Numerical Prediction of Failure in Single Point Incremental Forming Using a New Yield Criterion for Sheet Metal

H. Quach, X. Xiao, J. J. Kim, and Y. S. Kim

Abstract A new yield function depends on the second stress invariant J2 and the third stress invariant J3 is proposed to describe the elastoplastic behavior of sheet metals. Additionally, a series of basic fracture testing covering a wide range of stress state and different material orientations for aluminum alloy is carried out. The ductile fracture of the aluminum alloy is investigated using a hybrid experimental–numerical approach. Besides, a new uncoupled ductile fracture that is concerned with the micro-mechanisms of voids is introduced to predict the failure of material. The new yield criterion and fracture model are implemented into the ABAQUS/Explicit code to predict the fracture in different stress states. The incremental sheet-forming tests are performed to verify the efficiency of the proposed yield criterion and fracture criterion. The proposed yield criterion and fracture model can be utilized for predicting plastic deformation and initial fracture in sheet metal forming.

Introduction

Incremental sheet forming (ISF) is a flexible sheet-forming process that has gained significant interest since the pioneering work of Iseki et al. [1]. ISF is a highly localized deformation process in which a tool is programmed to move along to a certain path to create the desired part geometry. A simple incremental sheet-forming process to manufacture a truncated cone is depicted in Fig. 1 [2]. Without complex tools and dies, the process can form various part geometries directly from computer-aided design models and computer numerical control codes. The process has great potential for rapid parts prototyping requiring small quantities.

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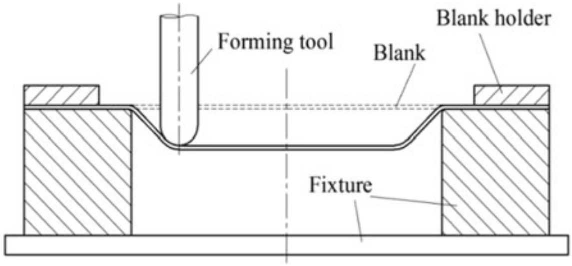

Fig. 1 Single point incremental forming for truncated cone

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 plastic deformation and the fracture initiation in several manufacturing processes especially in automotive industry. The prediction of anisotropic plastic deformation of metals is critical for the design of lightweight structure. Although there are a lot of efforts in prediction of anisotropic plastic deformation and fracture initiation in sheet metal forming, these works still remain significant issues. In this paper, a new yield function named Kim-Van equation describes the elastoplastic behavior of sheet metals. This yield function depends not only on the second stress invariant J2 for the yield but also on the third stress invariant J3, both may effect on the shape of the yield surface. The extension of this criterion is developed using generalized invariants of the stress deviator for anisotropy. The proposed yield function greatly enhances the flexibility of describing the strong anisotropic materials. Besides, a uncoupled ductile fracture which is concerned with the micro-mechanisms of void nucleation, void growth, and evolution of void coalescence is used to predict the failure of material. These two models are implemented into Abaqus/Explicit using a user subroutine to predict fracture in ISF. Compared with the experiment results, the proposed yield criterion and ductile fracture criterion can be utilized for predicting plastic deformation and initial fracture in single point incremental sheet metal forming.

Anisotropic Yield Function

Kim-Van Yield Function

In the present study, the proposed yield function represents a symmetric yield function, which is applied to materials such as aluminum and steel, and it is expressed as follows:

$$f \equiv J_2^6 + \alpha J_3^4 + \beta(J_2^3 \times J_3^2) = \mathrm{k}^{12} \tag{1}$$

where J_2 and J_3 are the invariants discussed in the introduction, k denotes the yield stress in pure shear, and α and β_j are material constants.

