JOURNAL OF MATERIALS SCIENCE 18 (1983) 2407–2413

Strain distribution in the superplastic Pb–Sn eutectic alloy

MOHAMED M. I. AHMED[†], TERENCE G. LANGDON
Departments of Materials Science and Mechanical Engineering, University of Southern California, Los Angeles, California 90089-1453, USA

Experiments were conducted to investigate the distribution of strain within the gauge length for specimens of the superplastic Pb–62 wt % Sn eutectic alloy tested at room temperature. It is shown that deformation is quasi-uniform at low strain rates in region II so that the necks are diffuse rather than localized, but failure occurs by the formation of a sharp neck at high strain rates in region III. Using a specimen grain size of 6.1 μm, the transition from region II to region III occurs at an initial strain rate in the vicinity of 10^{-4} sec^{-1}.

1. Introduction

In superplasticity, the flow stress, σ, is generally related to the imposed strain rate, $\dot{\epsilon}$, by an equation of the form

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

where B is a constant which contains the dependence on temperature and grain size and m is the strain rate sensitivity. Measurements show that the value of m usually changes from a low value (~ 0.2) at low strain rates to a high value (~ 0.5) at intermediate strain rates and then again to a low value (~ 0.2) at high strain rates [1]: these three regimes of behaviour are termed regions I, II and III, respectively.

The overall ductility observed in a superplastic material under any selected testing conditions may be limited by the formation and growth of necks within the gauge length and/or by the development and interlinkage of internal cavities. The formation of macroscopic necking is determined primarily by the value of m, since it can be shown [2] that the change in the specimen cross-sectional area, A, with time, t, is given by

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

where P is the tensile force. It follows from Equation 2 that the probability of necking decreases as $m \rightarrow 1$, so that, in the absence of failure by cavitation, a value of $m \gtrsim 0.5$ will lead to the development of diffuse necks and thus to high elongations to failure. An example of this behaviour is given by the Pb–62 wt % Sn eutectic alloy, where $m \simeq 0.61$ under optimum conditions in region II at 413 K [3] and the corresponding elongation to failure is > 4850% [4].

True superplasticity strictly requires Newtonian viscous flow with $m = 1$ and a consequent infinite elongation to failure. In practice, however, this condition is not attainable in real metals, and there is instead an optimal superplastic condition when $m \gtrsim 0.5$ and failure occurs by quasi-stable plastic flow [5]. Under these conditions, where m is significantly < 1, it is important to examine the distribution of strain, and thus the extent of necking, within the gauge length.

Experiments were described earlier in which the local strain was measured within 14 adjacent segments along the deformed gauge lengths of specimens of the Zn–22 wt % Al eutectoid alloy [6], and the present investigation was conducted to provide similar measurements on the Pb–62 wt % Sn eutectic alloy tested at room temperature. It should be noted that similar experiments were performed to measure the local strains in the Pb–Sn eutectic in the very early work of Morrison [7]: however, the gauge lengths (of either 2.54 or

---

[†] Permanent address: Department of Metallurgy, Faculty of Engineering, Cairo University, Giza, Egypt.

5.08 cm) were divided into only five equal sections in these early tests, and there was no attempt to distinguish between the separate behaviour in regions II and III.

The Pb–Sn eutectic alloy was selected for this investigation for three reasons: (i) the alloy exhibits exceptionally high superplastic elongations under optimum conditions in region II [4], (ii) unlike Zn–22 wt% Al [8–10], it appears that there is relatively little cavity formation in the Pb–Sn eutectic in region II [11–13] although there is some evidence for cavitation at room temperature in region III [14], and (iii) it was established earlier that regions II and III are both readily attainable in this alloy using room temperature testing [15].

