Different Mechanisms of ε -M and α' -M Variant Selection and the Influencing Factors of ε -M Reversion During Dynamic Tension in TRIP Steel

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Abstract The variant selection of martensites (ε -M and α' -M) and ε -M reversion in dynamic tensile high-manganese TRIP steel were investigated. α' -M variant pairs with a zigzag morphology frequently formed, and the pairs of neighboring α' -M variants were examined in terms of mechanical work and strain energy reduction. The occurrence of a primary α' -M variant is determined by mechanical work, but high products of mechanical work and strain energy reduction are essential for secondary variant selection. In contrast to α' -M variant pair selection, ε -M variant selection can be attributed to the highest mechanical work. During ε -M $\rightarrow$ α' -M transformation, the mechanical work of ε -M reversion is higher than that of α' -M variant, thereby implying that ε -M reversion in $\langle 110 \rangle_\gamma$ grain is possible. ε -M plate distribution also affects the feasibility of ε -M reversion.

KEY WORDS: TRIP-assisted steel; Dynamic plastic deformation; Martensitic transformation; Variant selection; Orientation relationship

1 Introduction

High-manganese transformation-induced plasticity (TRIP) steel possesses a good combination of strength and toughness because of deformation-induced martensite in austenite (γ) grains [1, 2]. Martensitic transformation is accomplished in a sequence of $\gamma \rightarrow \varepsilon$ -M (hexagonal close-packed martensite) $\rightarrow \alpha'$ -M (body-centered cubic martensite) in TRIP steel [3–5]. Kurdjumov–Sachs (K–S) orientation relationship exists between parent austenite γ and transformed martensite α' -M, $\{111\}_\gamma // \{110\}_{\alpha'-M}$ and

$\langle 110 \rangle_\gamma // \langle 111 \rangle_{\alpha'-M}$ [5, 6]. Twenty-four α' -M variants may consequently form in a γ -phase grain [7, 8]. The total number of selected variants is generally lower than the upper limit, indicating that variant selection occurs during martensitic transformation. Several criteria have been proposed to explain variant selection during martensitic transformation. Miyamoto [8] and Malet [9] reported that variants whose $(110)_\alpha$ planes are nearly parallel to the primary slip plane in γ develop preferentially. Morito et al. [10–14] found that strain accommodation plays an important role in variant selection. Kundu et al. [15–17] demonstrated that variant selection can be predicted by the highest interaction energy between residual stress and phase transformation strain. In different approaches, mechanical work induced by local stress and transformation strain is calculated to analyze martensite variant selection [18, 19].

In our previous work [20], mechanical work and strain energy are considered to examine α' -M variant selection in $\langle 111 \rangle_\gamma$ grain under dynamic tension. However, the effects of mechanical work and strain energy on α' -M variant pair

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selection are unclear. Differences in the mechanisms of variant selection during ε -M and α' -M transformation are also poorly understood. ε -M reverse transformation in $\langle 110 \rangle_\gamma$ grain has been reported [21], but its corresponding mechanism has yet to be described.

In this study, the variant selections of martensites (ε -M and α' -M) and ε -M reversion under dynamic tension are quantitatively evaluated, and α' -M variant pairs with a zigzag morphology are discussed. The possibility of ε -M reversion is investigated by combining the results of electron backscatter diffraction (EBSD) and theoretical calculation.

2 Experimental

High-manganese TRIP steel with a composition of Fe-19.4 Mn-3.41 Si-2.28 Al-0.036 C (wt%) was used in this study. Ingots were heated at 1323 K for 2 h and quenched in water. A tensile specimen was then cut from these quenched ingots. Tensile deformation was performed on a split-Hopkinson tension bar. Metallographic examination was conducted on the cross section perpendicular to the tensile axis of the specimens. The specimens were electrolytically polished with 5% HClO₄ and etched with 4% Nital solution. A scanning electron microscope equipped with HKL EBSD systems was applied to evaluate orientation relationships, phase distribution, and variant selection.

