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Micromechanical modeling of the work-hardening behavior of single- and dual-phase steels under two-stage loading paths

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ABSTRACT

Work-hardening behavior of single-phase steel and dual-phase steel which is made of hard martensite surrounded by soft ferrite is analyzed by using an elastoplastic crystal plasticity model in conjunction with the incremental self-consistent model. Two-stage loading paths consisting of uniaxial tension, unloading and subsequent uniaxial tension/compression for various directions are applied. Bauschinger effect and transitional re-yielding behavior, which depends on the direction of the second loading path, are predicted and analyzed with respect to the distribution of the residual resolved shear stresses within the material. These features, which are caused by the inhomogeneity of the residual stress field, are especially pronounced in the case of the dual-phase steel because of the strong mechanical contrast between ferrite and martensite phases.

1. Introduction

In the context of metal forming processes, a sheet metal undergoes complex strain paths. In the last decades, intensive experimental works have been carried out to understand the deformation behavior of low carbon and IF steels under complex strain paths. In some of the studies [1–3] various two-stage strain paths were applied to sheet samples and the mechanical behavior and dislocation substructures were observed. A lower re-yield stress with work-hardening stagnation was observed under the reverse loading path (i.e. the directions of strain increment in the first and second paths are opposite). An increase of the re-yield stress followed by work softening was detected under the orthogonal loading path (i.e. the contracted product of the strain increments in the first and second path is zero). These behaviors are often called as the Bauschinger and cross-hardening effects, respectively. Based on TEM observations, these mechanical behaviors were correlated to dislocation substructures. When the loading is reversed, dislocation cell structure dissolves and mobile dislocations annihilate with the dislocations with the opposite sign. Consequently, the re-yield stress is lowered. The cross-hardening effect is caused by dislocation cells walls formed parallel to the active slip systems in the first loading, which becomes obstacles to mobile dislocations on new active slip systems during the second loading. The work-hardening behavior of IF steel is now well recognized in terms of the dislocation substructure.

Unlike IF and mild steels, there have been fewer studies on the plastic deformation behavior of dual-phase steel under complex loading paths. In some of the experimental works [4–8] complex loading paths were applied to dual-phase steels, and it was observed that in the reverse loading path, the stress–strain curve during unloading deviates from the one estimated by the Hooke's law, and large Bauschinger effect and permanent softening were observed. The Bauschinger effect is more pronounced for the dual-phase steel than for IF steel. In the work of Haddadi et al. [6] and Gardey et al. [4], the orthogonal loading path is applied to a dual-phase steel and they revealed that almost no cross-hardening effect takes place for the material, which is clear difference from the IF/mild steels. Following the traditional approach, Gardey et al. [4] observed dislocation substructure by means of TEM and found that the dislocation cell structures were more difficult to form and to dissolve in dual-phase steel than in IF steel. However, there is quite a difference in the formation of dislocation cell structures and this observation cannot explain the different mechanical behaviors observed in the two kinds of steels. Unlike IF steel, there is no clear one to one correlation between dislocation substructure and work-hardening behavior.

The two following mechanisms could explain the difference in the work-hardening behavior: (i) martensite is formed by displacive transformation so that internal residual stresses can exist

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within the material at the initial state, and/or (ii) the mechanical contrast between ferrite and martensite leads to a highly heterogeneous stress field. From the latter point of view, the Bauschinger effect was numerically studied by Zhonghua and Haicheng [9] for a dual-phase steel and by Terada et al. [10] for a ferrite–cementite two-phase material, for instance. In both studies, two-dimensional finite elements model consisting of hard phase surrounded by soft phase is constructed, and uniaxial tension followed by uniaxial compression was considered in [9] while plane strain tension followed by plane strain compression was applied in [10]. They reported that the heterogeneous stress field derives the Bauschinger effect. In these works, however, isotropic phenomenological constitutive model was adopted so that the heterogeneity among grains was neglected. Furthermore the work-hardening behavior was investigated only for the tension–compression loading.