2. Experimental material and procedure

The experiments were performed on a Pb–62 wt% Sn alloy prepared from 99.999% pure Pb and 99.995% pure Sn. The preparation of the alloy is described elsewhere [15], and the final material contained the following impurities (in ppm): Ag, 0.2; Al, 0.5; Au, 1; Bi, 0.7; Ca, 0.1; Cd, 0.1; Cu, 2; Fe, 1; In, 1; Mg, 0.2; Mn, 0.1; Si, 0.3; and Tl, 0.5. Tensile specimens were cut parallel to the rolling direction with an initial gauge length, L_0, of 1.27 cm, a gauge width of 0.64 cm and a thickness of 0.254 cm. Each specimen was annealed in silicone oil for 1 hour at a temperature of 433 K to give an average spatial grain size, d (defined as 1.74 × mean linear intercept), of 6.1 μm.

Prior to testing, a sharp needle was used to scribe two specimens with a series of parallel lines, perpendicular to the longitudinal axis, to divide the initial gauge length, L_0, into 14 sections, each of approximately the same length. A travelling microscope was used to measure carefully the exact separation, ℓ_0 ($\simeq L_0/14$), between adjacent lines before testing. All subsequent measurements were made with reference to the initial values of ℓ_0 for each section.

These two specimens were pulled in tension on an Instron testing machine operating at a constant rate of cross-head diplacement, and the tests were conducted in air at a constant temperature of 298 ± 2 K. The experimental procedure consisted of interrupting each test at a selected interval of strain, removing the specimen from the Instron machine, and then using a travelling microscope to measure the longitudinal separation between adjacent marker lines. These measurements were used to calculate the percentage strain in each of the 14 sections, $\Delta\ell/\ell_0\%$, where $\Delta\ell$ is the increase in length and ℓ_0 is the initial length for the appropriate section. The total percentage strain within the specimen was calculated as $\Delta L/L_0\,\%$, where ΔL is the overall increase in length within the gauge section. After taking the measurements, the specimen was returned to the Instron machine for further testing. Using this procedure, it was possible to build up a series of plots for each specimen to show the variation of $\Delta\ell/\ell_0\%$ along the gauge length as a function of $\Delta L/L_0\%$.

In addition, and to provide a qualitative illustration of the degree of strain homogeneity within the gauge length, several specimens without marker lines were tested to selected strains for subsequent optical examination.

3. Experimental results

It was demonstrated earlier [15] that the Pb–62 wt% Sn alloy exhibits a transition at room temperature from the non-superplastic region III to the superplastic region II at a strain rate in the vicinity of $\sim 10^{-4}\,\text{sec}^{-1}$. Figure 1 shows the total elongation to failure, $\Delta L/L_0\%$, plotted against the initial strain rate, $\dot{\epsilon}$, for specimens tested over a range of strain rates from 6.6×10^{-6} to $6.6 \times 10^{-2}\,\text{sec}^{-1}$ [15]: the elongations are $<500\%$ at $\dot{\epsilon} \gtrsim 10^{-4}\,\text{sec}^{-1}$ but there is a marked increase in elongation to $>2000\%$ at the lowest strain rate used experimentally.

In the present investigation, the two specimens with scribed marker lines were tested at the points labelled A and B in Fig. 1. Specimen A was tested at an initial strain rate of $6.6 \times 10^{-5}\,\text{sec}^{-1}$ in region II and specimen B was tested at an initial strain rate of $6.6 \times 10^{-3}\,\text{sec}^{-1}$ in region III: the elongations to failure at these initial strain rates are $\sim 650\%$ and $\sim 125\%$, respectively.

Detailed measurements were taken on specimens A and B at selected elongations to provide values for $\Delta\ell/\ell_0\%$ at each of the 14 sections within the two gauge lengths. The results are shown in Fig. 2 for (a) specimen A tested in region II and (b) specimen B tested in region III: the section numbers on the lower axes indicate the 14 segments, and they are numbered from 0 to ± 7 with zero corresponding to the mid-point of the gauge length.

