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Neck formation and cavitation in the superplastic Zn–22% Al eutectoid

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The mechanical behaviour of the superplastic Zn–22 % Al eutectoid is divisible into three distinct regions. Experiments show the deformation is quasi-uniform at intermediate strain rates in region II, but neck formation is important at low strain rates in region I. Extensive cavitation occurs in regions I and II, but fracture in region I is due to necking. The results provide strong evidence for a decrease in the true value of the strain rate sensitivity in region I.

1. Introduction

Considerable progress has been made recently in documenting the mechanical properties of highly superplastic materials such as the Zn–22% Al eutectoid. In general, tests are conducted under tensile conditions, and the flow stress, σ, is related to the imposed strain rate, $\dot{\epsilon}$, by an equation of the form

$$\sigma = B\dot{\epsilon}^m \quad (1)$$

where B is a constant which incorporates the dependence on grain size and temperature, and m is the strain rate sensitivity.

Experiments on the superplastic Zn–22% Al eutectoid show that a logarithmic plot of σ versus $\dot{\epsilon}$ is sigmoidal in shape, so that the mechanical behaviour is divisible into three distinct regions. The corresponding values of m in each region are, respectively, ~0.25 at very low strain rates in region I, ~0.45 over about three orders of magnitude at intermediate strain rates in region II, and ~0.1 to 0.2 at high strain rates in region III [1–3].

These three regions have a major influence on the total ductility attained at fracture. This is demonstrated by typical experimental results shown in Fig. 1, where ΔL is the total increase in length at the point of fracture, L_0 is the specimen gauge length, and the percentage elongation of each specimen at fracture, $\Delta L/L_0$ (%), is plotted against the initial imposed strain rate using a testing machine having a constant rate of cross-head displacement. These results were obtained at a constant temperature of 503 K, and with identical specimens having an initial average spatial grain diameter of 2.5 μm; † full details of these, and similar, experiments are given elsewhere [4, 5].

Although most experiments on the Zn–22 % Al eutectoid have been concerned with the influence of various parameters on the mechanical behaviour, two recent observations provide some limited information on the fracture characteristics. First, specimens pull out to a very fine point in region II, but at lower strain rates, in region I, the ductility appears to be limited by neck formation

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†The average spatial grain diameter, d, is defined as 1.74 × the mean linear intercept. In practice, some grain growth occurs during the tests, especially during the very long times at the slowest strain rates. For example, measurements show that the grain size had increased by a factor of two after testing to failure at the slowest strain rate (1.33×10^{-5} sec^{-1}) at 503 K [5].

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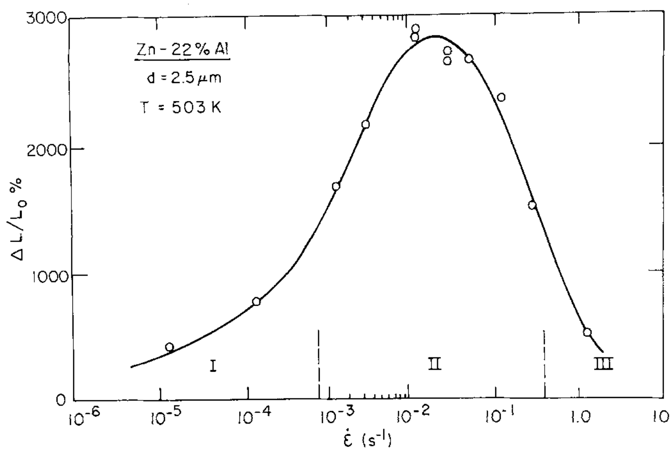

Figure 1 Tensile fracture strain as a percentage versus initial strain rate for an initial grain size of 2.5 μm and a temperature of 503 K.

[5]. Second, there is evidence for the formation of cavities in this material, not only in region I when the ductility is relatively low but also in region II when the elongation to failure is > 2000 % [6]. Furthermore, very recent work indicates that cavity formation is equally important both in commerical Zn–22 % Al and in a very high purity material containing only ~15 p.p.m. impurities [7]. Accordingly, the present work was undertaken to investigate in more detail the formation of necks and cavities in this material.

2. Experimental procedure

Sheets of the Zn–22 % Al eutectoid alloy, 0.254 cm in thickness and of commercial purity, were obtained in superplastic form from The New Jersey Zinc Company. A semi-quantitative spectrographic analysis revealed the following impurities in p.p.m.: Cr < 10, Cu 20, Fe 70, Mg < 10, Mn < 10, and Si 70. Tensile specimens were cut from the sheets with a gauge length of 0.635 cm, and the specimens were annealed for one hour at 533 K to give an average spatial grain diameter of 2.5 ± 0.2 μm.

