepsilon}_2$, are strain rates corresponding to testing temperatures T_1 and T_2 in degrees Kelvin. The average value of Q in this investigation was found to be 18.53 k cal/mole. Thus, 7475 Al has the characteristic of exhibiting an activation energy of deformation in region II of superplasticity which is comparable to that for the grain boundary diffusion in aluminium. Thus the present work emphasizes that grain boundary diffusion is rate controlling process in this dispersion hardened aluminum alloy. The corresponding strain rate sensitivity 'm' (defined as m = d log stress /d log strain rate) values are also high, indicative of the high superplastic ductility of the alloy in region II.

Having established the testing condition for maximum cavitation with respect to temperature and strain-rate from the results shown in Figs. 1 and 3, it was observed that the amount of cavitation increased with increasing strain as was also observed previously (Humphries and Ridley, 1974). Straining to various levels at 457°C and at a strain rate of 1×10^{-4} s^{-1}, resulted in a gradual increase in the dislocation density leading to the formation of dislocation tangles.

Other TEM micrographs revealed that the large cavities shown in the SEM micrograph of Fig. 5 are associated with large dislocation entanglements in the microstructure as shown in Figs. 7 and 8. Thus increased dislocation activity is concomitant with cavity growth. Further support to such an observation can be obtained from the superplastic cavity growth model (Stowell; 1980). This model has been applied to correlate the cavitation results for two alloys, IN 744 and IN 836. Cavitation was found to be diffusion controlled when the average size of the cavity was less than 0.5 µm. However, for an average cavity size greater than 0.5 µm, cavitation is plasticity controlled. Thus according to the model (Stowell, 1980), the transition in the mechanism from diffusion-controlled to plasticity controlled growth occurs at an average cavity size of 0.5 µm in these two alloys.

In this alloy, the cavities are nucleated by decohesion of dispersoid particle/matrix interface. Hence, even at nucleation stage these cavities are nearly 0.5 µm or larger depending upon the dimension of the nucleating particles. Hence, there is a cavity size in any cavitating superplastic alloy at which the growth rates for these two mechanisms are equal, and the above which matrix plasticity controlled hole-growth process dominates. This concept is an extension of an earlier suggestion (Hancock, 1976) for creep cavity growth to the area of superplastic cavitation process. Since the average cavity size observed in 7475 aluminuim alloy is greater than 0.5 µm, it is quite possible that we are in a regime where plasticity-controlled hole growth mechanism is rate controlling. The increase in the density of dislocation tangles as a function of strain around the growing cavity further supports this conjecture.

CONCLUSIONS

1. The percentage cavitation increased with decreasing temperature and strain-rates of testing.
2. The percentage cavitation at a testing temperature of 457°C and strain-rate of $1 \times 10^{-4} s^{-1}$ increased with increasing strain levels.
3. Since the activation energy of deformation is equal to that for the grain boundary diffusion, creep deformation of matrix, and hence associated dislocation activity plays an important role in the growth of cavities during superplastic flow in this alloy.

ACKNOWLEDGEMENT

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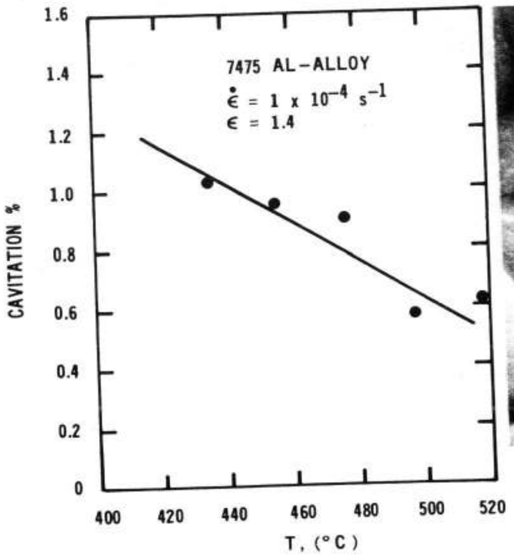

Fig. 1. Variation of percentage cavitation with testing temperature.

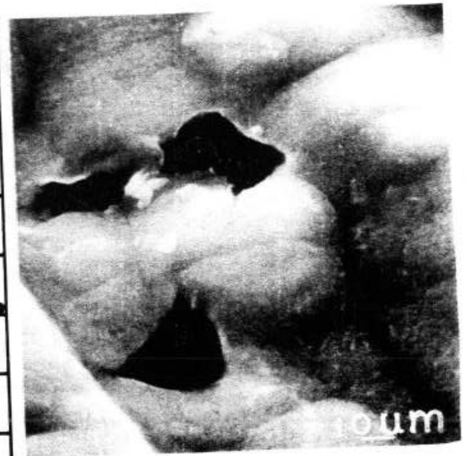

Fig. 2. Scanning electron micrograph of the cavitation in an ion-beam milled 7475 Al alloy after a true strain of 1.4.

