A novel uncoupled ductile fracture criterion for prediction of failure in sheet metal forming

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Abstract. The ductile fracture behavior of anisotropic materials was modeled by the uncoupled ductile fracture criterion. The ductile fracture model was concerned with the micro mechanisms of void nucleation, void growth, and evolution of void coalescence. The advance plastic model of Hill’48 non-associated flow rule is considered in proposed ductile fracture criterion. A series of basic fracture testing covering a wide range of stress state for aluminum alloy 6016-AC200 are carried out. Strain field on the surface of specimens is captured by the non-contact measurement DIC system. The fracture locus constructed using the proposed criterion is close to the experimental data points over a wide stress triaxiality range from negative to intermediate and high stress triaxiality. Then, a square cup drawing test is conducted in order to verify efficiency of the proposed fracture criterion in predicting fracture behavior of metal sheet. The results indicate that the proposed ductile fracture criterion can be utilized for predicting initial fracture in sheet metal forming.

1. Introduction

Generally, the necking is the initial failure mode in sheet metal forming processes, which is commonly predicted by conventional Forming Limit Diagram (FLD) firstly introduced by Keeler and Backofen [1] and extended by Goodwin [2]. The FLD methods mainly describes the prediction of the failure of tension stress states in sheet metal forming. However, the shear fracture, which is observed both tension, shear and compression loading states with negligibly thickness reduction, cannot be explained by FLD.

Ductile fracture of metals is commonly induced by the micro-mechanism of the void nucleation, the void growth, and the coalescence of voids finally resulting in a macroscopic crack. Gurson [3] proposed a strain-controlled nucleation model to show that the rate of void nucleation is a function of the equivalent plastic strain. Rice and Tracey [4] suggested that the stress triaxiality is the key parameter that controls the void growth. The voids nucleation and coalescence of voids were later taken into study by Chu and Needleman [5]. Besides, fundamental work by Xue [6] confirmed that the Lode angle parameter and the stress triaxiality have essential influence on the initiation of ductile fracture.

Aluminum sheets are well known to develop considerable plastic anisotropy on the mechanical properties due to the extrusion and rolling processes. The anisotropy properties have strong effect on the fracture initiation in several manufacturing processes especially in automotive industry. The prediction of anisotropic ductile fracture of metals is critical for the design of lightweight structure. Although there are a lot of efforts in prediction of anisotropic fracture initiation in sheet metal forming, these works still remain a significant issue for automotive industry to produce car parts. Recently, Stoughton and Yoon [7] and Park and Chung [8] proved the flexibility of non-associated flow rule in modeling metal sheet forming applications. In this research, the prediction initiation of anisotropic ductile fracture with Hill’48 [9] non-associated flow rule has been investigated. Hill’48 non-associated flow rule coefficients are identified by...
series of uniaxial tension and bugle test. The ductile fracture parameters are calculated by essential fracture
tests such as in plane shear tension, central hole tension, plane strain tension for AA6016-AC200. The strain
field on the surface of specimens are carried out under non-contact measurement method of digital image
correlation (DIC) method. The anisotropic ductile fracture criterion is implemented into a VUMAT
subroutine to simulate and predict the anisotropic initiation ductile fracture behaviors in a square cup
drawing for AA6016-AC200.

2. Anisotropic ductile fracture criterion

2.1 Advanced plastic constitutive model

In the present study, the anisotropic Hill’48 function was adopted to describe the yield model and
plastic flow. The Hill’48 yield function is defined as

$$\tilde{\sigma}_H = \sqrt{F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2}$$  \hspace{1cm} (1)

Where $F$, $G$, $H$, $L$, $M$, and $N$ are anisotropic coefficients and $x$, $y$ and $z$ are orthogonal principal
anisotropic axes materially embedded along the rolling, transverse and thickness directions. Several dog-
bone specimens were cut from the sheet along 0°, 45°, and 90° with respect to the rolling direction to
identify the Lankford r-value and the yield stress at three directions. Besides, a bugle test were prepared
to determine the biaxial yield stress. The Lankford r-values were utilized to calibrate the Hill’48 plastic
potential function parameters, and the different yield stress were well known to calibrate the Hill’48 yield
function parameters. It is notes that $F$, $G$, $H$, and $N$ are constants and identified by above experiments, and
$L$ and $M$ are assumed as 1.5 in this research. The Hill’48 non associated flow rule coefficients are
presented in table 1.

