International Journal of Mechanical Sciences 123 (2017) 151–161

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Experimental and numerical studies of AL7020 formability under orthogonal loading paths with considering yield surface distortion

Z.M. Yue[a,*], H. Badreddine[b], K. Saanouni[b], E.S. Perdahcioglu[c]

[a] School of Mechanical and Electrical Engineering, Shandong University at Weihai, China
[b] ICD-LASMIS, University of Technology of Troyes, France
[c] Group of Applied Mechanics, Faculty of Engineering Technology, University of Twente, P. O. Box 217, 7500 AE Enschede, The Netherlands

A R T I C L E I N F O

Keywords:
Ductile damage
Anisotropy
Yield surface
Distortion
Biaxial tension

A B S T R A C T

In metal forming, material points are often subject to complex loading paths even if the applied loading imposed by the forming tools is simple monotonic loading paths. Including the yield surface distortion effect in constitutive equations is expected to highly enhance the capability of the model in simulating the material forming behavior under complex loading paths. In the present work, fully coupled anisotropic constitutive equations with mixed isotropic and kinematic nonlinear hardening strongly coupled with isotropic ductile damage are improved, considering the subsequent yield surfaces distortion. A model based on the framework of non-associative plasticity theory has been developed recently. In this model, a distortion stress tensor $\underline{S}_d$ replaces the usual deviator stress tensor $\underline{S}$ in the yield criterion and dissipation potential. Three parameters X_{l1}^c,X_{l1}^p, and X_{l2} are introduced in the coupled constitutive equations, to be used to control the subsequent yield surfaces distortion. This model is applied and compared with the experiments specifically performed for that purpose. Series of experiments are conducted using the material AL7020 to identify and validate the proposed model. Through the combined loading tests performed on Twente biaxial testing machine, the results of non-proportional loading paths demonstrate that the proposed model can fully represent the forming behavior when complex loading paths. The influence of the yield surface distortion on the plastic flow and on the ductile damage evolution is also discussed in this study.

1. Introduction

Aluminum alloy is widely used to manufacture structural thin components for automotive and aircraft industries. Different kinds of manufacturing techniques, such as extrusion, drawing, rolling and other forming processes have been used to obtain these structural components. During these manufacturing processes, the material is subject to changing complex loading paths leading to extreme directional strains and severe texture evolution. Consequently, the initial anisotropies of the material are modified and the yield surface distortion that induces further anisotropies is observed. These induced anisotropies should be considered and accurately included in constitutive equations, in order to predict, as accurately as possible, the mechanical behavior of aluminum sheets.

During the past decades, modeling the evolution of the subsequent yield surfaces distortion has been the aim of considerable attention. Teodosiu and Hu [20,21] proposed evolving fourth-rank structure tensors to account for the anisotropic hardening induced by yield surface distortion, considering the isotropic and kinematic hardening. These tensors represent the dislocation reorganization under the changing loading paths. The transient work hardening and stagnation behavior after orthogonal loading path changes can be fully represented, but the yield surface is distorted. Peeters et al. [13] developed a crystal plasticity model to describe the induced anisotropy and observed the yield surface distortion phenomena using dislocation interaction. François [7] proposed a new distortional stress tensor replacing the classical stress deviator tensor in the classical elastoplasticity framework and successfully obtained the anisotropy induced by the subsequent yield surface distortion. However, the distortion rate has to be adjusted following the direction of the loading paths. A macroscopic phenomenological model was developed by Vincent et al. [22] to account for the yield surface distortion and was applied to multiaxial loading paths. Feigenbaum and Dafalias [6] also introduced a fourth-rank tensor to account for the distortion of the initially elliptical shape of the yield surface (initial anisotropy of the plastic flow). They derived a complete set of evolution equations based on the fulfillment of the dissipation inequality with which they described successfully the evolution of distortional hardening. Similar works have been conducted

* Corresponding author.
E-mail address: yuezhenming@sdu.edu.cn (Z.M. Yue).

http://dx.doi.org/10.1016/j.ijmecsci.2017.02.010
Received 27 September 2016; Received in revised form 5 February 2017; Accepted 10 February 2017
Available online 12 February 2017
0020-7403/

by Stoughton and Yoon [19] and Noman et al. [12], but using a different fourth-rank tensor to control the yield surface distortion. Their model is based on a thermodynamically-consistent framework and determines the isotropic, kinematic, and directional distortional hardening under small strains with initial anisotropy of Hill48 type. Based on purely geometrical considerations, Barlat et al. [4] used a linear transformation of stress tensor to describe the induced plastic anisotropy. They developed an anisotropic hardening model based on the dislocation interactions and incorporated several microstructural factors that fully describe the anisotropic behavior of mild steel [3].

