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Determination of the relative density changes in the presence of high strain gradient

During the plastic deformation of a material containing second phase particles, damage occurs either by decohesion at the interface between the particle and the matrix [1] or by fracture of the particles [2–4]. This damage can be quantified by metallurgical observations [5], measurements of Young's modulus [6], by hydrogen diffusion [7] or by relative density change measurements [8, 9]. In the present work, only metallurgical observations and relative density change measurements using a Ratcliffe's method [10] were performed. The metallurgical observations only allow very local measurements (areas of about $20\,\mu m \times 20\,\mu m$ were observed at a magnification of 4000 times by scanning electron microscope) but in contrast the relative density change measurements required a specimen of weight greater than 0.5 g in order to be sure of accuracy (uncertainty less than $\pm 5 \times 10^{-5}$ for the relative density measurement) [11]. The size of such a specimen compared to the size of the necking zone is important and it is a limitation to the use of this method. The aim of this work was to assess the relative density change in the necking zone at very high strain gradients.

The results are presented for a tough pitch copper which allows very high local tensile strain,

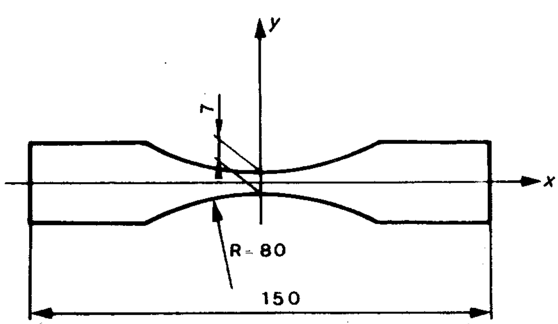

Figure 1 Shape of tensile sample (thickness: 2 mm).

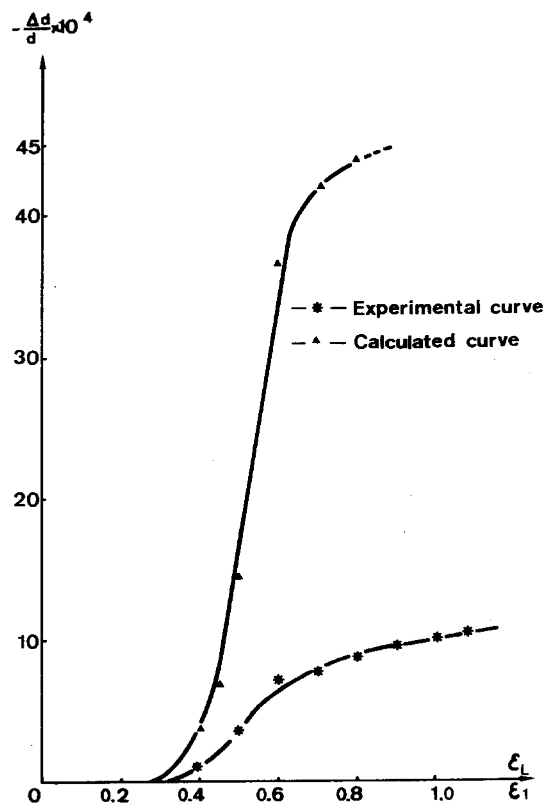

Figure 2 Relative density change curves for a tough pitch copper (experimental curve and curve calculated using a step-by-step method). The experimental curve shows the mean relative density change value on a sample 10 mm long, plotted against the tensile strain ϵ_1 measured by the strain gauge at each step of strain. The calculated curve represents the real value of the relative density at a given local strain ϵ_L on any area in the sample.

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ϵ_L, (ϵ_L more than 1.8). A tensile test was performed on a notched tensile specimen, in order to localize the plastic flow, taken from a 2 mm thick cold rolled sheet (half hard) (see Fig. 1). The tensile strain ϵ_l was measured in the middle of the sample (where the plastic flow occurs) by a strain-gauge of length 0.8 mm. The relative density change measurements were carried out on specimens of about 1 g in weight which corresponded, for the studied tough pitch copper, to an area in the plane of the sample of about 50 mm^2 (i.e. a sample of about 10 mm in length along the tensile direction). The experimental curve determined in this way is shown on Fig. 2. A saturation of the damage evolution is pointed out at strains greater than 0.5. This is not in agreement with theoretical [12, 13] and other experimental analyses [5, 14]. This experimental fact can be attributed to two phenomena:

