RECENT ADVANCES IN MODELLING DUCTILE RUPTURE

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ABSTRACT

A brief account of recent advances in modelling ductile rupture is given. The importance of the inhomogeneity in the distribution of cavity nucleation sites is firstly emphasized. Then some recent extensions of the Gurson model to account for non spherical void shape are presented. Finally recent progress in modelling cavity coalescence is highlighted.

1 INTRODUCTION

Ductile fracture of metallic materials involves void nucleation and void growth to coalescence. Many studies have been devoted to the mechanisms accompanying void nucleation from second-phase particles (see, eg Garrison and Moody [1]). However very much remains to be done to include important aspects of cavity nucleation sites. Similarly recent advances have been made to model void growth and void coalescence. However a large research effort remains to be done for a better analysis of these two steps of ductile fracture.

For a long time ductile rupture has been analysed using uncoupled models (see eg. Mc Clintock [2], Beremin [3]). In these studies it was assumed that rupture occurred for a critical fraction of cavities, f_c, initiated from inclusions. More recently coupled models in which the effect of growing cavities on the constitutive equations of porous materials have been introduced (Rousselier [4], Gurson [5]). Tvergaard and Needleman [6, 7] introduced a model to analyse ductile fracture using the Gurson potential. Their formulation involves two parameters, the so-called critical porosity, f_c, and the acceleration factor, δ. In this model, f_c is equivalent to a critical void growth ratio and is intended to represent the initiation of a macroscopic crack, while δ has been introduced to let the load bearing capacity vanish as a consequence of accelerated void growth and void coalescence. The (f_c, δ) approach provides a phenomenological description of the fracture behaviour. However it has been shown that the f_c and δ parameters have no unique values to fit the experimental results (Zhang and Niemi [8, 9], Benzerga [10]). This led to further improvements in the analysis of these two steps of ductile rupture. In this paper, these improvements are also briefly summarized.

2 HETEROGENEOUS VOID NUCLEATION

One aspect of cavity nucleation which has not yet received enough attention is the inhomogeneity in spatial void distribution. This specific aspect has been investigated to some extent in cast duplex stainless steels (Devillers-Guerville et al. [11]). In these materials cavities are nucleated from cleavage microcracks initiated in the thermally embrittled ferrite. Then the cavities grow in the austenite phase. Due to the coarse grain microstructure and the crystallographic character of these materials, it was shown that the cavities are preferentially initiated in grains with specific orientations. The cavities are grouped in relatively large clusters of ~ 1 mm^3. The density of cleavage microcracks increases linearly with plastic strain. The proportionality factor was found to be statistically distributed. Similar results were obtained in a plain carbon steel (A 48) in which the distribution of MnS inclusions, which were the initiation sites, was also thoroughly analysed using quantitative metallography (Decamp et al. [12]). In both materials it was shown that it was possible to partly account for the scatter and the size effect without using the δ accelerating factor provided that the inhomogeneity in cavity initiation sites was taken into account. It seems therefore that the use of this parameter is not necessary when the spatial distribution of initiation sites for ductile rupture is properly taken into account.

3 CAVITY GROWTH

In this field much progress has been made since the pioneering theoretical works by Berg [13], Mc Clintock [14], Rice and Tracey [15] and Gurson [5]. In particular recent models have been introduced to account for matrix plastic anisotropy and cavity shape anisotropy.

Many materials exhibit plastic anisotropy due to texture development. This anisotropy can influence damage evolution : (i) at a microscopic level by modifying the void growth rate, (ii) at a macroscopic level as different strain/stress conditions can be generated in testing specimens or components. Following the method used by Gurson [5] a yield surface for a plastically anisotropic material described by the Hill quadratic criterion has been derived (Benzerga [16], Benzerga and Besson [17]). Cavities are still supposed to remain spherical. The new equation for the yield surface is written as :

$$\phi_{GA} = \left(\frac{\sigma_H}{\sigma_0}\right)^2 + 2f \cosh\left(\frac{1}{h}\frac{\sigma_{kk}}{\sigma_0}\right) - 1 - f^2 = 0 \qquad (1)$$

where σ_H is the Hill equivalent stress defined by :

$$\sigma_H^2 = \frac{3}{2}\left(h_{11} s_{11}^2 + h_{22} s_{22}^2 + h_{33} s_{33}^2 + 2h_{12} s_{12}^2 + 2h_{23} s_{23}^2 + 2h_{31} s_{31}^2\right) \qquad (2)$$

In this expression, σ_0 is the matrix flow stress, and s is the stress deviator while the h_{ij} coefficients are those of the Hill tensor expressed in the orthotropy frame. The parameter h in eqn (1) has been expressed as a function of the hij coefficients. For an isotropic material h = 2 and eqn (1) corresponds to the Gurson potential.

