Exceptional Ductility in the Superplastic Pb-62 Pct Sn Eutectic

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Superplasticity refers to the ability of some metals to deform in tension without fracture to strains of several hundreds of pct. As demonstrated in a recent review,[1] the maximum elongation at failure in superplasticity is generally in the range from ~200 pct to ~1000 pct, although some materials deform to ~1000 to 2000 pct.

For several years, the maximum elongation obtained under superplastic conditions was 2100 pct, reported by Lee[2] for the Mg-Al eutectic alloy. However, a recent systematic investigation of ductility in the superplastic Zn-22 pct Al eutectoid revealed that, for a testing temperature of 473 K and an initial grain size of 2.5 μm, there was a range of strain rate covering almost two orders of magnitude within which the strains at failure were consistently >2000 pct.[3] The maximum tensile elongation attained within this optimum range was 2900 pct.

Generally, the strain at failure tends to increase with an increase in the strain rate sensitivity, m [$= (\partial \ln \sigma/\partial \ln \dot{\epsilon})$, where σ is the applied stress and $\dot{\epsilon}$ is the steady-state strain rate], although the relationship is complex because markedly different ductilities may be achieved in the same material under various experimental conditions, such as different temperatures or grain sizes, even when m remains essentially constant.[4] Since earlier work had shown that the maximum value of m in Pb-62 pct Sn was ~0.61,[5] and this is significantly higher than the maximum value of m ~0.5 in Zn-22 pct Al,[3] the present tests were undertaken to investigate the possibility of very high ductilities in the Pb-62 pct Sn eutectic.

The material was prepared by melting 99.999 pct purity Pb and 99.995 pct purity Sn in air in a graphite crucible, chill-casting into an ingot of 1.0 cm thickness, and rolling at room temperature to a final thickness of 0.254 cm. The final material was at the eutectic composition of 38.1 wt pct Pb plus 61.9 wt pct Sn.

Four tensile specimens, each having a gage section 0.635 cm in length and 0.508 cm wide, were cut from the sheet parallel to the rolling direction, and annealed for 1 h at 433 K to give an average spatial grain diameter (equal to 1.74 × mean linear intercept) of 6.9 μm. The specimens were tested by immersing in an electrically-heated silicone oil bath, stirred with bubbling argon, in which the temperature was maintained constant at 413 ± 1 K. After holding at temperature for 25 min, the specimens were pulled in an Instron testing machine at a constant rate of cross-head displacement which was equivalent to an initial strain rate of 1.33×10^{-4} s^{-1}. This strain rate was selected because earlier work indicated that it was within the region for which $m = 0.61$.[5]

Some scatter was evident in the overall tensile behavior of these four specimens. Three of the specimens failed at elongations of 3400 pct, 3800 pct, and 4000 pct, respectively, where the elongation is defined as $\Delta L/L_o$ pct where ΔL is the total increase in length at the point of failure and L_o is the initial specimen gage length. For the fourth specimen, the test was terminated prior to fracture at an elongation of 4850 pct, when it became apparent that further deformation would bring the upper portion of the specimen grip above the surface of the silicone oil. The latter specimen, shown at *B* in Fig. 1, pulled down to a very thin wire, with no evidence of any macroscopic necking within the gage section. For comparison, an untested specimen is shown at *A* in Fig. 1.

The exceptional ductilities observed in these four specimens, with a maximum in one case of 4850 pct without failure, represent the highest elongations reported to date in any superplastic material. It is therefore appropriate to compare these experimental results with the predictions of two relationships which were specifically developed for the percentage elongation at failure.

Burke and Nix[6] presented a theory for the development of plastic instabilities in tension creep due to macroscopic irregularities in the cross-sectional area of the specimen. According to this theory, the percentage elongation at failure is given by[7]

$$\text{Pct elongation} = \frac{mK_1}{1-m} \times 100 \qquad [1]$$

where K_1 is a constant typically equal to ~2 to 3.

Taking an upper value of $K_1 = 3$, and putting $m = 0.61$, Eq. [1] predicts an elongation at failure of ~470 pct, which is about an order of magnitude lower than the experimental elongations from 3400 pct to >4850 pct. Furthermore, the theory of creep stability was developed by ignoring the possibility of cavity nucleation and growth at the grain boundaries, so that, in principle at least, Eq. [1] essentially represents an upper limit for the percentage elongation. Although no cavities have been reported to date during superplastic flow of the Pb-62 pct Sn eutectic, extensive cavitation was observed in a specimen of the Zn-22 pct Al eutectoid deformed to fracture at ~2600 pct.[8]

In early work on the Pb-Sn eutectic alloy, Morrison[9] suggested the following empirical relationship for the percentage elongation at failure:

$$\text{Pct elongation} = K_2 m^2 \left[\frac{D_o}{L_o}\right] \times 100 \qquad [2]$$

where K_2 is a material constant and D_o is the initial diameter of a round tensile specimen. For the Pb-Sn eutectic, the value of K_2 was determined as ~280 for round specimens having $0.1 < D_o/L_o < 0.5$.

It is difficult to use Eq. [2] for the present work on sheet specimens, especially as specimen geometry is an important feature since flat sheet specimens generally exhibit lower elongations than round bar specimens under identical testing conditions.[1] However, if D_o is taken as the specimen thickness (0.254 cm), the ratio D_o/L_o is 0.4, and Eq. [2] predicts an elongation at failure of ~4200 pct. The predicted value is therefore of similar magnitude to the elongations observed experimentally.