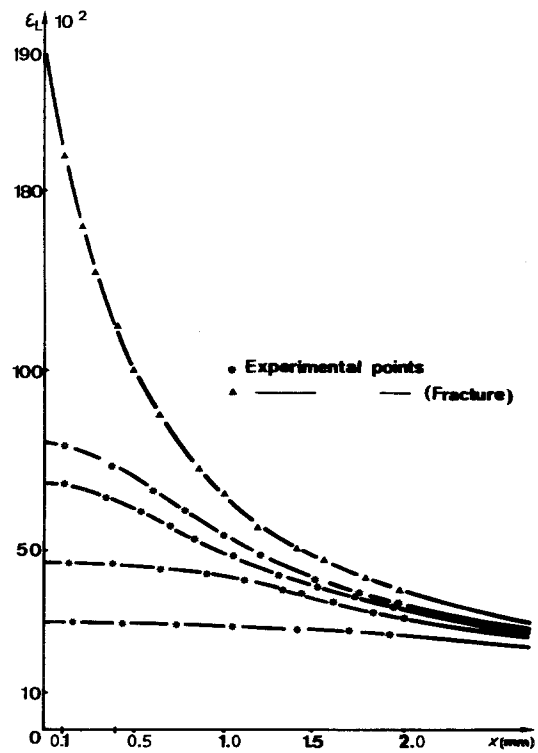

Figure 3 Local strain (ϵ_L) gradient curves along a tough pitch copper sample at different strain (ϵ_l) (some curves only are represented). $x = 0$ defines the middle of the tensile sample, $0 < x < 0.1$ mm defines first slice for calculation and $0 < x < 0.4$ mm is half of the strain guage length.

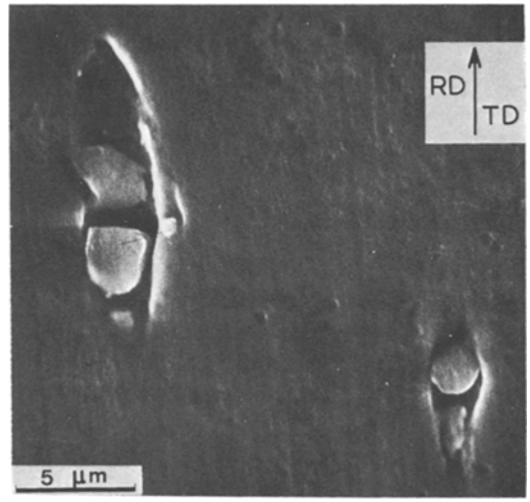

Figure 4 Voids around particles in a tough pitch copper specimen after a tensile test up to a local strain ϵ_L of 0.55. The plane of the micrograph is the plane of the sheet. TD is the tensile direction and RD is the rolling direction.

(a) the volume concerned with the necking process remains always small compared to the volume of the measured sample, so the measured relative density change is a mean value and then the relative density change value is lower than the real value;

(b) the measured strain ϵ_l is measured in the necking zone by a strain-gauge, so the strain indicated in Fig. 2 is greater than the mean strain measured over all the studied sample.

In order to assess the local relative density changes, it is necessary to know the local strain distribution along the specimen used for the density measurements; such information allows correction of the experimental results. In fact, as long as the strain gradient remains smooth along the weighted sample (10 mm in length), the local values are almost identical to the mean values measured. As soon as a strain gradient begins to develop, the local relative density change in the more deformed part can be calculated using the measured mean value of relative density change along the sample and the exact local value of this relative density change in the less-deformed region previously known (neglecting the variation of the tri-axiality of the stresses). Then, step-by-step, it is possible to correct the whole experimental curve.

For the tough pitch copper studied, the evolution of the strain gradient along the sample for different strain ranges, determined by the measurement of the local thickness of the samples, is shown in Fig. 3. For the determination of the calculated curve, the sample was divided into slices of length 0.1 mm. The supplementary strain gradient curves needed for the calculation were extrapolated at different intermediate strain values. The correction leads to the calculated curve shown in Fig. 2 (an example of the method is given in Appendix 1). It can be seen in the calculated curve that the amount of damage is emphasized and its rate of evolution is much greater than that shown by the experimental curve. The difference between the two curves occurs at very low strain because the sample used develops a high strain gradient very quickly. Nevertheless, a saturation is still observed at very high strain: this is due to the large size of the slices used for calculation of the strain gradient near fracture. It would be necessary to diminish the calculation increment where the strain gradient becomes very high. However, in most cases, such further refinement of the calculation is not necessary.