The results in Fig. 2a were obtained at total elongations of 50%, 100%, 200% and 300%, respectively: thereafter, it was not feasible to obtain

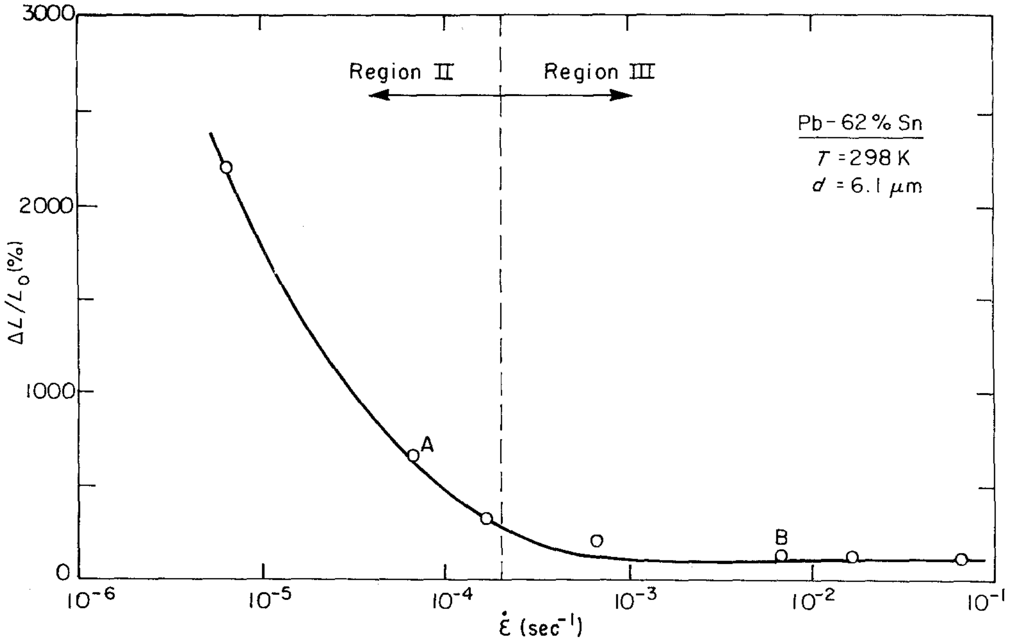

Figure 1 Elongation to failure against initial strain rate for Pb–62 wt % Sn having a grain size of 6.1 μm tested at 298 K [15]: measurements of the strain distribution were made on specimens tested at points A and B.

accurate measurements because the marker lines were no longer sharply defined. The individual datum points show that the deformation is essentially uniform at the lowest elongation of 50%, but it becomes quasi-uniform at $\Delta L/L_0 = 100\%$ with evidence for the formation of two very diffuse necks [at sections 2 (left) and 3 (right)]. These two necks continue to develop up to $\Delta L/L_0 = 300\%$, but they retain their diffuse nature so that failure by necking is not likely to occur under these conditions. Due to the loss of definition of the marker lines at high strains, the accuracy of each individual measurement was estimated as ± 10% at a total elongation of 300%: these error bars are indicated in Fig. 2a.

The general uniformity of deformation in region II at an initial strain rate of $6.6 \times 10^{-5}\,\text{sec}^{-1}$ is illustrated by the specimens tested to different elongations without marker lines, as shown in Fig. 3: specimen A is untested, and specimens B to G were pulled to elongations of 100%, 200%, 300%, 475%, 550% and to failure at 775%, respectively.* Figure 3 shows that, even at room temperature at an initial strain rate which is only just within region II, the specimens pull out reasonably uniformly so that the occurrence of necking, such as is visible in specimen F at 550%, tends to be very diffuse rather than localized.

Figure 2b shows the results obtained in region III at total elongations of 25%, 50%, 75% and at fracture at 100%, respectively. Under these conditions, a marked non-uniformity in strain develops in the gauge length and, for the specimen shown in Fig. 2b, this leads to final fracture in section 2 (right) such that the macroscopic specimen elongation is $\Delta L/L_0 \simeq 100\%$ but the local elongation in the necked region at the point of fracture is $\Delta \ell/\ell_0 \simeq 275\%$: the error bars in Fig. 2b again indicate the estimated accuracy of ± 10%. These results are therefore fairly similar to earlier measurements on the Zn–22 wt % Al alloy in region III, where $\Delta L/L_0 \simeq 395\%$ at fracture and the local strain in the necked segment was $\Delta \ell/\ell_0 \simeq 1340\%$ [6].