An extension of the Gurson model by Gologanu, Leblond and Devaux (GLD) [18, 19] has been proposed to account for cavity shape anisotropy. The GLD model considers axisymmetric ellipsoidal cavities characterized by their aspect ratio, W. The model is therefore limited to transversely isotropic porous plastic materials, and is expressed in terms of a Gurson-like plastic potential :

$$\phi_{GLD} = C \frac{\left\| \underline{s} + \eta \sigma_h \underline{X} \right\|^2}{\sigma_0^2} + 2 q_w (g+1)(g+f)$$

$$x \cosh\left(\frac{k \sigma_h}{\sigma_0}\right) - (g+1)^2 - q_w^2 (g+f)^2 = 0 \qquad (3)$$

with $\sigma_h = \alpha(\sigma_{xx} + \sigma_{yy}) + (1-2\alpha)\,\sigma_{zz}$

In this expression, $\|\cdot\|$ is the von Mises norm, C, η, q_w, g, k and α are function of the porosity and the cavity shape factor. $\underline{X}$ is a constant tensor. The axis of the cavities corresponds to the z-direction. For round cavities (S = 1), eqn. (3) is equivalent to the Gurson potential. As for this model the plastic strain rate tensor is obtained using the normality rule and the porosity is obtained using mass conservation. The evolution of the shape factor is given by an additional differential equation :

$$\frac{\dot{W}}{W} = H \dot{\varepsilon}'_{zz} + K \dot{\varepsilon}_m$$

(4)

where ε'_{zz} is the component of the deviator of the strain tensor along the cavity axis and $\dot{\varepsilon}_m$ is the mean deformation rate. H and K are parameters which are functions of f, S and the stress triaxiality ratio, τ. More recently a potential including both sources of anisotropy, ie that due to matrix plastic anisotropy and that corresponding to cavity shape has been proposed [20, 21].

4 CAVITY COALESCENCE

Significant progress has been recently made in modelling the onset of void coalescence by internal necking in ductile materials (Pardoen and Hutchinson [22], Benzerga [10], Benzerga et al. [21]. This last stage of ductile rupture was modelled using an extension of the Thomason model (Thomason [23]) in which it is assumed that fracture occurs when the plastic limit load criterion originally proposed by this author is reached. The model in [10, 16] gives a set of constitutive equations including a closed form of the yield surface after void coalescence with appropriate evolution laws for void shape and the size of the ligament between cavities. In both models the derivation of the evolution laws was guided by unit-cell calculations. The main implication of these models is that the load bearing capacity of the elementary volume decreases as a natural outcome of the void spacing reduction without imposing an a priori value to the δ coefficient in the Gurson [5], Tvergaard Needleman [6] model. These models are very encouraging since they are able to predict the drop in the macroscopic stress occurring during cavity coalescence when the initial microstructural parameters of the material (volume fraction of cavities, shape of the cavity initiation sites, void spacings) are known. The comparison between experimental results and theoretical results are still limited (see Benzerga et al. [21]), since these models require more information about the microstructure of the materials.

5 CONCLUDING REMARKS

Significant progress has been made in modelling ductile rupture over the last recent years. The models shortly presented above apply to volume elements or to components in which the stress-strain gradients are limited. These models require large computational facilities when they are applied to real components or real test specimens. A good example is provided by the simulation of the Charpy test in the ductile-to-brittle transition where cleavage fracture is initiated after significant ductile crack growth. Sophisticated constitutive equations accounting for large strain rates and adiabatic heating have to be used (see eg. Tanguy and Besson [24]). Moreover the numerical simulations must take into account the friction phenomena. These simulations are tridimensional to account for ductile crack growth tunnelling effect (Tanguy et al. [25]). The increase in the computational power must progressively alleviate this difficulty related to the size of the calculations. The difficulty associated with strong stress-strain gradients is more serious. In the situation corresponding to a crack tip the results are dependent on the mesh size. It is felt that this mesh size dependence will remain for some time as the last fitting parameter in the models for ductile fracture as the stage of the development of non-local damage models has not yet reached a situation applicable to structural applications.

REFERENCES

[1] Garrison, W.M., Moody, N.R. Ductile rupture. J. Phys. Chem. Solids, 48, 1035-1074, (1987).

