Validation of Void Coalescence Model for Ductile Damage

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VALIDATION OF VOID COALESCENCE MODEL
FOR DUCTILE DAMAGE

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ABSTRACT
A model for void coalescence for ductile damage in metals is presented. The basic mechanism is void linking through an instability in the intervoid ligament. The formation probability of void clusters is calculated, as a function of cluster size, imposed stress, and strain. Numerical approximations are validated in a 1 D hydrocode.

INTRODUCTION: High strain rate ductile fracture is caused by the nucleation, growth, and link up of voids. We describe a model for microscale void cluster growth via the coalescence of initially existing voids, based on earlier work. [Tonks et al, 94, 95, 96] The general phenomenology at high strain rates is that a random initial void configuration produces a spatially disordered damage morphology, where widely separated voids have little time to communicate with each other via stress waves. This inhibits the potential for large damage clusters to grow faster than the smaller ones. The sample breaks when widespread damage finally accumulates to the point where a damage surface forms. This fracture point is modeled with random percolation theory [Stauffer, 1985]. At lower strain rates, a sample breaks with less damage at smaller strains, when the biggest crack rapidly outstrips its neighbors. This occurs because there is time for the size enhancement of stress and strain fields to occur at its periphery. [Tonks 94, 95]. The fracture is modeled by refining a probabilistic theory for cluster growth [Domb, 1990].

MODELING AND FORMULAS: Void linking occurs through a local plastic instability than thins out the intervoid ligament, unloading surrounding material. [6]. The stress conditions triggering the instability, which depend on cluster geometry and the applied stresses, were given by Thomason[1990] for arrays of voids for the quasistatic situation. We have generalized this work to treat single voids linking to a growing void cluster with range enhanced by the concentrated stress and strain fields at the cluster periphery. We have included shear and tensile stresses and linking strain effects. The stress linking range of two potential ring voids, \( r_g \), i.e. the threshold center to center separation below which the local intervoid instability occurs, is qualitatively based on two dimensional results of Thomason [1990] for void arrays and plane strain slip line fields: \( r_g = D[1 + g(\sigma_0, \sigma_1)(2r/D)] \), where \( D \) is the void diameter, \( r \) is the disk radius, \( \sigma_1 \) is the normal stress at the disk surface, \( \sigma_0 \) is the uniaxial plastic yield stress, and \( g \) is a parameter roughly equal to 1. The factor \( 2r/D \) approximates the effect of the disk size to enhance the local stress/strain at the periphery of the disk.
Once a void ligament instability is established, external strain is still required to thin it down. The thinning is assumed to depend on $\varepsilon_f$, the accumulated effective external strain that includes both shear and volumetric components, but which is incremented only when the instability is active. For a given amount of strain $\varepsilon_f$, pairs of voids closer than a certain model distance, $r_e$, the strain interviod linking distance, will have coalesced. A 2D version of $r_e = D(1 + \eta e R/D)$ where $\eta$ is 12, a qualitative, adjustable value.

We seek the most probable damage configuration. We assume disks of linked voids that have their flat surfaces normal to the direction of greatest principal stress. This orientation, appropriate for plate impact spallation, intercepts the greatest applied stress and causes the greatest cluster size enhancement of the applied stress at the cluster periphery. The disks are assumed to be one void thick. The disks will be grown from the basic voids and will not interact. This should be accurate for the early and middle regions of damage growth. A disk is "grown" in a stepwise fashion by adding rings of linked voids to a previously existing disk. The ring voids and the disk periphery voids are given the same model stress and strain linking ranges, which are enhanced by the disk size.

$P(\beta)$, the probability for formation of a void disk of radius, $r$, from void rings is obtained by multiplying together the probabilities of ring formation, for which an approximate formula of Domb [1990] is used. An approximation for the probability product is then derived by an integral approximation for its logarithm. $\beta = \alpha' \Gamma(p) D^3$, where $\alpha'$ is a constant of magnitude about $\pi$, and $\rho$ is the number density of void centers. Thus, $P(\beta)$ is a function of $\varepsilon_1$ and $\beta$, which can be considered to be a scaled version of the disk radius, $r$. The scaling involves the strain $\varepsilon_1$ and the porosity of the individual voids, $\Phi_0 = \pi \rho D^3 / 6$. A graph showing log($P$) is shown in Fig. 1. Note that the solution for large $\beta$, or large $r/D$, if $D$ is less than $r$ and is held fixed, asymptotes to a constant. Therefore, a cluster can grow arbitrarily large with probability one after reaching a threshold size. Hence, a system will surely break if it is large enough to contain a cluster of the threshold size.

Time delay effects are added to $P(\beta)$ by limiting $r/D$ in $f$ to $C t_k / D$, where $C$ is a release wave velocity and $t_k$ is the total linking strain time. $P$ will then assume an exponential decay in some power of $r$, greatly curtailing disk growth.

In the above, $D$ is a parameter for with a supplementary growth law is needed.

There are two fracture criteria for a computational cell. The first, low strain rate criterion assumes that failure occurs when the probability of a void disk large enough to span the cell is one: $P N = 1$, where $N$ is the number of voids in the computational cell. This law was validated in a 1D hydrocode calculation of a symmetric Ta gas gun impact experiment with flyer velocity of 254 m/s, in which the recovered sample
was close to fracture. The total strain, $\varepsilon_1$ was 0.3 and $\Phi_0$ was about 0.28. When $\eta$ was adjusted to 4, and the power of $f$ in $\beta$ was set to two, the probability, $P$, was about 0.5, just short of fracture. This reasonable “fit” using $\eta=4$ indicates that 2D linking is more realistic than 3D linking and that the original derivation overdoes the strain effect.

Stress linking volumes are imaginary volumes extending in every direction from the physical disk by half a stress linking range. The second, percolation fracture criterion is that the stress linking volumes of the disks sufficiently fill in the computational cell, so that no one dimensional path of solid and unlinked material, i.e. no strong beam of material, still exists that completely spans the cell. In this case, a sheet of stress linked voids spans the cell, the plastic flow localizes, and the cell breaks with little additional external strain. This criterion is equivalent to a random volume percolation of the disk stress linking range volumes, which will occur when the sum of linking volumes per unit volume (overlaps included) equal 2.53. This criterion can be plausibly made to yield the 30% spallation porosity limit. With the restriction of no coalescence or deviatoric stress, the percolation criteria is equivalent to a pressure dependent fracture porosity 

\[ \Phi_{pw} = \frac{2.53}{1 + \eta \Sigma_m / \sigma_n} \]

where $\Sigma_m$ is the volumetric tension.

An approximate formula for the extra porosity produced by coalescence by intervoid ligament thinning is the following: $\Phi_{extra} = \Phi_{coal} - \exp(-\Phi_{coal})$, where $\Phi_{coal}$ is $\Phi_0(f^2 - 1)$. $\Phi_{coal}$ is based on the “2D” annulus outside the void, of the 2D single void linking figure, with linking ranges $f$ in two dimensions and $D$ in the 3rd dimension. In $\Phi_{extra}$, the duplication volumes from the 2D annuluses which randomly overlap are eliminated. Using $\eta=4$, the 2D formula predicted for the Ta gas gun experiment, that about 0.3 of the final porosity was due to coalescence, i.e. intervoid ligaments, which is roughly seen in the recovered gas gun sample.

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REFERENCES:
Tonks D. L. 1994, J. Physique IV, C8, C8-665.