Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 58 (2010) 85–91
Acta MATERIALIA
www.elsevier.com/locate/actamat

Transformation potential predictions for the stress-induced austenite to martensite transformation in steel

A. Creuziger *, T. Foecke

National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, MD 20899, USA

Received 29 May 2009; received in revised form 24 August 2009; accepted 27 August 2009
Available online 28 September 2009

Abstract

The stress-induced transformation behavior of retained austenite is considered in this work. With the development of transformation-induced plasticity (TRIP) steels this deformation mode is of growing importance. Twinned martensite structures were calculated using the crystallographic theory of martensite. An available work criterion was used to predict the transformation potentials for 16 different in-plane stress states for sheet sample geometry. By rotating the twinned martensite structures over all crystallographic orientations using Euler angles, the magnitude of the transformation potential was plotted as an orientation distribution plot for comparison with typical texture components. From these data, the Brass and Copper orientation components that are typical in retained austenite such as in TRIP steels were found to have low transformation potential values. Grains aligned with these orientations would require higher stresses to transform than other orientations, and may therefore never transform. This correlates to experimental observations that heavily deformed TRIP steel contains residual retained austenite.
Published by Elsevier Ltd. on behalf of Acta Materialia Inc.

Keywords: TRIP steel; Texture; Austenitic steels; Martensitic phase transformation

1. Background

1.1. TRIP steel

Transformation-induced plasticity (TRIP) steels are a relatively new class of advanced high-strength steels (AHSS) that show both high strength and high ductility [1] and are being considered for widespread use in automotive applications to lighten automobile bodies. High strength and high ductility are typically mutually exclusive, but are obtained in TRIP steels by stabilization of the austenite phase and strain-induced deformation from the retained austenite into the martensite phase, as was first published by [2]. There are two categories of TRIP steels, TRIP-H and TRIP-L [3], also referred to as TRIP steel and TRIP-assisted steel, respectively [4]. TRIP-H steels are almost entirely austenite, due to high volume fractions (≈10% mass fraction) of Ni and Cr added for austenite stabilization. These high-alloy steels are fairly expensive due to the addition of these alloy elements, and have not been widely used in automotive applications [3]. In comparison, the TRIP-L steels are initially a mixture of ferrite, bainite and austenite, with the austenite composing (5–25)% of the total mass fraction depending on alloying elements and thermomechanical treatment [5]. For these alloys, the austenite is stabilized by additions of ≈2% mass fraction Mn and ≈2% mass fraction Al or Si, making these low-alloy steels [6,7]. The lower cost of the TRIP-L steels has lead to interest in use of these materials in automotive production. However, the lack of knowledge about the forming behavior in multiaxial strain states has limited the automotive use of these alloys.

This paper focuses on the crystallographic texture of the austenite phase and its effect on the transformation behavior. Prior investigations into the texture of the austenite phase [8,9] showed that the initial texture exhibits Brass

* Corresponding author. Tel.: +1 301 975 6015.
E-mail addresses: adam.creuziger@nist.gov (A. Creuziger), tim.foecke@nist.gov (T. Foecke).

1359-6454/$36.00 Published by Elsevier Ltd. on behalf of Acta Materialia Inc.
doi:10.1016/j.actamat.2009.08.059

or Copper orientations, typical for rolled face-centered cubic (FCC) materials. Materials with FCC structure also tend to recrystallize in cube orientation [10, page 221;11]. However, there has been little data on how favorable any of these orientations are to transformation.

Stress-induced martensite can transform into two possible structures: a single variant of martensite or twinned martensite. Transformation into a single variant of martensite is rare, due to the specific requirements on the lattice parameters needed for transformation [12]. However, twinned martensite has been observed in both TRIP-H steels [13] and TRIP-L steels [14].

There have been a few attempts at predicting the dependence of the orientation on transformation. Van Rompaey et al. [15] used the single-variant assumption, finite element analysis (FEA) and analytic solutions to calculate the mechanical driving force energy under multiaxial loading conditions, suggesting the use of a twinned martensite technique to advance their analysis. Zhang et al. [16] also assumed a single-variant transformation, and for uniaxial compression loading predicts that cube orientations will transform first. More detailed transformation analysis, including the difference between Kurdjumov–Sachs (K-S) and Nishiyama–Wasserman (N-W) was performed in Ref. [9], but the stress state was not taken into account.

