European Journal of Mechanics / A Solids 69 (2018) 255–265

Contents lists available at ScienceDirect

European Journal of Mechanics / A Solids

journal homepage: www.elsevier.com/locate/ejmsol

Prediction of forming limit curve at fracture for sheet metal using new ductile fracture criterion

Shahram Abbasnejad Dizaji[a,*,1], Haluk Darendeliler[b], Bilgin Kaftanoğlu[c]

[a] Department of Mechanical Engineering, TED University, 06420, Ankara, Turkey
[b] Department of Mechanical Engineering, Middle East Technical University, 06800, Ankara, Turkey
[c] Department of Manufacturing Engineering, Atilim University, 06836, Ankara, Turkey

ARTICLE INFO

Keywords:
Fracture
Anisotropic material
Constitutive behavior
Energy methods
Finite elements

ABSTRACT

The application of ductile fracture criteria (DFCs) in numerical analysis of sheet metal forming processes can lead to the accurate determination of the fracture initiation. In this study, a new uncoupled ductile fracture criterion (DFC) has been developed which considers the effects of material parameters on the forming limit curves (FLCs) and can be easily implemented in the finite element codes. Two different constitutive models have been employed with the new DFC in order to evaluate the results obtained for fracture prediction. Various experimental tests have been utilized to validate the new criterion and its results are also compared with other well-known uncoupled DFCs. It is observed that the new criterion predicts the ductile fracture for all aluminum, steel and stainless steel materials better than the former criteria.

1. Introduction

Forming limit curves (FLC) have been extensively used to evaluate formability in the sheet metal forming industry. The first FLC was experimentally plotted using the grids of circles printed or etched before the forming. There are many theoretical FLCs developed by simply drawing the curve and avoiding the costly and time-consuming experimental tests. The most well-known models are based on the localization and bifurcation theories. However, FLCs have some shortcomings which limit their effectiveness in the processes involving nonlinear strain paths or fracture phenomena. Chakrabarty and Chen (2005) and Yoshida et al. (2007) and Nurcheshmeh and Green (2011) studied the effect of changing strain paths on the forming limit curves (FLC) and forming limit stress curves (FLSC) of sheet metals using phenomenological plasticity models. They showed that a nonlinear loading path will significantly affect the FLC's functionality.

Some researchers tried to find the relations between material parameters and FLCs to decrease the uncertainty of the FLCs. Bleck et al. (1998) studied three kinds of theoretical forming limit curves in the forming of (IF) steels. They concluded that the forming limit diagram is affected by the thickness of the blank, the yield and tensile strength, the strain hardening and the strain-rate sensitivity. Boudeau and Gelin (2000) studied some macroscopic and microscopic effects of material parameters on the forming limit curves. They understood that the anisotropy has less effect on the FLCs while strain ratio, $\rho = \varepsilon_{minor}/\varepsilon_{major}$, is negative but it has significant effects when it is positive. Aghaie-Khafri and Mahmudi (2004) proposed an analytical approach for calculation of forming limits in sheets having planar anisotropy. This method can estimate the FLC of the steel materials but it is not suitable for aluminum alloys.

Employing the DFCs to draw effective forming limit curves has attained so much attention lately because they are able to consider nonlinear stress and strain loading histories successfully and since different approaches are employed to draw the curves, most of the time the shortcomings of the conventional FLCs are not an issue after all. To differentiate the conventional FLCs which were drawn by employing the necking instability from the forming limit curves drawn using fracture initiation approach, the latter one is named as forming limit curves at fracture (FLCF). Chen et al. (2010); Han and Kim (2003), Ozturk and Lee (2004) and Takuda et al. (1999) are some of those researchers who studied the application of a DFC and material parameters for the prediction of the forming limit curve at fracture of the sheets. The main goal was to predict fracture initiation time and place by employing a ductile fracture criterion using the finite element methods.