All specimens were tested on an Instron machine having a constant rate of cross-head displacement. For each test, the specimens were immersed in a silicone oil bath which was electrically heated and stirred with bubbling argon, and the temperature of the bath was maintained constant at 503 ± 1 K. The imposed strain rate was calculated in each case from the *initial* gauge length of the specimen.

To investigate the change in shape of the specimens with strain (and time), two tests were initially conducted by pulling specimens to failure at strain rates of 1.33×10^{-2} and 1.33×10^{-5} sec^{-1}, respectively; as indicated by the data shown in Fig. 1, these rates correspond to regions II and I, respectively. These two tests yielded failure times of ~36 min and ~84 h at these two strain rates, and additional specimens were then tested at the same strain rates for shorter periods of time and removed from the testing machine prior to failure.

To investigate the incidence of cavitation, additional specimens were pulled to failure at strain rates up to 3.33×10^{-1} sec^{-1}, and sections were cut from the gauge lengths and prepared metallographically.

3. Experimental results

3.1. Neck formation

Fig. 2 shows the series of specimens tested for different times at an initial strain rate of 1.33×10^{-2} sec^{-1} in region II. Specimen A is untested, and the other specimens were tested for 10 min (B), 15 min (C), 20 min (D), 25 min (E), and to failure after 36 min (F). The failure strain was ~2850 %, and the other specimens show strains of 800 % (B), 1200 % (C), 1600 % (D), and 2000 % (E), respectively.

This series of specimens reveals a quasi-uniform deformation within the gauge length in region II, and necking appears to be diffuse rather than localized. The specimens gradually pull out to a fine wire at this strain rate, and failure ultimately occurs almost at a point.

A similar sequence is shown in Fig. 3 for the specimens tested at 1.33×10^{-5} sec^{-1}. In this case, Specimen A is untested, and the other specimens were tested for 24 h (B), 48 h (C), 60 h (D), 72 h (E), and to failure after approximately 84 h (F). The failure strain was ~400 %, and the other specimens show strains of 115% (B), 230 % (C), 290 % (D), and 345 % (E), respectively.

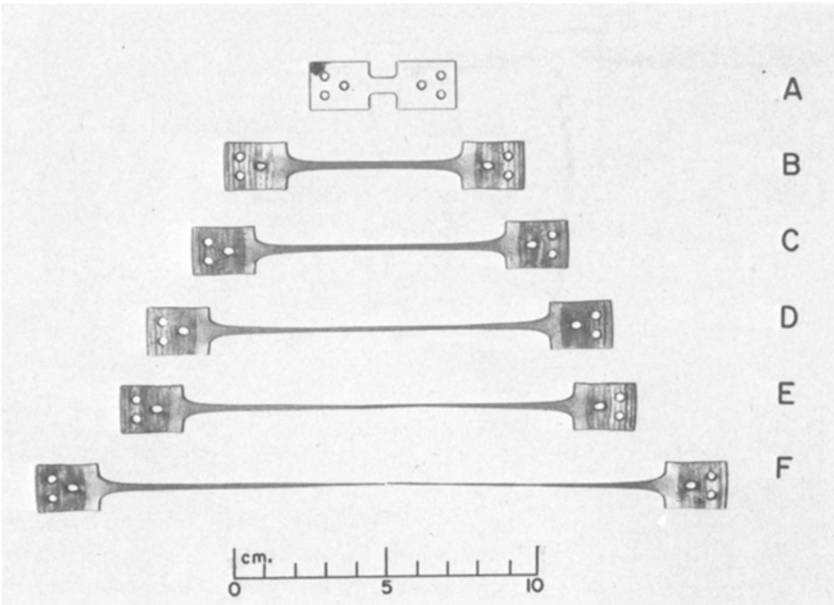

Figure 2 Tensile specimens having an initial grain size of 2.5 μm. Specimen A is untested. The other specimens were tested at 503 K and an initial strain rate of 1.33×10^{-2} sec^{-1} for times of 10 min (B), 15 min (C), 20 min (D), 25 min (E), and to failure after 36 min (F).

This sequence indicates that neck formation is an important factor which limits the extent of ductility in region I. Although the gauge section in Specimen C appears reasonably smooth, some macroscopic necking is clearly evident in Specimen D deformed to only 290 %. Thereafter, deformation is confined almost exclusively to the necked region (Specimen E), leading to failure at the relatively low strain of ~400 % (Specimen F).

