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Fracture-based forming limit criteria for anisotropic materials in sheet metal forming

Namsu Park [a], Hoon Huh [a,*], Sung Jun Lim [a], Yanshan Lou [b], Yeon Sik Kang [c], Min Hong Seo [c]

[a] School of Mechanical, Aerospace and Systems Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] Institute for Forming Technology and Lightweight Construction (IUL), TU Dortmund University, Baroper Str. 303, Dortmund 44227, Germany
[c] POSCO Global R&D Center, 180-1, Songdo-dong, Yeonsu-gu, Incheon 406-840, Republic of Korea

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ABSTRACT

This paper is concerned with modeling of fracture-based forming limit criteria for anisotropic materials in sheet metal forming to predict the sudden fracture in complicated forming processes. The Lou–Huh ductile fracture criterion is modified using the Hill's 48 anisotropic yield function instead of the von Mises isotropic yield function to take account of the influence of anisotropy on the equivalent plastic strain at the onset of fracture. For the derivation of an anisotropic ductile fracture criterion, the principal stresses $(\sigma_1,\sigma_2,\sigma_3)$ are expressed in terms of the stress triaxiality, the Lode parameter, and the equivalent stress $(\eta_H, L_P, \overline{\sigma}_H)$ based on the Hill's 48 yield function. Three different kinds of fracture-based forming limit criteria are suggested and investigated with an assumption that the stress state is under the plane stress condition with proportional loading. To determine the parameters of the model proposed, the two-dimensional digital image correlation (2D-DIC) method is utilized to measure the strain histories on the surface of three different types of specimens during deformation and the measurement results are investigated to identify the anisotropy effect on the equivalent plastic strain at the onset of fracture. This paper also discusses about a scaling method for a strain-based fracture forming limit criterion in order to capture the onset of fracture using a single forming limit curve for an anisotropic material. From the comparison of various forming limit criteria suggested, it is concluded that a polar effective plastic strain-based (PEPS) fracture forming limit diagram (FFLD) is suitable for prediction of the sudden fracture in AHSS sheets in complicated sheet metal forming processes on the basis of its path independence and simplicity of measuring strains in real forming processes.

1. Introduction

A major current issue in analysis and design of sheet metal forming processes is how to predict the sudden fracture in advanced high-strength steel (AHSS) sheets during a forming process since the usage percentage of the AHSS sheets is remarkably increasing to enhance the safety and fuel efficiency. In sheet metal forming, the traditional strain based forming

* Corresponding author. Tel.: +82 42 350 3222; fax: +82 42 350 3210.
E-mail address: hhuh@kaist.ac.kr (H. Huh).

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Nomenclature

$\varepsilon_1^p, \varepsilon_2^p$	Principal strains in the plane stress condition, $\varepsilon_1^p \geq \varepsilon_2^p$
$\overline{\varepsilon}^p$	Equivalent plastic strain
$\overline{\varepsilon}_f^p$	Equivalent plastic strain at the onset of fracture
$\overline{\varepsilon}_H^p$	The Hill's 48 equivalent plastic strain
$\dot{\varepsilon}_1^p, \dot{\varepsilon}_2^p, \dot{\varepsilon}_3^p$	Principal plastic strain rates, $\dot{\varepsilon}_1^p \geq \dot{\varepsilon}_2^p \geq \dot{\varepsilon}_3^p$
σ_m	Mean or hydrostatic stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
$\overline{\sigma}_v$	The von Mises equivalent stress
$\overline{\sigma}_H$	The Hill's 48 equivalent stress
$\overline{\sigma}_f$	Equivalent stress at the onset of fracture
η_v	Stress triaxiality based on the von Mises yield function, $\eta_v = \sigma_m/\overline{\sigma}_v$
η_H	Stress triaxiality based on the Hill's 48 yield function, $\eta_H = \sigma_m/\overline{\sigma}_H$
$\sigma_1,\sigma_2,\sigma_3$	Principal stresses, $\sigma_1 \geq \sigma_2 \geq \sigma_3$
s_1,s_2,s_3	Deviatoric principal stresses, $s_1 \geq s_2 \geq s_3$
τ_{max}	Maximum shear stress
L_P	Lode parameter, $L_P = (2\sigma_2 - \sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)$
C_i	Material constants in the anisotropic ductile fracture criterion, $i = 1, 2, 3$
θ_s	The angle of maximum principal stress to the rolling direction
$f_l(\theta_s)$	The normalized fracture-based forming limit in the plane strain
C_O	Sensitivity of the cut-off value for the stress triaxiality
D,d_i	Damage index and incremental damage index at the i-th component during numerical integration

