Journal of Manufacturing Processes xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

A mixed hardening model combined with the transformation-induced plasticity effect

Yu HaiYan [a,b,*], Chen Si Ji [a]

[a] School of Automotive Studies, Tongji University, Shanghai 201804, China
[b] Shanghai Key Lab of Vehicle Aerodynamics and Vehicle Thermal Management Systems, China

ARTICLE INFO

Article history:
Received 25 July 2016
Received in revised form 9 December 2016
Accepted 11 December 2016
Available online xxx

Keywords:
Mixed hardening model
TRIP effect
Backstress
Springback simulation
Shear

ABSTRACT

A mixed isotropic–kinematic hardening model considering the transformation-induced plasticity (TRIP) effect was proposed for TRIP steels in this study. Besides the nonlinear Chaboche backstress and linear Prager–Ziegler backstress, a third backstress that depicts the contribution of TRIP effect to the kinematic hardening was presented. The TRIP effect was modeled using an equivalent plastic strain and a stress triaxiality coefficient as the variant. Forward–reverse shear experiments were performed for a cold rolled TRIP780 steel. A new clamper was designed to reduce the buckling during reverse shear. Cyclic loading–unloading–reloading uniaxial tension experiments were conducted and the degradation of elastic modulus with the plastic strain was discussed. Micro-indentation tests were performed to check the true elastic modulus. U-bending springback simulation was performed with the new hardening model combined with the Yoshida's elastic modulus. The results showed that the investigated TRIP780 steel has prominent kinematic hardening behavior, Bauschinger effect, transient hardening and permanent softening during forward–reverse shear deformation. The percentage of the third backstress component due to the TRIP effect in the total backstress reaches 31% at 0.25 plastic strain. Springback simulation with the proposed hardening model combined with the degradation of elastic modulus is more precise than the isotropic model.

1. Introduction

As environment and energy problems are increasingly urgent, light weighting has been a key issue in the automotive industries. Adopting high strength steels is an effective and economical method and has been widely used in automotive companies. Transformation-induced plasticity steels (TRIP) combine high strength and good ductility as well as the prominent TRIP effect. Compared with other high strength steels, TRIP steels have more serious springback in practice. As is well known, a precise material model combined with accurate material parameters is the most important aspect for an accurate springback simulation. Among the constituents of the material model, the hardening model that depicts the evolution of shape, location and size of the yield surface with the plastic strain has been proved to be a decisive factor for springback simulation.

Commonly used hardening models can be traced to isotropic, kinematic and combined hardening theories. The isotropic hardening theory regards the subsequent yield surface only expands along the normal direction without movement. According to this theory, the subsequent yield surface only has size change during plastic deformation, which is unable to describe the Bauschinger effect of some metals since the isotropic hardening models cannot reproduce the material behavior during reverse loading. In order to solve this problem, kinematic hardening theory considers the movement of the yield surface while neglects the size change during plastic deformation. This theory can predict some kinematic hardening phenomenon very well, such as, Bauschinger effect, permanent softening, and transient hardening and cross hardening. A tensor, which is named backstress, is used to characterize the location of the centers of the yield surfaces. According to the relation between backstress and plastic strain, the kinematic hardening model can be classified as a linear and a nonlinear type. Prager [1] presented a linear kinematic hardening model to describe the translation of the yield surface during plastic deformation. In Prager's model, the

* Corresponding author.
E-mail addresses: yuhaiyan@tongji.edu.cn (H. Yu), chensiji327@sina.com (S.J. Chen).

http://dx.doi.org/10.1016/j.jmapro.2016.12.012
1526-6125/

translation of the yield surface occurs in the direction of plastic strain increment ($d\varepsilon_p$). Thus, the back stress is:

$$dX = c d\varepsilon_p \quad (1)$$

where dX is the backstress increment; c is a material constant which is independent on plastic strain. Being different from Prager's model, Ziegler's model [2] adopted a different linear equation Eq. (2) to describe the backstress.

$$dX = \frac{c}{\sigma_{eq}}(\sigma - X)\,dp \quad (2)$$

where dp is the modulus of the plastic strain rate; σ_{eq} is the equivalent stress; c is a material constant. Both Prager's model and Ziegler's model regard the parameter c a constant. Thus, they were proved to be inadequate in predicting the highly nonlinear behavior of metal materials subject to non-proportional loading paths.

On the basis of Prager's model, Mroz [3] generalized the linear kinematic rule to a multi-surface model using the concept of the field of work hardening moduli, which correspond to a series of yield surfaces each with a constant hardening modulus. Mroz's model can predict the Bauschinger effect well and can be fit by the uniaxial flow curve. It is very simple in practical use. In the meantime, just this simplicity presents some shortcomings. It is unable to describe the correct material response in some situations. It is also computationally expensive because each yield surface requires a scalar to describe its size and a tensor to remember its position [4].

