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# Evaluation of ductile fracture in sheet metal forming using the ellipsoidal void model

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The ductile fracture in the simulation of sheet-metal-forming processes is evaluated by the ellipsoidal void model previously proposed by the author. In the present study, the simulation and experiment of the hole expansion test are performed using six types of metals. For an alloy, the relationship between prestrain and hole expansion ratio calculated using the ellipsoidal void configuration and ellipsoidal void shape and that calculated using the ellipsoidal void configuration and circular void shape agree with the relationship obtained experimentally. For a pure metal, the relationship between prestrain and hole expansion ratio calculated using the average void configuration and average void shape agrees with that obtained experimentally. Furthermore, the method of introducing prestrain to an as-rolled sheet is proposed, and the prestrain in this sheet is estimated.



## 1. Introduction

Ductile fracture, which occurs when a material is subjected to a large plastic deformation, is a problem in metal-forming processes. Numerous ductile fracture criteria for various materials have been proposed. However, no ductile fracture criterion that is applicable to all metal-forming processes has been found (Clift et al., 1990; Wierzbicki et al., 2005).

Since ductile fracture occurs through nucleation, growth, and coalescence of voids (Dodd and Bai, 1987), it is a microscopic phenomenon (Wilsdorf, 1983). Because the ductile fracture criteria that are widely used for metal-forming processes, such as those introduced by Freudenthal (1950), Cockcroft and Latham (1968), Brozzo et al. (1972) and Oyane (1972), are derived from a macroscopic perspective, improving the accuracy of prediction of a microscopic ductile fracture phenomenon using a macroscopic ductile fracture criterion is challenging.

On the other hand, in sheet metal forming processes, the formability of a sheet metal is limited by the occurrence of localized necking. Thus, the effect of the strain path on the forming limit has been investigated (Needleman and Triantafyllidis, 1978; Kim et al., 2003; Son and Kim, 2003) using various yield functions for the voided material in conjunction with the localized necking model introduced by Marciniak and Kuczyński (1967).

Recently, the author has been attempting to predict the ductile fracture in metal-forming processes from a microscopic viewpoint (Komori, 2011, 2013a). The author's proposed model of void coalescence is based on the Thomason model (Thomason, 1968), which is derived from a microscopic viewpoint. The Thomason model assumes that the void is rectangular, whereas the author's proposed model assumes that the void is ellipsoidal. The Thomason model assumes that the direction of the major axis of the void coincides with that of the maximum principal stress, whereas the author's proposed model does not assume the two directions to coincide. Hence, the author's void model can be used in the simulation of metal-forming processes.

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In the preceding paper (Komori, 2013a), an ellipsoidal void model for evaluating ductile fracture in sheet metal forming was proposed. Although several simulations of the hole expansion test were performed to evaluate the ductile fracture criteria (Takuda et al., 1999; Huang and Chien, 2001; Ko et al., 2007; Uthaisangsuk et al., 2009), the effect of prestrain on the hole expansion ratio was not demonstrated. Hence, the simulation of the hole expansion test was performed and the effect of prestrain on the hole expansion ratio has been clarified (Komori, 2013a). The simulation results obtained through the author's model agreed with the experimental results, whereas the simulation results obtained using the conventional ductile fracture criteria (Freudenthal, 1950; Cockcroft and Latham, 1968; Brozzo et al., 1972; Oyane, 1972) differed from the experimental results. Because the prestrain was provided by rolling, in which stress triaxiality is negative, the prestrain hardly affected the hole expansion ratio in most of the conventional ductile fracture criteria (Cockcroft and Latham, 1968; Brozzo et al., 1972; Oyane, 1972).

In the preceding paper, the experimental results obtained using cold- and hot-rolled steel sheets were compared with the simulation results. However, the applicability of the ellipsoidal void model to other metals needs to be examined. In the experiment on cold-rolled steel sheet, the hole expansion ratio of the specimen rolled in the direction parallel to the rolling direction of the as-rolled sheet was slightly smaller than that rolled in the direction perpendicular to the rolling direction of the as-rolled sheet. This is because the cold-rolled steel sheet had a slight prestrain. Therefore, the applicability of the ellipsoidal void model to a rolled metal sheet having large prestrain, such as a stainless steel sheet, should also be examined.

