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Modeling of large strain multi-axial deformation of anisotropic metal sheets with strength-differential effect using a Reduced Texture Methodology

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ABSTRACT

This paper works on the macroscopic modeling of the anisotropic plasticity of a 6260-T6 thin-walled aluminum extrusion with a focus on the large strain multi-axial deformation with Strength-Differential Effect (SDE). Based on the framework of the self-consistent polycrystalline plasticity, the recently developed Reduced Texture Methodology (RTM) (Rousselier et al., 2012) is employed to provide the computational efficiency needed for industrial applications while keeping the physically-based nature of the plasticity model. In particular, the new model features a novel hardening law at slip-system level to better capture large strain behaviors, as well as a generic method designed to describe the stress/strain history effect. All model parameters (including texture) are identified from mechanical experiments using a special optimization procedure. An extensive experimental program covering more than 30 distinct multi-axial stress states with both proportional and non-proportional loadings is used to calibrate and validate the present model. Both full- and reduced-thickness specimens are tested to capture the through-thickness heterogeneity of texture and grain size. It is shown that the present model predicts well the stress–strain responses in most of the multi-axial loading conditions which have been tested. Moreover, the model is able to capture various interesting behaviors of the present material during plastic deformation, including anisotropy, through-thickness heterogeneity, SDE of tension/compression or shear, and cross-hardening during non-proportional loadings. Furthermore, successful simulation of two structural level tests including a circular punch indentation and a three-point bending shows the applicability and potential of the new model in industrial practices.

1. Introduction

Predicting the large strain behaviors of metallic materials under multi-axial loading is crucial to various industrial applications, such as sheet metal forming, impact/crash failure analysis, etc. In the past decades, the increasing demand of physically sound and experimentally verified metal plasticity models draws huge attention to various phenomena that have been observed during the plastic deformation of metals. Among these phenomena, the shape, anisotropy, and asymmetry/Strength-Differential Effect (SDE) of the initial and subsequent yield surfaces are extensively studied and extremely important, especially for metal sheets.

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The shape or so-called stress state dependency of the yield surface has been the focus of many studies. The classical J_2 plasticity assumes no influence of either hydrostatic stress state I_1 or the deviatoric stress state J_3 on the quadratic yield function, which provides only poor approximation of the yield surfaces of FCC and BCC polycrystalline materials (Bishop and Hill, 1951; Hutchinson, 1964; Stout et al., 1983; Woodthorpe and Pearce, 1970). One way to describe the complex shape of the yield surface is to use non-quadratic yield functions (e.g. Hosford, 1972), which provide better modeling of the yield surfaces of FCC materials. An alternative approach is to model explicitly the influence of J_3 or Lode angle on plasticity, which has long been recognized and studied by the geo-mechanics community (Bardet, 1990; Menetrey and Willam, 1995) but overlooked by the metal plasticity until recently. Miller and McDowell (1996) showed the deficiency of the J_2 plasticity model in describing the torsional softening of stainless steel 304L and proposed a J_3-dependent yielding and hardening model for metals. Bai and Wierzbicki (2008) characterized the Lode angle (J_3) effect on the plasticity of aluminum 2024-T351 through a series of tensile and compression experiments and modeled this effect using a Lode angle (J_3) dependent hardening model. The same group also extensively investigated the Lode angle (J_3) effects on ductile fracture (Bai and Wierzbicki, 2010; Beese et al., 2010; Li et al., 2010; Luo et al., 2012; Luo and Wierzbicki, 2009; Luo and Wierzbicki, 2010). Gao et al. (2009) observed a differential effect in stress–strain curves of tension and torsion tests and proposed a $J_2 - J_3$ yield function to capture this phenomenon. On the other hand, numerous phenomenological yield functions (e.g. Barlat et al., 2003; Hosford, 1972; Karafillis and Boyce, 1993; Logan and Hosford, 1980) have been developed for plastic anisotropy of metals after the original development of Hill (1948). Among them, the formulations based on linearly transformed stress tensors draw utmost attention (e.g. Barlat et al., 2003; Bron and Besson, 2004; Karafillis and Boyce, 1993), due to the convexity consideration and their high flexibility in describing the anisotropic behavior of metal sheets.