3 Results and Discussion

3.1 Microstructural Characterization

The microstructure of experimental TRIP steel prior to deformation is shown in Fig. 1a. Equiaxed γ grains and a small amount of ε -M exist. The sizes of the austenitic grains range from 100 to 200 μm . During dynamic deformation, $\gamma \rightarrow \varepsilon$ -M and ε -M $\rightarrow \alpha'$ -M transformation occur (Fig. 1b). EBSD revealed a typical zigzag-type α' -M

(marked by arrows in Fig. 1c) is widely distributed in γ grains with orientation between $\langle 111 \rangle$ and $\langle 112 \rangle$. Also the neighboring α' -M are found to be different α' -M variants (marked by a and b in Fig. 1c), which will be described later in Fig. 2. One α' -M variant is selected in the presence of the highest driving force because strain energy, which is the resisting force of phase transformation, of each variant is the same. The other one appears subsequently because of strain accommodation, leading to its zigzag morphology. Considering that the orientation dependence of martensitic transformation exists during dynamic tension, we found that α' -M easily forms in $\langle 111 \rangle_\gamma$ and $\langle 112 \rangle_\gamma$ grains, whereas the volume of α' -M in $\langle 110 \rangle_\gamma$ and $\langle 100 \rangle_\gamma$ grains is less than those in $\langle 111 \rangle_\gamma$ and $\langle 112 \rangle_\gamma$ grains [20]. The variant selection of two kinds of martensites (ε -M and α' -M) and the ε -M reversion in differently oriented γ grains will be discussed later. Four ε -M variants developed from (111) , $(\bar{1}11)$, $(1\bar{1}1)$, $(11\bar{1})$ are expressed as ε_1 , ε_2 , ε_3 , and ε_4 , respectively. The α' -M variants formed on these ε -M variants are expressed as V1–V6, V7–V12, V13–V18, and V19–V24, respectively [7, 8].

3.2 Variant Selection Mechanisms of ε -M and α' -M

Mechanical work at a particular external stress ($\sigma = 200$ MPa) is calculated by expressing transformation strain (ε) in a macroscopic reference frame. The lattices of ε -M and α' -M are obtained from a specific deformation of γ and ε -M lattice; thus, the corresponding shape strain (D) and transformation strain (ε) can be calculated, where cell parameters are $a_\varepsilon = 2.5282$ Å, $c_\varepsilon = 4.1198$ Å, and $a_{\alpha'} = 2.8715$ Å [18, 19]. Taking into account the crystal symmetry, the mechanical works of four ε -M and twenty-four α' -M variants are calculated.

Figure 2 illustrates the EBSD orientation image maps and the corresponding pole figures of γ , ε -M, and α' -M phases in grain A at a strain rate of 1600 s^{−1}. Two ε -M variants (ε_2 and ε_3) out of four possible variants are selected, with ε_2 as the dominant variant. The mechanical work $[(1/2)\sigma \cdot \varepsilon_{\gamma \rightarrow \varepsilon-M}]$ of four possible ε -M variants is

Fig. 1 Microstructure of TRIP steel: **a** before deformation, **b** after deformation, **c** enlarged view of zigzag-type α' -M variant pairs after deformation

Fig. 2 Orientation maps and pole figures of grain A (a deviated $\langle 111 \rangle \gamma$ grain) during tension at a strain rate of 1600 s^{-1} (TD-tensile direction): **a** orientation map I (gray color— γ , red color— ε -M, blue color— α' -M), **b** orientation map II (gray color— γ , red color— ε -M, Euler angles— α' -M), **c** pole figures of γ , ε -M, and α' -M

calculated on the basis of the experimental data in grain A (Fig. 3a), in which $\varepsilon_{\gamma \rightarrow \varepsilon-M}$ is the transformation strain required for one specific ε -M variant formation. In Fig. 3a, the highest and second highest values belong to ε_2 and ε_3 , respectively. This finding means that ε -M variants with higher mechanical work are selected preferentially in grain A. The data of 17 differently oriented γ grains also indicate that the mechanical work of ε -M variant can be denoted as the criterion for the variant selection of 93.9% ε -M.