Anisotropic generalizations of the second and third invariants are expressed as follows:

$$J_2^0 = \frac{a_1}{6}(\sigma_{xx} - \sigma_{yy})^2 + \frac{a_2}{6}(\sigma_{yy} - \sigma_{zz})^2 + \frac{a_3}{6}(\sigma_{xx} - \sigma_{zz})^2 + a_4\sigma_{xy}^2 + a_5\sigma_{xz}^2 + a_6\sigma_{yz}^2 \tag{2}$$

$$\begin{aligned} J_3^0 = {} & \frac{1}{27}(b_1 + b_2)\sigma_{xx}^3 + \frac{1}{27}(b_3 + b_4)\sigma_{yy}^3 + \frac{1}{27}[2(b_1 + b_4) - b_2 - b_3]\sigma_{zz}^3 \\ & - \frac{1}{9}\left(b_1\sigma_{yy} + b_2\sigma_{zz}\right)\sigma_{xx}^2 - \frac{1}{9}(b_3\sigma_{zz} + b_4\sigma_{xx})\sigma_{yy}^2 \\ & - \frac{1}{9}\left[(b_1 - b_2 + b_4)\sigma_{xx} + (b_1 - b_3 + b_4)\sigma_{yy}\right]\sigma_{zz}^2 + \frac{2}{9}(b_1 + b_4)\sigma_{xx}\sigma_{yy}\sigma_{zz} \\ & - \frac{\sigma_{xz}^2}{3}\left[2b_9\sigma_{yy} - b_8\sigma_{zz} - (2b_9 - b_8)\sigma_{xx}\right] \\ & - \frac{\sigma_{xy}^2}{3}\left[2b_{10}\sigma_{zz} - b_5\sigma_{yy} - (2b_{10} - b_5)\sigma_{xx}\right] \\ & - \frac{\sigma_{yz}^2}{3}\left[2b_7\sigma_{xx} - b_6\sigma_{yy} - (2b_7 - b_6)\sigma_{zz}\right] + 2b_{11}\sigma_{xy}\sigma_{xz}\sigma_{yz} \end{aligned} \tag{3}$$

In the above expressions, a_i (i = 1…6) and b_j (j = 1…11) are coefficients that describe anisotropy. If $a_i = b_j = 1$, it becomes isotropic yield functions.

Calibrate Plastic Model

The strain hardening behavior of aluminum 5052-H32 (AA5052-H32) is determined from uniaxial tension results at rolling direction (Fig. 2). The stress–strain relation is modeled by Kim-Tuan hardening equation [3] as follows:

$$\sigma = \sigma_0 + K(\varepsilon + \varepsilon_0)^h\left(1 - \exp^{-t\varepsilon}\right) \tag{4}$$

where σ represents the equivalent stress, σ_0 denotes the initial yield stress, K denotes a material constant to control the expansion of hardening stress, t and h denote parameters of the hardening model, ε_0 denotes the initiation of plastic deformation, and $\varepsilon_0 = 0.002$.

Several dog-bone specimens were cut from the sheet along 0°, 15°, 30°, 45°, 60°, 75°, and 90° with respect to the rolling direction to identify the Lankford r-value and the yield stress at these directions. Besides, the cruciform specimens were prepared

