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Numerical determination of the forming limit curves of anisotropic sheet metals using GTN damage model

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ABSTRACT

In this paper, the Gurson–Tvergaard–Needleman (GTN) damage model is used to determine the forming limit curve of anisotropic sheet metals. The mechanical behavior of the matrix material is described using Hill'48 quadratic yield criterion and an isotropic hardening rule. For this purpose, a VUMAT subroutine has been developed and used inside the ABAQUS/Explicit finite element code. The implementation of the constitutive model in the finite element code is presented in detail. Finally, the forming limit curve of an AA6016-T4 sheet metal is constructed using the developed VUMAT subroutine and running numerical simulation of Nakjima tests. The quality of the numerical results is evaluated by comparison with an experimental forming limit curve. Furthermore, theoretical forming limit curves of the AA6016-T4 sheet are obtained using Marciniak–Kuczynski (M–K) and modified maximum force criterion (MMFC) models. The results show that the forming limit curve predicted by the anisotropic GTN model is in better agreement with the experimental results especially in the biaxial tension region. This fact indicates that the GTN model is a useful tool in analyzing the formability of anisotropic sheet metals.

1. Introduction

The forming limit curve (FLC) is a very useful and common tool in industries involved in sheet metal forming. This curve is actually a plot of the major principal strain vs. minor principal strain characterizing the onset of sheet necking. Consequently, FLC divides the possible combinations of the major and the minor strains into safe and unsafe regions. More precisely, the strain combinations which stand below the FLC are considered as safe (acceptable), while the strain combinations located above the FLC are considered as unsafe.

Since the introduction of the FLC by Keeler and Backhofen (1963), many attempts have been made to construct it using experimental, theoretical and numerical methods. Because of the expenses involved by the experimental procedures of FLC construction, the theoretical (Hill, 1952; Marciniak and Kuczynski, 1967) and numerical (Li et al., 2010) methods have been more attractive to researchers. One of the suitable theoretical approaches for determination of the FLC is the Gurson–Tvergaard–Needleman (GTN) damage model (Gurson, 1977; Tvergaard, 1981, 1982; Tvergaard and Needleman, 1984). The original formulation of this model has been proposed by Gurson (1977) by assuming that the degradation of the load carrying capacity and finally the fracture of ductile metals are caused by the evolution of voids. Gurson's model takes into account only the growth of pre-existing voids, without assuming any generative mechanisms. In order to overcome this limitation, Tvergaard (1981, 1982) and Tvergaard and Needleman (1984) have proposed mathematical descriptions of the void nucleation and coalescence. The final modified model is known as Gurson–Tvergaard–Needleman (GTN) damage model.

As the metallic sheets are commonly produced by rolling, they exhibit high levels of anisotropy. Due to this characteristic, it is very important to include the anisotropy of the matrix material in the GTN model. There are few works that have dealt with this aspect. Liao et al. (1997) utilized a similar approach to that proposed by Gurson (1977) to derive an approximate potential formulation for the prediction of damage in the metallic sheets. The original feature of their model consists in the fact that the equivalent stress is described by Hill's quadratic (Hill, 1948) and non-quadratic (Hill, 1979) anisotropic expressions. Liao et al. (1997) used anisotropy parameters defined as the ratio of the transverse plastic strain rate to the through-thickness plastic strain rate under in-plane uniaxial loading along different directions. Wang et al. (2004) replaced

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the directional parameters in the model proposed by Liao et al. (1997) with the average anisotropy parameter. Chen and Dong (2008) extended the GTN model to characterize the matrix material through Hill quadratic (Hill, 1948) and Barlat–Lian 3-component (Barlat and Lian, 1989) expressions of the equivalent stress. Chen and Dong (2009) proposed extensions of the GTN potential based on Hill's quadratic anisotropic expression of the equivalent stress (Hill, 1948).

