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Strain hardening response and modeling of EDDQ and DP780 steel sheet under non-linear strain path

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ABSTRACT

The anisotropic hardening behaviors of dual phase (DP780) and extra deep drawing quality (EDDQ) steel sheets under non-proportional strain paths were investigated. Two-step uniaxial tension tests, which consisted of the first loading in the rolling (RD) or transverse (TD) and the second loading in every 15° from the first loading axis, were conducted. For DP780 steel, a significant Bauschinger effect accompanied by a transient hardening behavior after reverse loading was the prominent phenomenon. In contrast, EDDQ exhibited stress overshooting followed by strain hardening stagnation with respect to the monotonic flow curve near cross-loading conditions. The extended HAH model combined with the Yld2000-2d yield function were used to reproduced the anisotropic hardening behavior of the two materials. For DP780, the extended HAH model could capture the Bauschinger effect and transient hardening behavior well for tension reloading at 0°, 15°, 75° and 90° from the RD or TD prestraining direction. However, the predictions at 30°, 45° and 60° were slightly different from the experiments. For EDDQ, this approach reproduced the strain hardening anisotropy well including flow stress overshooting followed by a stage of strain hardening stagnation.

1. Introduction

Sheet metal is widely used for numerous industrial applications such as automotive structural components, aerospace parts and home appliances. Among the different sheet materials available for these applications, steels have been used extensively due to their economical manufacturing cost and desirable mechanical properties. In a sheet forming process, each material point is subjected to in-plane principal major and minor strains, ε_1 and ε_2, respectively. The deformation history can be represented by the quantity $\rho = d\varepsilon_2/d\varepsilon_1$, which is efficiently used to define the strain path. If ρ is constant, the strain path is said to be linear, for instance, biaxial stretching, plane strain, uniaxial tension and pure shear. Sometimes the terminology "proportional loading" is used as equivalent to "linear strain path" but this is only valid for isotropic hardening assumption. Kinematic and distortional hardening assumptions might cause non-proportional strain path changes due to yield surface distortion or translation for proportional loading.

Non-proportional deformation includes abrupt strain path changes which affect the mechanical behavior of materials dramatically (Golovashchenko et al., 2011; Min et al., 1995). In a simple forming process such as deep drawing, the strain state changes from pure shear to biaxial tension when a material point flows from the flange area to the die cavity (Esche et al., 2000). Many studies were published over many decades on the material responses under non-proportional strain paths (Barlat et al., 2003b; Boers et al., 2010; Gracio et al., 2000; Harrysson and Ristinmaa, 2007; Lee et al., 2011; Lloyd and Sang, 1979; Schmitt et al., 1985, 1994; Tarigopula et al., 2008; Thuillier and Rauch, 1994; Vegter et al., 2003; Verma et al., 2011; Vincze et al., 2005). They reported that strain path changes can

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dramatically affect the mechanical behavior of materials. For instance, in the case of load-reversal, the material response exhibits phenomena such as the Bauschinger effect, transient strain hardening, strain hardening stagnation and permanent softening, which make the stress–strain curve significantly different from that of monotonic loading.

For the past few years, many constitutive approaches have been proposed to describe strain hardening during complex loading paths. Although the classical isotropic hardening assumption has provided a successful description for monotonic loading deformation, this simple model cannot represent the material's complex behavior under non-proportional strain paths. Thus, in order to describe the anisotropic hardening behavior for load reversal or cyclic deformation, especially for the Bauschinger effect, the linear kinematic hardening law was introduced (Prager, 1956; Ziegler, 1959), which was extended to a non-linear formulation by Armstrong and Frederick (1966) and Chaboche (Chaboche, 1986, 2008; Lee et al., 2007). Different variations of kinematic hardening have been successfully applied to the sheet metal forming simulations, especially for springback predictions (Chung et al., 2005; Lee et al., 2005a,b). Recently, a constitutive model that takes into account the combined isotropic, kinematic and distortional hardening was proposed to predict the evolution of plastic flow anisotropy (Pietryga et al., 2012).