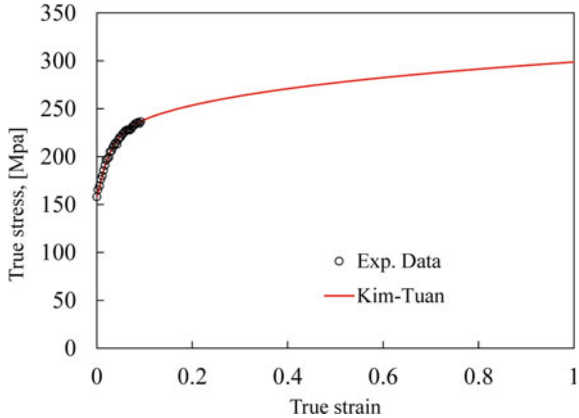

Fig. 2 Stress–strain curve fitted by Kim-Tuan hardening equation

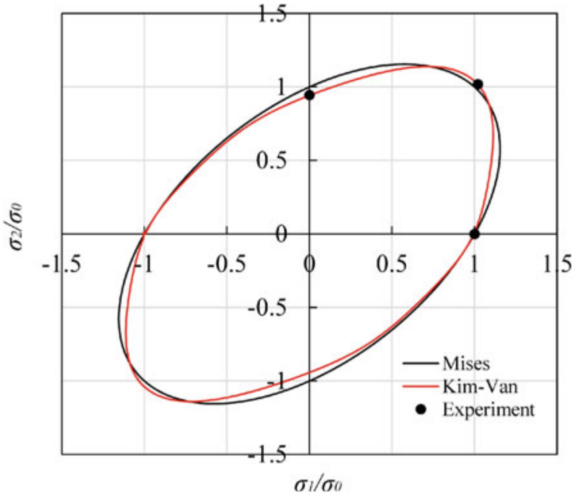

Fig. 3 Yield locus fitted by Kim-Van yield function for aluminum alloy 5052-H32

to determine the biaxial yield stress. The Lankford r-values and yield stress were utilized to calibrate the Kim-Van yield function as shown in Fig. 3.

Ductile Fracture in ISF

Single point incremental sheet forming has some limitations and encounters the challenges in application of some lightweight alloys, especially for failure and fracture during forming the desired geometric components. As a microscopic crack, ductile fracture occurs with damage accumulation and the material softening after large plastic deformation stage, including the nucleation of voids, the growth of voids and eventually the coalescence of voids. So the study for prediction initiation and propagation of failure and fracture in SPIF is necessary and promising. Because the prediction of failure and fracture in SPIF can reveal the deformation mechanics and failure evolution, and provide some reference for practical SPIF process. Mirnia et al. [4] have incorporated ductile fracture models into SPIF to simulate damage accumulation and propagation of fracture. It is noted that the fracture forming limit diagram (FFLD) in SPIF is different in shape and value from conventional forming process and other findings. Li et al. [5] utilized the Gurson–Tvergaard–Needleman (GTN) damage model in order to analyze the fracture prediction in ISF. Jin et al. [6] combined the Lemaitre damage model into a modified constitutive model and implemented the model to FE simulations of ISF.

In efforts to predict the anisotropic ductile fracture behaviors in ISF, an extent of ductile fracture criterion of Quach et al. [7] work for anisotropic material is introduced as

$$\overline{\varepsilon}_f = \frac{C_1}{\left(\eta + \frac{3-\mu}{3*\sqrt{\mu^2+3}} + \frac{1}{\sqrt{\mu^2+3}}\right)^{C_2}\left(\frac{3+\sqrt{3}C_3}{\sqrt{\mu^2+3}} - C_3\right)} \tag{5}$$

where

$$\eta = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3 * \tilde{\sigma}} \tag{6}$$

$$\mu = \frac{2\sigma_{yy} - \sigma_{xx} - \sigma_{zz}}{\sigma_{xx} - \sigma_{zz}} - 1 \le \mu \le 1, with\ \sigma_{xx} \ge \sigma_{yy} \ge \sigma_{zz} \tag{7}$$

$\overline{\varepsilon}_f^p$ is equivalent plastic strain at the failure; η is stress triaxiality; μ is Lode stress parameter; C_1, C_2, *and* C_3 are material parameters which are calibrated from fracture experiments testing. $\tilde{\sigma}$ is effective stress presented by Kim-Van yield function.

ISF Experiments

In the ISF experiments, an AA5052 specimen with a size of 130 mm × 130 mm was cut to be formed using CNC machine as shown in Fig. 4. Two types of incremental sheet-forming test with pyramid and varying wall-angle conical frustums (VWACF) specimens are performed in order to verify the efficiency of the proposed yield criterion and fracture criterion in predicting fracture behavior (Fig. 5).

In these tests, forming angle of the pyramid model is 70°, and for VWACF model, the forming angle is from 40° to 90°. While the forming parameter is shown in Table 1. And in each cases, liquid lubricant was used. After fracture happened, record the final forming depth. The results of each experiments are shown in Fig. 6a, b.