Of course, it is possible to solely use the GTN damage model to predict the fracture of the ductile materials during deformation. On the other hand, the GTN model could be also used to construct the forming limit curve. Brunet et al. (1996) studied the occurrence of necking in square cup deep drawing of a mild-steel sheet and also extracted the limit strains of the sheet using an anisotropic Gurson–Tvergaard criterion (Gurson, 1977; Tvergaard, 1981). Brunet et al. (1998) and Brunet and Morestin (2001) proposed a necking criterion based on the load-instability and plane strain localization assumptions in which the failure of the material is defined by Gurson–Tvergaard damage model with Hill (1948) and Barlat and Lian (1989) anisotropy models. He et al. (2011) predicted the forming limit stress diagram of 5052 aluminum alloy based on the GTN model. Abbasi et al. (2012a, 2012b) used GTN model to predict the forming limit curve of an IF-steel and a tailor welded blank made from IF-steel, respectively. Furthermore, the GTN damage model has been employed to predict the forming limits of other sorts of sheets like the AA5052/polyethylene/AA5052 (Liu et al., 2013; Liu and Xue, 2013) and AA3105/Polypropylene/AA3105 (Parsa et al., 2013) sandwich sheets, dual-phase and multi-phase (Uthaisangsuk et al., 2009; Ramazani et al., 2012) steels.

In this paper, a GTN model based on Hill's quadratic expression of the equivalent stress is used to construct the forming limit curve. The model is implemented as a VUMAT routine in the ABAQUS/Explicit finite-element code (ABAQUS analysis user's manual, 2011). Furthermore, the plastic strain and void volume fraction distributions near the fracture section are analyzed. The material parameters involved in the constitutive relationships are determined by means of an identification procedure that combines the response surface methodology (RSM) and the simulation of a uniaxial tensile test.

2. Formulation of the constitutive model and its Abaqus/Explicit implementation

Abaqus/Explicit allows the implementation of solid material models by means of the VUMAT routine. Because Abaqus/Explicit uses corotational components of the Cauchy stress and logarithmic strain as input/output when communicating with VUMAT, plain time derivatives of such tensor quantities can be involved in the formulation of the rate-type constitutive relationships, without any concern about their objectivity. The model presented below assumes that the Abaqus/Explicit corotational frame also reflects the plastic orthotropy of the sheet metal, being initially coincident with the frame defined by the rolling direction – RD (axis 1), transverse direction – TD (axis 2) and normal direction – ND (axis 3). The following symbols will denote macroscopic strain and stress quantities:

ε_{ij} components of the corotational logarithmic strain tensor separable into elastic $\varepsilon_{ij}^{(e)}$ and plastic $\varepsilon_{ij}^{(p)}$ terms, i.e.

$$\varepsilon_{ij} = \varepsilon_{ij}^{(e)} + \varepsilon_{ij}^{(p)} \tag{1}$$

σ_{ij} components of the corotational Cauchy stress tensor
p hydrostatic pressure:

$$p = -\frac{\sigma_{\ell\ell}}{3} \tag{2}$$

$\bar{\sigma}$ Hill'48 equivalent stress:

$$\bar{\sigma} = \sqrt{\sigma_{ij} P_{ijk\ell} \sigma_{k\ell}}, \tag{3}$$

where P_{ijkl} are components of a fourth-order tensor by means of which the constitutive model approximates the plastic orthotropy of the sheet metal. In general, P_{ijkl} (i, j, k, ℓ =1, 2, 3) are subjected to the constraints

$$P_{ijk\ell} = P_{jik\ell} = P_{ij\ell k} = P_{k\ell ij}, \quad P_{iik\ell} = 0. \tag{4}$$

Two other strain/stress parameters will be associated to the fully dense matrix material:

$\bar{\varepsilon}^{(p)}$ equivalent plastic strain ($\bar{\varepsilon}^{(p)} \geq 0$, $\dot{\bar{\varepsilon}}^{(p)} \geq 0$)

Y yield stress defined as function of $\bar{\varepsilon}^{(p)}$ by means of a hardening law $Y = Y[\bar{\varepsilon}^{(p)}] > 0$.

