Hole Nucleation by Inclusion Separation in Ductile Fracture

by A. S. Argon and J. Im
Massachusetts Institute of Technology, Cambridge, Mass. U. S. A.

I. *Introduction*

It is now clear that ductile fracture consists of several stages which are in order: nucleation of holes by the internal fracturing or interfacial decohesion of inclusions, plastic growth of holes, localization of hole growth in inextensional zones, formation and growth of a crack. All but the first of these processes have been studied in detail by many investigators over the past decade (see e.g. McClintock 1968, 1969, Rice and Tracy 1969, Berg 1970). Although some microstructural studies have also been made on inclusion separation (See, e.g. Roesch and Henry 1968, Palmer and Smith 1968, Gurland 1969) the quantitative conditions for the process remain insufficiently understood. Here we report the results of an approximate analysis, and an experimental investigation on hole nucleation from non-deformable equiaxed inclusions in ductile matrices.

II. *Analysis*

Experiments on non-cleavable ductile metals, free of inclusions, show that in tension such materials undergo only rupture by thinning to a point or line; and that when inclusions are present holes nucleate preferrentially by interfacial decohesion. This suggests that very large plastic strains alone do not produce decohesion in a ductile metal, and that the inclusions not only produce local strain concentrations, but also provide surfaces of lower cohesive strength. We assume therefore that the local criterion for hole nucleation is one of critical interfacial normal stress, and that this stress can be affected by both a plastic drag which the plastically deforming matrix sets up on the less deformable inclusion, and by the general level of mean normal stress in the locality. We only consider inclusions of such a size (>200Å) for which the stored elastic energy in the inhomogeneous strain field around the inclusion is many times the surface energy of the interfacial cavity. We idealize the problem by considering the inclusion as a rigid circular cylinder and the matrix a rigid plastic continuum with either a constant flow stress Y and no hardening, or with zero yield stress and linear hardening. As discussed by McClintock and Rhee (1962) these two conditions for matrix behavior form bounds for all other plastic matrices with strain hardening. The choice of a continuum view is justified for inclusions of a radius much larger than mean dislocation spacings, which is normally the case for most inclusions important in ductile fracture.

a) Non-hardening continuum: The interfacial normal stress around a circular rigid inclusion in a rigid plastic continuum was investigated by a finite element program for a square region under boundary shear tractions containing a central circular inclusion occupying 1% of the area. The analysis was continued beyond the point where the entire region became fully plastic until the distribution of plastic strain increments over the region showed little change. The maximum interfacial tensile stress was found to be nearly $(\sqrt{3}/2)Y$ at the point across the direction of maximum tensile stress.

b) Linearly-hardening continuum: The interfacial tensile stress for a linearly hardening continuum was obtained directly from Muskhelishvili (1953) from the solution for a rigid circular inclusion in an elastic continuum under shear tractions, for which the Poisson's ratio was taken to be 0.5. The maximum interfacial tensile stress was found to be twice the magnitude of the boundary shear traction which of course must be equal to $Y/\sqrt{3}$, where Y is the current flow stress in tension.

Taking these two results as bounding limits the interfacial tensile stress $\sigma^{P}_{rr} = \sigma_{rr} - \sigma_{T}$ resulting from plastic drag must be

$$(\sqrt{3}/2)Y < \sigma_{rr} - \sigma_{T} < (2/\sqrt{3})Y \qquad (1)$$

where σ_{rr} is the total interfacial tensile stress and σ_{T} the local mean normal stress. The solution of Huang (1970) for a strain hardening material of a Ramberg-Osgood type with a stress exponent $n=7$ falls within these limits. Considering that the limits are quite close together we take the average value which these two limits give for the total interfacial tensile stress

$$\sigma_{rr} = Y(\bar{\varepsilon}^{p}_{n}) + \sigma_{T}$$

where, $Y(\bar{\varepsilon}^{p}_{n})$ represents the average tensile flow stress in the locality of the inclusion where the average local equivalent plastic strain at hole nucleation is $\bar{\varepsilon}^{p}_{n}$. Holes would nucleate when σ_{rr} reaches the interfacial strength.

III. Experiments

Experiments were conducted on a) a spheroidized 1045 steel with iron carbide inclusions of 1μ average size, and b) an unaged maraging alloy (VM-300) of the nominal composition of 0.04C, 0.1Mn, 0.1Si, 18Ni, 9Co, 4.5Mo, 0.6Ti, 0.1Al, bal. Fe. with titanium carbide inclusions of also 1μ average size.

Experiments were performed on round bars with pre-machined "natural-neck" geometries of initially different a/R ratios (where a is the radius of the minimum cross section at the neck and R is the lateral radius of curvature at the neck) to obtain different distributions of local mean normal stress. The natural-neck contours for increasing a/R ratios were determined experimentally from measurements of strained round bars of inclusion free material of the same strain hardening capacity. This procedure was necessary to avoid unknown strain distributions which would otherwise arise (see Clausing, 1967 and McClintock, 1971).

