

A Comprehensive Plasticity and Fracture Model for Metal Sheets under Multi-Axial Stress and Non-Linear Strain Path

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ABSTRACT

A comprehensive plasticity and fracture model was built for metal sheets with application to metal sheet forming and vehicle crash simulations. The combined Bai-Wierzbicki (BW [1]) and CPB06ex2 [2] (or Yld2000-2D [3]) anisotropic plasticity model was further extended to consider elevated temperature effects in addition to the effect of multiaxial stress states. A fully modularized framework was established to combine isotropic, kinematic, and cross hardening behaviors under non-linear loading conditions. The all strain based modified Mohr-Coulomb (eMMC) fracture model was used to consider material anisotropy and nonlinear strain path. The model has been implemented into Abaqus/Explicit as a user material subroutine (VUMAT). Test results on advanced high strength steels, aluminum alloy sheets and magnesium alloy sheets are used to validate the modeling and testing methodologies. Very good correlation was observed between experimental and simulation results.

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1. INTRODUCTION

Sheet metal forming is an essential part of automobile industry because it allows for manufacturing high quality products with complex geometry with low costs. Recently, more and more lightweight materials like high strength steels or nonferrous metallic alloys (aluminum or magnesium) are adopted due to the urgent need to reduce vehicle weight and increase fuel efficiency and performance. However, these material are relative brittle and vulnerable to fracture during forming or subsequent services (i.e. vehicle crash impact). It is necessary to have an adequate plasticity and fracture model to precisely predict the final stamped shape without producing strains that exceeds the forming limit during metal forming. Many mechanical tests have revealed and proven that the material ductility is highly dependent on stress states, which can be described by both stress triaxiality and the Lode angle parameter [1,4]. The Modified-Mohr-Coulomb (MMC) fracture model can successfully capture this dependency and predict the fracture locus using the stress state parameters [4]. With the anisotropic effect in sheet metal fracture behavior, the relationship between stress state and fracture strain is usually difficult to be fully determined without a good plasticity model. The objectives of this paper are to, a) develop and apply constitutive model sets for high strength steel, aluminum alloy sheets and magnesium alloy sheets, covering both monotonic and non-proportional loading conditions, b) conduct a sufficient set of

experiments under non-linear strain path, including both reversal and two-stage cross-loading condition, c) describe the anisotropic fracture properties by decoupling it from plasticity and transfer the MMC into an all strain based space under the assumption of proportional loading and Mises-Levy flow rule, d) develop and apply constitutive model under high temperature for aluminum alloys. The experimental results of three materials, TRIP780 steel sheets, aluminum 7075-T6 alloy sheets, and magnesium AZ31B-H24 alloy sheets, are used to the proposed modeling and testing methodologies.

2. CONSTITUTIVE MODELING

Different types of metal sheets need different constitutive models. Magnesium alloy is the most complex material among three studied metal sheets, so it is used here as a main example material to describe the material constitutive model. A de-twinning phenomenon occurs under compression-tension reversal loading when the subsequent tensile load is performed along the c-axis of the twinned areas, generating an unusual concave shape in the tensile stress-strain curve [5, 6, 7]. Very strong anisotropic effects have been observed. The CPB06ex2 anisotropic yield criterion was calibrated for magnesium AZ31B-H24 with extension of BW model for different stress states, which could

concurrently fulfill a) different material strengths and plastic flows along different orientations, and b) the asymmetric yield strength between tension and compression, based on the work from [8-9].

