HOLE NUCLEATION AND DUCTILE FAILURE IN MULTIAXIAL STATES OF STRESS

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ABSTRACT

Axisymmetric notched tensile specimens, which in full plasticity develop triaxial stress fields, have been used to study the nucleation, growth and coalescence of voids leading to ductile failure. The nucleation conditions have been established by numerically solving the void growth equations in conjunction with both dilating and incompressible plastic finite element solutions. Significant features of the solutions are the statistical nature of the particle-matrix interface and the effect of void growth in relieving the aggregate stress level in the dilating plastic material. Void growth is known to be strongly dependent on triaxiality and this is reflected in the ductile failure locus, in which the failure strain decreases with increasing triaxiality. From this locus, and the nucleation and growth equations, the void geometry, porosity and aggregate hardening rate at failure have been determined.

KEYWORDS

Ductile failure; void nucleation; void growth; triaxiality

INTRODUCTION

An important mechanism of ductile fracture involves the nucleation of voids from second phase particles. Such voids subsequently grow in the plastic strain field until coalescence occurs by a flow localisation process. These processes are of particular interest in the triaxial stress states which occur ahead of blunting cracks and in regions of stress concentration in engineering structures. The nucleation of voids has been widely studied, notably by Argon, Im and Safoglu (1975) who used axisymmetric notched tensile specimens to develop triaxial stress fields and subsequently determined the coordinates of the point on the axis of symmetry at which nucleation had just occurred. Finite element analysis gave the corresponding stress and strain. In the present work, finite element analysis has been used to give the deformation history of voids observed on the minimum cross section of the specimen. These deformation histories were used in conjunction with the void growth equations to calculate the strain and stress states at nucleation, and the corresponding conditions at the inclusion interface by reference to the solutions of Orr and Brown (1974) and Argon, Im and Safoglu (1975).

Hole growth has been established (McClintock (1968), Rice and Tracey (1969) to depend on the non-dimensional grouping $\sigma_m/\overline{\sigma}$ or triaxiality, in which σm is the mean stress and $\overline{\sigma}$ the effective flow stress. Consequently, the effective plastic strain to initiate failure, $\overline{e}^p$, depends markedly on the triaxiality, as shown by Hancock and Mackenzie (1976), and Mackenzie, Hancock and Brown (1977) In the present case, the ductile failure locus of a relatively pure iron containing 1% volume fraction of iron oxide particles is presented. From this locus, the nucleation data and the hole growth equations, the void geometry and porous hardening rates at flow localisation were calculated as a function of stress state.

EXPERIMENTS AND ANALYSIS

Axisymmetric notched tensile specimens, as shown in Fig. 1, have been tested under transverse strain control as described by Hancock and Mackenzie (1976) and Mackenzie, Hancock and Brown (1977). The ductile failure locus, defined as the strain to form a distinct internal crack, $\overline{e}^p$, is presented in Fig. 2 as a function of triaxiality. Finite element analyses of these specimens were performed using a power hardening stress strain law both for a Von Mises yield surface with incompressible constitutive equations, and Gurson's (1977) yield surface with dilating plastic constitutive equations which allow the possibility of strain softening through void growth. A detailed discussion of similar solutions and the effect of plastic dilation has been given by Brown, Hancock, Thomson and Parks (1980). Here it is sufficient to note that the notches produce triaxial stress fields whose severity depends on the ratio of the radius of the cross-section to the notch radius, and although plastic dilation significantly reduces both the mean and effective stresses ($\overline{\sigma}_m$ and $\overline{\sigma}$) for the porous aggregate, both $\overline{e}^p$ and the triaxiality are insensitive to the levels of dilation produced and there are no major differences in the corresponding ductile failure loci.

Prior to coalescence and failure, voids formed by decohesion of the particle-matrix interface were observed on metallographic sections as ellipses whose major axes grew in the direction of the maximum principal stress, but whose minor axes were pinned by the inclusion as shown in Fig. 3. Experiments on simple model systems showed that this restriction on the minor axes did not affect the growth of the major axes or the applicability of the McClintock growth equations. The measured coordinates of a void on the minimum cross-section and the finite element analysis enabled its original coordinates and its deformation history to be determined, and with this information, a nucleation strain was calculated such that the subsequent growth would result in a void of the observed size. The range of particle coordinates and the geometries of the notches provided nucleation sites in a wide range of stress states, and the actual stress states at nucleation are shown in Fig. 2. Figure 4 gives the corresponding maximum interfacial radial stress σ_r, normalised with respect to the initial yield stress $\overline{\sigma}_0$. The statistical nature of void nucleation is a significant feature.

Using the nucleation conditions as a base, the void growth equations were again applied to calculate the porosity and void geometry up to flow localisation, as given in Table 1. The aggregate strain hardening rates corresponding to the void geometry in the appropriate stress states were calculated from Gurson's (1977) yield locus using the average volume fraction of voids, and are given in Column 4 of Table 1. These hardening rates are positive. Since failure must initiate where the local void spacing is less than average, the aggregate hardening rates appropriate to such localities where the volume fraction was statistically likely to be an order of magnitude greater than the average are given in Column 5 of Table 1. As shown, these local hardening rates are negative.

