Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

VOID GROWTH AND LOCALIZATION OF SHEAR IN PLANE STRAIN TENSION

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INTRODUCTION

The observation that void growth is a characteristic feature of ductile fracture has led to several theoretical studies of the growth of isolated voids in plastically deforming media [1, 2, 3]. However, careful experiments with which existing theories can be compared are almost totally lacking. For this reason, experiments were conducted with the objective of determining the growth of an isolated cylindrical void in plane strain.

We chose to examine void growth as a function of triaxiality of stress and of material work-hardening rate because these are the dominant variables in the theories which have been proposed. Plane strain tension specimens were prepared which contained cylindrical void nuclei extending normal to the plane of deformation. The metallurgical system which was used differed markedly from standard structural alloys in that the cylindrical nuclei were isolated and were of a single, known size. Because the matrix did not adhere to the nuclei, there was no ambiguity concerning a criterion for void nucleation. The experimental design therefore made possible direct comparisons of void growth observations with existing theories.

MATERIALS AND METHODS

The experimental programme consisted of testing copper plane strain specimens and examining cross sections of the deformed ligaments metallographically to determine the extent of void growth. Three specimen shapes (corresponding to included notch angles of $2\omega_o = 180°$, $2\omega_o = 90°$, and $2\omega_o = 0°$ in Figure 1a) were tested to investigate the influence of triaxial stress elevation on void growth. The specimens were designed to ensure plane deformation and full plastic constraint [4, 5]. An actual specimen having $2\omega_o = 180°$ is shown in Figure 1b.

Specimens containing a single void nucleus were produced by embedding a graphite filament, 8.5 μm in diameter, symmetrically between the notch roots. That is, the axis of the filament was coincident with the third axis in Figure 1a. Specimens which contained a periodic array of nuclei were also produced. In these specimens, the filaments extended in the direction of the third axis and were evenly spaced in the direction of the second axis.

The combination of copper and graphite was selected because (a) carbon is exceedingly insoluble in copper, (b) compounds are not formed in this system, and (c) copper does not wet graphite. High-purity copper (99.999%) was selected to inhibit the nucleation of voids at secondary sites in the matrix.

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The filaments were embedded in the copper matrix by directionally solidifying the matrix in a modified Czochralski crystal-growing furnace. The resulting crystals were cold-worked in a plane-strain compression fixture, then recrystallized and prestrained. Specimens having the proper orientation with respect to the filaments were then machined. Two work-hardening rates were obtained by preparing half the specimens in the annealed condition and half in the prestrained condition. Void growth was erratic in the annealed specimens, presumably because slip was not uniformly distributed in the large, relatively dislocation-free grains. For this reason, except where noted otherwise, the results presented here are from prestrained specimens. Typically, the initial ligament width W_0 was 2.5 mm; so the ratio of ligament width to filament diameter was greater than 250 to 1. After a desired increment of deformation had been applied to a specimen, it was sectioned in the 1-2 plane at a distance of $4W_0$ from its end and was examined metallographically.

RESULTS AND DISCUSSION

The Uniform Growth of an Isolated Void

The micrographs in Figure 2 present the progressive change in void shape with increasing extension for a prestrained, unnotched specimen. The value of $\ln(W_0/W)$ is the nominal axial strain, where W_0 and W are the initial and current ligament widths. The filament is the gray area in the centre of the void in Figure 2a. The first indication of void growth is the separation of the matrix from the filament in the direction of the tensile axis. The void predicted by McClintock's analysis [1] for the appropriate state of stress, work-hardening exponent, and deformation history is given in Figure 2d, superimposed on a trace of the outline of the observed void. (The work-hardening exponent n in the empirical power-law expression relating equivalent stress to equivalent plastic strain was 0.15 for this material.)

At the nominal strain of 0.25 (Figure 2b), the cavity has further elongated in the direction of the tensile axis. The observed cavity has extended much more rapidly in the direction of the tensile axis than would be expected on the basis of McClintock's theory. His approach predicts a substantial contraction of the cavity in the transverse direction. Of course, any tendency toward contraction would have been resisted by the rigid filament.

The difference between experimental results and theoretical predictions increases with increasing strain. At a nominal strain of 0.37, the growth in the axial direction is severely underestimated. However, a more important observation is that the void is extending rather than contracting in the transverse direction.

The observed values of mean radius ratio R/R_0 and eccentricity m are presented as a function of nominal strain in Figures 3a and 3b. The mean void radius is defined as $R = (\alpha+\beta)/2$, where α and β are the semimajor and semiminor axes, respectively. The eccentricity is defined as $m = (\alpha-\beta)/(\alpha+\beta)$. Comparisons of the observed values of mean radius ratio with the predicted values show that agreement is poor, especially for large strains. Our experimental data for eccentricity are compatible with the trend which is predicted by McClintock's analysis, but the scatter in the data is rather large.

