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Constitutive modeling for path-dependent behavior and its influence on twist springback

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A B S T R A C T

The aim of this study is to investigate the path-dependent elastic-plastic behavior of dual-phase steel and its influence on the prediction of twist springback in the channel forming process. The anisotropic hardening responses of the sheet material for non-proportional loading, as well as the degradation of the elastic modulus in uniaxial and biaxial tension are investigated. A recently proposed distortional plasticity model combined with a dislocation density-based hardening approach was adopted to describe the flow behavior of the material. The results indicate that the present model simultaneously reproduces all of the experimentally observed features for both load reversal and changes of the principal strain axis. This constitutive description is employed in the finite element analysis of the forming of two channels with obvious twist springback characteristics. The complex strain path changes during the forming process are then analyzed using a proposed indicator. Finally, the relevance of the load changes and the stress distribution in the channel regarding twist springback predictions are discussed. The influence of loading path-dependent elastic modulus degradation for the prediction of twist springback is also assessed based on two different application geometries.

1. Introduction

The springback analysis of sheet metal parts based on finite element modeling has received considerable attention in the past several decades, particularly owing to the increasing demands of advanced high strength steels (AHSS) (Wagoner et al., 2013). However, these materials give rise to unique challenges in springback prediction because of their high strength and complex elastic-plastic behaviors under non-proportional loading (Khan et al., 2012; Sun and Wagoner, 2013).

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In an effort to increase the accuracy of the numerical prediction of springback, anisotropic hardening models have replaced the more classical approaches because they can reproduce phenomena such as the Bauschinger effect under load reversal conditions (Boger et al., 2005; Chun et al., 2002; Cao et al., 2009; Choi et al., 2015; Lee et al., 2012; Rauch et al., 2007; Yoshida et al., 2002, 2015) and stress overshooting under cross-loading conditions (Teodosiu and Hu, 1995; Bouvier et al., 2006; Noman et al., 2010; Clausmeyer et al., 2014; Ha et al., 2013; Hama et al., 2016). Among the proposed advanced models, kinematic hardening has prevailed owing to its effectiveness in the describing the Bauschinger effect under cyclic loading conditions (Chaboche, 1986; Ohno and Wang, 1993; Chung et al., 2005; Chaboche, 2008). More sophisticated models based on combined isotropic and kinematic hardening or on multi-surface approaches with anisotropic yield functions were also proposed (Chun et al., 2002; Geng and Wagoner, 2002; Yoshida and Uemori, 2002; Lee et al., 2007) to better describe work hardening stagnation and permanent softening effects.

As an alternative, distortional plasticity models, possibly combined with kinematic hardening, were also proposed to capture the latent hardening during cross-loading (Aretz, 2008; Feigenbaum and Dafalias (2007, 2008); Dafalias and Feigenbaum, 2011; Shutov and Ihlemann, 2012). Recently, Barlat et al. (2011, 2013, 2014) proposed the so-called homogeneous anisotropic hardening (HAH) model, a distortional plasticity approach without kinematic component, that provides a reasonable description of the complex hardening behaviors under various strain path changes.

In spite of these efforts for advanced constitutive modeling, only limited attempts have been made to study the influence of strain path-dependent behavior on springback predictions in sheet forming processes. Bouvier et al. (2005) evaluated the accuracy and efficiency of the Teodosiu-type hardening model for springback simulations. Haddag et al. (2007) investigated the influence of hardening models on the springback prediction in strip drawing tests. Oliveira et al. (2007) focused on the influence of the hardening model in the springback prediction of U-draw bending at a large strain. Furthermore, Thuillier et al. (2010) investigated the effect of the loading change on the punch force prediction for the deep drawing of cylindrical cups. Lee et al. (2012) assessed the effect of the hardening model on springback prediction after U-bending of a pre-strained material. Clausmeyer et al. (2014) analyzed the influence of latent hardening on the springback prediction in two industrial forming cases. Their pioneering work provided some insights into the understanding of path-dependent behavior and its influence in industrial sheet forming processes. However, further investigations regarding other types of anisotropic hardening responses and their influence on the elastic distortion after load removal, including twist springback, should be further performed.

Another important phenomenon for springback predictions is the reduction of the apparent elastic modulus during plastic deformation (Chatti and Hermi, 2011; Chatti and Fathallah, 2014; Cleveland and Ghosh, 2002; Eggertsen and Mattiasson, 2010; Ghaei et al., 2015; Komgrit et al., 2016; Zhan et al., 2014; Zhu et al., 2012). This effect was measured using uniaxial loading-unloading-reloading (ULUL) tension tests (Govik et al., 2014; Chen et al., 2016a, b). However, the recent work by Lee et al. (2016) showed that the degradation of the elastic modulus in AHSS is also dependent on the loading path.

The present study aims to investigate the influence of the path-dependent elastic-plastic behavior of dual-phase steel on the twist springback in the deep drawing of two model channels. First, material characterization under various loading conditions including proportional, reverse, and cross-loading conditions is described. Second, the evolution of anisotropic hardening with the recently enhanced HAH model (Barlat et al., 2014) complemented with the nonlinear elastic modulus evolution as a function of the accumulated strain in uniaxial or biaxial loading states, is assessed. Finally, this elastic-plastic constitutive model is applied to forming simulations of two channels, which exhibit obvious twist springback characteristics. The influences of the constitutive approach on the stress distribution in the channels as well as the twist springback are analyzed.

2. Experiments

2.1. Material

The material considered in this study is a 0.8-mm-thick dual-phase steel DP500. The material consists of hard martensitic particles embedded in a soft ferritic phase. The volume fraction of martensite is 14%, and the average ferrite grain size is 22 μm. The chemical composition of the steel is listed in Table 1. A series of proportional and non-proportional tests were conducted to characterize the elastic-plastic behavior of this material.

2.2. Proportional loading tests

Uniaxial tension tests were performed using a Shimadzu tensile testing machine (maximum capacity 100 kN) according to ASTM-E8 standards with longitudinal directions at 0°, 45°, and 90° from the rolling direction. All tests were conducted at room temperature with a constant strain rate of 10^{-3} s^{-1}. The balanced biaxial bulge test was performed to measure the

Table 1
Chemical composition of DP500 in weight percent.

C	Si	Mn	P	S	N	Cr	Ni	Cu	Al	V	B
0.079	0.31	0.65	0.009	0.003	0.003	0.03	0.03	0.01	0.038	0.01	0.0003

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