Available online at www.sciencedirect.com
ScienceDirect
Scripta Materialia 100 (2015) 32–35
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

In situ observations of transgranular crack propagation in high-manganese steel

Sung-Il Baik,[a] Tae-Young Ahn,[a] Woong-Pyo Hong,[a] Yeon-Seung Jung,[b] Young-Kook Lee[b] and Young-Woon Kim[a,*]

[a]*Department of Materials Science and Engineering, Research Institute of Advanced Materials, Seoul National University, Daehak-dong, Gwanak-gu, Seoul 151-744, Republic of Korea*
[b]*Department of Metallurgical Engineering, Yonsei University, Shinchon-dong 134, Seodaemun-gu, Seoul, Republic of Korea*

Received 19 November 2014; accepted 8 December 2014
Available online 23 December 2014

Crack propagation in high-Mn steel was investigated using in situ transmission electron microscopy. Preferential slips developed in the early stages of deformation on {111}, followed by the formation of a crack, which propagated along the pre-developed slip traces. A sharp corner was observed at the crack tip along two adjoining {111} planes. Surface ripples developed when the tip of the crack crossed pre-existing twins on the crack path, which was frequently observed in the surface during the final stage of fracture.

Keywords: TWIP steel; Dislocation; Twinning; Fracture; In situ TEM

Manganese is an austenite-stabilizing element that is widely used in stainless and austenitic steels. Varying the quantity of Mn can control the fraction of the austenite phase, affecting the characteristics of the steel. The amount of austenite in multi-phase steel can be controlled by varying the quantity of both Mn and C to increase the fraction of austenite in transformation-induced plasticity steel to achieve fully austenitic steel. Fully austenitic steel can be obtained using an Mn content greater than 13% [1,2], commonly termed twin-induced plasticity (TWIP) steel [3,4], which is known to exhibit hardening from the formation of twins. TWIP steel has recent attracted the attention of a number of researchers because it exhibits extraordinary elongation properties while maintaining high strength, despite its face-centered cubic (fcc) structure.

fcc crystals are known to exhibit ductile fracture at room temperature because of the high degree of symmetry of the slip planes and directional variants. Cleavage fracture, on the other hand, is commonly observed in systems with limited slip and those deformed at low temperature. Although it is uncommon to observe faceted, cleavage-like fracture in fcc structure metals, some fcc austenitic steels have been reported to exhibit cleavage-like fracture when tested under extreme deformation conditions [5–13]. When high-Mn TWIP steel is strained and fractured, cleavage-like fracture surfaces consisting of {111} planes have been observed, even at room temperature. The {111} slip plane of an fcc crystal can be worked as a twin plane, and both slip mechanisms can occur in TWIP steel.

Here, we investigate the propagation of crack tips to form cleavage-like fractures with two different deformation mechanisms using an in situ transmission electron microscope (TEM), and we discuss the origin of the surface ripples observed on the cleavage-like fracture surface.

The material used was a high-Mn steel with 0.6% C, 18% Mn and 1.5% Al by mass. Tensile tests were carried out using an Instron 5582 tensile tester at a strain rate of $2 \times 10^{-3}\ s^{-1}$ until failure. The fractured surface was investigated using a scanning electron microscope (SEM;JSM 6390LV). In situ tensile specimens were formed from the fractured tensile specimen using a wire-feed electric-discharge machine to form grip holes for in situ extension in TEM. The target area for the tensile tests was thinned using electrochemical etching, and the surfaces were further cleaned using Ar^+ ion bombardment to remove surface oxides. The in situ TEM tensile tests were carried out using a JEM-2010F microscope, which was operated at 200 kV, in combination with a tensile straining holder. Strain was applied using a linear motor at a speed of $10^{-7}\ m\ s^{-1}$, with a maximum load of 600 N. The microstructural changes were recorded using a Gatan ES 500 W camera at 30 fps. Following the development of a crack, the area of the crack tip was sectioned using focused ion beam milling (FEI DB-235) for further analysis using scanning transmission electron microscopy.

The fractured surfaces following tensile tests exhibited two distinct regions of ductile and cleavage-like

* Corresponding author; e-mail: youngwk@snu.ac.kr

http://dx.doi.org/10.1016/j.scriptamat.2014.12.005
1359-6462/

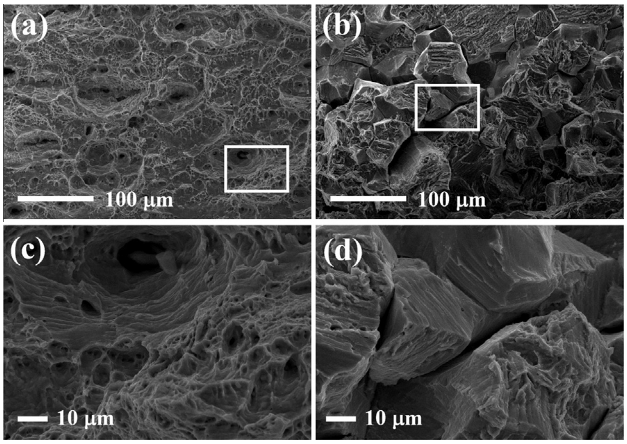

Figure 1. SEM cross-sectional images of the fracture surfaces of TWIP steel. (a) The edge part of the fracture area. (b) The middle part of the fracture surface. (c) and (d) Show high-magnification images of the boxes in (a) and (b), respectively.

