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Dual-phase steel sheets under cyclic tension–compression to large strains: Experiments and crystal plasticity modeling

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ABSTRACT

In this work, we develop a physically-based crystal plasticity model for the prediction of cyclic tension–compression deformation of multi-phase materials, specifically dual-phase (DP) steels. The model is elasto–plastic in nature and integrates a hardening law based on statistically stored dislocation density, localized hardening due to geometrically necessary dislocations (GNDs), slip-system-level kinematic backstresses, and annihilation of dislocations. The model further features a two level homogenization scheme where the first level is the overall response of a two-phase polycrystalline aggregate and the second level is the homogenized response of the martensite polycrystalline regions. The model is applied to simulate a cyclic tension–compression–tension deformation behavior of DP590 steel sheets. From experiments, we observe that the material exhibits a typical decreasing hardening rate during forward loading, followed by a linear and then a non-linear unloading upon the load reversal, the Bauschinger effect, and changes in hardening rate during strain reversals. To predict these effects, we identify the model parameters using a portion of the measured data and validate and verify them using the remaining data. The developed model is capable of predicting all the particular features of the cyclic deformation of DP590 steel, with great accuracy. From the predictions, we infer and discuss the effects of GNDs, the backstresses, dislocation annihilation, and the two-level homogenization scheme on capturing the cyclic deformation behavior of the material.

1. Introduction

In order to arrive at a solution of the governing equations of continuum mechanics such as the balance of linear momentum, an appropriate constitutive law describing the material behavior from its internal constitution under the action of applied deformation is required. The solution in terms of stress and strain measures is usually obtained numerically using full-field methods such as finite element (FE) methods (Bathe, 1996) or mean-field methods such as self-consistent (SC) models (Eshelby, 1957). The accuracy of the numerical solution is strongly dependent on the accuracy of constitutive law selected, also called a material model. Complex multiaxial deformation paths exerted on the material are routinely encountered in simulations of metal forming processes (Hosford and Caddell, 1993) putting stringent demands on the sensitivity of material models to strain path changes and the underlying path dependence of plastic deformation (Li et al., 2002).

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Plastic deformation of polycrystalline metals induces anisotropy in the mechanical response, which oftentimes manifests itself in strong changes of the response characteristics upon change in the loading direction. Reversal of the strain path is achieved by applying strain in the opposite direction to that applied during forward pre-straining. Upon application of strain in the reversed direction, the material exhibits non-linear unloading (Cullen and Korkolis, 2013; Deng et al., 2016; Wagoner et al., 2013; Yoshida et al., 2002) and reduction of yield stress from the one reached at the end of pre-straining followed by rapid hardening known as the Bauschinger effect (BE) (Bauschinger, 1886). Additionally, the hardening rate that follows with continuation of straining in the reverse direction is also different from that during monotonic pre-straining. This stress offset between forward and reversed flow is referred to as the permanent softening (Hasegawa et al., 1975; Zang et al., 2013). These characteristics of material behavior are governed by the evolution of the underlying physical phenomena within the material microstructure, which are briefly summarized below. In particular, the presence of a second phase in the microstructure is known to enhance the non-linear unloading, the BE and the permanent softening effects (Bate and Wilson, 1986; Beyerlein, 2008).

First, the unloading of a pre-strained material consists of an initial linear elastic response, followed by a small nonlinear departure from the linear response (Deng et al., 2016; Pavlina et al., 2015; Sritharan and Chandel, 1997; Yoshida et al., 2002). The origin of the nonlinear unloading is in the partial re-emission of dislocations impeded by grain and phase boundaries during forward loading (Mompiou et al., 2012; Sritharan and Chandel, 1997). Dislocations incorporated in the boundaries during forward loading are referred to as the dislocation pile-ups. The re-emission process of the loosely-tangled dislocation population from the pile-ups is facilitated by the relaxation of micro backstresses arising from the dislocations pile-ups during unloading (Sritharan and Chandel, 1997). The level of pre-strain achieved during forward loading increases the magnitude of deviation from the linear elastic unloading behavior. Hence, to predict the non-linear unloading, material models must first accurately model pre-straining.