Nowhere in the literature does a complete solution appear for the strain distribution across a necked section which is undergoing plane plastic flow. Cowper and Onat considered the plane deformation of a rectangular bar composed of a rigid work-hardening material [6]. For a specimen of the geometry used in our experiment, the displacement field obtained by Cowper and Onat at incipient necking suggests constant strain across the section. In our experiment, the measure of strain $\ln(W_0/W)$ only approximates the value of strain in the vicinity of the filament.

Void Growth by Localized Shear

Continued extension caused severe necking of the unnotched specimens. Frequently, the internal void lay in the plane of the minimum section, and in these cases, the internal void became quadrilateral with vertices pointing in the axial and transverse directions. Figure 4a shows a section of an annealed, unnotched specimen at a nominal strain of 0.82. The void diagonals are approximately 400 μm in length, which is more than 40 times the diameter of the initial void nucleus. The size, shape, and orientation of the quadrilateral void did not change perceptibly with distance in the direction of the third coordinate, indicating that local grain orientation had not markedly influenced its growth.

In 1949, Orowan suggested that a quadrilateral void could form by localized shear in the neck of a perfectly plastic solid which was deforming in a plane [7]. In Orowan's sketch of such a solid (Figure 4b), the broken lines represent zones of localized shear on planes of maximum shear stress. Deformation will proceed by shear along planes AB-CD or along planes of A´B-CD´ because this mode of deformation requires the smallest tensile force.

A necessary condition for the localization of shear is the reduction of the work-hardening rate below a critical value [7]. Consistent with this requirement is the observation that a quadrilateral void became evident at a smaller nominal strain in the prestrained specimen than in the annealed specimen.

Void Growth in a Band of Uniform Shear

An unnotched specimen was produced which contained a periodic array of filaments at a spacing of approximately 500 μm. The material from which this specimen had been machined was prestrained but unrecrystallized. Tensile deformation of the specimen led to the formation of a shear band which intersected the plane containing the filament array. The band lay at an angle of approximately 45° to the direction of the tensile axis. From the rotation of the straight annealing twin boundaries which intersected the band, it was possible to establish the magnitude of the uniform shear strain. The growth and rotation of the voids in the band were compared with the prediction of McClintock, Kaplan, and Berg [2]. Void mean radius, void eccentricity, and void orientation with respect to the direction of shear were plotted as a function of shear strain. Although the theory predicted the observed change in void eccentricity rather well, it underestimated both void growth and void rotation. The void growth results and predictions are similar to those in Figure 3a if "Nominal Strain" is replaced by a "Shear Strain" of twice ε_1.

Void Growth Under Transverse Constraint

Space limits us to a few qualitative comments on the 90° and 0° notched specimens. In sections of the unnotched specimen, voids initially elongated in the direction of the tensile axis. By contrast, voids in sections of the 90° notched specimen exhibited pronounced transverse growth from the beginning of the test. Sections of this specimen contained a much larger void than did corresponding sections of the unnotched specimen at the same value of the ligament reduction. The 0° notched specimen fractured at an exceedingly small strain.

CONCLUSIONS

The analysis of McClintock and his co-workers is physically sound in the sense that it predicts reasonable trends for the growth and rotation of voids. However, our results show a more rapid growth and rotation, by a factor of about two, than is predicted for a material with a strain-hardening exponent of n = 0.15.

One reason for the frequently reported overestimation of fracture strain by ductile fracture criteria appears to be the theoretical underestimation of void growth rate. Also, mechanisms other than uniform void growth, such as shear localization and slipping off, undoubtedly contribute to and accelerate ductile fracture.

ACKNOWLEDGEMENT

The authors acknowledge with appreciation the financial support of the Lawrence Livermore Laboratory under LLL Task 5439-85 and the National Science Foundation under NSF Grant ENG 74-24365.