| Table 1. The Hill’48 anisotropy coefficients of AA6016-AC200 |
|-------------------------------------------------------------|
| AA6016-AC200     | F   | G   | H   | N   | L | M |
| Hill’48-r        | 0.6593 | 0.5780 | 0.4219 | 1.1754 | 1.5 | 1.5 |
| Hill’48-s        | 0.5421 | 0.4843 | 0.5157 | 1.6353 | 1.5 | 1.5 |

The strain hardening behavior of aluminum 6016-AC200 is determined from uniaxial tension results. The
stress-strain relation is modeled by Kim-Tuan hardening equation [10] as:

$$\sigma = \sigma_0 + K(\varepsilon + \varepsilon_0)^h(1 - \exp^{-t\varepsilon})$$  \hspace{1cm} (2)

Where $\sigma$ represent the equivalent stress, $\sigma_0$ denotes the initial yield stress, $K$ denotes a material constant to
control the expansion of hardening stress, $t$ and $h$ denotes parameters of the hardening model, $\varepsilon_0$ denotes
the initiation of plastic deformation, and $\varepsilon_0=0.002$. The flow stress of material was combined by the
uniaxial tensile test and the hydraulic bugle test and fitted by the Eq. 2. Table 2 introduced the hardening
parameter of AA6016-AC200

| Table 2. The hardening parameters of AA6016-AC200 |
|--------------------------------------------------|
| $\sigma_0$       | $\varepsilon_0$ | $K$     | $t$     | $h$     |
| 123.700          | 0.002           | 267.316 | 0.2897  | 28.926  |
2.2 Ductile fracture criterion

Ductile fracture behavior is a well-known important property of metal that leads to crack in metal parts. Microscopically, such failure due to micro mechanism of void nucleation, void growth and coalescence of void under moderate and high stress triaxiality or shear band movement under low stress triaxiality. Macroscopically, failure is associated as the progressive degradation of metals. Under larger plastic deformation the metal show a decrease in material stiffness and strength. In this investigation, a phenomenon logical uncoupled ductile fracture is proposed for predicting the onset of ductile fracture. In efforts to predict the anisotropic ductile fracture behaviors, an extend of ductile fracture criterion of Quach et al [11] work for anisotropic material is introduced as

$$\bar{\varepsilon}_f = \frac{C_1}{\left( \eta + \frac{3 - \mu}{3 \sqrt{\mu^2 + 3}} + \frac{1}{\sqrt{\mu^2 + 3}} \right) \left( \frac{3 + \sqrt{3} C_3}{\sqrt{\mu^2 + 3}} - C_3 \right)}$$

Where

$$\eta = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3 \sqrt{F (\sigma_{yy} - \sigma_{zz})^2 + G (\sigma_{zz} - \sigma_{xx})^2 + H (\sigma_{xx} - \sigma_{yy})^2 + 2 L \tau_{yz}^2 + 2 M \tau_{zx}^2 + 2 N \tau_{xy}^2}}$$

$$\mu = \frac{2 \sigma_{yy} - \sigma_{xx} - \sigma_{zz}}{\sigma_{xx} - \sigma_{zz}} \quad -1 \leq \mu \leq 1, \text{with } \sigma_{xx} \geq \sigma_{yy} \geq \sigma_{zz}$$

$$d\bar{\varepsilon}^p = \sqrt{\frac{2}{3}} d\bar{\varepsilon}^p; d\bar{\varepsilon}^p$$ is equivalent plastic strain increment, $$\bar{\varepsilon}_f$$ is equivalent plastic strain at the failure, $$\eta$$ is stress triaxiality, $$\mu$$ is Lode stress parameter; $$C_1, C_2$$ and $$C_3$$ is material parameter which are calibrated from fracture experiments testing. Three parameters of ductile fracture criterion for anisotropic fracture model are calibrated by fracture strain from the in-plane shear, central hole and plane strain tension tests. These experimental test are selected to cover wide range of stress triaxiality and Lode parameter for sheet metal forming.

To account for non-proportional loading conditions, a linear incremental relationship is utilized between the damage indicator D and the equivalent plastic strain to fracture as

$$D(\bar{\varepsilon}^p) = \int_0^{\bar{\varepsilon}_f} \frac{d\bar{\varepsilon}^p}{\bar{\varepsilon}_f(\eta, \mu)}$$

When the damage indicator is reached ($$D(\bar{\varepsilon}^p) = 1$$) the material element is considered to fail and delete. The average value of stress state parameters ($$\eta, \mu$$) are calculated by

$$\eta_{av} = \frac{1}{\bar{\varepsilon}_f} \int_0^{\bar{\varepsilon}_f} \eta(\bar{\varepsilon}) d\bar{\varepsilon}^p$$

$$\mu_{av} = \frac{1}{\bar{\varepsilon}_f} \int_0^{\bar{\varepsilon}_f} \mu(\bar{\varepsilon}) d\bar{\varepsilon}^p$$

