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An ellipsoidal void model for simulating ductile fracture behavior

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ABSTRACT

An ellipsoidal void model, which is based on a parallelogrammic void model, is proposed for simulating ductile fracture behavior. It is used to analyze ductile fracture behavior in three plastic deformation modes: plane strain tension, uniaxial tension, and simple shear. The relationship between the fracture strain and the initial void volume fraction in uniaxial tension calculated using the void model agrees with that calculated using a finite-element void cell and agrees reasonably well with experimentally determined relationships in previous studies. For a specified initial void volume fraction, plane strain tension and simple shear respectively have the smallest and largest nominal fracture strains of the three plastic deformation modes.

1. Introduction

Ductile fracture, which occurs when a material is subjected to a large plastic deformation, is problematic in metal-forming processes. Consequently, it has been considerably investigated (Dodd and Bai, 1987). Microscopically, ductile fracture occurs through nucleation, growth, and coalescence of voids. Modeling void growth has been investigated by the finite-element method, which revealed how voids deform (Needleman, 1972; Tvergaard, 1981). However, void nucleation (Argon and Im, 1975; Goods and Brown, 1979; Le Roy et al., 1981) and coalescence are insufficiently understood.

Several analytical studies have investigated void coalescence on a microscopic level (Thomason, 1990; Melander and Stahlberg, 1980; Koplik and Needleman, 1988; Pardoen and Hutchinson, 2000; Benzerga, 2002; Ragab, 2004b; Bacha et al., 2008). Of these studies, the series of studies by Thomason (1990) is the best known. Although Thomason proposed three-dimensional void models (Thomason, 1985a,b), two-dimensional void models (Thomason, 1968a, 1981, 1982) are still beneficial. Two-dimensional modeling of internal necking of voids (Thomason, 1968a) is particularly effective since it employs a simple void model and is based on upper-bound theory (Avitzur, 1968), which is a method for analyzing metal-forming processes. The relationship between the fracture strain and the void volume fraction calculated using this void model agrees reasonably well with that obtained experimentally by Edelson and Baldwin (1962). Recently, there have been many experimental studies of void coalescence on a microscopic level (Worswick et al., 2001; Tinet et al., 2004; Narayanasamy and Narayanan, 2006; Weck and Wilkinson, 2008; Weck et al., 2008).

The Thomason model (Thomason, 1968a) and the Melander and Stahlberg model (Melander and Stahlberg, 1980) (which was derived from the Thomason model) assume that voids are rectangular and that the longitudinal direction of a void coincides with the direction of maximum principal stress. In other words, these models assume that the principal strain direction remains constant during plastic deformation. However, these models cannot be utilized to simulate metal-forming processes since the principal strain direction varies during plastic deformation in these processes.

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Nomenclature

a, b	major and minor diameters of void, respectively
$\boldsymbol{C}$	right Cauchy–Green deformation tensor
E	ratio of energy dissipation rate of internal necking to energy dissipation rate of homogeneous deformation
$f, \dot{f}$	void volume fraction and fraction rate of material, respectively
f_0	initial void volume fraction
k	shearing yield stress of material
$2l_1, 2l_2$	lengths of velocity discontinuity lines
L, L'	rectangle dimensions in x'- and y'-directions, respectively
n	strain hardening exponent
p	distance between two neighboring voids
$\boldsymbol{R}$	orthogonal rotation tensor
r_0	radius of cylindrical, spherical, or toroidal void
S_0, S_f	initial and final cross-sectional areas, respectively
u, v, w	displacements in x- or r-, y-, and z-directions, respectively
u^*, v^*, w^*	displacements in x-, y-, and z-directions, respectively
$\boldsymbol{U}$	right stretch tensor
u', v'	material velocities in x'- and y'-directions, respectively
V, V_0	volumes of material and matrix, respectively
$\Delta v_1, \Delta v_2$	velocity discontinuities
x_v, y_v	x- and y-coordinates of neighboring void, respectively
$\dot{\bar{\varepsilon}}$	equivalent strain rate
ε_f	logarithmic fracture strain
ε_M	strain of matrix
θ_1, θ_2	angles between maximum principal stress and velocity discontinuity lines
$\lambda_{max}, \lambda_{min}$	maximum and minimum principal values of $\boldsymbol{C}$, respectively
$\bar{\sigma}$	equivalent stress
σ^*	imposed hydrostatic stress
σ_M	tensile yield stress of matrix
ϕ	angle between line connecting two neighboring voids before deformation and x-axis
ϕ_a	angle between direction of major diameter of void a and x-axis
ϕ_{max}	angle between maximum principal direction of $\boldsymbol{C}$ and x-axis
ϕ_R	angle of rotation due to $\boldsymbol{R}$
Φ, Φ'	original and approximate Gurson yield functions, respectively
Ψ, Ψ'	original and approximate Gurson–Tvergaard yield functions, respectively

In a previous study (Komori, 1999), we proposed a void model based on these models that can be utilized to simulate metal-forming processes. It assumes that voids are parallelograms and that the longitudinal direction of a void differs from the direction of maximum principal stress. In other words, it assumes that the direction of principal strain varies during plastic deformation. It is identical to the Melander and Stahlberg model in uniaxial tension. Hence, in uniaxial tension, the relationship between the fracture strain and the void volume fraction calculated using our void model is identical to that calculated using the Melander and Stahlberg model, while it is close to that calculated using the Thomason model.

Our void model (Komori, 1999), the Thomason model (Thomason, 1968a), and the Melander and Stahlberg model (Melander and Stahlberg, 1980) all suffer from two problems. The first problem is that the fracture strain is calculated to be zero when the void volume fraction of the material exceeds 10%. However, the fracture strain obtained experimentally by Edelson and Baldwin is nonzero even when the void volume fraction of the material exceeds 20%. The second problem is that the calculated relationship between the fracture strain and the void volume fraction has not been demonstrated for plastic deformation modes except for uniaxial tension.

To overcome these problems, this study proposes an ellipsoidal void model based on our earlier parallelogrammic void model for simulating ductile fracture behavior. It is used to analyze ductile fracture behavior in three plastic deformation modes: plane strain tension, uniaxial tension, and simple shear.

From a macroscopic point of view, ductile fracture is highly dependent on the stress triaxiality of a material (Bridgman, 1952), which is zero in simple shear. Hence, it is not easy to predict ductile fracture in simple shear from a macroscopic point of view (Pardoen, 2006; Barsoum and Faleskog, 2007a,b). It is thus particularly valuable to obtain the relationship between the fracture strain and the void volume fraction for simple shear.

2. Analysis method

2.1. Overview of whole analysis

Fig. 1 shows an overview of the whole analysis procedure at each time step. Macroscopic analysis and microscopic analysis are performed alternately (Zhang and Niemi, 1995; Zhang et al., 2000; Komori, 2006a,b, 2008). First, in macroscopic analysis, the deformation of the material is analyzed by the conventional rigid–plastic finite-element method. The displacement gradient rate and the void volume fraction rate of the material calculated by macroscopic analysis are utilized in the subsequent microscopic analysis. Next, in microscopic analysis, fracture of the material is evaluated by our void model. The microscopic analysis determines whether the material fractures and this information is utilized in the macroscopic analysis of the next time step.