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Material Model based on Stress-rate Dependency Related with Non-associated Flow Rule for Fracture Prediction in Metal Forming

Tetsuo Oya[a*], Jun Yanagimoto[b], Koichi Ito[c], Gen Uemura[c] and Naomichi Mori[c]

[a]*Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*
[b]*The University of Tokyo, Institute of Industrial Science, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[c]*M&M Research Inc., 4-15-3 Jingumae, Shibuya-ku, Tokyo 150-0001, Japan*

Abstract

Fracture prediction in metal forming has captured attention because of its practical importance. Recently, demand for fracture prediction has grown to conduct an effective forming process design using numerical simulation; however, the increasing use of high-strength steels and anisotropic materials prevents accurate simulation in large strains in which fracture tend to occur. In this study, a fracture prediction framework based on the bifurcation theory is constructed. The core is a material model based on stress-rate dependency related with non-associate flow rule. This model is based on non-associated flow rule with arbitrary higher order yield function and plastic potential function for any anisotropic materials. And this formulation is combined with the stress-rate-dependency plastic constitutive equation, which is known as the Ito-Goya plastic constitutive equation, to construct a generalized plastic constitutive model in which non-normality and non-associativity are reasonably included. Then, by adopting the three-dimensional bifurcation theory, more accurate prediction of the initiation of shear band is realized, leading to general and reliable construction of forming limit diagram.

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Keywords: Material model, Fracture prediction, Bifurcation analysis, Stress-rate dependency, Non-associated flow rule.

* Corresponding author. Tel.: +81-45-566-1803; fax: +81-45-566-1816.
E-mail address: oya@sd.keio.ac.jp

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1. Introduction

Fracture prediction in metal forming has captured attention because of its practical importance. Recently, demand for fracture prediction has grown to conduct an effective forming process design using numerical simulation; however, the increasing use of high-strength steels and anisotropic materials prevents accurate simulation in large strains in which fracture tend to occur.

For constructing reliable fracture prediction model, the bifurcation theory has been adopted in this research, and novel material model to conduct bifurcation analysis was developed. The bifurcation theory as a fracture prediction method is advantageous in terms of generality and objectivity, but it is known that the bifurcation analysis using conventional material models sometimes exhibit poor result. The reason is that the previous bifurcation analyses based on the original proposed by Hill [1] have used plane-stress condition and normality rule. Under these assumptions, accurate prediction of the initiation of shear band, which is regarded as a close sign of fracture, is almost impossible. Even with the SR (Stören-Rice) theory [2] in which stress-rate dependency was considered, there is still a restriction of plane-stress condition. Thus, to conduct fully three-dimensional bifurcation analysis appropriately, a new framework that can deal with three-dimensional bifurcation mode and abrupt change in stress field should be created.

In this study, a fracture prediction framework based on the bifurcation theory is constructed. The core is a material model based on stress-rate dependency related with non-associate flow rule. This model is based on non-associated flow rule with arbitrary higher order yield function and plastic potential function for any anisotropic materials [3][4]. And this formulation is combined with the stress-rate-dependency plastic constitutive equation, which is known as the Ito-Goya plastic constitutive equation [5], to construct a generalized plastic constitutive model in which non-normality and non-associativity are reasonably included. Then, by adopting the three-dimensional bifurcation theory [5], more accurate prediction of the initiation of shear band is realized, leading to general and reliable construction of forming limit diagram.

In this paper, the above-mentioned theoretical framework is developed and described. Then, by using virtual material data, numerical simulation is carried out to exhibit fracture limit diagram for demonstrating the effectiveness of the proposed methodology.

2. Proposed model and framework for fracture prediction

2.1. Material model

First, the material model proposed by the authors, which plays an essence role in this research, is described. This model is constructed to express deformation anisotropy and yield stress anisotropy by using non-associated flow rule formulation with the number of material constants same as that of Hill's 1948 model. The following is the definition of the yield function and the plastic potential function and the equivalent plastic strain increment. In the proposed model, we defined the yield function $f(\boldsymbol{\sigma})$ as being equal to the equivalent stress $\bar{\sigma}$; namely, the expression is

$$f(\boldsymbol{\sigma}) = \bar{\sigma} = \sqrt[2m_y]{\frac{3}{2(F+G+H)}\left(\boldsymbol{s}_{m_y}^T \cdot \boldsymbol{A} \cdot \boldsymbol{s}_{m_y}\right)} \quad . \tag{1}$$

Here, the matrix $\boldsymbol{A}$ has the anisotropic parameters in its diagonal terms; and the pseudo-vector $\boldsymbol{s}$ is a set of deviatoric stress components to the power of m_y. This higher-order function preserves the form of Hill's quadratic yield function, that is, it contains the same anisotropic parameters F, G, H, L, M, and N. This feature is important because it is possible to construct a higher-order yield function by changing the power m_y without increasing the number of undetermined variables.

In our non-associated flow rule-based formulation, a function different from the yield function is adopted as a plastic potential function, which provides the direction of the plastic strain increment of the subsequent state of current stress. In this study, the previously introduced function $f(\boldsymbol{\sigma})$ is used as the yield function, and another