Figure 2b also reveals that the V7, V9, V10, and V12 of α' -M are preferentially selected in ε_2 , and the V7/V12 pair is dominant which may be associated with strain accommodation. The misorientations of V7/V12, V7/V9, V7/V10, and V9/V10 pairs are $\langle 110 \rangle 50^\circ$, $\langle 110 \rangle 60^\circ$, $\langle 110 \rangle 10^\circ$, and $\langle 111 \rangle 60^\circ$, respectively. The mechanical works $[(1/2)\sigma \cdot \varepsilon_{\varepsilon-M \rightarrow \alpha'-M}]$ of α' -M variants in ε_2 are calculated (Fig. 3b), in which $\varepsilon_{\varepsilon-M \rightarrow \alpha'-M}$ is the transformation strain required for one α' -M variant formation. The strain energy

Fig. 3 **a** Calculated mechanical works of four ε -M variants in grain A, **b** calculated mechanical works and P value of six α' -M variants in grain A

of a single α' -M variant can be calculated according to Eq. (2). The shape strain (D_{ij}) and the strain energies of α' -M variant pairs with different misorientations in one ε -M plate can be calculated according to Eqs. (1) and (2) [19]. Consequently, strain energy reduction can be determined if α' -M variant exists in the pairs instead of individual variants.

$$D_{ij} = \frac{1}{2}(D_i + D_j). \quad (1)$$

$$S = \frac{E}{2(1+\nu)} \cdot \left[(\delta_1^2 + \delta_2^2 + \delta_3^2) + \frac{\nu}{1-2\nu} (\delta_1 + \delta_2 + \delta_3) \right]. \quad (2)$$

where D_i and D_j is the shape strain of two α' -M variants ($i, j = 1-6$), D_{ij} is the shape strain of variant pairs, δ_k ($k = 1-3$) is the principal strain, S is the strain energy, $\nu = 0.3$ (Poisson ratio), and E is Young's modulus.

The shape strain accompanying the appearance of one α' -M variant introduces severe elastic and plastic deformations around the γ/α' -M interface, thereby inducing the autocatalytic nucleation of other α' -M variants; non-parallel α' -M variants are possibly associated with strain accommodation [11, 12, 14, 22]. Therefore, either V7 or V12 is selected preferentially, and the other one appears subsequently because of strain accommodation; a zigzag morphology consequently develops. Humbert *et al.* [18] reported that variant selection is mainly controlled by the highest mechanical work induced by local stress. Kundu and Bhadeshia [23] emphasized that interaction energy and mechanical work can exactly produce the same result on variant selection. Considering that the strain energy (a resisting force to phase transformation) of any single variant is the same, single α' -M variant easily appears at a high amount of mechanical work if other factors are disregarded. In this study, our calculation shows that the mechanical work of V7 is the highest (Fig. 3b). Second, single V7, aside from the variant pair V12/V7, forms (Fig. 2b). These findings imply that V7 should be the primary variant and V12 is the secondary variant. The strain energy reduction of the α' -M variant pairs V7/V8, V7/V11, V7/V9, V7/V12, and V7/V10 is 73.93, 63.42, 63.42, 60.70, and 5.06% compared with that of single α' -M variant, respectively. Only V14 is observed in ε_3 . Therefore, the variant selection of α' -M variant pairs in ε_3 is not discussed.