In this study, the applicability of the ellipsoidal void model previously proposed by the author (Komori, 2013a) is examined. The hole expansion test was simulated and conducted on alloys in the preceding paper; in the present study, not only alloys but also pure metals are evaluated. Consequently, the appropriate void configurations and void shapes for both alloys and pure metals are clarified. Furthermore, the hole expansion test is simulated and performed on two types of stainless steels. The as-rolled sheets should impart large prestrain. The magnitude of the prestrain in the as-rolled sheets is estimated by introducing the prestrain of the as-rolled sheets into the ellipsoidal void model.

## 2. Simulation method

The simulation method used in this study that is the same as that in the preceding study (Komori, 2013a) is described briefly, while the new simulation method is described in detail.

### 2.1. Outline

A multiscale simulation is performed. The deformation of the material is simulated macroscopically by the rigid-plastic finite-element method, whereas the fracture of the material is evaluated using the ellipsoidal void model through microscopic simulation. The deformation gradient and void volume fraction calculated in the macroscopic simulation are used in the microscopic simulation. The multiscale simulation is performed until the material fractures.

### 2.2. Outline of macroscopic simulation

The deformation of the material is simulated using the conventional rigid-plastic finite-element method (Kobayashi et al., 1989). Axisymmetry is assumed in the simulation of the hole expansion test, whereas the plane stress state is assumed in the simulation of the uniaxial tensile test. The yield function proposed by Gurson (1977) is adopted:

$$\Phi = \frac{3}{2}\cdot\frac{\sigma'_{ij}\sigma'_{ij}}{\sigma_{\mathrm{M}}^2} + 2f\cosh\left(\frac{\sigma_{kk}}{2\sigma_{\mathrm{M}}}\right) - 1 - f^2 = 0, \quad (1)$$

where $\sigma_{\mathrm{M}}$ is the tensile yield stress of the matrix, and $f$ is the void volume fraction of the material. Since the yield function $\Phi$ is not a function of the second power of stress, it is not easy to perform a rigid-plastic simulation using Eq. (1). Hence, $\cosh x$ is approximated to be $1 + x^2/2$ (Tomita, 1990). Therefore, the approximated yield function $\Phi'$ used in the present study is

$$\Phi' = \frac{3}{2}\cdot\frac{\sigma'_{ij}\sigma'_{ij}}{\sigma_{\mathrm{M}}^2} + \frac{f}{4}\cdot\left(\frac{\sigma_{kk}^2}{\sigma_{\mathrm{M}}^2}\right) - (1-f)^2 = 0. \quad (2)$$

The following two types of evolution equations, which denote the change in the void volume fraction, are assumed:

$$\dot{f} = (1-f)\dot{\varepsilon}_{kk} + A_1 R\left(\frac{\sigma_{kk}}{3\bar{\sigma}} - B_1\right)\dot{\bar{\varepsilon}}, \quad (3)$$

$$\dot{f} = (1-f)\dot{\varepsilon}_{kk} + A_2 H\left(\frac{\sigma_{kk}}{3\bar{\sigma}} - B_2\right)\dot{\bar{\varepsilon}}, \quad (4)$$

where $\bar{\sigma}$ is the equivalent stress; $\dot{\bar{\varepsilon}}$ is the equivalent strain rate; and $A_1$, $A_2$, $B_1$, and $B_2$ are the material constants. $R(x)$ in Eq. (3) denotes the ramp function, which is the same as the Macaulay bracket defined in the preceding paper, whereas $H(x)$ in Eq. (4) denotes the Heaviside step function. In other words, when $x$ is positive, $R(x)$ is equal to $x$ and $H(x)$ is equal to one, whereas when $x$ is negative, both $R(x)$ and $H(x)$ are equal to zero. The first and second terms on the right-hand sides of Eqs. (3) and (4) denote void growth and void nucleation, respectively.

### 2.3. Outline of microscopic simulation

Following is an outline of the microscopic simulation performed in each step, from the calculation of the void volume fraction and the deformation gradient to the determination of whether the material fractures:

(1) The void volume fraction $f$ and deformation gradient $\partial\boldsymbol{x}/\partial\boldsymbol{X}$ are calculated by the macroscopic rigid-plastic finite-element simulation.
(2) The void configuration and void shape are calculated.