Scanning electron microscope observations were carried out in order to confirm the accuracy of the calculated curve. The volume of the voids associated with the particles (Fig. 4) was measured on deformed samples. For example, local observations were performed on a sample in an area where the local strain was found to be equal to 0.55, according to the strain gradient curve at a tensile strain of about $\epsilon_1 = 0.8$. The measured volume of voids leads to a relative density change of 2×10^{-3} which is in better agreement with the calculated curve than with the experimental one.

The experimental relative density change curve is only valid before a localization of plastic flow occurs. This is sufficient in most cases for plastic instability calculation. For example, in the calculation of the forming limit diagrams and for all cases in which strain gradients do not develop before necking.

It has been demonstrated that it is possible to assess the relative density changes of a material during plastic deformation at very high strain using a step-by-step method, in agreement with

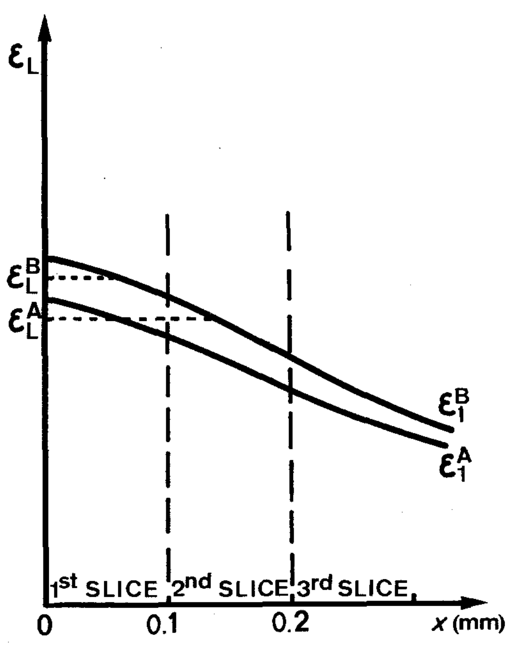

Figure A1 Two successive hypothetical strain gradient curves at two different tensile strains ϵ_1^A and ϵ_1^B measured by the strain gauge.

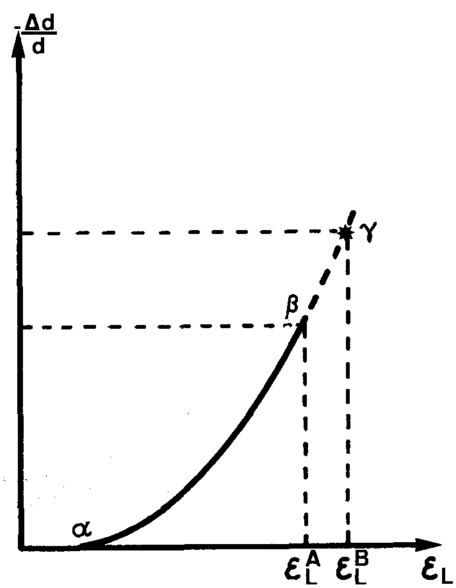

Figure A2 The calculated curve of relative density change against the local strain ϵ_L. The curve between α and β shows values of relative density change calculated before the example was studied and γ is the mean relative density change value in the more deformed slice of the strain gradient curve corresponding to a tensile strain ϵ_1^β.

metallurgical observations. This method is of interest in the analysis of fracture phenomena by the growth and coalescence of voids. This macroscopic method is easier and quicker to perform than the necessary great number of metallurgical observations.

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Appendix 1
It is assumed that the sample is deformed up to a tensile strain ϵ_I^A measured by the strain-gauge. At this strain, the local strain gradient is known by the measurement of the thickness of the sample (Fig. A1). According to a previous calculation, the calculated curve of the relative density changes is known up to a strain ϵ_L^A (curve between α and β in Fig. A2). The tensile strain is increased up to ϵ_I^B in such a way that the mean local strain value in the second slice does not exceed the previous upper limit for strain ϵ_L^A (Fig. A1). Assuming that the relative density change values depend only on the strain, they are known in each slice where ϵ_L is lower than ϵ_L^A. As the mean relative density change value is known by a measurement for a strain ϵ_I^B, the mean relative density change value can be estimated from the first slice, i.e. for a mean local strain ϵ_L^B (point γ in Fig. A2).

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