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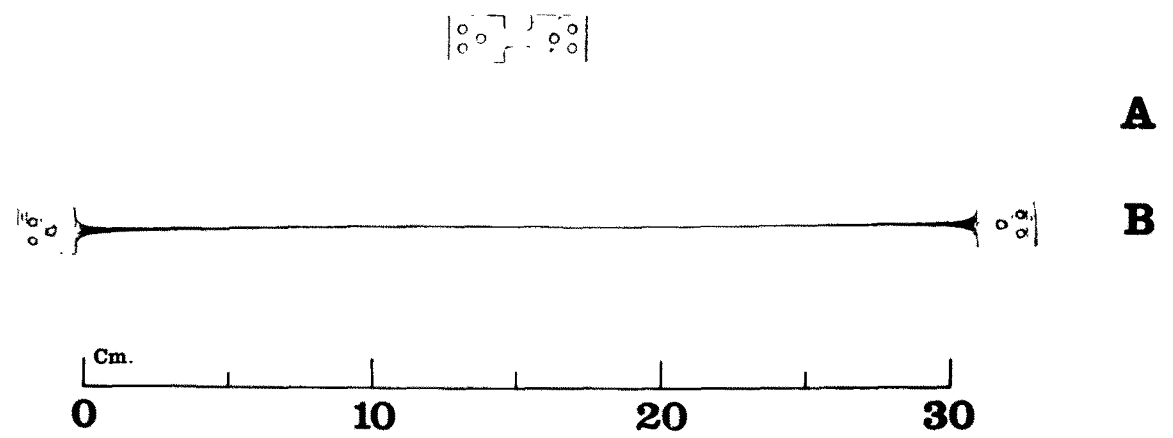

Fig. 1—An example of exceptional superplasticity in the Pb-62 pct Sn eutectic alloy. Specimen *A* is undeformed. Specimen *B*, having a grain size of 6.9 μm, was pulled in tension at 413 K with an initial strain rate of 1.33×10^{-4} s^{-1}; the test was discontinued prior to failure at an elongation of 4850 pct.

In summary:

1) Four specimens of the Pb-62 pct Sn eutectic alloy, having a grain size of 6.9 μm, exhibited exceptional ductility when pulled in tension at 413 K with an initial strain rate of 1.33×10^{-4} s^{-1}. The elongations at failure were ≥3400 pct; for one specimen, the test was discontinued prior to failure at an elongation of 4850 pct, representing the highest strain so far reported in a superplastic material.

2) The percentage elongations at failure are about an order of magnitude higher than the value predicted by the theory of plastic instabilities in tension creep developed by Burke and Nix,[6] but they are in reasonable agreement with the empirical relationship derived by Morrison[9] for round bar specimens of the Pb-Sn eutectic.

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1. J. W. Edington, K. N. Melton, and C. P. Cutler: *Progr. Mater. Sci.*, 1976, vol. 21, pp. 61-170.
2. D. Lee *Acta Met.*, 1969, vol. 17, pp. 1057-69.
3. H. Ishikawa, F. A. Mohamed, and T. G. Langdon: *Phil. Mag.*, 1975, vol. 32, pp. 1269-71.
4. F. A. Mohamed, M. M. I. Ahmed, and T. G. Langdon: *Met. Trans A*, 1977, vol. 8A, pp. 933-38
5. F. A. Mohamed and T. G. Langdon *Phil. Mag.*, 1975, vol 32, pp. 697-709.
6. M. A. Burke and W. D. Nix: *Acta Met.*, 1975, vol 23, pp 793-98.
7. R. W. Lund and W. D. Nix: *Acta Met.*, 1976, vol. 24, pp. 469-81.
8. H. Ishikawa, D. G. Bhat, F. A. Mohamed, and T. G. Langdon: *Met. Trans. A*, 1977, vol. 8A, pp. 523-25
9. W. B. Morrison *Trans. TMS-AIME*, 1968, vol 242, pp. 2221-27.

Communication: A Note on the Determination of Accurate Flow Properties from Simple Compression Tests

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The simple compression test is ideal for the determination of stress-strain data at high strains and high strain rates as is required for predictions of the behavior of metallic armor materials. The principal limitations of the test are caused by friction between the plattens and specimen ends at large diameter to height ratios (squat samples) and buckling of the specimen at small diameter to height ratios (slender samples). Little can be done to remove the buckling problem but it is possible, by doing several tests, to account for friction. Sachs[1] and Cook and Larke[2] developed a method of accounting for the frictional work done in compression tests by carrying out the tests at several diameter to height ratios and extrapolating the data obtained to zero diameter to height ratio. In this note a method is described which allows a considerable reduction in the work involved in obtaining true stress-strain data from simple compression tests; only two compression tests are required.

From a simple uniform compression test the strain is calculated from the initial and progressive sample dimensions and the applied stress is obtained from the load divided by the current specimen cross sectional area. It is then necessary to remove the frictional work contribution so that the true material flow stress can be obtained from the applied stress. Avitzur[3] developed an upper bound solution to the problem of uniform compression of a solid cylinder between flat dies; here the applied stress (P) is related to the material flow stress (σ_o) by

$$\frac{P}{\sigma_o} = 1 + C\frac{d}{h} \qquad [1]$$

where

d is the cylinder diameter,
h is the cylinder height and
C is a constant relating the shear stress at the platten/specimen interface to the material flow stress (σ_o).

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