The development of non-uniformities in strain at low elongations is clearly visible in Fig. 4 for several specimens tested in region III at an initial strain rate of $6.6 \times 10^{-3}\,\text{sec}^{-1}$: specimen A is untested and specimens B to G were pulled to elongations of 10%, 25%, 50%, 75%, 100% and to failure at 125%, respectively. There is very clear evidence for the formation of a neck in specimen F at 100%

---

*There is always some scatter between individual specimens when measuring the elongations to failure: this is shown by the elongation of 775% exhibited by specimen G in Fig. 3 and the elongation to failure of 650% obtained for an identical specimen at the same initial strain rate in Fig. 1 [15].

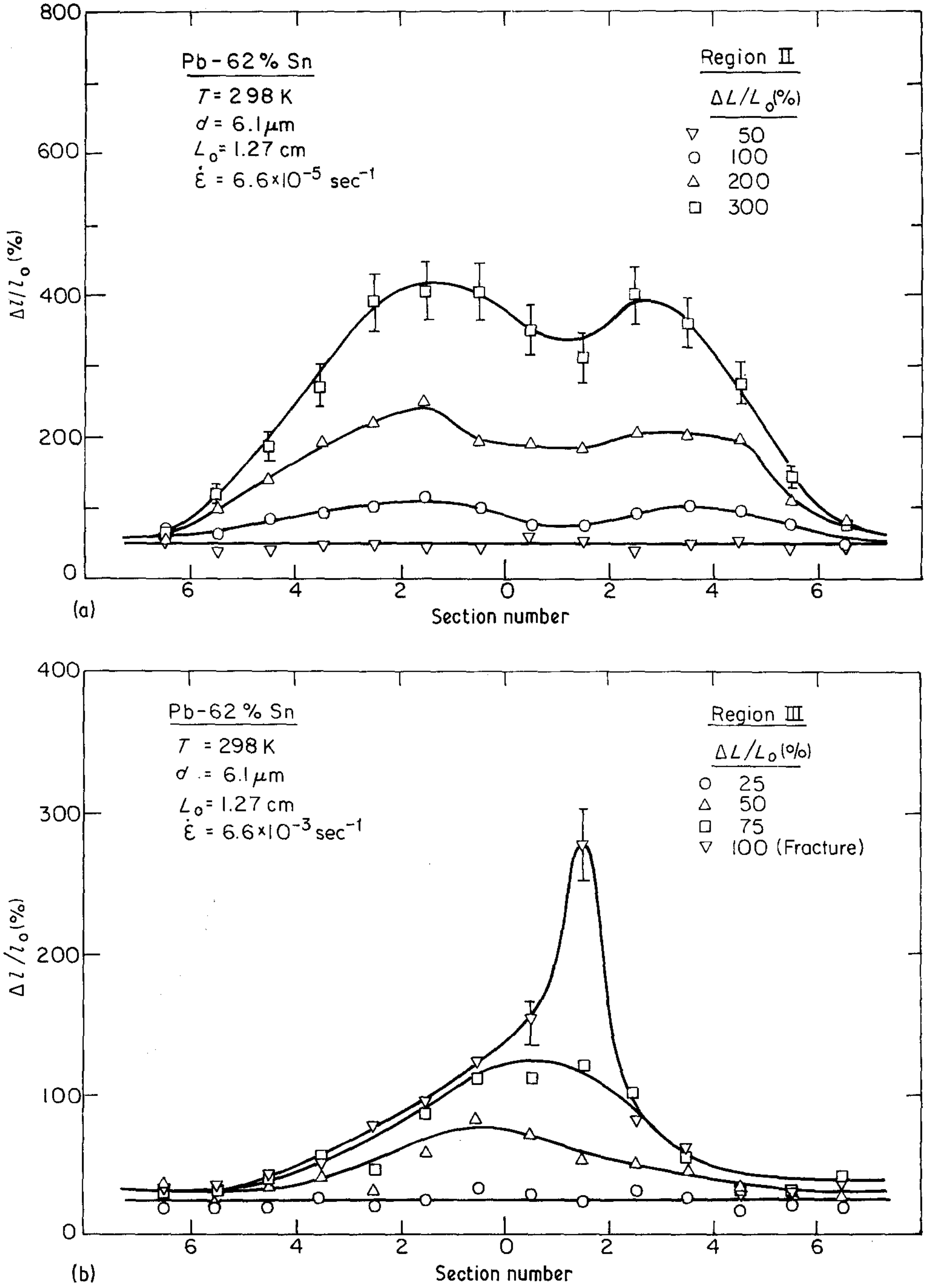

Figure 2 Variation in local strain along the gauge length for specimens tested at room temperature at initial strain rates of (a) $6.6 \times 10^{-5}\ \text{sec}^{-1}$ in region II and (b) $6.6 \times 10^{-3}\ \text{sec}^{-1}$ in region III.

elongation, and the profile within the gauge length may be contrasted with specimen B in Fig. 3 which was tested in region II to the same total elongation of 100%.