The present investigation is an attempt to capture the influence of stress and strain heterogeneities within the polycrystal on the work-hardening behavior under complex loading paths. The mechanical behavior of single- and dual-phase steel is estimated by means of homogenization techniques in the framework of crystalline plasticity. To give an insight into the sole influence of the stress heterogeneity, other mechanisms which contribute to Bauschinger and cross-hardening effects are neglected. For instance, initial residual stresses are not considered, the slip systems are assumed to harden isotropically while texture evolution is neglected. The brief outline of the paper is as follows. In Section 2, a rate-independent crystal plasticity model and the Hill's incremental self-consistent model [11], which is one of the most customary approaches, are briefly reviewed. In Section 3, two-stage loading paths and material properties used in simulation are given. For comparison, in addition to a dual-phase steel, a single-phase steel the strength of which is almost the same as the dual-phase steel is also considered. In Section 4, the heterogeneity within single-phase steel, which emerges due to the crystalline anisotropy of the grains, is investigated first. Then, in Section 5, the work-hardening behavior of dual-phase steel is studied.

2. Theoretical frameworks

2.1. Rate-independent crystal plasticity model

In this study, we use the crystal plasticity formulation described in [12,13]. We confine attention to small strain conditions. The strain rate is given by the symmetry part of $\partial \mathbf{v}/\partial \mathbf{x}$, where $\mathbf{v}$ and $\mathbf{x}$ are velocity and position, respectively. We consider additive decomposition of strain rate into elastic and plastic parts.

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}. \tag{1}$$

Elastic relation is given by Hooke's law.

$$\dot{\boldsymbol{\sigma}} = \mathbf{C}^{\mathrm{e}} : \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} = \mathbf{C}^{\mathrm{e}} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}), \tag{2}$$

where $\boldsymbol{\sigma}$ and $\mathbf{C}^{\mathrm{e}}$ are the true stress and the forth-order elastic moduli tensor, respectively.

Crystallographic slips are considered to be the source for the plastic deformation, and the plastic strain rate takes the form

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}} = \sum_{\alpha} sgn(\tau^{(\alpha)}) \dot{\gamma}^{(\alpha)} \mathbf{p}^{(\alpha)}, \tag{3}$$

$$\mathbf{p}^{(\alpha)} := \tfrac{1}{2}(\mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)} + \mathbf{m}^{(\alpha)} \otimes \mathbf{s}^{(\alpha)}), \tag{4}$$

where $\dot{\gamma}^{(\alpha)}$, $\mathbf{s}^{(\alpha)}$, and $\mathbf{m}^{(\alpha)}$ are the positive slip rate, the slip direction and the slip plane normal for the αth slip system, respectively.

Based on the Schmid law, the yield function is written as

$$f^{(\alpha)} = |\tau^{(\alpha)}| - g^{(\alpha)} = 0, \tag{5}$$

where the resolved shear stress for the αth slip system, $\tau^{(\alpha)}$, is given as

$$\tau^{(\alpha)} = \mathbf{s}^{(\alpha)} \cdot \boldsymbol{\sigma} \cdot \mathbf{m}^{(\alpha)} = \boldsymbol{\sigma} : \mathbf{p}^{(\alpha)} \tag{6}$$

Based on yield function, potentially active and inactive slip systems are classified as

$$\dot{\gamma}^{(\alpha)} \geq 0, \quad \text{for} f^{(\alpha)} = 0 \quad \text{and} \quad \dot{f}^{(\alpha)} = 0, \tag{7a}$$

$$\dot{\gamma}^{(\alpha)} = 0, \quad \text{for} f^{(\alpha)} < 0, \quad \text{or} \quad f^{(\alpha)} = 0 \quad \text{and} \quad \dot{f}^{(\alpha)} < 0. \tag{7b}$$