2.1 Modified Sachs Hardening Model

For magnesium AZ31B-H24 sheets, the CPB06ex2 [2] model (Appendix A.1) was used to describe the shape of anisotropic yield locus and anisotropic plastic flow under monotonic loadings. The modified semi-analytical Sachs model [9] is further improved to incorporate the kinematic hardening behavior, using the state variables. The kinematic term in the hardening model can be represented as

$$\bar{\sigma}_K = \text{sign}(\dot{\mu}) \left[(A_{K1}\mu - A_{K2}\varepsilon_C)(\bar{\varepsilon}^p + \varepsilon_0 - \varepsilon_C)^n + X_K \sqrt{\|\alpha^{dev}\|} \right] \quad (1)$$

Here, μ is the ad-hoc de-twinning state variable, evolves from 1 (no de-twinning) to 0 (de-twinning finished). ε_C is the compressive strain in previous loading history. A_{K1} and A_{K2} are material coefficients. X_K is the loading history state variable identifying the transition area, reads,

$$X_K = \frac{1 - \frac{\sigma:\alpha}{\|\sigma\|\|\alpha\|}}{2}$$

α^{dev} is the deviatoric part of the “dummy” back stress. The involvement of parameter X_K is to describe the loading history effect without explicitly incorporating the back stress, separating the isotropic and kinematic hardening behaviors. The main item responsible for the isotropic hardening is defined as, based on the modified Sachs hardening model in [9],

$$\bar{\sigma}_{NewSachs} = A_1(1 - \chi)X_T + [A_2\chi X_T + A_3(1 - X_T)](\bar{\varepsilon}^p + \varepsilon_0 - h\varepsilon_B)^n,$$

where χ indicates the fraction of the to-be-twinning grains that have already twinned, ranges from 0 to 1. This empirical state variable is specifically applied for describing the twinning behavior. It is defined as follows,

$$\chi = 1 - \exp \left[-4 \left(\frac{\bar{\varepsilon}^p - h\varepsilon_B}{\varepsilon_1} \right)^a \right].$$

X_T is the fraction of grains expected to be twinned. ε_B is the historical accumulated plastic strain from the previous loading transitions, excluding the de-twinning process. h is an additional material coefficient attached to ε_B to control the isotropic hardening. A_1 , A_2 , and A_3 are simplified material coefficients. The kinematic hardening behavior during cross loading can be further compensated by an additional item $\bar{\sigma}_C$, defined as

$$\bar{\sigma}_C = -X_C \lambda \sqrt{\alpha^{dev}:\alpha^{dev}},$$

Here, X_C is the key state variable governing the smoothness in transition during cross loading,

$$X_C = 1 - \left| \frac{\sigma:\alpha}{\|\sigma\|\|\alpha\|} \right|.$$

λ is an exponential material coefficient. Conclusively, the final constitutive model for magnesium AZ31B-H24 can be obtained by summing the isotropic, kinematic, and cross item together, as follows

$$\bar{\sigma} = (\bar{\sigma}_{NewSachs} + \bar{\sigma}_K + \bar{\sigma}_C)f_{ext}(\eta, \bar{\theta})$$

2.2 Multiaxial Stress States Considered by Bai-Wierzbicki (BW) Plasticity Model

Considering the effect of multi-axial stress states in magnesium sheets, the dependency of stress triaxiality (η) and I_{m+1}^{dev} angle (θ) was also introduced through a correction item [10, 11] ($\frac{\gamma}{m}$, for the purpose of obtaining a smoother yield locus) based on [1]

$$f_{ext}(\eta, \bar{\theta}) = \left[1 - c_\eta(\eta - \eta_0)^2 \right] \left[c_\theta^s - \frac{m+1}{m}(c_\theta^{ax} - c_\theta^s) \left(\gamma - \frac{\gamma^{m+1}}{m+1} \right) \right]$$

where

$$c_\theta^{ax} = \begin{cases} c_\theta^t & \bar{\theta} \geq 0 \\ c_\theta^c & \bar{\theta} < 0 \end{cases}.$$

Here c_η , η_0 , c_θ^s , c_θ^t , c_θ^c , and m are material coefficients. γ is defined as

$$\gamma = \frac{\sqrt{3}}{2 - \sqrt{3}} \left[\sec \left(\frac{\bar{\theta}\pi}{6} \right) - 1 \right]$$

where $\bar{\theta}$ is the normalized Lode angle parameter. It is expressed, under plane stress condition, as follows,

$$\bar{\theta} = 1 - \frac{2}{\pi} \arccos \left[-\frac{27}{2} \eta \left(\eta^2 - \frac{1}{3} \right) \right]$$

The material parameters were optimized to simultaneously correlate with the tested equivalent stress-strain curves under different monotonic loading conditions.

