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The simultaneous occurrence of martensitic transformation and reversion of martensite

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ABSTRACT

We use a 3D elastoplastic phase-field model to study the simultaneous occurrence of martensitic transformation as well as the reversion of martensite in steels under uni-axial tension. Our results show that although martensite nucleates and grows as a single lath (variant), it reverts and splits into two independent martensite laths, due to "unfavorable" local stresses.

1. Introduction

Phase transformations and phase reversion play an important role in enhancing the materials properties. The martensitic transformation, a solid state phase transformation of parent austenite to product martensite, gives rise to excellent mechanical properties of steels. Reverse phase transformations, i.e. the reversion of the product phase (martensite) back to the parent phase (austenite), through annealing (heat treatment) have been reported to improve both strength and ductility of steels [1–3]. The high dislocation density of reversed austenite, retained from martensite, is also considered to be an important factor in improving the strength of steels [4,5]. Moreover, the shape memory effect is based on the reversion of martensite to austenite through heating and has lead to widespread usage of shape memory alloys [6].

Traditionally, phase transformations and phase reversion have been considered to occur independently under different processing conditions, i.e. martensitic transformation during cooling and reversion of martensite during heating. However, it is interesting to study whether the martensitic transformation and reversion can occur together and at the same time. An understanding of the mechanisms underlying the simultaneous occurrence of phase transformation and reversion can lead to new thermo-mechanical processes to improve mechanical properties of steels.

The phase-field approach [7,8] has been successfully used to study martensitic transformation under different thermo-mechanical conditions [6,9–21]. In the present work, we study the simultaneous occurrence of both martensitic transformation and reversion of martensite in steels under uni-axial tension, by using a 3D elastoplastic phase-field model [20].

2. Phase-field model

The microstructure evolution is governed by the phase-field equation:

$$\frac{\partial \eta_p}{\partial t} = -\sum_{q=1}^{q=v} L_{pq} \frac{\delta G}{\delta \eta_q} \tag{1}$$

where η_q is the phase field variable that tracks the evolution of martensite, v is the total number of martensite variants and L_{pq} is a matrix of kinetic parameters. As the 24 different martensite variants can be grouped together into three Bain groups [22,23], three phase-field variables (η_1, η_2, η_3) are considered in the present work [20].

From a physical point of view, the Gibbs energy of a system undergoing stress-assisted martensitic transformation can be expressed as

$$G = \int_V \left(G_v^{chem} + G_v^{grad} + G_v^{el} + G_v^{appl} \right) dV \tag{2}$$

where G_V^{chem} corresponds to the chemical part of the Gibbs energy density, G_V^{grad} is the gradient energy term, G_V^{el} is the elastic strain energy density and G_v^{appl} is the extra Gibbs energy density due to the externally applied stress.

G_v^{chem} is expressed as a Landau-type polynomial and G_V^{grad} is expressed in terms of the gradients of η_p [10,14].

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G_V^{el} can be expressed as

$$G_V^{el} = \int_{\varepsilon_{ij}^0(\mathbf{r})}^{\varepsilon_{ij}(\mathbf{r})} c_{ijkl}\varepsilon_{kl}^{el}(\mathbf{r})\, d\varepsilon_{ij}(\mathbf{r}) \tag{3}$$

where c_{ijkl} is the tensor of elastic constants, $\varepsilon_{ij}(\mathbf{r})$ is the total strain and $\varepsilon_{ij}^0(\mathbf{r})$ is the stress–free transformation strain expressed in terms of η_q and Bain strains (ε_{ij}^{00}). $\varepsilon_{kl}^{el}(\mathbf{r})$ is the elastic strain, given by

$$\varepsilon_{kl}^{el}(\mathbf{r}) = \varepsilon_{kl}(\mathbf{r}) - \varepsilon_{kl}^0(\mathbf{r}) - \varepsilon_{kl}^{pl}(\mathbf{r}) \tag{4}$$

where $\varepsilon_{kl}^{pl}(\mathbf{r})$ is the plastic strain.