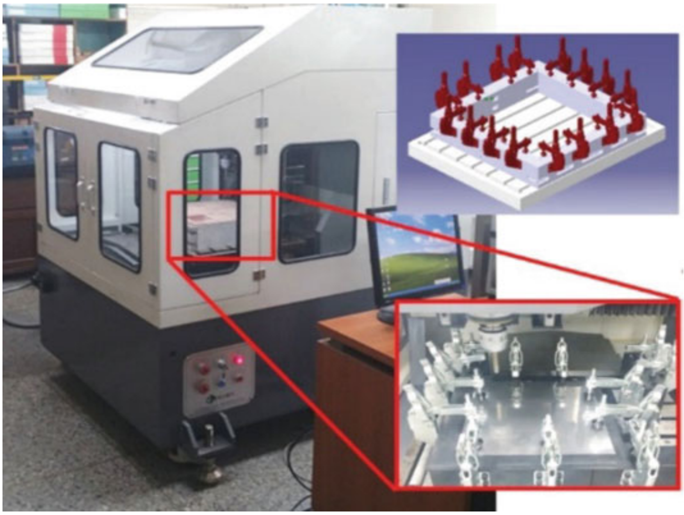

Fig. 4 The CNC machine used in this study

Fig. 5 The shape of pyramid model (**a**) and VWAFC model (**b**)

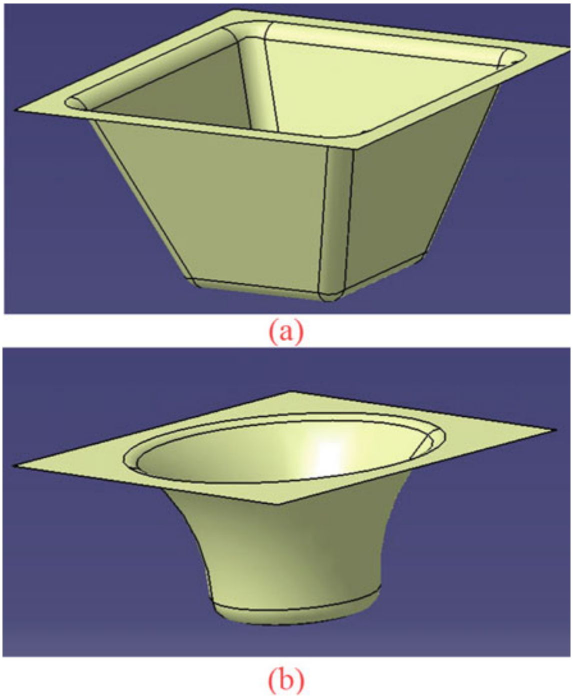

Table 1 Forming parameter in ISF experiment

Parameter	Tool diameter (mm)	Step depth (mm)	Feed rate (mm/min)
Value	10	0.5	500

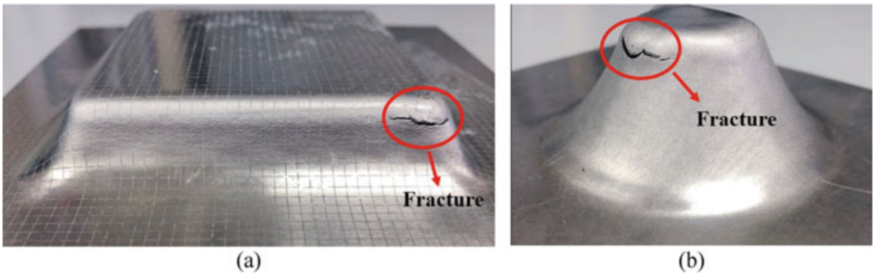

Fig. 6 Forming result of **a** pyramid model and **b** VWAFC model

Conclusion

A new anisotropic yield function and an extended ductile fracture for anisotropic material are utilized in considering effect of anisotropy property for incremental sheet metal forming applications. The yield locus constructed by Kim-Van yield function fitted well with experimental data. The proposed yield function greatly enhances the flexibility of describing the strong anisotropic effect in metal sheet.

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