The experimental investigations on the yield surface distortion focus mostly on the bulk or tube-shaped metals. Since the 1970s, Phillips and Juh-Ling [14] research team conducted many tests using thin-walled aluminum tube and observed the complex form of yield surfaces. Specifically, the yield surfaces showed a blunt nose in the loading direction with flat in the opposite direction (egg shaped surface). A similar form of subsequent yield surface distortion has been obtained by Wu and Yeh [23] and [8,9,10] with the stainless steel materials, annealed-type AISI 304, AL alloys, and several other materials.

Many studies on yield surface distortion have been conducted. However, open problems still exist in this field, including the physical meaning of the new introduced parameters and the mechanical tests required to determine their values. The most observed phenomena on the distortion of subsequent yield surfaces are focused mostly on thin-walled tube specimens under combined tension–torsion machine and are unsuitable for metal sheets.

By contrast, the influence of yield surface distortion including the ductile damage evolution has been rarely discussed. Thus, yield surface distortion for damage prediction throughout the full and strong coupling against plastic flow, hardening, and ductile damage must be considered. In this study, the recently developed fully coupled ductile damage model investigated in Yue [25] is used. This model includes nonlinear isotropic and kinematic hardening strongly coupled with ductile isotropic damage in presence of anisotropic plastic flow under large plastic strain. The forming behavior of AL7020 under orthogonal loading paths is investigated. A series of tests are conducted for the identification and validation purposes, including quasi-linear loading tests and combined loading path tests. The quasi-linear loading tests include uniaxial tensile (UT), pre-notched tensile (PNT), in-plane torsion (IPT), and simple shear (SS) tests. The elastoplastic and damage parameters can be determined in this step. In the second step, AL7020 sheet is loaded under the combined loading paths with Twente biaxial machine, developed by Riel and Boogaard [15], including plane strain tension–shear and pre-shear plane strain tension loading paths. The forming behavior of AL7020 under complex loading conditions is investigated. The predictive capabilities of the proposed model are assessed by comparing the numerically predicted and experimentally obtained responses.

Throughout this paper, the following notations are used: $\underline{T}$ and $\underline{\underline{T}}$ represent second-rank and fourth-rank tensor respectively. $\underline{T}:\underline{T}$ denotes the double contraction inner product and $\underline{T}\otimes\underline{T}$ denotes the classical tensor product. $\underline{\tilde{T}}$ represents the effective tensor which is defined at the fictive undamaged configuration.

2. About the constitutive equations

The elastoplastic constitutive equations strongly coupled with the isotropic ductile damage proposed in [1,17,18] and extended recently in [25,26] to account for the yield surface distortion are used. This model accounts for isotropic hardening, kinematic hardening, distortion-induced hardening fully coupled with isotropic ductile damage. The constitutive equations are developed in a thermodynamically-consistent framework with an additive decomposition of the total strain rates assuming the small elastic strain and defined on the actual deformed and rotated configuration in order to ensure the required objectivity conditions. This model includes the following couples (strain-like and associated stress-like) of state variables:

- $(\underline{\varepsilon}^e, \underline{\sigma})$ represents the elastoplastic flow with $\underline{\varepsilon}^e$ is the small elastic strain tensor, and $\underline{\sigma}$ is the Cauchy stress tensor;
- $(\underline{\alpha}, \underline{X})$ represents the kinematic hardening strain and stress deviatoric tensors respectively, giving the translation of the yield surface center;
- (r, R) represents the isotropic hardening strain and associated stress, depicting the change of yield surface radius;
- (d, Y) represents the isotropic ductile damage in Lemaitre and Chaboche' sense [11]. It should be noted that the damage variable has a values between 0 and 1. The total fracture of the any material point (or RVE: representative volume element) is achieved when $d = d_c = 0.99 \approx 1$.