[2] Mc Clintock, F.M. Plasticity aspects of fracture. In "Fracture", ed. H. Liebowitz, Academic Press, New York and London, Vol. 3, pp. 47-225, (1971).

[3] Beremin, F.M. Cavity formation from inclusions in ductile fracture of A 508 steel, Met. Trans. 12A, pp. 723-731, (1981).

[4] Rousselier, G. Ductile fracture models and their potential in local approach of fracture. Nucl. Eng. Des., 105, pp. 97-111, (1987).

[5] Gurson, A. Continuum theory of ductile rupture by void nucleation and growth : Part I – Yield criteria and flow rules for porous ductile media. J. Eng. Mat. Technol., 99, pp. 2-15, (1977).

[6] Tvergaard, V., Needleman, A. Analysis of cup-cone fracture in a round tensile bar. Acta Metall., 32, pp. 157-169, (1984).

[7] Tvergaard, V. Material failure by void growth to coalescence. Advances in Applied Mechanics, 27, pp. 83-151, (1990).

[8] Zhang, Z.L., Niemi, E. Analyzing ductile fracture using dual dilational constitutive equations. Fatigue Fract. Eng. Mater. Struct., 17, pp. 695-707, (1994).

[9] Zhang, Z.L., Niemi, E. A new failure criterion for the Gurson-Tvergaard dilational constitutive model. Int. J. Fract., 70, pp. 321-334, (1995).

[10] Benzerga, A.A. Micromechanics of coalescence in ductile fracture. J. Mech. Phys. Solids, 50, pp. 1331-1362, (2002).

[11] Devillers-Guerville, J., Besson, J., Pineau, A. Notch fracture toughness of a cast duplex stainless steel : modelling of experimental scatter and size effects. Nucl. Eng. Des., 168, pp. 211-225, (1997).

[12] Decamp, K., Bauvineau, L., Besson, J. and Pineau, A. Size and geometry effect on ductile rupture of notched bars in a C-Mn steel : experiments and modelling. Int. J. Fract., 88, pp. 1-18, (1997).

[13] Berg, A. Proc. of the motion of cracks in plane viscous deformation. 4^{th} US National Congress of Applied Mechanics, ed. R.M. Rosenberg, University of California, June 18-21, pp. 885-892, (1962).

[14] Mc Clintock, F.A. A criterion for ductile fracture by the growth of holes. J. Appl. Mech., 35, pp. 363-371, (1968).

[15] Rice, J.R., Tracey, D.M. On the ductile enlargment of voids in triaxial stress fields. J. Mech. Phys. Solids, 17, pp. 201-217, (1969).

[16] Benzerga, A.A. Rupture ductile des tôles anisotropes. Ph. D. thesis, Ecole des Mines de Paris, (2000).

[17] Benzerga, A.A., Besson, J. Plastic potentials for anisotropic porous solids. Eur. J. Mech. A/Solids, 20, pp. 397-434, (2001).

[18] Gologanu, M., Leblond, J., Devaux, J. Approximate models for ductile metals containing non-spherical voids-Case of axisymmetric prolate ellipsoidal cavities. J. Mech. Phys. Solids, 41, pp. 1723-1754, (1993).
[19] Gologanu, M., Leblond, J., Devaux, J. Approximate models for ductile metals containing non-spherical voids-Case of axisymmetric oblate ellipsoidal cavities. Trans. ASME; J. Eng. Mat. Technol., 116, pp. 290-297, (1994).
[20] Benzerga, A., Besson, J., Pineau, A. Coalescence-controlled anisotropic ductile fracture. J. Eng. Mat. and Tech., 121, pp. 221-229, (1999).
[21] Benzerga, A., Besson, J., Pineau, A. Anisotropic ductile fracture. Part II : Theory. Submitted to Acta Material. (2004).
[22] Pardoen, T., Hutchinson, J.W. An extended model for void growth and coalescence. J. Mech. Phys. Solids, 48, pp. 2467-2512, ((2000).
[23] Thomason, P.F. Three-dimensional models for the plastic limit-loads at incipient failure of the intervoid matrix in ductile porous solid. Acta Metall., 33, pp. 1079-1085, (1985).
[24] Tanguy, B., Besson, J. An extension of the Rousselier model to viscoplastic temperature dependent materials. Int. J. Fract., 116, pp. 81-101, (2002).
[25] Tanguy, B., Besson, J., Piques, R., Pineau, A. Ductile-to-brittle transition of an A 508 steel characterized by Charpy impact test. Part I : experimental results; Part II : modeling of the Charpy transition curve. Submitted to Eng. Fract. Mech. (2004).