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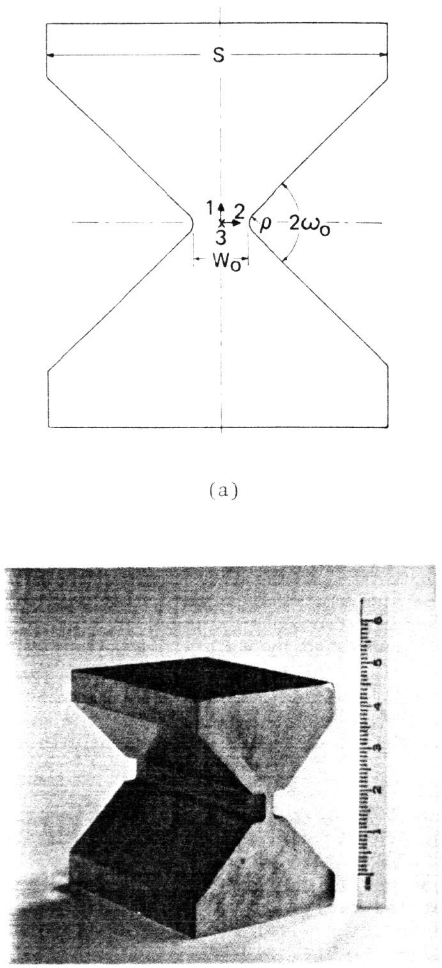
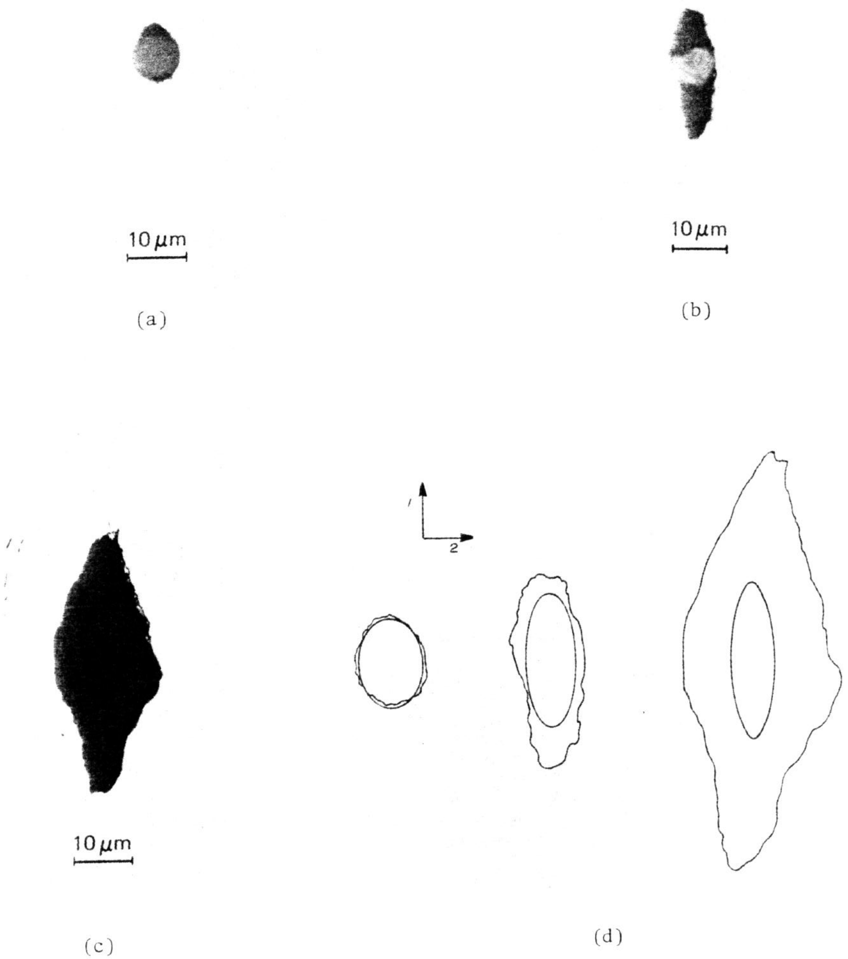


(a)

(b)

Figure 1 Plane-Strain Tension Specimens

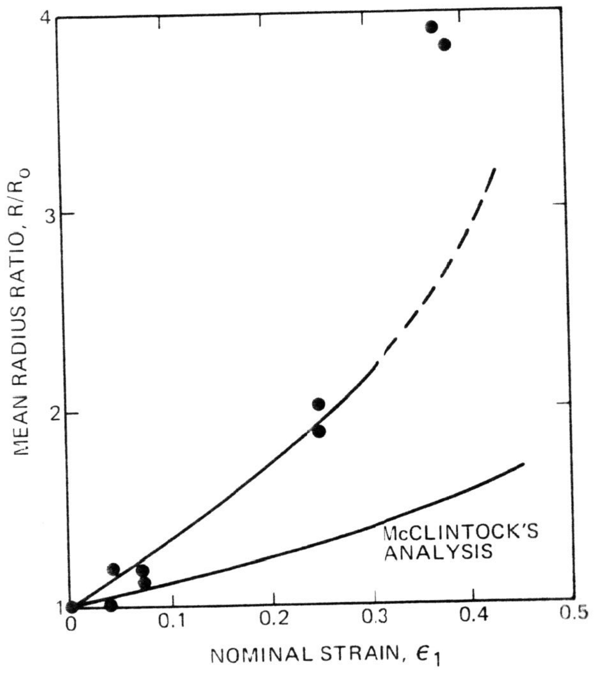
(a) Geometry of the Double-Notched Specimens
(b) An Unnotched ($2\omega_o$ = 180°) Specimen with W_o = 2.54 mm, S = 44.6 mm, B = Thickness in the Third Direction = 54.0 mm