The elasticity of the sheet metal is described by the isotropic Hooke's law

$$\sigma_{ij} = \frac{E}{1+\nu}\left[\varepsilon_{ij}^{(e)} + \frac{\nu}{1-2\nu}\varepsilon_{\ell\ell}^{(e)}\delta_{ij}\right], \tag{5}$$

where E and ν are Young's modulus and Poisson's ratio, respectively, while δ_{ij} denotes Kronecker's symbol.

The plastic part of the constitutive model is based on the GTN potential (Chen and Butcher, 2013)

$$\Phi = \left\{\frac{\bar{\sigma}}{Y[\bar{\varepsilon}^{(p)}]}\right\}^2 + q_1 f^*(f)\left\{2\cosh\left\{-q_2\frac{3p}{2Y[\bar{\varepsilon}^{(p)}]}\right\} - q_1 f^*(f)\right\} - 1, \tag{6}$$

where

$$f^*(f) = \begin{cases} f, & \text{if } f \leq f_C, \\ f_C + \dfrac{f_F^* - f_C}{f_F - f_C}(f - f_C), & \text{if } f_C < f < f_F, \quad \text{with } f_F^* = 1/q_1, \\ f_F^*, & \text{if } f \geq f_F, \end{cases} \tag{7}$$

is a porosity parameter depending on the void volume fraction f. The quantities denoted as q_1, q_2, f_C, and f_F in Eqs. (6) and (7) are material constants. The inequality $\Phi \leq 0$ defines all the admissible stress states of the sheet metal. More precisely, $\Phi < 0$ is associated to the elastic states and $\Phi = 0$ corresponds to the elastoplastic ones.

The flow rule associated to the potential Φ can be expressed in the form

$$\dot{\varepsilon}_{ij}^{(p)} = \dot{\lambda}\frac{\partial\Phi}{\partial\sigma_{ij}}, \quad \text{with} \begin{cases} \dot{\lambda} = 0, & \text{if } \Phi < 0, \\ \dot{\lambda} \geq 0, & \text{if } \Phi = 0, \end{cases} \tag{8}$$

or, if Eqs. (6), (3) and (4) are taken into account,

$$\dot{\varepsilon}_{ij}^{(p)} = \frac{1}{\bar{\sigma}}\dot{\varepsilon}^{(p,dev)} P_{ijk\ell}\sigma_{k\ell} + \frac{1}{3}\dot{\varepsilon}^{(p,vol)}\delta_{ij}, \tag{9}$$

where

$$\dot{\varepsilon}^{(p,dev)} = \dot{\lambda}\frac{\partial\Phi}{\partial\bar{\sigma}}, \quad \dot{\varepsilon}^{(p,vol)} = -\dot{\lambda}\frac{\partial\Phi}{\partial p}, \tag{10}$$

and

$$\frac{\partial\Phi}{\partial\bar{\sigma}} = \frac{2\bar{\sigma}}{\{Y[\bar{\varepsilon}^{(p)}]\}^2}, \quad \frac{\partial\Phi}{\partial p} = -3q_1 q_2 \frac{f^*(f)}{Y[\bar{\varepsilon}^{(p)}]}\sinh\left\{-q_2\frac{3p}{2Y[\bar{\varepsilon}^{(p)}]}\right\}. \tag{11}$$

Eq. (10) allows deducing the following consistency condition that accompanies the constraint $\Phi = 0$ in the elastoplastic states of the sheet metal:

$$\dot{\varepsilon}^{(p,dev)}\frac{\partial\Phi}{\partial p} + \dot{\varepsilon}^{(p,vol)}\frac{\partial\Phi}{\partial\bar{\sigma}} = 0. \tag{12}$$