Note

Quasi-cleavage Fracture along Annealing Twin Boundaries in a Fe–Mn–C Austenitic Steel

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1. Introduction

Martensitic transformation from FCC (γ) to HCP (ϵ) is often observed in austenitic high Mn steels. For example, the ϵ -martensitic transformation occurs at cryogenic temperature in twinning induced plasticity steels^{1,2)} and at room temperature in shape memory alloys.^{3,4)} The ϵ -martensitic transformation produces the shape memory effect¹⁾ and high work hardening rates,⁵⁾ however, it is also known to cause premature fracture resulting in tensile deformation. The fracture mode is known to be either an intergranular^{6,7)} or quasi-cleavage^{2,6,7)} fracture when this occurs.

The premature fracture associated with the ϵ -martensitic transformation is reported to be caused by the interactions between ϵ -martensite plates and boundaries in Fe–27Mn–0–7Si and Fe–20Mn–4Cr–0.5C–0.5Si alloys.^{6,7)} The cracks are thought to be induced from the stress concentration arising from the interactions. However, the crack initiation sites of the premature fracture caused by ϵ -martensitic transformation are still unclear in ternary Fe–Mn–C austenitic steels which have recently been determined to be transformation induced plasticity (TRIP)⁸⁾ and twinning induced plasticity (TWIP) steels.^{2,8–10)}

Primary ϵ -martensite plate,⁶⁾ grain boundary,^{6,7)} and twin boundary have been considered as possible boundaries that interact with ϵ -martensite for the occurrence of the premature fracture. We found that the annealing twin boundaries were the crack initiation sites in the Fe–17Mn–0.3C steel in this study and will provide the evidences.

2. Experimental

A steel with a chemical composition of Fe–16.8Mn–0.29C (wt%) was prepared by vacuum induction melting. The steel was hot forged and rolled at 1 273 K. Then it was solution treated at 1 273 K for 3.6 ks under an argon atmosphere and water quenched. The starting temperature for the

ϵ -martensitic transformation was 272 K.¹¹⁾ Note that the ϵ -martensitic transformation occurred in the Fe–17Mn–0.3C steel during tensile deformation at 294 K and deteriorated its ductility.¹²⁾

The elongation and strength of specimens with dimensions of 4.0 mm^w × 1.0 mm^t × 30.0 mm^l with a grip section on both ends were obtained from the tensile tests at ambient temperature (294 K) with an initial strain rate of $1.7 \times 10^{-4} \text{ s}^{-1}$. The elongation was determined by measuring the gauge length before and after the tensile test.

Microstructural observations were made by optical microscopy, atomic force microscopy (AFM), and scanning electron microscopy (SEM) to produce a fractograph. Electron backscatter diffraction (EBSD) analyses were also conducted at 20 kV with a beam step size of 1 μm to characterize the boundaries. The specimen for optical microscopy, AFM, and EBSD analyses was electrolytically polished at 277 K after mechanical polishing. All the microstructural observations were conducted at the same view field before and after the tensile deformation. In addition, X-ray diffraction (XRD) analyses were carried out with a Cu target at 35 kV, 300 mA and a scan rate of $0.02^\circ \text{ s}^{-1}$.

3. Results and Discussion

Figure 1 shows an engineering stress-strain curve of the Fe–Mn–C steels. The serrations at ambient temperature in the steels were reported to be attributed to dynamic strain aging.^{2,9)} The fracture appeared without necking, indicating the occurrence of a premature fracture. The fracture that occurred before the plastic instability condition was confirmed by an analysis of the stress-strain curve and the corresponding work hardening rates. The premature fracture was observed in the two tensile specimens including Fig. 1, and a stress-induced ϵ -martensitic transformation was detected as shown in **Fig. 2**. Thus, the premature fracture would be attributed to the stress-induced ϵ -martensitic transformation.

Figure 3 shows that the premature fracture was caused by a quasi-cleavage fracture. A stress concentration is caused by the ϵ -martensitic transformation where there is an obstacle and induces the quasi-cleavage fracture with the step-like ridges^{6,7)} which is typically seen in high Mn steels.

Fig. 1. Engineering stress-strain curve of the Fe–17Mn–0.3C steel.

Fig. 2. XRD showing ϵ -martensite in the Fe-17Mn-0.3C steel in the as solution-treated condition and with 5% tensile strain.

Fig. 3. Typical fractograph showing quasi-cleavage fracture with step-like ridges.

Figure 4 shows a set of microstructure observations on an identical view field before and after the deformation. Figure 4(a) is a boundary map obtained from an EBSD analysis and shows numerous annealing twin boundaries as indicated by the red lines. Figure 4(b) shows the corresponding optical micrograph with differential interference in the steel deformed till fracture (12%) near the fractured part. The arrows indicate the cracks and the corresponding boundaries. All the cracks denoted 1–5 were found along the annealing twin boundaries. Figures 4(c) and 4(d) show the magnified image taken by AFM and the corresponding three-dimensional image of the part denoted as 1 in Figs. 4(a) and 4(b), which more clearly exhibit the crack. Figures 4(e) and 4(f) show a schematic of Fig. 4(c) and a rolling direction (RD)-inverse pole figure map corresponding to the same view field with Fig. 4(c) in the as-solution-treated condition. The normal direction (ND) and RD orientations in grains A and B are $(18\ -13\ 15)[\bar{8}\ \bar{3}\ 7]$ and $(\bar{3}\ 4\ \bar{12})[16\ \bar{9}\ \bar{7}]$, respectively. The misorientation between grains A and B is 59.9° about a $[11\bar{1}]$ crystal axis, indicating that the grains A and B show a twin relation. Hence, the crack in Fig. 4(c) was concluded to propagate along the $(11\bar{1})$ annealing twin boundary. The bend of the crack (Dif. 4(c)) would be caused by interactions between twins and dislocations. The interactions are known to produce steps on a twin boundary.^{13–16)}

Fig. 4. (a) Boundary map taken by an EBSD analysis in the as-solution-treated condition, and (b) the corresponding optical micrograph with differential interference after fracture. (c) Differentiated height image and (d) three dimensional image corresponding to part 1 in Figs. 4(a) and 4(b). (e) The schematic of Fig. 4 showing grain boundaries and the crack (c). (f) RD-IPF map in the same area with Fig. 4(c) in the as-solution-treated condition. The red lines in Fig. 4(f) indicate twin boundaries.

These results indicate that the annealing twin boundaries are the crack initiation sites. Annealing twin boundary cracking has been reported to occur at 77 K in high nitrogen steels.^{17,18)} Thus, annealing twin boundaries are potential crack initiation sites in austenitic steels. The crack initiation and propagation in the present steel are assisted by the stress concentration caused by ϵ -martensite/twin boundary interactions. As a consequence, this crack initiation along the annealing twin boundaries is the cause of the premature fracture in the present Fe-Mn-C steel.

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