The uncoupled DFCs are used to indicate the initiation of the fracture by physical or phenomenological relations, while the coupled criteria use the concept of nucleation, growth, and coalescence of the cracks until the fracture. What is common to all approaches is that finite

* Corresponding author.
E-mail address: sehram.dizeci@tedu.edu.tr (S.A. Dizaji).
[1] Previously affiliated with Middle East Technical University, Turkey

https://doi.org/10.1016/j.euromechsol.2018.01.003
Received 26 July 2017; Received in revised form 18 December 2017; Accepted 6 January 2018
Available online 12 January 2018

element codes, together with experimental tests, are needed to verify, validate or identify the model parameters (Li et al., 2011). It has been concluded that most of the coupled criteria need more than one experimental test to be calibrated and the implementation method to the numerical analysis is far more difficult than the uncoupled criteria. The same result was also confirmed by Khan and Liu (2012), where they proposed an empirical, phenomenological and uncoupled fracture criterion considering the magnitude of first stress vector and the first invariant of stress tensor for AL materials and by comparisons showed that it performs better than some well-known physics-based coupled criteria.

The uncoupled approaches have gained much interest lately from the industry because of the simplicity in the validation and utilization. Most of these macro-scale approaches use the function $\int_0^{\bar{\varepsilon}_f} f(\sigma, \bar{\varepsilon}) d\bar{\varepsilon}$ somehow to calculate the material energy capacity. Freudenthal (1950) is the first one who implemented the generalized plastic work to estimate the onset of the fracture in the metals. Cockroft and Latham (1968) observed that the maximum tensile stress plays an important role in the ductile fracture and assumed that the fracture takes place where the maximum stress exists. Brozzo et al. (1972) assumed that, in addition to maximum tensile stress, the mean stress (σ_m) has a significant effect on the ductile fracture. Oh et al. (1979) expressed that the main factors affecting the ductile fracture are maximum tensile stress and equivalent stress. Ayada et al. (1984) proposed a model based on the assumption that the ratio of mean stress to equivalent stress ($\sigma_m/\bar{\sigma}$) is the most effective factor in the DFCs.

Most of the above uncoupled criteria, which still are employed extensively, use a single experimental test, usually a uniaxial tension test, to identify the single constant which leads to inaccurate predictions of the fracture points especially for non-linear strain paths. Some of these problems in the conventional DFCs have been spotted by Watanabe et al. (2014) where they tried to overcome these shortcomings by modifying the DFC equation and employing the stress components instead of the equivalent stress value. To overcome the problems originating from utilizing a single test, it was proposed to include the material parameter effects in the general plastic work formula. Han and Kim (2003) showed that for the higher thicknesses, the FLCFs tend to become linear. It is also reported that the maximum shear stress can be combined with the energy function to make the criterion applicable for low ductile materials as well. Sebek et al. (2016) mentioned that strain hardening has significant effects on the uncoupled DFCs and proposed an approach to consider its influences implicitly. Davis (2004) mentioned that the low flow stress to elastic modulus ratio (σ_F/E) will enhance the formability of the sheets, hence moving the FLCF curve upward. Chen et al. (2010) proposed to include material parameter effects and modified the general plastic work function to contain the effect of anisotropy and strain hardening coefficient. Dahli et al. (2016) showed that loading path has significant effects on the fracture prediction using some uncoupled and coupled DFCs and they proposed that loading path parameters be considered in the calibration steps to overcome this path dependency.

In the present work, a robust universal ductile fracture model based on the general plasticity function has been proposed. This DFC can be applied for different materials or forming processes to predict the fracture place and time. The model has been calibrated and validated with experimental tests and can be used for sheet metal forming processes by carrying out a simple uniaxial tensile test. To verify the reliability of the criterion, finite element analyses implementing VUMAT subroutines were conducted and the results have been compared with the ones obtained by existing uncoupled DFCs.