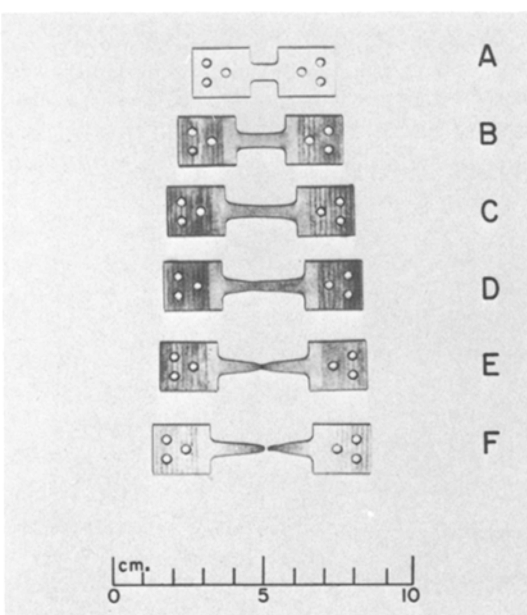

Figure 3 Tensile specimens having an initial grain size of 2.5 μm. Specimen A is untested. The other specimens were tested at 503 K and an initial strain rate of 1.33×10^{-5} sec^{-1} for times of 24 h (B), 48 h (C), 60 h (D), 72 h (E), and to failure after ~ 84 h (F).

3.2. Cavity formation

No cavities were visible in the specimen pulled to fracture at an initial strain rate of 3.33×10^{-1} sec^{-1}, probably because of the exceptionally short duration of the test (42 sec). However, there was very clear evidence of cavitation in all other specimens tested at strain rates up to 3.33×10^{-2} sec^{-1}.

Fig. 4 shows the fracture tip of a specimen pulled at 3.33×10^{-2} sec^{-1} to a failure strain of 2620% in ~13 min. In this case, cavities are

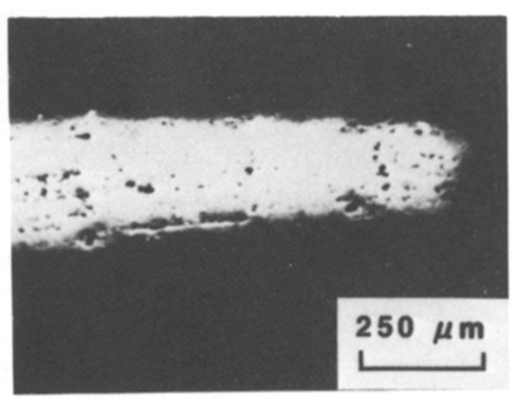

Figure 4 Optical photomicrograph of the fracture tip of a specimen pulled to fracture at 503 K at an initial strain rate of 3.33×10^{-2} sec^{-1}. The tensile axis is horizontal.

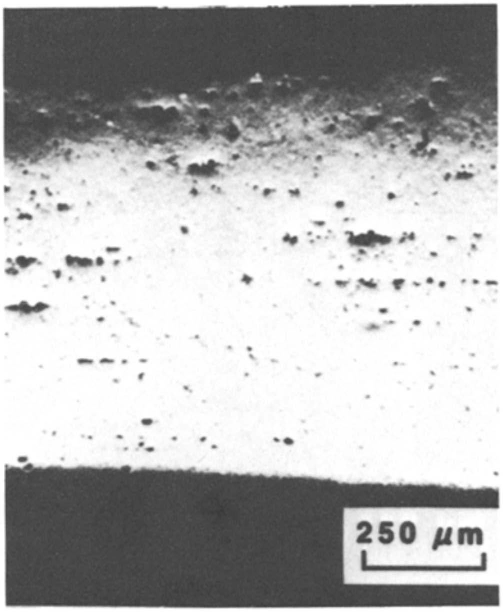

Figure 5 Optical photomicrograph near the fracture tip of a specimen pulled to fracture at 503 K at an initial strain rate of 1.33×10^{-3} sec^{-1}. The tensile axis is horizontal.

visible both at the tip and along the gauge section. A decrease in strain rate to 1.33×10^{-3} sec^{-1} leads to very extensive cavitation, as shown in Fig. 5 at a position near to the fracture tip and in Fig. 6 at a point in the gauge section. This specimen failed at a strain of 1620% after a testing time of 204 min.