DISCUSSION

Void nucleation is essentially a statistical event reflecting the nature of the cohesion of the particle-matrix interface. That this is a physical effect and not the result of the numerical analysis is confirmed by Fig. 3, which shows the difference in void geometry at inclusions subject to similar deformation histories. In addition, the sample of voids analysed showed many examples in which the interface had no cohesive strength, although this data has been omitted from the analysis. The trend of the results, shown most clearly by the well bonded particles, is that nucleation strain decreases with triaxiality in accord with the maximum radial stress criterion proposed by Argon, Im and Safoglu (1975). Here the radial stress is considered as the sum of two components, the first due to the hydrostatic stress appropriate to the stress state, and the second resulting from the flow stress and strain hardening. Once nucleation has begun, the void growth and consequent dilation and increased porosity reduce both the mean and effective stresses, and tend to reduce the hardening rate. This in turn inhibits further nucleation by increasing the strain increments required to continue the process. Void coalescence in the centre of the notches occurs by flow localisation at a porosity of 3 - 4 %, which does not depend strongly on stress state. Although the corresponding porous hardening rates are positive, in regions of high porosity the local hardening rate is negative. This clearly has a destabilising influence on homogeneous flow and leads to void coalescence.

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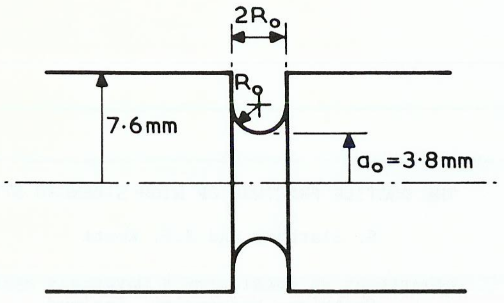

AXISYMMETRIC SPECIMENS

NOTCH	a_o	R_o
A	3·8mm	3·8mm
D	3·8mm	1·27mm
UNNOTCHED	3·8mm	—

Fig. 1

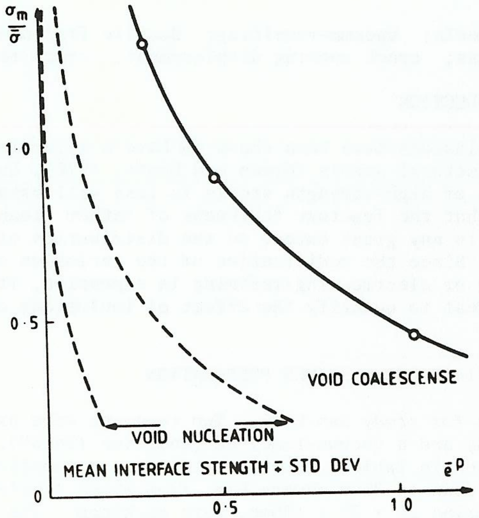

Fig. 2

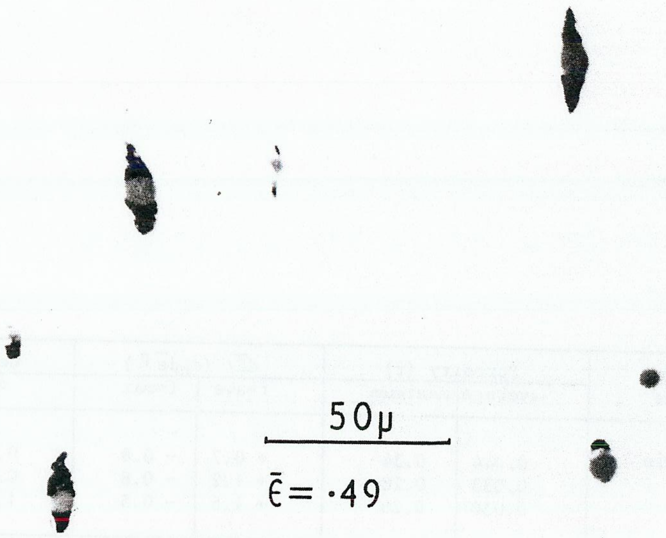

Fig. 3

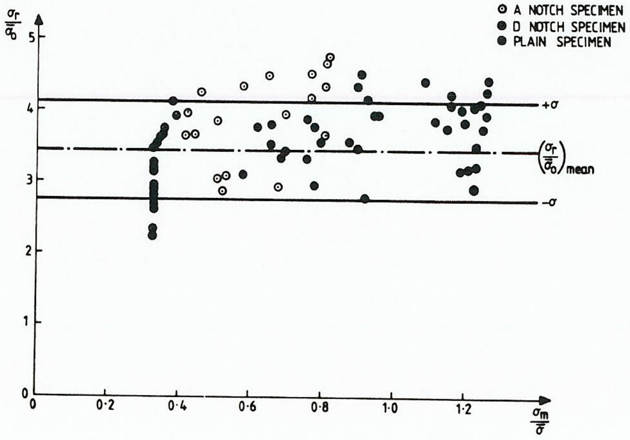

Fig. 4

Notch type	Porosity (f)		$d\bar{\Sigma}/(\sigma_0 d\bar{e}^p)$		Central axis	
	average	maximum	f=ave	f=max	$\sigma_m/\bar{\sigma}$	$\bar{e}^p$
Plain	0.044	0.34	+ 0.7	- 0.8	0.446	1.05
A	0.033	0.28	+ 1.2	- 0.8	0.912	0.50
D	0.030	0.26	+ 1.6	- 0.5	1.281	0.29

TABLE 1. Conditions at the initiation of failure in the centre of the notches.