All tests were continued to fracture while the current a/R ratio was continuously monitored. One side of the fractured specimens was cut and polished along the central plane parallel to the axis, and examined in the SEM to determine the position of the inclusion on the axis and farthest from the fracture surface, which had just undergone separation. The local equivalent plastic strain at this point was determined from the change of geometry with reference to the undeformed shape, while the local mean normal stress was determined both from an extension of the Bridgman (1952)(B) solution along the specimens axis and also from the solution of Needleman (1972) (N) for a necked bar with a strain hardening stress exponent of 3. The total interfacial tensile stress for decohesion was calculated from (2). The results are given in Tables I and II.

Table I

Spheroidized 1045 Steel

Spec No.	$(\frac{a}{R})_i$	$(\frac{a}{R})_f$	$(\frac{z}{a_i})$	$(\bar{\varepsilon}^p_n)$	$Y(\bar{\varepsilon}^p_n)$ (ksi)	$(\frac{\sigma_T}{Y})_B$	$(\frac{\sigma_T}{Y})_N$	σ^B_{rr} (ksi)	σ^N_{rr} (ksi)
1	0.10	1.00	0.770	0.36	146	0.34	0.403	196	205
2	0.10	0.95	0.735	0.43	148	0.34	0.416	198	209
3	0.25	0.96	0.558	0.66	154	0.34	0.565	206	241
4	0.25	0.98	0.562	0.56	151	0.34	0.498	202	226
5	0.50	1.35	0.522	0.55	151	0.36	0.701	205	259
6	0.50	1.44	0.675	0.33	144	0.34	0.646	193	237
7	1.00	2.13	0.450	0.98	165	0.44	0.932	238	318
8	1.00	2.33	0.422	0.66	154	0.61	0.990	248	306

Table II

Unaged VM 300 Steel

1	0.10	0.357	0.710	0.844	218	0.34	0.20	291	261
2	0.25	0.615	0.750	0.660	202	0.34	0.273	270	258
3	0.50	0.725	0.640	0.660	202	0.34	0.400	270	283
4	1.00	1.070	0.360	0.844	218	0.48	0.650	322	360

IV. Conclusions

Inspection of Table I shows that the data on external contour at fracture and the position of separated inclusion is subject to considerable scatter due to the difficulty in resolving cracks around inclusions. This becomes amplified by the uncertainties in the computation of the mean normal stress by either the extension of the Bridgman analysis or the solution of Needleman for bars with initially contoured geometry. If this spread in results is ignored and only the average value of all specimens for one material is considered, we find σ_{rr} = *211-252* ksi for spheroidized 1045 steel and σ_{rr} = *289-292* ksi for the VM 300 steel, by the Bridgman, and Needleman analyses respectively. These values are nearly 1% of the Young's modulus of iron and are in a range of the expected interfacial cohesive strength between the iron matrix and a non-metallic inclusion.

The work has been supported partially by NSF through Grant No. GK1875X and partially by ARPA through Contract No. DAHC15 70 C 0283.

References

C.A. Berg, (1970) in Inelastic Behavior of Solids, (Eds. M.F. Kanninen et al.) McGraw-Hill, N.Y. p. 171.

P.W. Bridgman, (1952) Studies in Large Plastic Flow and Fracture, McGraw-Hill, New York, Chapter 1.

D.P. Clausing, (1967) Trans. ASM, 60, 504.

J. Gurland, (1969) "Observations on the Fracture of Cementite Particles in a Spheroidized 1.05%C Steel Deformed at Room Temperature", Brown University Report NYO-2394-39.

W. Huang, (1970) "Theoretical STudy of Stress Concentrations at Circular Holes and Inclusions in Strain Hardening Materials", Harvard University Report SM-45.

F.A. McClintock, (1968) J. Appl. Mech, 35, 363; (1969) in Physics of Strength and Plasticity, (Ed. A.S. Argon) M.I.T. Press, Cambridge, Mass. p. 307; (1971) in Fracture, (Ed. H. Liebowitz) Academic Press, New York, Vol. 3, p. 47.

F. A. McClintock and S. S. Rhee, (1962) in Proc. 4th U.S. National Congress of Applied Mechanics, ASME, New York, Vol. 2, p. 1007.

N.I. Muskhelishvili, (1953) Some Basic Problems of the Mathematical Theory of Elasticity, Nordhoff Ltd., Groningen, The Netherlands, p. 335.

A. Needleman, (1972) J. Mech. Phys. Solids, 20, 111.

J. G. Palmer, and G. C. Smith, (1968) in Proc. 2nd Bolton Landing Conference on Oxide Dispersion Strengthening, Gordon and Breach, N.Y. p. 253.

J. R. Rice, and D. M. Tracy, (1969) J. Mech. Phys. Solids, 17, 201.

L. Roesch, and G. Henry, (1968) "Relationship Between Precipitation and Dimple Fracture in an 18% Nickel Maraging Steel", IRSID Report RE.PHY.AP.302-LR/CC.