Fig. 7 shows the fracture tip of a specimen tested at 1.33×10^{-5} sec^{-1} in region I to a failure

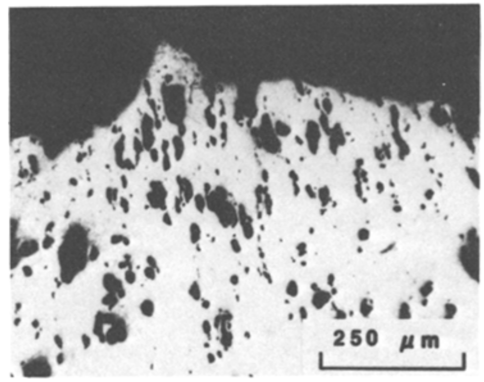

Figure 7 Optical photomicrograph of the fracture tip of a specimen pulled to fracture at 503 K at an initial strain rate of 1.33×10^{-5} sec^{-1}. The tensile axis is vertical.

strain of ~400% after ~84 h. Excessive cavitation is visible near to the point of fracture, and there are many examples of thin ligaments of material between adjacent voids. Large cavities were also present throughout the gauge length at points far removed from the fracture tip, and an example is shown in Fig. 8. There is very clear evidence for cavity interlinkage at points such as A, but this is compatible with the ductility of ~400% because the interlinkage occurs in the direction of the tensile axis.

4. Discussion

It is well known that the total ductility achieved in a tensile test depends, at least in part, on the value of the strain rate sensitivity. This arises from the relationship [5]

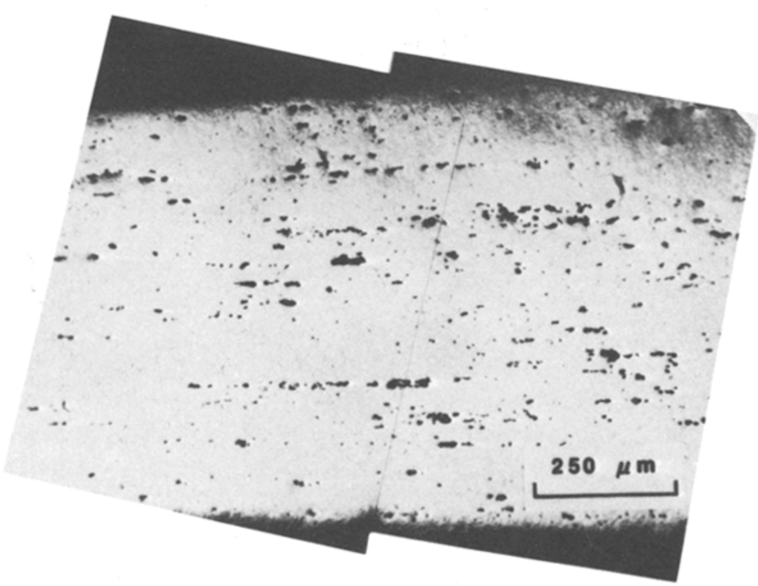

Figure 6 Optical photomicrograph of a section within the gauge length of a specimen pulled to fracture at 503 K at an initial strain rate of 1.33×10^{-3} sec^{-1}. The tensile axis is horizontal.

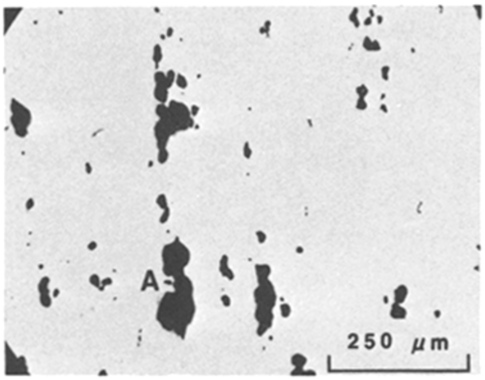

Figure 8 Optical photomicrograph of a section within the gauge length of a specimen pulled to fracture at 503 K at an initial strain rate of $1.33 \times 10^{-5}\ \text{sec}^{-1}$. Cavity interlinkage is visible at point A. The tensile axis is vertical.

$$-\mathrm{d}A/\mathrm{d}t = (P/B)^{1/m} A^{(m-1)/m} \qquad (2)$$

where A is the cross-sectional area of the specimen, t is the time, and P is the tensile force. It follows from Equation 2 that the probability of failure by necking becomes less important as the value of m increases, although, as noted elsewhere [8], experimental results show that the magnitude of the strain rate sensitivity is not sufficient to predict entirely the fracture strain.

The present results are in excellent agreement with the prediction of Equation 2. In region II, when $m \sim 0.45$, the specimens pull out and fail at a fine point (Fig. 2); region I, when $m \sim 0.25$, a neck develops at an early stage of the test (at strains $< 300\%$), and, thereafter, deformation is concentrated in the neck region giving premature failure (Fig. 3).

