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NUMERICAL STUDIES OF FAILURE IN DUCTILE MATERIALS

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Summary. *Analyses of failure development and crack growth in ductile materials are presented. The modified Gurson model gives a good representation of void growth to coalescence when rather high stress triaxiality applies. Applications in recent three dimensional analyses are discussed. Also the use of cohesive zone models to represent crack growth is discussed, including a standard traction-separation law applied to an anisotropic solid and special interface elements representing ductile failure by the void growth mechanism.*

1 INTRODUCTION

Predictions of ductile failure by the nucleation and growth of voids to coalescence can be obtained numerically by using the modified Gurson model. Much experience has been gained with the use of this mechanism based model[1]. It is well known that the model has limitations in the range of low or negative stress triaxialities, but also that the model works well at the higher stress triaxialities that often occur at ductile fracture. Recent three dimensional analyses[2,3] will be discussed. One set of analyses has focus on Charpy V-notch tests for welded joints, where the specimen can be cut in different ways relative to the heat affected zone (HAZ) that tends to promote brittle cleavage fracture. The other study considers microstructural effects on plane strain crack growth.

An alternative method for the analysis of crack growth makes use of cohesive zone models. Thus, the local fracture process is modeled by a traction-separation law along the crack plane, with a specified work of separation per unit area, while the surrounding material is modeled as elastic-plastic. In a recent study[4] the effect of plastic anisotropy has been investigated for different anisotropies and for different orientations of the crack relative to the principal axes of the anisotropy.

Special interface elements have been developed that use the modified Gurson model to describe crack growth by void growth to coalescence along the interface. In a recent study[5] mixed mode interface crack growth has been analysed by application of these special interface elements.

2 3D ANALYSES OF DUCTILE FRACTURE

The Charpy V-notch test is a standard procedure for characterizing the ductile-to-brittle transition in steels[6,7]. In a recent study[2] full three dimensional transient analyses of Charpy impact specimens have been carried out. The elastic-plastic material response and the ductile failure mechanism by the nucleation and growth of voids to coalescence is represented in terms of the modified Gurson model[1], while the onset of cleavage is taken to occur when the average of the maximum principal true stress over a specified volume attains a critical value. The weld analysed here is overmatched, so that the yield strength for the weld is larger than that of the base material. According to European standards for destructive tests on welds in metallic materials the specimens are cut out so that they are perpendicular to the weld and parallel to the surface of the test piece. The specimen can be cut at various depths below the surface of the test piece, and the notch face of the impact test specimen is chosen either parallel or perpendicular to the surface of the test piece, with the location of the notch measured relative to the center of the weld or relative to the fusion-joint line. The first type of geometry can be approximated by a planar analysis, but the second type of specimen cannot be approximated as planar. Both types of specimens allow for impact tests where the notch is in the base material, in the weld material, or in the heat affected zone (HAZ), and this has been analysed for both types of specimens in [2].

In recent 3D analyses of crack growth in a ductile solid[3] two populations of inclusions have been accounted for, both modeled in terms if the modified Gurson model[1]. Larger inclusions with low strength are modeled as ‘islands’ of the amplitude of stress controlled nucleation, while smaller second-phase particles are represented by a uniform amplitude of strain controlled nucleation. Where planar analyses can only consider 2D microstructures, with the larger inclusions represented as long cylinders, the 3D analysis allows for geometrically more realistic spherical inclusions, and the 3D analyses are used to study the effect of different three dimensional inclusion distributions on the crack path and on the overall crack growth rate. Overall plane strain conditions are enforced in these computations, by considering a slice of material between two planes perpendicular to the initial crack-tip line, but due to the discretely represented larger inclusions the predicted crack paths are fully three dimensional.

3 COHESIVE ZONE MODELS FOR CRACK GROWTH

Studies of crack growth in ductile metals can be carried out by using a traction-separation law along the crack plane to model the local fracture process, while the surrounding material is represented as elastic-plastic. For isotropic plasticity this procedure has been used[8,9,10] to study the fact that due to plastic work in the material surrounding the crack-tip the macroscopic work of fracture is often much larger than that of the local fracture process near the tip.

Recently, the effect of plastic anisotropy has been investigated[4] for different anisotropies and for different orientations of the crack relative to the principal axes of the anisotropy. One anisotropic material considered is an aluminium alloy Al 7108-T7 modeled in terms of a quadratic yield criterion[11], while the other anisotropic material is an aluminium alloy Al 2090-T3 modeled in terms of the higher order yield criterion proposed by Barlat *et al.*[12]. For a given level of local crack growth resistance, as represented by a fixed set of parameter values in the cohesive zone model, it is found that the steady-state fracture toughness in the two solids varies considerably with the angle of inclination between the crack plane and the principal axis of the anisotropy. Naturally, also the size of the plastic zone around the crack-tip varies with this angle in the anisotropic materials.