Second, the BE is observed and extensively studied in both single crystal (Demir and Raabe, 2010; Gough et al., 1927) and polycrystalline metals (Abel, 1987; Nieh and Nix, 1986; Stout and Rollett, 1990; Verma et al., 2011). The origin of BE in single crystals is a backstress having intra-granular source. This backstress arises from the incompatibility between hard regions of dislocation cell walls and soft regions of cell interiors (Kassner et al., 2013; Mughrabi, 1983). These long range internal stresses are known as the type III stresses. The built up of the type III stresses (Withers and Bhadeshia, 2001) acts against the applied stress during forward loading. Upon loading in the reverse direction, the applied stresses combine with the backstresses, which results in a drop of the reverse yield stress. Orowan's theory states that there is an anisotropy in resistance to dislocation motion between forward and reverse motion, and thus, it offers an additional explanation of the BE in single crystals (Orowan, 1959). Intuitively, dislocations move easier in the reversed direction because obstacles on the same path have been overcome during the forward motion. The mechanism causing the BE in single crystals is partly responsible for the BE in polycrystalline materials.

In single-phase polycrystalline metals backstresses, develop from interactions between individual grains of different crystal orientation during deformation. The origin of these backstresses is the anisotropy of grains with different crystal orientation, which causes varying properties over a material volume. These intergranular stresses are known as the type II stresses. A harder grain surrounded by softer grains will undergo lower plastic deformation than its surrounding neighbors. Incompatibility of accommodated plastic strain between the grains causes accumulation of dislocations around the strong grain, which results in the plastic strain gradient. The dislocations creating the gradient are referred to as the geometrically necessary dislocations (GNDs) (Bayley et al., 2006; Fleck et al., 1994).

The type II intergranular stresses act concurrently with intra-granular backstresses at phase boundaries in a multi-phase material. However, the density of GNDs surrounding grains of a harder phase inside grains of a softer phase is much larger than in single-phase grains due to typically large strength incompatibilities between grains of different phases than grains of the same phase and, thus, have a strong influence on the local and overall mechanical behavior of the multi-phase material (Brown and Stobbs, 1971; Kadkhodapour et al., 2011; Nesterova et al., 2015; Taupin et al., 2013). The GNDs layer of increased dislocation density induces directional internal stress originating from the layer to surrounding regions, which combines with the intergranular backstresses in individual phases, intra-granular backstresses in single crystals and the applied loading to determine the overall material behavior.

Third, the permanent softening effect originates from the annihilation/dissolution of the loosely-tangled dislocations contained in dislocation substructures such as cell walls formed during the primary deformation path, as well as the slow buildup of new dislocation substructures during deformation in the opposite direction (Kitayama et al., 2013; Stout and Rollett, 1990; Wilson et al., 1990). The presence of a harder second phase enhances the process of dislocation annihilation during reverse loading (Bate and Wilson, 1986; Gardey et al., 2005; Hasegawa et al., 1975; Wilson and Bate, 1986).

Simple phenomenological material models that are based on isotropic continuum plasticity are recognized to be incapable of capturing the above summarized effects (Armstrong and Frederick, 1966; Li et al., 2002), which motivated the development of more sophisticated phenomenological models. A range of models combining isotropic and linear or nonlinear kinematic hardening laws have been developed (Armstrong and Frederick, 1966; Chaboche and Rousselier, 1983; Chaboche, 1977, 2008; Hu et al., 1992; McDowell, 1992). These phenomenological models, while computationally efficient and relatively easy to implement within FE codes, are not physically-based and therefore do not directly account for the mechanistic sources of backstresses and dislocation processes. A significant limitation of these models is that it is difficult to identify the values of model parameters, which demands expensive and complex mechanical tests and inverse methodologies to fit the parameters (Smith et al., 2014). Additionally, these models apply only to a specific material state and, sometimes, to the specific loading conditions used in the model fitting process.