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Stress integration method for a nonlinear kinematic/isotropic hardening model and its characterization based on polycrystal plasticity

Rui P.R. Cardoso[a], Jeong Whan Yoon[b,a,*]

[a] Center for Mechanical Technology and Automation, Univ. of Aveiro, 3810-193 Aveiro, Portugal
[b] Alcoa Technical Center, 100 Technical Dr., PA 15069-0001, USA

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ABSTRACT

Sheet metal forming processes generally involve non-proportional strain paths including springback, leading to the Bauschinger effect, transient hardening, and permanent softening behavior, that can be possibly modeled by kinematic hardening laws. In this work, a stress integration procedure based on the backward-Euler method was newly derived for a nonlinear combined isotropic/kinematic hardening model based on the two-yield's surfaces approach. The backward-Euler method can be combined with general non-quadratic anisotropic yield functions and thus it can predict accurately the behavior of aluminum alloy sheets for sheet metal forming processes. In order to characterize the material coefficients, including the Bauschinger ratio for the kinematic hardening model, one element tension–compression simulations were newly tried based on a polycrystal plasticity approach, which compensates extensive tension and compression experiments. The developed model was applied for a springback prediction of the NUMISHEET'93 2D draw bend benchmark example.

1. Introduction

Sheet metal forming processes involve material, geometric, and contact nonlinearities resulting in various loading paths (loading, unloading, reloading, reverse loading, etc.). These changes on loading occur from contact with forming dies and/or removal from forming dies during springback stage.

* Corresponding author. Address: Alcoa Technical Center, 100 Technical Dr., PA 15069-0001, USA. Tel.: +1 724 337 1938.
E-mail address: jeongwhan.yoon@alcoa.com (J.W. Yoon).

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Depending on the complexity of die shapes, the numerical methods must be able to account for combinations of loading and reverse loading in an efficient way. Especially, springback prediction has been also a major subject of intense research in sheet metal forming processes. Springback refers to the undesirable shape change due to the release of the tools after a sheet forming operation. Previous studies indicated that the final part shape after springback depends on the amount of elastic energy stored in the part during forming (Pourboghrat and Chu, 1995; Yoon et al., 2002; Oliveira et al., 2007; Zeng and Xia, 2005). Unfortunately, the elastic energy stored is a function of the process parameters, geometry of the tools and the blank, friction conditions and material behavior. Moreover, the prediction of springback is very sensitive to the numerical parameters used in the simulations (Lee and Yang, 1998; Li and Wagoner, 1998). Therefore, predicting and compensating springback are very complicated tasks. The analytical and finite element approaches for the prediction of springback were well summarized by Wagoner (2004). Further, numerical solutions have been proposed for the understanding of springback (for example, Wagoner and Li, 2007; Alves de Sousa et al., 2007; Oliveira et al., 2007) and also to compensate it by, for example, modifications on die shapes (Cheng et al., 2007).

During springback, when the tools are removed from a formed part, the material unloads elastically and, depending on the geometry, some elements can experience reloading in the reverse direction even beyond the yield limit. This plastic deformation can, in turn, influence the amount of springback. Due to the Bauschinger effect, i.e., the yield stress for reverse loading is lower than the flow stress just before unloading, the springback can be affected by this behavior. Therefore, it is often necessary to account for the Bauschinger effect in springback simulations. The isotropic hardening is no longer valid and an effective way to model this effect is to assume that the yield surface translates in stress space. This assumption, called kinematic hardening, was introduced by Prager (1956) and some modifications were proposed by Ziegler (1959). In order to describe the expansion and translation of the yield surface during plastic deformation, the combination of isotropic and kinematic hardening is also commonly used (Chaboche, 1986). Yoshida (2000) developed a constitutive model for the cyclic plasticity of mild steels where several experiments were conducted for uniaxial tension, cyclic straining, and stress and strain controlled ratcheting. Later, Yoshida and Uemori (2002) created a model for large-strain cyclic plasticity capable to describe the deformation behavior and stress–strain response at small-scale re-yielding after large pre-strain, with a new equation for back-stress evolution in order to accurately simulate the transient Bauschinger effect. Continuing the work on cyclic plasticity for steels, Yoshida et al. (2002) studied the elasto-plastic behavior of steel sheets under in-plane cyclic tension–compression loads at large strains and found that cyclic hardening is strongly influenced by cyclic strain range and mean strain. A formulation for kinematic hardening that can accommodate any yield function is well summarized in Chung et al. (2005) and Lee et al. (2005a,b). Recently, several models were also published for the numerical and experimental investigation on kinematic hardening laws and the study of the effect of advanced strain-path dependent materials and hardening laws on sheet metal forming simulations (see Cao et al., 2008; Haddag et al., 2007; Duflou and Habraken, 2007).

Other approaches, based on two or multiple embedded yield surfaces, due to Mroz (1967), Krieg (1975), Dafalias and Popov (1976), account for the Bauschinger effect as well. Besides the Bauschinger effect, a transient hardening behavior is also observed during reverse loading. The use of multi-yield surfaces on Mróz model allowed reproducing the transient behavior, although on a stepwise way. Dafalias and Popov (1976) transformed later the Mróz model's concept and introduced the two-yield surface approach to reproduce simultaneously the Bauschinger effect and the transient behavior on steel alloys. Other authors (Tseng and Lee (1983), McDowell (1985, 1989), Khan and Huang (1995)) proposed also some remedies to deal with the large number of yield surfaces of the original Mróz model and constructed new theories based on the two-yield surface's approach. Recently, Lee et al. (2007) proposed a modification of the original work of Dafalias and Popov (1976) to extend the two-yield surface concept to general non-quadratic anisotropic yield functions based on the "forward-Euler" stress integration method. Teodosiu and Hu (1998) elegantly modeled the Bauschinger effect as well as its associated transient behavior, which resulted from dislocation pattern reorganization.

Most rate-independent plastic models are formulated in terms of rate-type constitutive equations, for which the integration method has a considerable influence on the efficiency, accuracy and convergence of the solution. In the simulation of sheet forming processes, the constitutive equation is inte-