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Modeling of ductile fracture: Significance of void coalescence

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Abstract

In this paper void coalescence is regarded as the result of localization of plastic flow between enlarged voids. We obtain the failure criterion for a representative material volume (RMV) in terms of the macroscopic equivalent strain (E_c) as a function of the stress triaxiality parameter (T) and the Lode angle (θ) by conducting systematic finite element analyses of the void-containing RMV subjected to different macroscopic stress states. A series of parameter studies are conducted to examine the effects of the initial shape and volume fraction of the primary void and nucleation, growth, and coalescence of secondary voids on the predicted failure surface $E_c(T, \theta)$. As an application, a numerical approach is proposed to predict ductile crack growth in thin panels of a 2024-T3 aluminum alloy, where a porous plasticity model is used to describe the void growth process and the expression for E_c is calibrated using experimental data. The calibrated computational model is applied to predict crack extension in fracture specimens having various initial crack configurations and the numerical predictions agree very well with experimental measurements.

Keywords: Ductile crack growth; Void coalescence; Critical strain; Failure surface; Stress triaxiality; Lode angle; Void shape; Failure mode

1. Introduction

Ductile fracture of many structural materials is a result of void nucleation, growth and coalescence. Based on the fracture mechanism, a straight-forward approach to simulate ductile failure process is to model individual voids explicitly using refined finite elements, e.g., Aravas and McMeeking (1985a,b), Tvergaard and Hutchinson (2002), Kim et al. (2003), and Gao et al. (2005). A distinct advantage of this approach is the exact implementation of void growth behavior. However, due to sizeable difference between the characteristic length scales involved in the material failure process and the dimensions of the actual structural component, it is impractical to model every void in detail in structure failure analysis, especially for situations involving extensive crack propagation. For this reason, various forms of porous material models have been developed to describe void growth and the associated macroscopic softening during the fracture process. Calibration of these porous material

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models requires the predicted macroscopic stress–strain response and void growth behavior of the representative material volume (RMV) to match the results obtained from detailed finite element models with explicit void representation (Faleskog et al., 1998; Kim et al., 2004). The most widely known porous material model for analyzing ductile fracture is that due to Gurson (1977). Tvergaard (1981, 1982) modified the Gurson model by introducing two adjustment parameters to account for void interaction and material strain hardening. The Gurson–Tvergaard (GT) model assumes voids are spherical in materials and remain spherical in the growth process. But many processed materials, such as rolled plates, have non-spherical voids. And even for materials having initially spherical voids, the void shape may change to prolate or oblate, depending on the state of the applied stress. In order to overcome the limitation of the GT model, Gologanu et al. (1993, 1994, 1995) derived a yield function for materials containing spheroidal voids. In the GLD model, both void volume fraction and void shape evolve as deformation increases. Since non-spherical voids are considered in the constitutive model, preferred material orientation exists and the macroscopic plastic behavior becomes anisotropic. The GLD model returns to the Gurson model when voids become spherical. Pardoen and Hutchinson (2000, 2003), Benzerga (2002), Benzerga et al. (2004), and Kim and Gao (2005) recently implemented the GLD model into finite element analysis and their results show the computational approach based on the GLD model provides a promising tool to predict ductile material failure.

In order to simulate crack formation and propagation, a criterion for void coalescence is required. After the onset of void coalescence, material loses load carrying capacity rapidly. Comparing to the amount research conducted in modeling the void growth process, void coalescence has not received sufficient attention. A critical void volume fraction (f_c) is often used to designate the final material failure, e.g., Needleman and Tvergaard (1987), Xia et al. (1995), and Gao et al. (1998a,b). However, further studies show that f_c cannot be taken as a constant—it depends strongly on factors such as void volume fraction, void shape, void spacing, stress triaxiality, strain hardening, etc. (Benzerga et al., 1999; Zhang et al., 2000; Pardoen and Hutchinson, 2000; Kim et al., 2004). In macroscopic, the equivalent strain is often used as a measurement of material ductility. Therefore, a critical equivalent strain has also been used to denote material failure. Bao and Wierzbicki (2004a,b) and Bao (2005) conducted a series of experiments and finite element analyses on an aluminum alloy 2024-T351 and found the critical equivalent strain is a function of the stress triaxiality.

In literature, the stress triaxiality ratio (T), defined as the ratio of the mean stress to the equivalent stress, is often used as the sole parameter to characterize the effect of the triaxial stress state on ductile fracture. However, multiple stress states with different principal stress values can result in the same stress triaxiality ratio. Recent studies by Kim et al. (2003, 2004) and Gao et al. (2005) found that the macroscopic stress–strain response and the void growth and coalescence behavior of the voided RMV are different for each stress state even though the stress triaxiality ratio remains the same. Another parameter, e.g., the Lode parameter, must be introduced to distinguish the stress states having the same triaxiality ratio. In this study, we obtain the material failure criterion in terms of the critical equivalent strain (E_c) as a function of the stress triaxiality ratio (T) and the Lode angle (θ) by conducting systematic finite element analyses of the void-containing RMV subjected to different macroscopic stress states. Failure of the RMV occurs when localization of plastic flow takes place in the ligament (Koplik and Needleman, 1988). Wierzbicki and Xue (2005) recently proposed a ductile failure criterion similar to what we obtained here based on analysis of an extensive set of experimental data. Next, the effects of the initial shape and volume fraction of the primary void and nucleation, growth and coalescence of the secondary voids on the failure surface $E_c(T, \theta)$ are investigated. Finally, as an application, a numerical approach is proposed to predict ductile crack growth in thin panels of a 2024-T3 aluminum alloy, where the GLD model is used to describe the void growth process and the expression for E_c is calibrated using experimental data. The calibrated computational model is applied to predict crack extension in fracture specimens having various initial crack configurations and the numerical predictions agree very well with experimental measurements.

2. Void coalescence and material failure criterion

2.1. Macroscopic stress state of the representative material volume

Ductile fracture in metallic alloys usually follows a multistep failure process involving several interacting, simultaneous mechanisms (Van Stone et al., 1985; Garrison and Moody, 1987): (1) nucleation of microvoids