4. Discussion

The results show that the superplastic Pb–62 wt % Sn eutectic alloy exhibits a transition at room temperature from failure by necking at a low elongation at an initial strain rate of $6.6 \times 10^{-3}\ \text{sec}^{-1}$ to relatively uniform deformation and a high elongation to failure at an initial strain rate of $6.6 \times 10^{-5}\ \text{sec}^{-1}$. The data therefore confirm the earlier observation of a transition from region III to

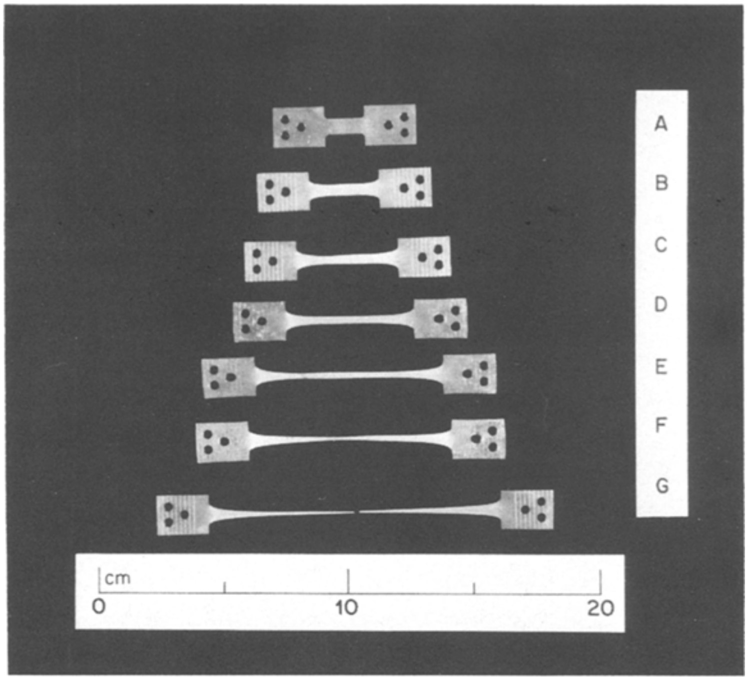

Figure 3 Appearance of specimens after testing to different elongations at room temperature at an initial strain rate of $6.6 \times 10^{-5}\,\text{sec}^{-1}$ in region II: specimen A is untested, and specimens B to G were pulled to elongations of 100%, 200%, 300%, 475%, 550% and to failure at 775%, respectively.

region II with decreasing strain rate at room temperature [15], and the general trends are consistent also with earlier detailed measurements on the superplastic Zn–22 wt % Al eutectoid alloy [6].