Based on Morz's work, Krieg [5] and Dafalias et al. [6] attempted to overcome that deficiency using two surfaces instead of multiple surfaces. The two surfaces are the yield surface and a bounding surface; the yield surface moves within the bounding surface and the bounding surface only has size change. The kinematic hardening of the yield surface describes the transient Bauschinger effect which is characterized by early re-yielding and the subsequent rapid change of workhardening rate. The isotropic hardening of the bounding surface can describe the global workhardening. One possible weakness of two-surface models is that they require search algorithm to find the common normal on the bounding surface. In order to consider the permanent softening and workhardening stagnation which are commonly found in forward–reverse deformation, Yoshida and Uemori (Y–U) assumed that the bounding surface also abides by a mixed isotropic-hardening rule. Recently, Yoshida et al. [7] considered the evolution of anisotropy and the Bauschinger effect in the classical Y–U model. This model was successfully used in modeling the anisotropic cyclic behavior of a 780 MPa advanced high strength steel.

Armstrong and Frederick [8] presented a nonlinear kinematic hardening law by adding a recall term to Prager's rule. The back stress evolves according to the following differential equation,

$$dX = c d\varepsilon_p - \gamma X dp \quad (3)$$

where c and γ are material constants. The second term on the right side is a recall term, whose direction depends on the current value of the back stress. This term also indicates that the back stress is dependent on the strain path.

Based on Armstrong and Frederick's non-linear kinematic hardening model, Chaboche [9] noted that this model could be generalized using several back stresses:

$$dX = \sum dX_i \quad (4)$$

$$dX_i = c_i d\varepsilon_p - \gamma_i X_i dp \quad (5)$$

The concept of multiple back stresses has been found to be useful in modeling some complex plastic problems. After that, the Chaboche model has been developed in many forms [10–13]. For example, Ohno et al. [14–16] introduces an additional kinematic hardening term that is activated when the material is in a non-hardening state, but the value of this term tends to be zero as the non-hardening surface is approached. Geng and Wagoner [17] updated the Chaboche model and adopted two stress tensors to describe the evolution of the centers of the yield surface and the bounding surface.

The above hardening models were built on the macro mechanical performances and the micro-mechanisms of plastic deformation was not taken into account. Teodosiu and Hu [18] presented a model in which the microstructures effect was considered by using three tensors which were related to the microstructures. The Teodosiu–Hu model was successful in predicting the working hardening stagnation and cross hardening using the microstructure tensors. There are 13 material parameters in the Teodosiu–Hu model and they should be identified from the experimental data, which presents some inconvenience in its practice.

TRIP steels are well known for the TRIP effect, i.e., the retained austenites are metastable and can easily transform to martensites during cold forming, which can provide extra work hardenability in return. Furthermore, TRIP effect can be affected by the stress state, strain rate and temperature [19,20]. So TRIP effect is an important factor in assessing the plastic performance of TRIP steels. Hänsel et al. [21] developed a temperature dependent isotropic constitutive model for TRIP steels. It made use of the isothermal transformation kinematics law proposed by Tsuta and Cortes [22], in which the martensite volume fraction was defined as a function of the von Mises equivalent plastic strain. Schedin et al. [23] updated the Hänsel model by introducing an anisotropic yield function. This empirical model has been implemented in the commercial software LS-DYNA, but it does not account for the effect of stress state on martensites evolution. Srivastava et al. [24] proposed a crystal plasticity constitutive equation for multiphase steel by discretely modelling the constituent phases. Zhang et al. [25] designed an in-plane tension-compression experiment device to calibrate the parameters of Yoshida–Uemori hardening model for TRIP800 steel. The results indicated that the Yoshida–Uemori model cannot capture the transient hardening behavior although it seemed to be better than other models. Lee et al. [26] pointed out that a hardening model that can precisely describe the transient hardening and permanent softening are crucial to springback simulation. If the material shows a visible reduction of elastic modulus, an variant elastic modulus can help to enhance the springback simulation precision.

This work aimed to introduce the TRIP effect into the classical Chaboche hardening model. Firstly, the TRIP effect was characterized by a martensitic transformation equation, in which the amount of the retained austenites was regarded as a variable that changes with the plastic strain and the stress triaxiality coefficient. Secondly, three terms of back stress that abides by different hardening law were used to model the kinematic hardening behavior of TRIP steels. Besides the nonlinear Armstrong–Frederick model and linear Prager's model, a third backstress equation was presented to depict the contribution of TRIP effect to the kinematic hardening. After that, this model was combined with the Voce isotropic hardening model and a mixed isotropic–kinematic hardening model was proposed. Thirdly, forward–reverse shear experiments of TRIP780 steel sheets were performed and the parameters of the hardening model were obtained by combining the finite element simulation and optimization. Cyclic loading–unloading–reloading uniaxial tension experiments and micro-indentation tests were also conducted to investigate the degradation of elastic modulus during plastic deformation. Finally, the new hardening model combined with the variable elastic modulus was introduced into the U-bending springback simulation.

Please cite this article in press as: Yu H, Chen SJ. A mixed hardening model combined with the transformation-induced plasticity effect. J Manuf Process (2017), http://dx.doi.org/10.1016/j.jmapro.2016.12.012