topography, as shown in Figure 1(a). This image was obtained from the region marked with a solid rectangle in the inset. A transgranular, cleavage-like fracture layer appeared at the edge of the side walls of the tensile specimen in the form of an ~200 μm thick band. Figure 1(b) shows an enlarged view of the cleavage-like fracture with {1 1 1} facets. The stress–strain relationship for the alloy has been reported by Jin and Lee [14]; here, we discuss only the microstructure. The fractured surface shown in Figure 1(b) had a similar surface morphology to that of the low-temperature fracture obtained from a Sharpy impact test, which typically occurs at a high strain rate at low temperature [5,15]. Close inspection of the surface revealed that the cleavage-like fracture was not smooth but exhibited ripples.

We may infer that the plate-shape tensile test samples reached a plane-stress condition, wherein material remains at the edge of the sample and a void forms at the center [16]. As the center part of the tensile specimen was cracked and formed a void, only the thin layer at the edge of the sample remained, where plane-stress conditions are expected just prior to rupture. The samples prepared for TEM analysis provided plane-stress conditions when the tensile stress was applied because of the nature of the thin foil. To investigate the paths of the cleavage-like crack propagation and the interaction with grain boundaries, thin foil samples were elongated inside the TEM.

Snapshots obtained from the streaming video obtained during the in situ straining in the TEM to visualize changes in the microstructure are shown in Figure 2. Figure 2(a) was imaged before the strain was applied, while Figure 2(b–h) show images of the microstructure as the strain was applied. A slight offset can be seen, which is due to drift of the sample during straining. At the initial stage of straining, gliding dislocation motion was visible on the 1 1 1 plane (see the three arrows in Fig. 2(b)). Dislocations formed during the initial stages of deformation and preferentially propagated along a specific 1 1 1 plane as the strain increased. Dislocation emission was related to slipping-off phenomena on the {1 1 1} slip planes, which has been reported to be a source of cleavage fracture of austenitic steel [9–11,15]. Further extension accumulated more dislocations and generated a crack, as marked by the arrow in Figure 2(d). Figure 2(e) and (f) clearly show that the stress induced by the accumulation of dislocation at the grain boundary (marked "L") generated a new propagation on a 1 1 1 slip plane in the next grain (marked "R"). A number of dislocations were observed in the region away from the crack, as shown by the circle in Figure 2(f); the origin of these cracks is attributed to dislocation multiplication and accumulation normal to the direction of propagation of the crack. The arrow in Figure 2(g) indicates a change in direction of the crack propagation at the grain boundary. When the crack reached the grain boundary, it followed the propagation direction of the dislocations in the neighboring grain, as shown in Figure 2(h).

The cleavage plane in fcc crystals is generally known to be {1 0 0}; however, the fractured surface of austenitic steel reveals {1 1 1} cleavage surfaces at low temperatures and

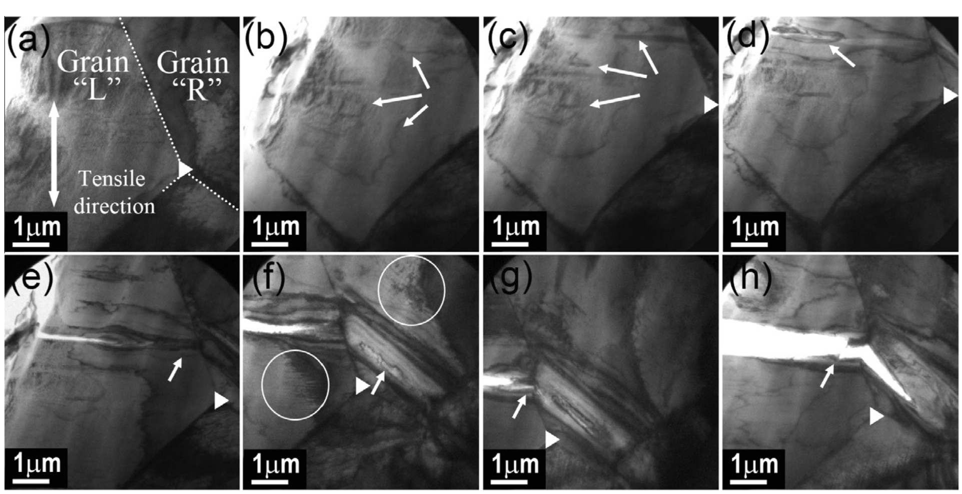

Figure 2. TEM sequential images from the in situ straining investigation. (a) The initial stage of straining; the direction of the elongation is indicated by arrows and the grain boundaries with neighbor grains are marked with dotted lines. (b) and (c) Show the preferential formation and propagation of dislocations. (d) Crack formation and the start of propagation. (e) Plastic deformation region; the accumulation of dislocations in the neighboring grains are visible. (f) Dislocations can be observed in the region normal to the crack propagation. (g) The crack propagation direction changed when the tip met the grain boundary. (h) A cleavage-like surface was generated by the different 1 1 1 planes of a neighboring grain. A triple junction of the grains is marked by a triangle in all figures to form a point of reference.