These studies have been continued[13] to consider a non-normality (vertex-type) flow rule for these anisotropic yield criteria proposed in[14]. It has been found that this results in smaller values of the steady-state fracture toughness than that found using standard normality. Apparently, the strongly non-proportional stressing inherently involved in crack growth gives less fracture toughness when the constitutive model applied is less resistant to non-proportional deformation.

4 A COHESIVE ZONE MODEL FOR DUCTILE FRACTURE

As an alternative to the procedures mentioned above, a special interface element for ductile fracture has been proposed in[15,5], first for mode 1 crack growth and subsequently also for growth under mixed mode loading conditions. These special interface elements make use of the modified Gurson model to describe crack growth by void growth to coalescence along the interface.

The interface elements are formulated such that they have a finite width w_0, which is taken to represent a length scale of the order of the void spacing. Other interface elements of similar type have been formulated before, but those elements have made use of stress or strain quantities taken from integration points in neighbouring elements outside the interface, whereas the present interface elements require only an approximate form of compatibility with neighbouring elements, as well as equilibrium. It has been shown[15] that the special interface elements give good agreement with predictions obtained by directly using a strip of porous finite elements, surrounded by elastic-plastic elements that do not form voids.

For an interface between dissimilar elastic-plastic materials the special interface elements have been used to study the effect of mixed mode loading. Earlier interface crack studies[9,10] have shown that plasticity effects explain the experimentally observed higher fracture toughness in cases where mode II loading dominates. This is also found for the special interface elements, representing ductile failure by void growth to coalescence. Thus, the smallest fracture toughness is predicted for cases where mode I conditions apply near the crack-tip, and the toughnass increases when mode II loading is superposed, in positive or negative direction.

REFERENCES

[1] V. Tvergaard, “Material failure by void growth to coalescence”, *Adv. Appl. Mech.*, **27**, 83-151 (1990).

[2] V. Tvergaard and A. Needleman, "3D analyses of the effect of weld orientation in Charpy specimens", *Engineering Fracture Mechanics*, **71**, 2179-2195 (2004).

[3] V. Tvergaard and A. Needleman,. "Three dimensional microstructural effects on plane strain ductile crack growth", *Int. J. Solids Structures*, to appear (2005).

[4] V. Tvergaard and B.N. Legarth, "Effect of plastic anisotropy on crack growth resistance under mode 1 loading", *Int. J. of Fracture*, **130**, 411-425 (2004).

[5] V. Tvergaard, "Predictions of mixed mode interface crack growth using a cohesive zone model for ductile fracture", *J. Mech. Phys. Solids*, **52**, 925-940 (2004).

[6] R.O. Ritchie, "On the relationship between fracture toughness and Charpy V-Notch energy in ultrahigh strength steels. In : *What does the Charpy test really tell us*? (Eds. A.R. Rosenfield, H.L. Gegel and D.F. Hasson) American Society for Metals, 54-73 (1978).

[7] D. Francois and A. Pineau (Eds.), *From Charpy to present impact testing*, Oxford, Elsevier (2002).

[8] V. Tvergaard and J.W. Hutchinson, "The relation between crack growth resistance and fracture process parameters in elastic-plastic solids", *J. Mech. Phys. Solids*, **40**, 1377-1397 (1992).

[9] V. Tvergaard and J.W. Hutchinson, "The influence of plasticity on mixed mode interface toughness", *J. Mech. Phys. Solids*, **41**, 1119-1135 (1993).

[10] V. Tvergaard, "Resistance curves for mixed mode interface crack growth between dissimilar elastic-plastic solids", *J. Mech. Phys. Solids*, **49**, 2689-2703 (2001).

[11] R. Hill, "A theory of the yielding and plastic flow anisotropic metals", *Proc. of the Royal Society of London*, **A193**, 281-297 (1948).

[12] F. Barlat, D.J. Lege and J.C. Brem, "A six-component yield function for anisotropic materials", *Int. J. of Plasticity*, **7**, 693-712 (1991).

[13] V. Tvergaard and B.N. Legarth, "Crack growth resistance for anisotropic plasticity with non-normality effects", *Int. J. Solids and Structures*, to appear (2005).

[14] M Kuroda and V. Tvergaard, "A phenomenological plasticity model with non-normality effects representing observations in crystal plasticity", *J. Mech. Phys. Solid*, **49**, 1239-1263 (2001).

[15] V. Tvergaard, "Crack growth predictions by cohesive zone model for ductile fracture", *J. Mech. Phys. Solids,* ***49**,* 2191-2207 (2001).