In this work, twinned martensite structures are used, in conjunction with calculation of a transformation potential, defined below, which includes the stress required for transformation. Sixteen different in-plane stress states are applied to the twinned martensite structures. The twinned martensite structures are rotated over all of orientation space to represent possible grain orientations. This technique allows simultaneous investigation of the stress state and orientation dependence on the austenite to twinned martensite transformation and will provide a more complete view of what orientations and stress states are favorable for transformation.

1.2. Crystallographic theory of martensite

To calculate the twinned martensite structure, the crystallographic theory of martensite (CTM) was used. The full details of this method are described in Refs. [12,17,18]. The terms a' and c' are defined to be the body-centered tetragonal (BCT) unit cell dimensions, and a_0 is defined as the FCC unit cell length. For this analysis, the FCC lattice is assumed to be in the $m3m$ space group and is taken to be the reference lattice. Using these definitions, for the FCC to BCT transformation, three stretch tensors or martensite variants are possible:

$$U_1 = \begin{bmatrix} \gamma & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \alpha \end{bmatrix}, \quad U_2 = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \gamma & 0 \\ 0 & 0 & \alpha \end{bmatrix},$$
$$U_3 = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \gamma \end{bmatrix}, \quad \alpha = \frac{2a'}{\sqrt{2}a_0}, \quad \gamma = \frac{c'}{a_0} \tag{1}$$

To calculate twinning, two variants labeled $\mathbf{U}^{(i)}$ and $\mathbf{U}^{(j)}$ are used as well as a rotation $\mathbf{R}$ of the martensite variant (j) in the following compatibility equation:

$$\mathbf{R}\mathbf{U}^{(j)} - \mathbf{U}^{(i)} = \mathbf{a} \otimes \hat{\mathbf{n}} \tag{2}$$

where $\mathbf{a}$ is the shearing vector of the twin and $\hat{\mathbf{n}}$ is the mirror plane normal between variants. The Bain transformation is assumed in the current analysis; the additional details of K-S or N-W transformations are not included in the twinning calculation. These transformations could be included, but most texture data is described in 5° increments, which makes the N-W and K-S transformations difficult to distinguish from the Bain transformation [19].

After the twinning equation is calculated, an additional compatibility equation between the twinned martensite and the austenite is required. The terms $\mathbf{U}^{(i)}, \mathbf{U}^{(j)}, \mathbf{R}$ terms are the same as used in Eq. (2), with the additional terms for the rotation of the twinned structure $\bar{\mathbf{R}}$ for compatibility with the austenite $\mathbf{I}$ and the variant volume ratio λ describing the relative proportion of the two martensite variants in the twinned structure. The compatibility equation for an austenite-twinned martensite interface is:

$$\overline{\mathbf{R}}\left(\lambda \mathbf{R}\mathbf{U}^{(\mathbf{j})} + (\mathbf{1}-\lambda)\mathbf{U}^{(\mathbf{i})}\right) - \mathbf{I} = \mathbf{b} \otimes \hat{\mathbf{m}} \tag{3}$$

The austenite to twinned martensite interface can thus be described as two vectors, containing the plane normal to the interface $\hat{\mathbf{m}}$ and the shearing direction and magnitude $\mathbf{b}$ for the twinned structure. For the FCC $m3m$ point group and the BCT 23 point group in Hermann–Mauguin notation, there are 24 possible interfaces. A program developed by T.W. Shield was used for these calculations [20].

1.3. Available work criterion

In order to predict which of the twinned martensite structures are likely to form, an available work criterion is applied:

$$W^{(k)} = \mathrm{b}_i^{(k)} \sigma_{ij} \hat{\mathrm{m}}_j^{(k)} \tag{4}$$

where b and $\hat{\mathrm{m}}$ are the interface vectors for the 24 possible interfaces (k) and σ is the stress state. The scalar W represents the value of a transformation potential and is derived from the Schmid law for plasticity and is similar to the critical resolved shear stress [21]. For a given stress state, the maximum value of $W^{(k)}$ for all k is denoted as $\widetilde{W}$. The interface associated with the maximum value $\widetilde{W}$, defined as $\tilde{k}$, is the interface that is most likely to form. This criterion has been used previously to predict the specific twinned martensite structure that forms in both uniaxial tension and around a notch in shape-memory alloys with good agreement [21–23]. To avoid confusion when discussing the magnitudes of the maximum transformation potential $\widetilde{W}$, $\widetilde{\bar{W}}$ will be referred to as the transformation potential for the rest of this paper.

For the current application, instead of predicting which interface will form, determining which orientations will