3. Calibration of the anisotropic ductile fracture model

A hybrid experimental and numerical method was applied to calibrate the fracture model. The force-displacement curves were extracted from each simulation and compared with the experimental measurements. To identify the material parameter of the proposed ductile fracture criterion, the equivalent plastic strain until fracture was measured by conducting experiments with at three different specimens,
namely, in plane-shear tension, central hole tension (CH), and plane strain tension (PS). The fracture parameters obtained are summarized in Table 3. Figure 1 and 2 respectively exhibit the fracture surface and fracture locus predicted by proposed ductile fracture at the rolling direction for AA6016-AC200.

| Table 3. Fracture parameter of proposed fracture criterion |
|---------------------------------|----------------|----------------|
| AA6016-AC200                    | $C_1$          | $C_2$          | $C_3$          |
|---------------------------------|----------------|----------------|----------------|
|                                 | 1.9328         | 1.8262         | 3.5241         |

The element contained the maximum equivalent plastic strain (PEEQ) of CH and PS are located in the central of the specimen, while its element of the in-plane shear tension stays on the surface of the specimen that can be explained by the in-plane shear tension is close to the pure shear condition where the thickness reduction behavior can be assumed to ignore. It is highlighted that the evolution of stress triaxiality and the Lode parameter moves away from the ideal-pure shear position ($\eta = 0$ and $L=0$). The reason can be seen from the shear specimen geometry. The in-plane shear tension contains both the pure shear, tension, and compression mode. Since the stress triaxiality and the Lode parameter have a tendency to move further away from the zero point. The fracture strain at the equi-biaxial mode was obtained from the bugle test by ARAMIS system.

4. Validation of anisotropic ductile fracture criterion

To verify the accuracy of proposed ductile fracture criterion, all the fracture experiment tests described above were conducted to predict the onset of fracture behavior. The proposed fracture criterion was implemented in ABAQUS/Explicit by using the VUMAT subroutine. Figures 3(a)–(c) show a comparison of the force-displacement results obtained in FEM simulations and the experimental results obtained with the in-plane shear, central hole, and plane strain tension.
Figure 3. Comparison of load-displacement curves: (a) in plane-shear, (b) central hole, (c) plane strain.
A cup drawing test was performed to evaluate the accuracy of the proposed ductile fracture criterion. As above discussions, the FLD remains a limitation in predicting failure of metal under shear effects, while the ductile fracture criterion can capture a large range of stress state in sheet metal forming. Since, the anisotropic ductile fracture criterion was chosen to predict the fracture behavior of square cup drawing test for AA6016-AC200 in this study.

Square plates (100 mm × 100 mm) were cut from the same metal sheet of Al6016-AC200 for testing. Figure 4 and figure 5 depict schematic of the experimental setup and fracture shape of square cup drawing specimen, which consisted of a cup square punch with a width of 50 mm and an edge radius of 5 mm, and a die with a width of 54 mm and an edge radius of 5 mm. The sheet was arranged along its rolling direction in the coordinate system of the punch. During the entire experimental operation, a constant blank holding force (BHF) of 40 ton was applied on the aluminum sheet metal, while the punch moved upward and drew the blank sheet.

The FE simulation of the cup-drawing test was performed in the ABAQUS/Explicit environment. Because of the symmetric load and geometry, a quarter of the square cup geometry of the specimens was simulated to reduce simulation time. Solid C3D8R elements with reduced integration, available from the ABAQUS element library, were used in the simulation. The element size in the fracture zone was set to 0.2 mm and a friction coefficient of 0.15 is generally used in the simulations. Notably, Hill’48 non-associated flow rule was adopted to introduce both effect of the Lankford r-values and the yield stresses. The force-displacement and fracture shape of square cup drawing simulation result are shown in figure 6 and figure 7 respectively.
The comparison of the experimental and simulated force-strokes in the cup drawing test showed that the proposed ductile fracture criterion captured well the prediction of anisotropic fracture initiation.

5. Conclusion
An extension of new ductile fracture for anisotropic material is developed in considering effect of anisotropy property for sheet metal forming applications. The proposed ductile fracture criterion showed a good performance in predicting fracture behavior in both standard fracture test and square cup drawing test. By incorporating effect of r-value and the yield stresses in Hill’48 non-associated flow rule in proposed ductile fracture criterion, it is clearly that the proposed fracture model has capability to predict the fracture behavior of the anisotropy material in sheet metal forming.

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