Other approaches to hardening are based on microscopic changes (Lee et al., 2010; Vincze et al., 2005). For example, Li et al. (2003) and Kitayama et al. (2013) took the individual slip systems and their interaction into account to describe hardening using crystal plasticity models. Teodosiu and Hu (1998) considered dislocation structure based state variables in a continuum plasticity theory, which can be applied for stress reversal as well as any possible strain path change such as orthogonal loading. Moreover, based on experimental evidence, Rauch et al. (2007, 2011) suggested evolution laws for dislocation densities as a way to capture strain hardening during a single strain path change. Harrysson and Ristinmaa (2007) proposed a constitutive model for the description of texture evolution at large strains.

An alternative approach, the homogeneous yield function based anisotropic hardening (HAH) model was proposed (Barlat et al., 2011; Ha et al., 2011) to capture the Bauschinger effect without using the kinematic hardening concept. It consists of a homogeneous yield function with a stable and a fluctuating component. The stable component can be any isotropic or anisotropic yield function, while the fluctuating component produces a distortion of the yield surface, which induces directional anisotropy. Thus, it can describe the material behavior for a wide range of continuous and discontinuous strain path changes. The HAH model was successfully implemented in a finite element (FE) code (Lee et al., 2012a) and simulations were conducted to predict springback in U-draw bending. The results were found to be in good agreement with the experiments (Lee et al., 2012b). More recently, based on an understanding of dislocation structure evolution, the HAH model (Barlat et al., 2011) was extended to the cross-loading case with latent hardening effect (Barlat et al., 2013).

The purpose of this paper is to characterize the mechanical response of steel sheets during proportional and non-proportional loading and to evaluate an extension of the HAH model to capture anisotropic hardening behavior. In Section 2, the experimental procedures, two-step uniaxial tension tests (also referred to as tension–tension tests) in different loading directions, are described. Section 3 reviews the main features of the extended HAH formulation and provides the corresponding optimized parameters for two steel sheet samples, EDDQ and DP780. Finally, in Section 4, numerical simulations of two-step uniaxial tension tests with the FE code ABAQUS are carried out for DP780 and EDDQ. The predicted results are compared with experimental data for validation.

2. Experiments

2.1. Materials

Two 1.2 mm thick steel sheet samples, namely EDDQ and DP780, were investigated in this study. DP780, an advanced high strength steel (AHSS), exhibits a high strength level with good ductility, which results from the presence of a martensite second phase structure in a ferrite matrix. The EDDQ steel is a low carbon steel, extra deep drawing quality type, with moderate strength, a high total elongation of about 50% and high *r*-value. The materials were characterized by monotonic uniaxial tension tests and two-step uniaxial tension tests. The monotonic uniaxial tension tests were conducted on standard ASTM E8 specimens oriented every 15° from the rolling (RD) or transverse (TD) direction. The directional r-values were measured from two extensometers. The true stress-true strain curves measured in the RD, at 45° from the RD (or diagonal direction, DD) and the TD are plotted in Fig. 1 and the corresponding mechanical properties are summarized in Table 1.

2.2. Tension–tension test

Tension–tension tests were performed to characterize the effect of strain path changes on the plastic flow behavior. Two-step uniaxial tension tests were conducted with the 1st loading in the RD or TD and the 2nd loading in different directions from the 1st tensile direction in 15° steps. 4% and 10% prestrains were first applied on large specimens, out of which smaller specimens were machined. Then, subsequent uniaxial tension tests were conducted on the sub-size specimens.

The specimen geometry for the 1st tension step, which was proposed in this work, is described in Fig. 2(a). The selected width was as large as possible considering the available grips. According to finite element (FE) simulations, the strain distribution in the large specimen remained homogeneous and a uniaxial stress state was maintained in the center area. For the 2nd tension step, the specimen geometry followed the ASTM E8 standard for sub-size specimen (see Fig. 2(b) for dimensions) with a gauge length of 25 mm. The sub-size specimens were machined at the center of the pre-deformed specimen by the 1st tension step