The tension/compression asymmetry, usually termed as SDE, has also been the focus of numerous studies in metal plasticity. One physical reason to explain this effect is the pressure sensitivity of flow stress, which has been observed for both iron-based metals (Spitzig et al., 1975, 1976) and aluminum (Spitzig and Richmond, 1984). Based on the classical theory developed by Drucker and Prager (1952) for granular materials, a number of recent publications (Bai and Wierzbicki, 2008; Brünig, 1999; Stoughton and Yoon, 2004) showed the applicability of the $I_1 - J_2$ type yield to metal plasticity in predicting the pressure dependent plastic flow and the SDE of metals, i.e. higher flow stress in compression than in tension. On the other hand, the increasing applications of Hexagonal Closed Packed (HCP) metals and alloys draw enormous attention to their pronounced SDE, which is caused by the directionality of twinning instead of pressure sensitivity. The SDE of these pressure insensitive materials has been successfully modeled by, e.g. Cazacu and Barlat (2004) and Cazacu et al. (2006), using modifications of Drucker's yield criterion (1952) in the $J_2 - J_3$ space. Last but not least, strain/stress history could also give rise to the SDE of sheet metal, which are usually plastically deformed or thermo-mechanically processed, e.g. rolling or extrusion processes. In this regard, Yoon et al. (2000) modeled the significant SDE of a 2090-T3 aluminum alloy sheet by introducing a constant non-zero back stress tensor, which gives certain translation of initial yield surface. In Beese and Mohr (2012), the large SDE of a 301LN stainless steel sheet is captured by specifying initial values to the back stress tensor that are governed by a nonlinear kinematic hardening law (Frederick and Armstrong, 1966).

The framework of physically-based polycrystalline metal plasticity, on the other hand, has intrinsic advantages in describing the anisotropy and distortion of the yield surface, as well as the anisotropic hardening. Under large deformation, e.g., during the rolling or extrusion processes, metals develop a preferred orientation or crystallographic texture in which certain crystallographic planes tend to orient themselves in a preferred manner in response to the applied loads or displacement (Miller and McDowell, 1996). The development of such crystallographic texture has long been recognized as the physical reason for the deformation-induced anisotropy, which is the case for most metal sheets and extrusions (Bunge and Roberts, 1969; Juul Jensen and Hansen, 1990; Kallend and Davies, 1972). Moreover, the polycrystalline plasticity can represent macroscopic yield surfaces with complex shapes given particular model in use. The convexity of these shapes and the normality rule for polycrystalline aggregates have been demonstrated by Bishop and Hill (1951), provided that the crystals individually deform by slip according to the Schmid Law. In addition, polycrystalline plasticity is able to capture the complex evolution of yield surfaces (e.g. Kuroda and Tvergaard, 1999;Kuroda and Tvergaard, 2001; Kuwabara, 2007), which involves texture evolution at large strains or intragranular substructure evolution (e.g. cross-hardening between different slip systems) and reorganization of dislocation substructures. The framework of polycrystalline plasticity models is well poised to model these physical phenomena and is constantly improved (Hoc and Forest, 2001; Holmedal et al., 2008; Peeters et al., 2001). Therefore, polycrystalline plasticity is a natural choice for the modeling of stress–strain behaviors under multi-axial and multi-path loadings.

Within the framework of crystal plasticity, the SDE can be modeled by generalized 'non-Schmid' rules, which were first studied by Asaro and Rice (1977). Following this approach, Dao and Asaro (1993) developed a rate-dependent constitutive model featuring a non-Schmid rule that incorporates pressure sensitivity. Nemat-Nasser (1983) proposed a more general constitutive framework incorporating dilatant, frictional and hydrostatic effects for geo-materials. Based on this generalized framework, Brünig (1998) successfully simulated numerically the experimentally observed SDE (Spitzig et al., 1975) using a crystal plasticity model with a non-Schmid law.

Although polycrystalline plasticity models have strong predictive power, their application in the industry is still rare, mainly due to the enormous CPU time involved to solve the constitutive equations. This computational cost brings difficulties not only in the Finite Element (FE) analysis of large scale structures, but also during the model parameter identification which usually relies on an iterative inverse procedure. Many efforts have been made to obtain reasonable computational times through a drastic reduction of the number of crystallographic orientations (e.g. Böhlke et al., 2005, 2006; Raabe and