(a) (b) (c) (d)

Figure 2 Sections of the Unnotched Prestrained ($2\omega_o$ = 180°, n = 0.15) Specimen

(a) Nominal Strain $\equiv \ell n(W_o/W)$ = 0.07
(b) Nominal Strain = 0.25
(c) Nominal Strain = 0.37
(d) McClintock's Predictions Superimposed on Traces of the Observed Voids Shown in (a), (b) and (c)



(a)

Figure 3 A Comparison of Experimental Results with McClintock's Analytical Predictions

(a) Void Mean Radius Ratio as a Function of Nominal Strain for the Unnotched Prestrained ($2\omega_o$ = 180°, n = 0.15) Specimen

continued

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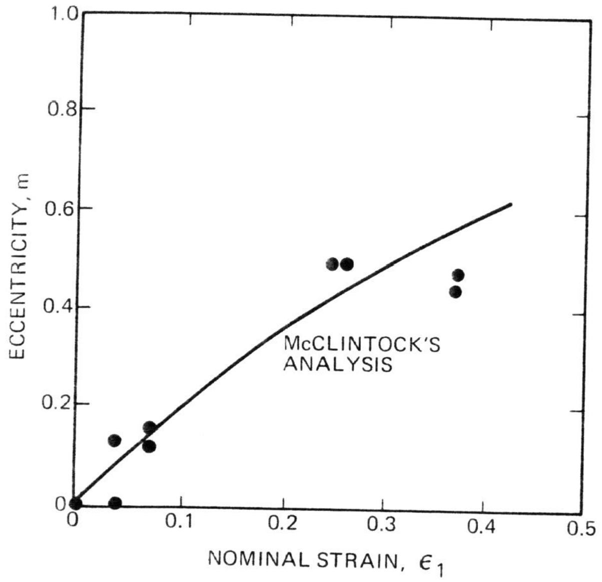
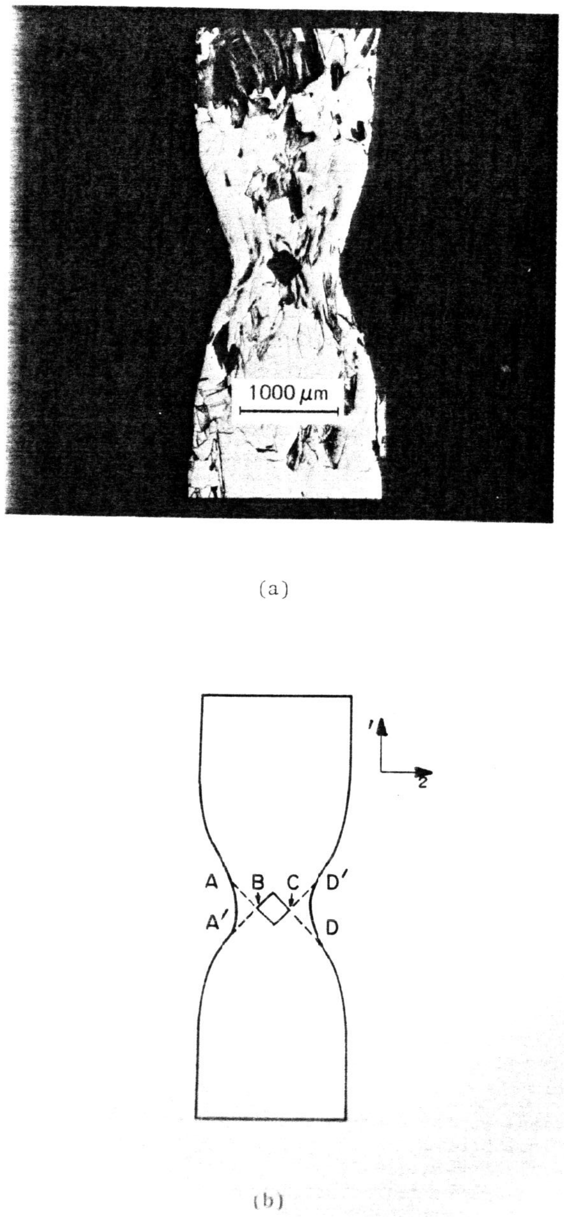


(b)

Figure 3 A Comparison of Experimental Results with McClintock's Analytical Predictions

(b) Void Eccentricity as a Function of Nominal Strain for the Unnotched Prestrained ($2\omega_0$ = 180°, n = 0.15) Specimen



(a)

(b)

Figure 4 Void Growth by Localized Shear

(a) A Section of the Unnotched Annealed ($2\omega_0$ = 180°, n = 0.50) Specimen at a Nominal Strain of 0.82

(b) Orowan's Prediction of Void Growth by Localized Shear in a Perfectly Plastic Solid which is Deforming in a Plane