2. Finite element method

The commercial finite element code ABAQUS explicit (Hibbitt and Sorenson, 1998) has been used in order to simulate the forming process of sheet metals. The general purpose, 4-node, quadrilateral S4R shell element with reduced integration was utilized. The Simpson thickness integration method with seven points was employed in the thickness direction. The mesh size for the critical regions where fracture was expected has been taken as $0.25\ mm \times 0.25\ mm$ and the friction coefficients, which had been determined based on the Coulomb law, were used as 0.05 for lubricated regions and 0.13 for dry regions in the simulations. The validity of the friction coefficients was confirmed using punch load diagram comparisons using deep drawing tests. The penalty contact algorithm was utilized to model the interaction between the surfaces. The mass scaling technique was employed to speed up the solution; furthermore, to reduce the dynamic effects, the ratio of the duration of the load to the fundamental natural period of the model has been kept greater than 5, as Kutt et al. (1998) recommended. The updated Lagrangian formulation was chosen to calculate strains and displacements, and the elasto-plastic constitutive model was adopted to model the material behavior throughout the deformation. The subroutine VUMAT was employed to define the hardening rules and desired material constitutive equations. Solution dependent state variables (SDVs) were employed to monitor the preferred output parameters.

3. Experiments

In this study, three tests were carried out to determine, verify or validate the necessary material parameters and empirical formulas. These are uniaxial tension test (UTT) based on ASTM E08, Nakazima test and deep drawing test.

Three materials; SS304, DKP6112 (DIN EN 10130-1999) and AA5450 aluminum alloy, with sheet thicknesses of $1\ mm$, $1\ mm$ and $1.45\ mm$, respectively, were used in the tests and simulations. The deformed specimens that have been obtained by the Nakazima test for DKP 6112 steel and their dimension are shown in Fig. 1. All specimens in the Nakazima test were cut from $\boldsymbol{\phi}\ 90\ mm$ blank and marked by $1.6\ mm$ circles. The specimens were formed at forming speed of $0.05\ mm/\boldsymbol{s}$ and also the combination of Teflon, oil and grease (machine grease between two $0.05\ mm$ thick Teflon sheets and DuPont KRYTOX oil at the outer surfaces of theTeflon sheets) were used as the lubricant to have the fracture point near to the apex. The tool geometries utilized to accomplish the Nakazima and deep drawing tests are given in Table 1. The material parameters which have been obtained using the uniaxial tension tests, are given in Table 2, where $\boldsymbol{E}$ is elastic modulus, $\boldsymbol{K}$ is strength coefficient, $\boldsymbol{\sigma_0}$ is yield stress in the rolling direction, $\boldsymbol{n}$ is hardening index, υ is Poisson's ratio, $\bar{\boldsymbol{r}}$ is normal anisotropy and $\bar{\boldsymbol{\varepsilon}}_{\boldsymbol{f}}$ is the equivalent strain at fracture. In addition, the $\boldsymbol{r}$-values ($\boldsymbol{r} = \boldsymbol{\varepsilon_w}/\boldsymbol{\varepsilon_t}$) and the normalized yield stress values of the three materials in the different directions are presented in Tables 3 and 4.

4. New ductile fracture criterion

In this study, a new uncoupled DFC has been developed and proposed. In the new criterion, the maximum shear stress has been considered in the function to make the criterion applicable and efficient enough for both low and high ductile materials. Moreover, to adopt different strain-path effects, strain ratio has been directly included into the criterion. The newly proposed criterion is in the form of

$$\int_0^{\bar{\varepsilon}_f} \bar{\sigma} d\bar{\varepsilon} = B\left(C_1 + C_2\,|2\rho|^{C_3}\right) + C_4\tau_{max} \tag{1}$$

where the term $\bar{\sigma}d\bar{\varepsilon}$ is the increment of energy, τ_{max} is the maximum shear stress, $\rho = d\varepsilon_2/d\varepsilon_1$ is the strain ratio, $\bar{\varepsilon}_f$ is the equivalent plastic strain at fracture, C_1, C_2, C_3, C_4 and B are the criterion unknowns.

The effect of different parameters on the FLCF can be evaluated from several data extracted from the previous research (Chen et al., 2010; Ozturk and Lee, 2004; Han and Kim, 2003; Takuda et al., 1999)