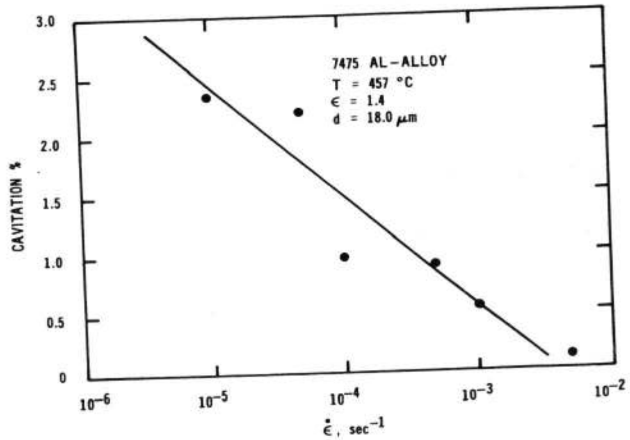

Fig. 3. Variation of percentage cavitation in 7475 Al alloy with strain-rate.

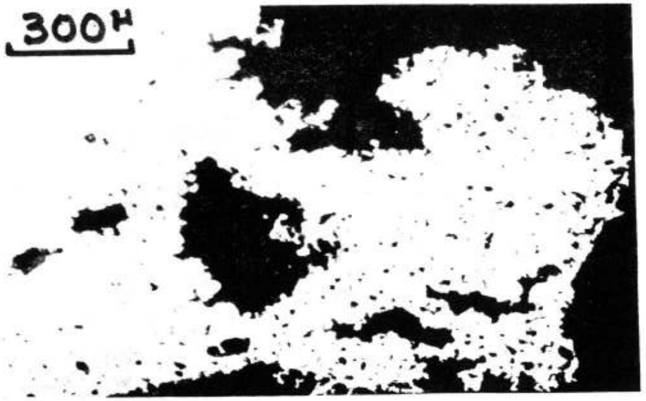

Fig. 4. Optical micrograph of the intense cavitation in 7475 Al alloy in the vicinity of fracture at a strain-rate of $5 \times 10^{-3}\ s^{-1}$.

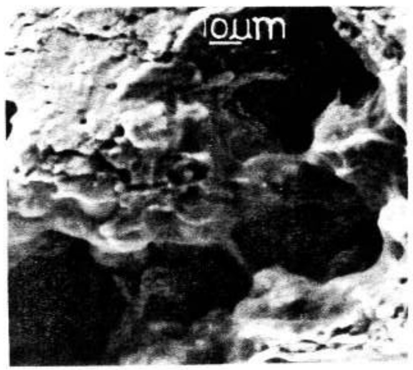

Fig. 5. Scanning electron micrograph of the cavitation in 7475 Al alloy tested at $1 \times 10^{-5}\ s^{-1}$ strain rate and 457°C to strain level of 1.4.

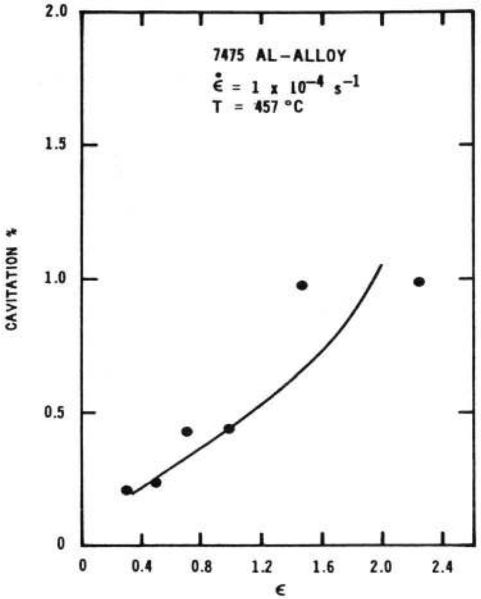

Fig. 6. Variation of percentage cavitation in 7475 Al alloy with strain.

Fig. 7. Transmission electron micrograph of 7475 Al alloy strained to 0.5.

Fig. 8. Transmission electron micrograph of 7475 Al alloy fractured after a strain of 2.24.

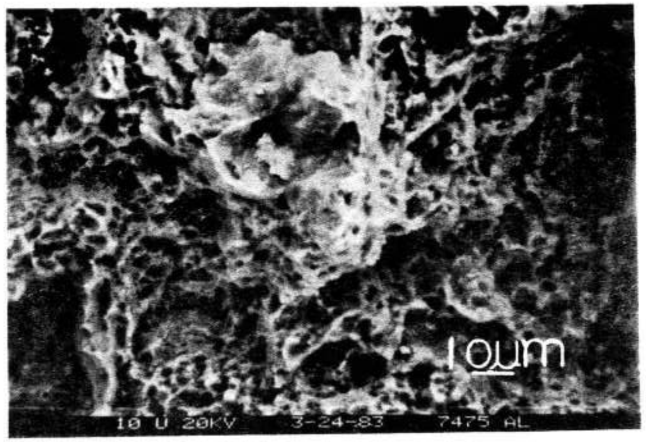

Fig. 9. SEM Fractograph of 7475 Al alloy tested at a temperature of 457°C and strain rate of $1 \times 10^{-4}\ s^{-1}$.