On the one hand, if the occurrence of a secondary α' -M variant depends solely on the strain energy, the variant pair V8/V7 should appear for the corresponding highest strain energy reduction (73.93%). On the other hand, if the occurrence of the secondary α' -M variant completely relies on mechanical work, the variant pair V10/V7 should be selected. In fact, V12 is observed after the occurrence of

V7 in grain A. The variant pair V8/V7 is not selected because of the negative mechanical work of V8, and the variant pair V10/V7 is not chosen because of the lowest strain energy reduction (5.06%). Hence, high mechanical work and strain energy reduction are essential for secondary variant selection. The maximum product (P) of mechanical work and strain energy reduction is 3.404 in ε_2 , which belongs to V12 (Fig. 3b). Maximum P value is necessary to choose the secondary variant V12. Eleven γ grains with orientations between $\langle 111 \rangle$ and $\langle 112 \rangle$ are considered to evaluate the selection criterion of α' -M variant pair with a zigzag morphology. The findings show that the primary α' -M variants possess the highest mechanical work; maximum product of mechanical work and strain energy reduction are essential for the selection of a secondary variant in 92.3% α' -M variant pairs with zigzag morphology.

Humbert *et al.* [18] revealed that the influence of mechanical work on the variant selection of α' -M is weaker than that of the variant selection of ε -M because of different values of local stress from the applied uniaxial stress. We also found that the variant selection of ε -M is determined by mechanical work, but a different phenomenon is observed in α' -M. Mechanical work plays a crucial role in primary α' -M variant selection, and the product of mechanical work and strain energy reduction determines secondary variant selection. This difference is attributed to various elastic strains in the two stages of transformation. Our calculation shows that the percentages of volume change during $\gamma \rightarrow \varepsilon$ -M and ε -M $\rightarrow \alpha'$ -M transformation are 2.28 and 3.82%, respectively. This result means that a large elastic strain exists, and strain energy participates in variant selection during α' -M formation.

3.3 ε -M Reversion Mechanism

Figure 4 shows the EBSD orientation image maps and the corresponding pole figures of γ , ε -M, and α' -M in a $\langle 110 \rangle \gamma$ grain (grain B) under dynamic tension. Two dominant ε -M variants are formed. The amount of α' -M is less compared with ε -M. Mechanical twins are found in ε -M, and reverse transformation from ε -M to γ occurs in ε -M twins. The calculation of mechanical work during $\gamma \rightarrow \varepsilon$ -M transformation shows that the highest and second highest mechanical works belong to ε_3 and ε_1 , respectively (Fig. 5a). Thus, ε_3 and ε_1 are selected. The transformation from γ to ε -M occurs dominantly because of high mechanical work. Considering that two dominant ε -Ms appear in grain B, we calculate the mechanical works of 12 possible α' -M variants (Figs. 5b, c). The results indicate that the highest mechanical work during ε -M $\rightarrow \alpha'$ -M transformation is only 4.1837 in grain B. Therefore, the

Fig. 4 Orientation maps and pole figures of grain B during tension at strain rate of $1.2 \times 10^3 \text{ s}^{-1}$ (TD-tensile direction): **a** orientation map I (gray color— γ , red color— ϵ -M, blue color— α' -M), **b** orientation map II (Euler angles color— γ , gray color— ϵ -M, blue color— α' -M), **c** orientation map III (gray color— γ , Euler angles color— ϵ -M, blue color— α' -M, red line— $\langle 1120 \rangle 86^\circ$ misorientation), **d** pole figure of γ , **e** pole figure of ϵ -M

Fig. 5 Calculated mechanical works in grain B: **a** four ϵ -M variants, **b** six α' -M variants in ϵ_1 (V1–V6), **c** six α' -M variants in ϵ_3 (V13–V18)

transformation from ϵ -M to α' -M is not promoted, and this finding is consistent with the result illustrated in Fig. 4.

The ϵ -M twins ($\epsilon 3'$ in grain B) are found in $\langle 110 \rangle \gamma$ grain, depicting $\langle 11\bar{2}0 \rangle 86^\circ$ misorientation between the twins and the matrix. The reverse transformation from ϵ -M to γ occurs in ϵ -M twins, thereby resulting in a differently oriented γ grain (marked by an arrow in Fig. 4d). Hexagonal twinning is activated because twinning easily occurs in a hexagonal crystal when ϵ -M $\rightarrow$ α' -M transformation is suppressed. Reverse transformation from ϵ -M to γ is observed in ϵ -M twins. As such, the possibility of reversion should be evaluated.