To delineate more precisely the uniformity of deformation within regions II and III, it is instructive to plot $\Delta\ell/\ell_0\%$ against $\Delta L/L_0\%$ for both regions of flow, as shown in Fig. 5. Uniform deformation, as in Newtonian viscous flow with $m = 1$, requires that $\Delta\ell/\ell_0\% \equiv \Delta L/L_0\%$; this is indicated by the solid line at 45° to the aixs.* The various broken lines plot the maximum (upper) and mini-

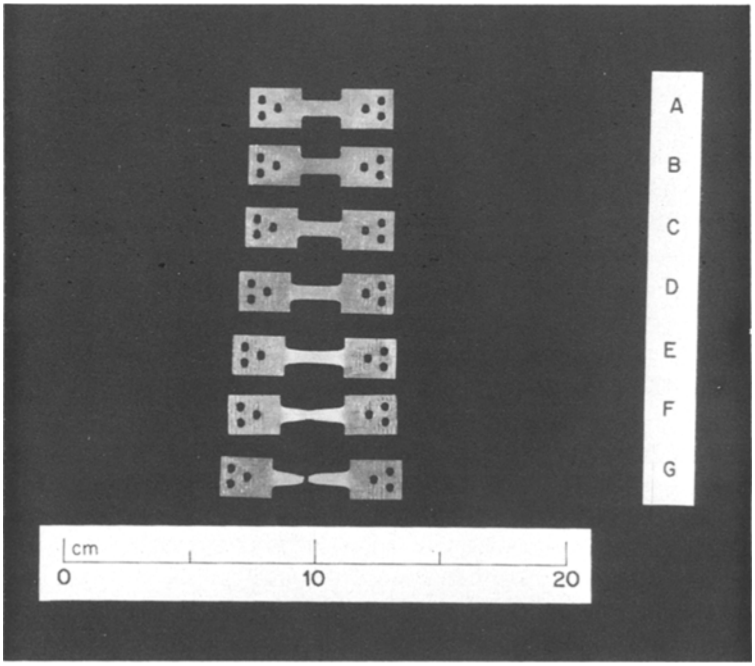

Figure 4 Appearance of specimens after testing to different elongations at room temperature at an initial strain rate of $6.6 \times 10^{-3}\,\text{sec}^{-1}$ in region III: specimen A is untested, and specimens B to G were pulled to elongations of 10%, 25%, 50%, 75%, 100% and to failure at 125%, respectively.

---

*The line labelled "uniform deformation" neglects the occurrence of end effects in a machined tensile specimen.

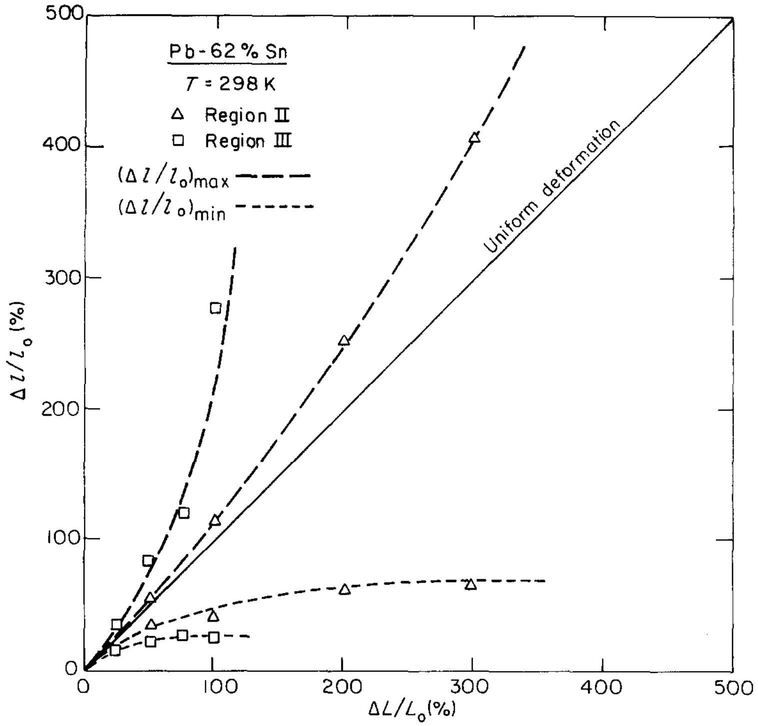

Figure 5 Uniformity of deformation within the gauge length for regions II and III.