Evolution of a resolved shear stress and slip resistance are written as

$$\dot{\tau}^{(\alpha)} = \mathbf{p}^{(\alpha)} : \mathbf{C}^{\mathrm{e}} : \dot{\boldsymbol{\varepsilon}} - \sum_{\beta} \dot{\gamma}^{(\beta)} \mathbf{p}^{(\alpha)} : \mathbf{C}^{\mathrm{e}} : \mathbf{p}^{(\beta)}, \tag{8}$$

$$\dot{g}^{(\alpha)} = \sum_{\beta} h^{(\alpha\beta)} |\dot{\gamma}^{(\beta)}|, \quad h^{(\alpha\beta)} = h_0 \left(1 + \frac{h_0 \gamma_{\mathrm{a}}}{\tau_0 n}\right)^{n-1},$$

$$\gamma_{\mathrm{a}} = \int_0^t \sum_{\alpha} |\dot{\gamma}^{(\alpha)}| \mathrm{d}t, \tag{9}$$

where $\mathbf{s}^{(\alpha)}$ and $\mathbf{m}^{(\alpha)}$ are assumed to be constant, $h^{(\alpha\beta)}$ denotes hardening moduli and τ_0, h_0 and n are material parameters. In Eq. $(9)_2$, the latent hardening is neglected.

From the consistency condition of the yield function, the slip rates, $\dot{\gamma}^{(\alpha)}$, on the active slip systems are determined as

$$\dot{f}^{(\alpha)} = R^{(\alpha)} - \sum_{\beta} X^{(\alpha\beta)} \dot{\gamma}^{(\beta)} = 0, \tag{10}$$

$$\dot{\gamma}^{(\alpha)} = \sum_{\beta} Y^{(\alpha\beta)} R^{(\beta)}, \tag{11}$$

where

$$R^{(\alpha)} := sgn(\tau^{(\alpha)}) \mathbf{p}^{(\alpha)} : \mathbf{C}^{\mathrm{e}} : \dot{\boldsymbol{\varepsilon}}, \tag{12a}$$

$$X^{(\alpha\beta)} := h^{(\alpha\beta)} + sgn(\tau^{(\alpha)}) sgn(\tau^{(\beta)}) \mathbf{p}^{(\alpha)} : \mathbf{C}^{\mathrm{e}} : \mathbf{p}^{(\beta)}, \tag{12b}$$

$$[Y^{(\alpha\beta)}] = [X^{(\alpha\beta)}]^{-1}, \tag{12c}$$

where $(\,\cdot\,)^{-1}$ denotes the inverse. Depending on $h^{(\alpha\beta)}$, $X^{(\alpha\beta)}$ may become singular. In that case, slip systems equal to or less than five linearly independent slip systems are selected as active systems from a set of potential slip systems and the other potentially active slip systems are taken to be inactive. The set of potentially active slip systems will be known from Eq. (7). In this computation, isotropic hardening of slip systems is assumed and texture evolution is neglected so that the selection of active slip systems has little influence on the predictions.

We finally obtain the rate-form of the constitutive equation, $\dot{\boldsymbol{\sigma}} = \mathbf{L} : \dot{\boldsymbol{\varepsilon}}$,

$$\mathbf{L} := \mathbf{C}^{\mathrm{e}} - \sum_{\alpha} \left\{ (sgn(\tau^{(\alpha)}) \mathbf{C}^{\mathrm{e}} : \mathbf{p}^{(\alpha)}) \otimes \sum_{\beta} (sgn(\tau^{(\beta)}) Y^{(\alpha\beta)} \mathbf{p}^{(\beta)} : \mathbf{C}^{\mathrm{e}}) \right\}. \tag{13}$$

2.2. Incremental self-consistent model

The incremental self-consistent model proposed by Hill [11], which is widely used for elastoplastic polycrystal, is adopted. With the assumption of equiaxed grains randomly distributed, the polycrystal is considered to consist of spherical phases with a given crystalline orientation. In the self-consistent approach, each constitutive spherical phase is assumed to be embedded in an infinite linear comparison homogenous medium which has a unique tangent moduli corresponding to the effective tangent ones. The phase