Considerable speculation has arisen concerning the significance (or otherwise) of region I in experiments on superplastic materials, especially as region I is not always observed (for example, in the work of Hayden *et al.* [9] on a Ni–Fe–Cr alloy). At the present time, there are two conflicting schools of thought concerning region I:

(1) Rai and Grant [10], using the Al–33% Cu eutectic, demonstrated the occurrence of a false "region I" in their material, due to inherent grain growth and a strain dependence of m at low strains (up to ~5%). For strains greater than 5%, and reasonably large grain sizes which avoided excessive grain growth, the results showed only two-stage behaviour (regions II and III). It should be noted that Rai and Grant [10] obtained maximum ductility in their experiments at the lowest strain rate, suggesting that there is a significant variation in behaviour between Al–33% Cu and Zn–22% Al.

(2) Some theories of superplasticity [11, 12] specifically predict experimental observations of a "region I" by incorporating a threshold stress, σ_0, below which there is no plastic flow. In this case, the effective stress is $(\sigma - \sigma_0)$, and a logarithmic plot of σ versus $\dot{\epsilon}$ will yield an apparent region I at low stress levels although the value of m remains unchanged.

The present results suggest that, at least for the Zn–22% Al eutectoid, both of these views are untenable, since the occurrence of neck formation in region I is strong evidence for a decrease in the true value of m in this region. Furthermore, it is clear that fracture in region I ultimately occurs by necking. Thus, despite the occurrence of substantial cavitation in this region, it appears that cavity growth and interlinkage is not of major significance in limiting the elongation at failure. This observation, combined with the earlier demonstration that there is an increase in the activation energy for plastic flow in Zn–22% Al in region I [3], suggests that this region probably arises through the occurrence of a new rate-controlling mechanism at the very low strain rates.

Finally, the results confirm that cavitation is important in Zn–22% Al, and they show, by comparing Figs. 6 and 7, that the morphology of the voids changes with the imposed strain rate. The cavities tend to be elongated and aligned along the tensile axis in region II, but they have a more rounded appearance in region I. This is similar to a trend noted earlier in a superplastic Cu alloy [13], and is consistent with the increasing importance of the diffusional growth of cavities at the very low strain rates.

5. Summary and conclusions

(1) Experiments on the superplastic Zn–22% Al eutectoid show that there are significant differences in the formation of necks in regions I and II. The deformation is quasi-uniform in region II, and necking appears to be diffuse rather than localized; whereas neck formation is important in region I, and macroscopic necking is evident at low total strains ($< 300\%$).

(2) Cavitation occurs up to strain rates of at least $\sim 3 \times 10^{-2}\ \text{sec}^{-1}$, and there is very extensive cavity formation in region I. However, fracture is due to necking in region I, and it appears that

the growth and interlinkage of cavities is not of major significance in limiting the ductility in this region.

(3) The results provide strong evidence for a decrease in the true value of the strain rate sensitivity in region I.

Acknowledgement

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References

1. F. A. MOHAMED and T. G. LANGDON, *Acta Met.* **23** (1975) 117.
2. T. G. LANGDON and F. A. MOHAMED, "Proceedings of the IV Interamerican Conference on Materials Technology" (Centro Regional de Ayuda Técnica, Mexico City, 1975) p. 498.
3. F. A. MOHAMED, S.-A. SHEI and T. G. LANGDON, *Acta Met.* **23** (1975) 1443.
4. H. ISHIKAWA, F. A. MOHAMED and T. G. LANGDON, *Phil. Mag.* **32**, (1975) 1269.
5. F. A. MOHAMED, M. M. I. AHMED and T. G. LANGDON, *Met. Trans. A* **8A** (1977) 933.
6. H. ISHIKAWA, D. G. BHAT, F. A. MOHAMED and T. G. LANGDON, *ibid.* **8A** (1977) 523.
7. D. A. MILLER and T. G. LANGDON, *ibid.* **9A** (1978) 1688.
8. T. G. LANGDON, *Scripta Met.* **11** (1977) 997.
9. H. W. HAYDEN, R. C. GIBSON and J. H. BROPHY, *Trans. ASM* **60** (1967) 3.
10. G. RAI and N. J. GRANT, *Met. Trans. A* **6A** (1975) 385.
11. M. F. ASHBY and R. A. VERRALL, *Acta Met.* **21** (1973) 149.
12. J. H. GITTUS, *J. Eng. Mater. Technol.* **99** (1977) 244.
13. S.-A. SHEI and T. G. LANGDON, *J. Mater Sci.* **13** (1978) 1084.

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