2.3 A Combination of Power Hardening and Linear Hardening for aluminum alloy at elevated temperature

For aluminum 7075-T6 sheets, the Yld2000-2D [3] model (Appendix A.2) was used to describe the shape of anisotropic yield locus and anisotropic plastic flow under monotonic loadings. In order to study the hardening behavior of aluminum alloy sheets under both room temperature and elevated temperatures, a combination of power hardening and linear hardening law is proposed, which is different from magnesium alloy.

$$\bar{\sigma}_c = Se(\varepsilon_p)K(\varepsilon_0 + \varepsilon_p)^n + (1 - Se(\varepsilon_p))(A + B\varepsilon_p) \quad (12)$$

$$Se(\varepsilon_p) = \frac{1}{e^{S_c(|\varepsilon_p - \varepsilon_d| + \varepsilon_r)}} \quad (13)$$

Here ε_p is plastic strain, K , ε_0 , n , A , B , S_c , ε_d and ε_r are material parameters. The parameter, $Se(\varepsilon_p)$, ranges from 0 to 1. Therefore, the material hardening is a combination of power hardening law and linear hardening law.

To include the thermal softening into the material hardening rule, a coefficient similar to the one in Johnson-Cook model is added.

$$\hat{\sigma} = \bar{\sigma}_c \left(1 - \left(\frac{T - T_{room}}{T_s - T_{room}} \right)^m \right) \quad (14)$$

Here, σ_c is combined hardening. T_{room} is room temperature, T_s is material parameter and T is current temperature. The strain rate effect can be introduced in a similar way, either coupled or decoupled with the temperature effect. This will be covered in the future research.

3. ALL-STRAIN BASED (EMMC) FRACTURE MODELING

Strong anisotropic fracture has been observed in magnesium AZ31B-H24. An eMMC fracture model is applied for this material with linear transformed anisotropic equivalent plastic strain, based on the work from [10]. In this paper, an additional assumption is made to incorporate the twinning/de-twinning effect under nonlinear strain paths as follows. The damage accumulation is temporarily deactivated, between the initialization and 90% completion of de-twinning.

The fracture locus of the original MMC fracture criterion reads

$$\bar{\varepsilon}_f(\eta, \bar{\theta}) = \left\{ \frac{A}{C_2} f_1 f_2 \right\}^{-\frac{1}{n}}$$

where

$$f_1 = \bar{C}_\theta^s + \frac{\sqrt{3}(\bar{C}_\theta^{ax} - \bar{C}_\theta^s)}{2 - \sqrt{3}} \left(\sec \frac{\bar{\theta}\pi}{6} - 1 \right)$$

$$f_2 = \sqrt{\frac{1 + C_1^2}{3}} \cos \frac{\bar{\theta}\pi}{6} + C_1 \left(\eta + \frac{1}{3} \sin \frac{\bar{\theta}\pi}{6} \right)$$

$$C_\theta^{ax} = \begin{cases} 1 & \bar{\theta} \geq 0 \\ \bar{C}_\theta^c & \bar{\theta} < 0 \end{cases}$$

Here, A , n , C_1 , C_2 , $\bar{C}_\theta^s$ and $\bar{C}_\theta^c$ are the model parameters. Please note that those parameters can be non-associated with the ones mentioned in BW plasticity model in the previous section due to the decoupling of plasticity and fracture. This model was transformed into an all-strain based space by involving the stress ratio and the ratio of in-plane principal strain increments. The strain incremental and stress ratio are defined as

$$\alpha = \frac{d\varepsilon_2}{d\varepsilon_1}, \quad \beta = \frac{\sigma_2}{\sigma_1}$$