It is reasonable to suppose that ϵ -M reversion follows the model: The dissociation of the $a/3 \langle 11\bar{2}0 \rangle$ dislocation into partials on the basal plane [24, 25]

$$\frac{a}{3} [\bar{1}2\bar{1}0] = \frac{a}{3} [01\bar{1}0] + \frac{a}{3} [\bar{1}100] \quad (3)$$

and ϵ -M reversion is achieved when every two (0002) planes are displaced toward the $[01\bar{1}0]$ direction by $\frac{\sqrt{2}a}{6C}$. Following the similar calculation method in martensitic transformation, the mechanical work for such reversion can be calculated.

In grain B, the mechanical work of ϵ -M reverse transformation and ϵ -M $\rightarrow$ α' -M transformation in $\epsilon 3'$ is 7.1698 and 4.4935 MJ m⁻³; thus, the former is promoted. Experimental data and theoretical calculation suggest that hexagonal twinning and the corresponding reversion in twins occur when martensitic transformation is inhibited in $\langle 110 \rangle \gamma$ grains.

Fig. 6 Orientation maps and pole figures of grains C and D during tension at a strain rate of $1.6 \times 10^{-3} \text{ s}^{-1}$ (TD-tensile direction): **a** orientation map I of grain C (Euler angles color- γ , red color- ϵ -M, blue color- α' -M), **b** orientation map II of grain C (gray color- γ , Euler angles color- ϵ -M, blue color- α' -M, red line- $\langle 1120 \rangle 86^\circ$ misorientation), **c** orientation map I of grain D (gray color- γ , red color- ϵ -M, blue color- α' -M), **d** Orientation map II of grain D (gray color- γ , Euler angles color- ϵ -M, blue color- α' -M), **e** pole figures of γ and ϵ -M in grain C, **f** pole figures of γ and ϵ -M in grain D

Figure 6 shows the EBSD results in other two $\langle 110 \rangle \gamma$ grains (grains C and D). The phase transformation of grain C is similar to that of grain B; ϵ -M is dominant and ϵ -M reversion occurs (the orientation of γ after ϵ -M reversion is marked by an arrow in Fig. 6a, e). However, the transformation from ϵ -M to α' -M occurs smoothly, and no ϵ -M reversion is observed in grain D. This difference may be attributed to the distribution of ϵ -M plates. Most ϵ -M plates are isolatedly distributed in grain B and C, while the collision of ϵ -M plates occurs more frequently, and the stress concentration likely promotes α' -M nucleation in grain D.

For $\langle 110 \rangle \gamma$ grain, the formation of ϵ -M is easier than that of α' -M. As a consequence, ϵ -M phase is dominant and ϵ -M $\rightarrow$ α' -M transformation is inhibited. The phenomenon is related to the difference in the corresponding mechanical work. Hexagonal twinning is activated when the transformation from ϵ -M to α' -M is suppressed. Afterward, the reversion of ϵ -M to austenite occurs in ϵ -M twins for the corresponding higher mechanical work. However, the distribution of ϵ -M plates also affects phase transformation, and more collision between ϵ -M plates promotes the nucleation of α' -M.

4 Conclusions

$\gamma \rightarrow \varepsilon$ -M and ε -M $\rightarrow \alpha'$ -M transformations occur during dynamic deformation, and typical zigzag types of α' -M are widely distributed in γ grains with orientation between $\langle 111 \rangle$ and $\langle 112 \rangle$. In α' -M variant pairs with a zigzag form, the primary variant is determined by the highest mechanical work. High products (P) of mechanical work and strain energy reduction are essential for secondary variant selection. The variant selection of ε -M is determined by the highest mechanical work during the transformation from γ to ε -M. In contrast to ε -M variant selection, strain energy affects the selection of α' -M pairs because of the larger elastic strain during ε -M $\rightarrow \alpha'$ -M transformation. ε -M to α' -M transformation is inhibited in $\langle 110 \rangle \gamma$ grains with a low mechanical work. In this case, ε -M twins are found, and reverse transformation from ε -M to γ occurs. These phenomena are attributed to the higher mechanical work of ε -M reversion as opposed to ε -M $\rightarrow \alpha'$ -M transformation. More collisions between ε -M plates will promote the ε -M $\rightarrow \alpha'$ -M transformation in $\langle 110 \rangle \gamma$ grains.