The evolution of plastic strain $\varepsilon_{ij}^{pl}(\mathbf{r})$, which comes into existence when the elastic stress exceeds the yield limit and the

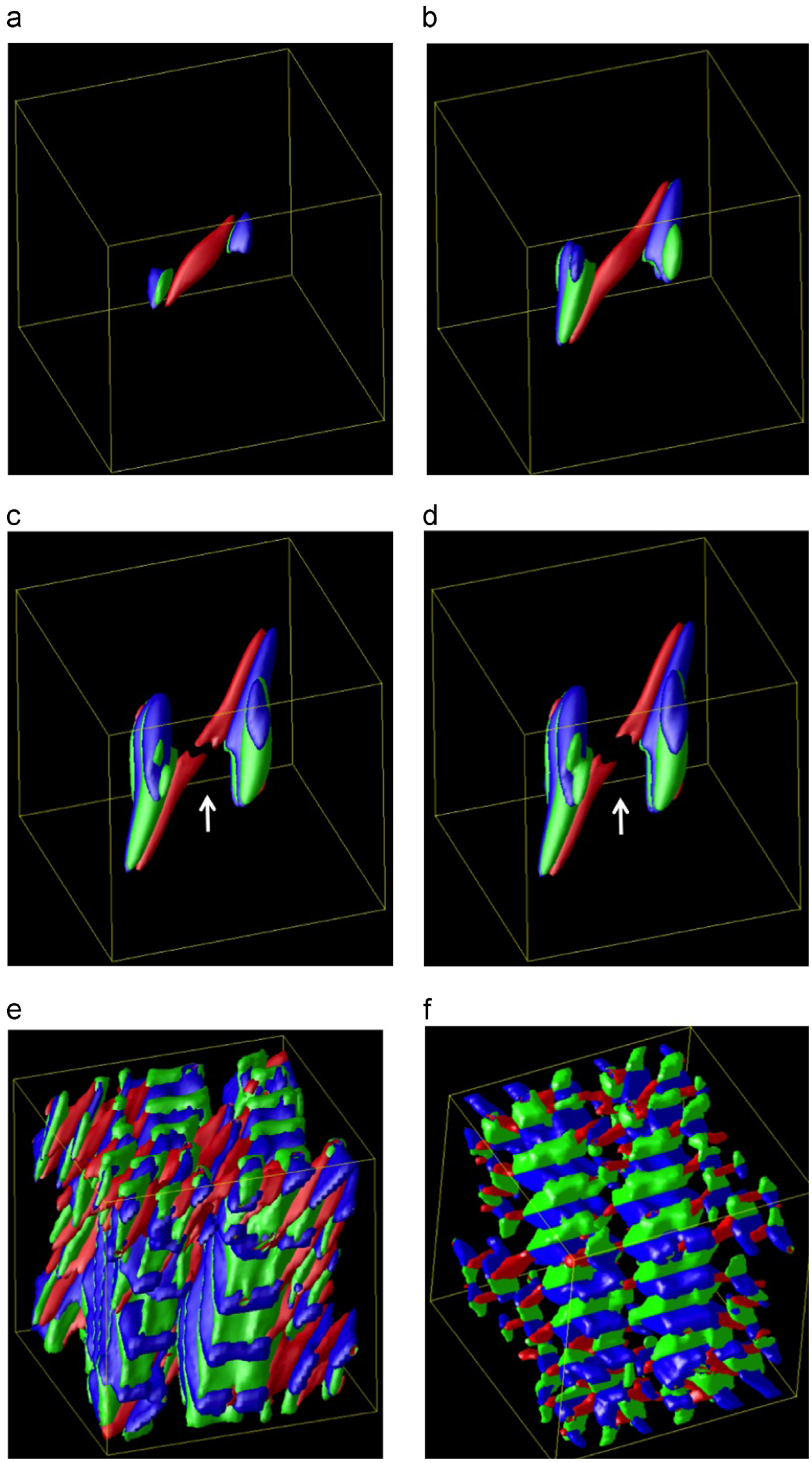

Fig. 1. Simultaneous occurrence of martensitic transformation and martensite reversion to austenite in carbon steels under uni-axial tension. Microstructure evolution at (a) $t^*=20$, (b) $t^*=25$, (c) $t^*=31$, (d) $t^*=32$, (e) $t^*=300$, (f) top view of (e). Austenite is shown in black color. Martensite variants - 1, 2 and 3 are shown in red, blue and green, respectively. Reversion of martensite (arrow) causes a single martensite lath to split into two independent laths, separated by austenite. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)