Assuming the Mises-Levy flow rule, it can be derived that

$$\beta = \frac{2\alpha + 1}{2 + \alpha}$$

Note the relationship between η and β is

$$\eta = \frac{\beta + 1}{3\sqrt{\beta^2 - \beta + 1}}$$

The fracture strain $\bar{\varepsilon}_f$ is hence expressed as a function of strain ratio (α), which can be directly measured by a digital image correlating (DIC) system. However, the strain ratio (α) could not distinguish different loading conditions between tensile dominated and compression dominated loadings. For example, it gives the same values for both equi-biaxial tension and equi-biaxial compression. In this manner, it is necessary to define another plastic strain based parameter to represent the effect of in-plane anisotropy under all the possible loading conditions. Therefore, the parameter Φ is used here and after, defined as

$$\Phi = \text{atan2}(-\dot{\varepsilon}_2^p, \dot{\varepsilon}_1^p) + 90^\circ$$

Where atan2 is the two arguments arctangent function with sign information included. The analogical equation in stress field can be used to calculate the Lode angle [12]. As a matter of fact, Φ denotes the angle to the positive minor strain direction in the forming fracture limit diagram (FFLD) under proportional loading, illustrated in Figure 1. The anisotropic effect is thus measured quantitatively by the angle offset to the specified loadings under the assumption of isotropic J2 plasticity, which are 45° for equi-biaxial tension, 90° for plain strain tension, 116° for uniaxial tension, 135° for pure shear and 153° for uniaxial compression etc..

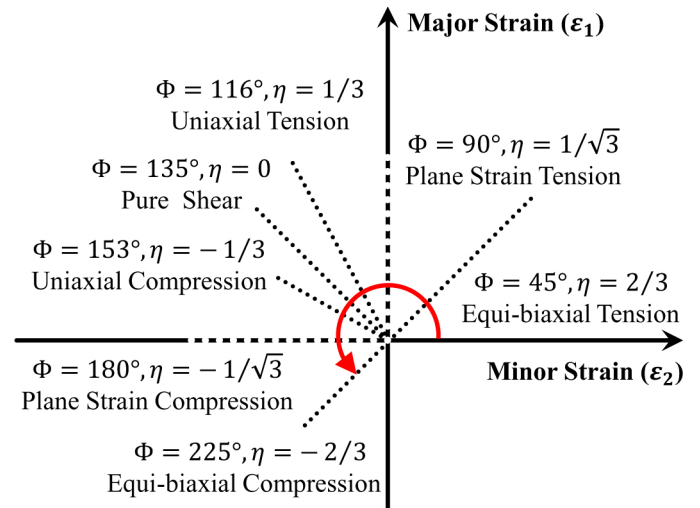


Figure 1. The schematic FFLD describes the definition of Φ under proportional loading. The symbol η means the stress triaxiality.

One big advantage of all-strain based fracture model is that it can be used to study fracture while bypassing plasticity. This model can comprehensively describe multi-axial stress status since all possible loading conditions for sheet metals are covered. It is also assumed to be partially non-associated with the anisotropic plastic criterion. Recalling the definition of Φ under tensile loading condition

$$\Phi = \text{atan2}(-\dot{\varepsilon}_2^p, \dot{\varepsilon}_1^p) + 90^\circ = 2\arctan \frac{-\dot{\varepsilon}_2^p}{\sqrt{(\dot{\varepsilon}_2^p)^2 + (\dot{\varepsilon}_1^p)^2 + \dot{\varepsilon}_1^p}} + 90^\circ$$

$$= 2\arctan \frac{-\alpha}{\sqrt{1 + \alpha^2 + 1}} + 90^\circ$$

The fracture strain $\bar{\varepsilon}_f$ is therefore expressed as a function of Φ only, by Eqs. (15) to (23), which becomes an all-strain based fracture locus. Furthermore, in order to describe the anisotropic fracture