mum (lower) values of $\Delta\ell/\ell_0$% from the 14 individual measurements within the gauge section. This plot confirms the high degree of flow uniformity in region II, up to elongations of at least 200%, and the sharp deviation from uniform flow in region III at an elongation of ~ 75%.[†]

The present results are qualitatively similar to those described earlier by Morrison [7] where the gauge lengths were divided into only five sections. For example, Morrison [7] reported a total elongation of 440% and relatively uniform deformation up to ~ 150% at room temperature, and this result is essentially intermediate in behaviour between the two sets of data obtained in the present investigation.

The profiles of the various specimens, shown in Figs. 3 and 4, indicate a quasi-stable flow in region II at the lowest strain rate, so that necking is very diffuse, and a failure by necking in region III due to the development of non-uniformities in strain at very low total elongations (< 100%). It is interesting to note that, although the tests were conducted in region III under conditions where there is some evidence for the occurrence of cavitation at room temperature [14], the measurements in Fig. 2b show that final fracture takes place through the development of a sharp neck within the gauge length.

5. Summary and conclusions

1. Detailed measurements were taken on the superplastic Pb–62 wt% Sn eutectic alloy to examine the strain distribution within the gauge length in regions II and III at room temperature.

2. The results show that (i) the deformation is quasi-uniform in region II and the necks are diffuse rather than localized and (ii) failure occurs by the formation of a sharp neck within the gauge length in region III.

3. The experimental measurements confirm the transition with decreasing strain rate from region III to region II at room temperature: the transition occurs at an initial strain rate in the vicinity of 10^{-4} sec^{-1}.

Acknowledgements

One of us (MMIA) is grateful for the award of a Peace Fellowship. This work was supported by the National Science Foundation under Grant No. DMR79-25378.

[†] The deviation from uniform deformation shown in Fig. 5 for the values of $(\Delta\ell/\ell_0)_{min}$ in region II is due to end effects in a tensile specimen: this behaviour is not strictly a characteristic of superplastic flow.

References

1. T. G. LANGDON, *Met. Trans. A* **13A** (1982) 689.
2. F. A. MOHAMED, M. M. I. AHMED and T. G. LANGDON, *Met. Trans. A* **8A** (1977) 933.
3. F. A. MOHAMED and T. G. LANGDON, *Phil. Mag.* **32** (1975) 697.
4. M. M. I. AHMED and T. G. LANGDON, *Met. Trans. A* **8A** (1977) 1832.
5. T. G. LANGDON, *Met. Sci.* **16** (1982) 175.
6. F. A. MOHAMED and T. G. LANGDON, *Acta Metall.* **29** (1981) 911.
7. W. B. MORRISON, *Trans. AIME* **242** (1968) 2221.
8. H. ISHIKAWA, D. G. BHAT, F. A. MOHAMED and T. G. LANGDON, *Met. Trans. A* **8A** (1977) 523.
9. D. A. MILLER and T. G. LANGDON, *Met. Trans. A* **9A** (1978) 1688.
10. M. M. I. AHMED, F. A. MOHAMED and T. G. LANGDON, *J. Mater. Sci.* **14** (1979) 2913.
11. A. E. GECKINLI and C. R. BARRETT, *J. Mater. Sci.* **11** (1976) 510.
12. D. W. LIVESEY and N. RIDLEY, *J. Mater. Sci.* **13** (1978) 825.
13. M. J. STOWELL, "Superplastic Forming of Structural Alloys," edited by N. E. Paton and C. H. Hamilton (The Metallurgical Society of AIME, Warrendale, Pennsylvania, 1982) p. 321.
14. R. K. YADAVA and K. A. PADMANABHAN, *J. Mater. Sci.* **17** (1982) 2435.
15. M. M. I. AHMED and T. G. LANGDON, *J. Mater. Sci. Lett.* **2** (1983) 59.

Received 22 November 1982
and accepted 6 January 1983