limit diagram (FLD) pioneered by Keeler and Backofen (1963) has been widely applied to evaluate localized necking and thickness reduction. The conventional strain-based FLD, however, is not appropriate for prediction of the fracture in AHSS sheets since AHSS sheets fail with little amount of necking different from that with the conventional steel sheets. Ductile fracture in advanced metals is observed in the shear and the compression region where the value of the stress triaxiality is low or negative in bulk metal forming as reported by Bao and Wierzbicki (2004), Børvik et al. (2010) and Khan and Liu (2012a, 2012b). Hence, prediction of the fracture in AHSS sheets needs a general ductile fracture criterion instead of a necking-based forming limit diagram which neither monitors the region for low and negative stress triaxiality nor predicts the sudden fracture.

Ductile fracture of metals is generally thought to be induced by the void nucleation, the growth, and the coalescence of voids eventually resulting in a visible macroscopic crack. Dozens of ductile fracture criteria had been introduced based on the microscopic mechanism with various hypotheses in addition to experimental observations of ductile fracture. Fundamental work by McClintock (1968) and Rice and Tracey (1969) noted that the stress triaxiality is the main parameter which controls the void growth. The nucleation and coalescence of voids were later taken into consideration by Chu and Needleman (1980) and LeRoy et al. (1981). With micromechanically inspired criteria, numerous phenomenological criteria were suggested by Cockcroft and Latham (1968), Brozzo et al. (1972), Oh et al. (1979), Oyane et al. (1980), Clift et al. (1990), and Ko et al. (2007). These criteria were widely employed to deal with various engineering problems such as compressive upsetting tests, axisymmetric extrusion, strip compression and tension due to their simple formulas with a few parameters for experimental calibration. Ductile fracture criteria reviewed above are, however, incapable of fully describing the ductile fracture behavior over a wide range of stress states necessary for the fracture prediction of AHSS sheets because these criteria were developed to solve for special problems. Recently, Bao and Wierzbicki (2004) proposed a phenomenological fracture criterion based on results of extensive fracture tests of AA 2024-T351, which reveals a clue to the influence of the stress triaxiality on the equivalent plastic strain to the fracture. Lode angle dependence on ductile fracture was reported by Xue (2007) and Xue and Wierzbicki (2008) and it was confirmed that the Lode angle parameter and the stress triaxiality have mutual influence on the initiation of ductile fracture from various experimental results performed by Barsoum and Faleskog (2007a, 2007b) and Korkolis and Kyriakides (2008). Bai and Wierzbicki (2010) modified the classical Mohr–Coulomb criterion which was developed for rock and soil mechanics to describe ductile fracture behavior over a wide range of loading states. Lou et al. (2012) developed a micro-mechanism-inspired macroscopic ductile fracture criterion on the basis of assumptions that micro-voids proportionally nucleate with the equivalent plastic strain, the growth of voids was controlled by the stress triaxiality, and the coalescence of voids was governed by the maximum shear stress resulting in shear-linking up. In order to appropriately consider a reasonable cut-off value for the stress triaxiality, Lou et al. (2014) proposed a cut-off value function which can be defined by Lode dependence, sensitivities to microstructures, temperature, and strain rate, etc. Pack et al. (2014) established the basic methodology with the aid of two-dimensional digital image correlation (2D-DIC) method in fracture modeling with a hybrid experimental–numerical method following the procedure by Dunand and Mohr (2010).

Sheet metal forming community has extensively accepted the conventional FLD due to its easy interpretation and convenience of measuring strains from both real forming tests and finite element simulations. The conventional FLD, however,