The strong coupling between the plastic flow with hardenings and the ductile damage, is performed in the framework of the total energy equivalence assumption [16]. This strong coupling strategy leads to the definition of the effective state variables $(\underline{\tilde{\varepsilon}}^e, \underline{\tilde{\sigma}})$, $(\underline{\tilde{\alpha}}\ \underline{\tilde{X}})$ and $(\tilde{r}, \tilde{R})$ which are defined on the deformed fictive (undamaged) configuration by:

$$\underline{\tilde{\varepsilon}}^e = \sqrt{1-d}\,\underline{\varepsilon}^e \quad \text{and} \quad \underline{\tilde{\sigma}} = \frac{\underline{\sigma}}{\sqrt{1-d}} \tag{1}$$

$$\underline{\tilde{\alpha}} = \sqrt{1-d}\,\underline{\alpha} \quad \text{and} \quad \underline{\tilde{X}} = \frac{\underline{X}}{\sqrt{1-d}} \tag{2}$$

$$\tilde{r} = \sqrt{1-d^\gamma}\,r \quad \text{and} \quad \tilde{R} = \frac{R}{\sqrt{1-d^\gamma}} \tag{3}$$

where γ is a parameter governing the ductile damage effect on the isotropic hardening.

To account for the microcracks closure effect on the damage growth under the compressive phase of the applied loading paths, while avoiding any loss of convexity and/or continuity of the state and dissipation potentials [16], the stress tensor $\underline{\sigma}$ is spectrally decomposed into positive and negative parts according to $\underline{\sigma} = \langle\underline{\sigma}\rangle_+ + \langle\underline{\sigma}\rangle_-$ where $\langle\underline{\sigma}\rangle_+ = \sum_{i=1}^{3}\langle\sigma_i\rangle\overrightarrow{E_i}\otimes\overrightarrow{E_i}$, $\langle\underline{\sigma}\rangle_- = \underline{\sigma} - \langle\underline{\sigma}\rangle_+$, σ_i is the ith eigenvalue of the tensor $\underline{\sigma}$ and $\overrightarrow{E_i}$ its associated eigenvector. Accordingly, the first couple of the effective state variables (Eq. (1)) is replaced by the following decomposition:

$$\begin{cases} \underline{\tilde{\varepsilon}}^e = \langle\underline{\tilde{\varepsilon}}^e\rangle_+ + \langle\underline{\tilde{\varepsilon}}^e\rangle_- = \sqrt{1-d}\,\langle\underline{\varepsilon}^e\rangle_+ + \sqrt{1-hd}\,\langle\underline{\varepsilon}^e\rangle_- \\ \underline{\tilde{\sigma}} = \langle\underline{\tilde{\sigma}}\rangle_+ + \langle\underline{\tilde{\sigma}}\rangle_- = \frac{\langle\underline{\sigma}\rangle_+}{\sqrt{1-d}} + \frac{\langle\underline{\sigma}\rangle_-}{\sqrt{1-hd}} \end{cases} \tag{4}$$

where the parameter h is the so called microcracks closure parameter. These effective state variables (Eq. (4)) have to be used in appropriate state potential in order to derive the damage energy release rate as a thermodynamic force associated to the ductile damage $Y = Y_+ + Y_-$ additively decomposed into positive part Y_+ which is active under the positive phase of the loading path, and negative part Y_- active under the negative phase of the loading path. A very comprehensive presentation of the CDM theory under large plastic strain including all the aspects discussed above can be found in the recent monographs [16].

When the effective state variables (Eqs. (2) to (4)) are introduced in the state and dissipation potentials written on the fictive undamaged, deformed and rotated configuration, the state relations as well the evolution equations of the dissipative phenomena can be derived. These are summarized in Table 1.

In the equations of Table 1, λ_e and μ_e are the classical Lamé's constants for the isotropic elasticity; the stress norm $\|\underline{T}\|_M = \sqrt{(3/2)\,\underline{T}^{dev}:\underline{T}^{dev}}$ for any symmetric second-rank stress-like tensor, is nothing but the isotropic von Mises equivalent stress. Any other anisotropic quadratic or non-quadratic stress norms can be used (see [2]). However, in this case the isotropic von Mises equivalent stress is used since the metal sheet is assumed to be isotropic. σ_y is the initial yield stress, C and Q are the hardening