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References

- [1] O. Grässel, L. Krüger, G. Frommeyer, L.W. Meyer, *Int. J. Plast.* **16**(10–11), 1391 (2000)
- [2] G. Frommeyer, U. Brüx, P. Neumann, *ISIJ Int.* **43**(3), 438 (2003)
- [3] C. Cayron, F. Barcelo, Y.D. Carlan, *Acta Mater.* **58**(4), 1395 (2010)
- [4] E. Nagy, V. Mertinger, F. Tranta, J. Sólyom, *Mater. Sci. Eng.* **A378**(1–2), 308 (2004)
- [5] J. Dash, H.M. Otte, *Acta Metall.* **11**(10), 1169 (1963)
- [6] H. Kitahara, R. Ueki, N. Tsuji, Y. Minamino, *Acta Mater.* **54**(5), 1279 (2006)
- [7] S.H. Lee, J.Y. Kang, H.N. Han, K.H. Oh, H.C. Lee, D.W. Suh, S.J. Kim, *ISIJ Int.* **45**(8), 1217 (2005)
- [8] G. Miyamoto, N. Iwata, N. Takayama, T. Furuhashi, *Acta Mater.* **60**(3), 1139 (2012)
- [9] L. Malet, M.R. Barnett, P.J. Jacques, S. Godet, *Scr. Mater.* **61**(5), 520 (2009)
- [10] S. Morito, H. Tanaka, R. Konishi, T. Furuhashi, T. Maki, *Acta Mater.* **51**, 1789 (2003)
- [11] H. Okamoto, M. Oka, I. Tamura, *Trans. JIM* **19**(12), 674 (1978)
- [12] J.C. Bokros, E.R. Parker, *Acta Metall.* **11**(12), 1291 (1963)
- [13] H.Z. Wang, P. Yang, W.M. Mao, F.Y. Lu, *J. Alloys Compd.* **558**, 26 (2013)
- [14] G.B. Olson, M. Cohen, *Annu. Rev. Mater. Sci.* **11**, 1 (1981)
- [15] S. Kundu, *Mater. Sci. Eng., A* **516**(1–2), 290 (2009)
- [16] J. Hamidreza, B. Ehsan, S. Akinobu, T. Nobuhiro, *J. Alloys Compd.* **577**(S1), S668 (2013)
- [17] J.R. Patel, M. Cohen, *Acta Metall.* **1**(5), 531 (1953)
- [18] M. Humbert, B. Petit, B. Bolle, N. Gey, *Mater. Sci. Eng.* **A454–455**, 508 (2007)
- [19] H. Schumann, *Kristall geometrie*, 1st edn. (VEB Deutscher Verlag, Leipzig, 1979), pp. 133–164
- [20] L.N. Wang, P. Yang, W.M. Mao, *Acta Metall. Sin.* **52**(9), 1045 (2016)
- [21] P. Yang, T.Y. Liu, F.Y. Lu, L. Meng, *Steel Res. Int.* **83**(4), 368 (2012)
- [22] C. Cayron, *Mater. Charact.* **94**, 93 (2014)
- [23] S. Kundu, H.K.D.H. Bhadeshia, *Scr. Mater.* **57**, 869 (2007)
- [24] Y.P. Lü, B. Hutchinson, D.A. Molodov, G. Gottstein, *Acta Mater.* **58**(8), 3079 (2010)
- [25] F. Gauzzi, R. Montanari, *Mater. Sci. Eng.* **A273–275**, 524 (1999)