ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–11

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Hydrogen-assisted failure in a bimodal twinning-induced plasticity steel: Delamination events and damage evolution

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ARTICLE INFO

Article history:
Received 6 October 2017
Received in revised form
14 November 2017
Accepted 24 November 2017
Available online xxx

Keywords:
Hydrogen Embrittlement
Twinning-induced plasticity steel
Bimodal grain size distribution
Delamination
Crack growth

ABSTRACT

The effect of the bimodal grain size distribution on the hydrogen susceptibility of a high-Mn fully austenitic twinning-induced plasticity (TWIP) steel was investigated by tensile testing under ongoing electrochemical hydrogen charging. Observation of the surface microstructure of the hydrogen-charged specimen yielded a correlation between the microstructure, crack initiation sites, and crack propagation path. The observed embrittlement arose from crack initiation/propagation along the grain and twin boundaries and delamination governed crack growth. In the present bimodal TWIP steel, the fine grained regions mostly showed intergranular cracking along the grain boundaries between the fine and coarse grains. By contrast, the coarse grained region exhibited transgranular cracking along the twin boundaries. The delamination cracking phenomena is rationalized by the evident nucleation, growth, and coalescence of microvoids in the tensile direction. The results reveal that the bimodal grain size distribution of TWIP steel plays a major role in hydrogen-assisted cracking and the evolution of delamination-related damage.

Introduction

Recently, high Mn-C twinning-induced plasticity (TWIP) austenitic steels have received increasing attention as potential next-generation high-strength materials for various loading conditions including operation at cryogenic temperatures [1–3], under cyclic loading [4–7], under high velocity loading [8–10], and in a hydrogen environment [11–14]. In particular, the close-packed structure of austenite has been expected to play an advantageous role in the resistance to hydrogen embrittlement owing to the low diffusivity [15–17]. A problem in austenitic steels is the low yield strength compared with the high strength of ferritic/martensitic steels. Therefore, steel researchers have attempted to increase the yield strength of austenitic TWIP steels.

A promising way to increase yield strength while maintaining austenite stability is grain refinement [18–21]. In

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https://doi.org/10.1016/j.ijhydene.2017.11.177
0360-3199/

general, hydrogen embrittlement susceptibility increases with increasing strength [22–24]. By contrast, the grain refinement methodology does not deteriorate resistance to hydrogen-related failure [24–29]. Thus, the effects of grain size on the deformation mechanisms and work hardening rates in TWIP steels have been intensively investigated [19,30–32]. In fact, grain refinement enables the simultaneous improvement of the yield strength and the resistance to hydrogen-related failure. The reasons for the reduction in hydrogen embrittlement susceptibility are related to the local hydrogen content [27–29,33,34], local stress concentration [16,35], and deformation twinning behavior [16,35,36]. In terms of the hydrogen content, grain-refined TWIP steel also shows a decrease in strength with increasing hydrogen content, but the loss of strength is significantly less than that of coarse-grained TWIP steels [27]. This can be attributed to the fact that the decreasing grain size reduces the local hydrogen content at grain boundaries where hydrogen-assisted cracking occurs preferentially. According to previous studies [19,37], the local stress concentration at grain boundaries in a fine-grained specimen is much lower than that in a coarse-grained one due to the decrease in the number of piled-up dislocations. This in turn reduces the accumulated local hydrogen content at the grain boundaries of the fine-grained specimen, which is a possible rationale for the improvement in the resistance to hydrogen embrittlement upon grain refinement [26,27]. Certainly, the decrease in the local stress concentration at grain boundaries contributes to the decrease in hydrogen embrittlement susceptibility even without a reduction in the local hydrogen content. In addition, deformation twinning is suppressed by grain refinement [38,39]. The interaction between twins and grain boundaries can lead to the growth of twins, e.g. Ref. [8]. As these act as crack initiation sites and propagation paths, the suppression of deformation twinning should also decrease the hydrogen susceptibility of TWIP steels [27,35].

A fine/coarse bimodal grain distribution can drastically increase not only the yield and tensile strengths but also the ductility [40–46]. For example, pure copper with a bimodal grain structure and FCC structure like TWIP steels has a 400 MPa tensile strength with over 60% elongation, which is a much higher ductility/strength balance than that of homogeneously grain-refined copper [42]. The bimodal grain structure enhances the work hardening capability because of plastic strain inhomogeneity that causes a high accumulation rate of dislocations [42]. The enhanced work hardening delays the onset of necking, thus increasing the uniform elongation [42–44,47,48]. In the same context, a fully austenitic TWIP steel with a bimodal grain structure has been reported to feature a superior ductility/strength balance. For instance, a TWIP steel with the bimodal grain structure demonstrated 600 MPa 0.2% proof strength, 800 MPa tensile strength, and 35% elastic engineering strain [49].

However, no systematic work has been reported on the effects of the bimodal grain size distribution on hydrogen embrittlement in TWIP steel. In this paper, we report a microstructural analysis of hydrogen embrittlement in such a material to understand the mechanisms of crack initiation and propagation under hydrogen charging.

Experimental procedure

Material

In the present study a Fe-15Mn-2.5Si-2.5Al-0.7C (wt%) fully austenitic TWIP steel with a bimodal grain structure that had been produced by warm rolling was used. As shown in Fig. 1 the as-received TWIP steel featured a bimodal microstructure with partial recrystallization. Fig. 1 also demonstrates that the as-received steel has fine grains along coarse grain boundaries. The initial microstructure does not contain deformation twins. The average grain size, including coarse and fine grains, is 25 μm. The micrograph was obtained by mechanical polishing with colloidal silica and chemical etching with a solution of 3% nital (nitric acid in ethanol), followed by cleaning with ethanol.

From the steel plates tensile specimen with gauge dimensions of 4 mm in width, 0.25 mm in thickness and 10 mm in length were cut by electrical discharge machining. Next, the thickness of the specimens was reduced by mechanical grinding. The resulting specimen geometry is shown in Fig. 2a. Finally, the surface of the specimens was mechanically polished to a mirror finish. It should be noted that this test geometry was designed to meet the specific requirements of the in-situ hydrogen charging tests, while still being close to conventional standard tensile test geometries.

Tensile tests and microstructure characterization

Tensile tests were conducted with and without hydrogen charging at an initial strain rate of 10^{-5} s^{-1}. A test was carried out for each experimental condition. Hydrogen was introduced to the specimen during the tensile tests by electrochemical charging in a 3% NaCl aqueous solution containing 3 g L^{-1} of NH_4SCN at a current density of 30 A m^{-2}. With this approach, hydrogen could enter the specimen deeply via hydrogen-decorated dislocation motion. The solution was continually added to fully cover the gauge part of the

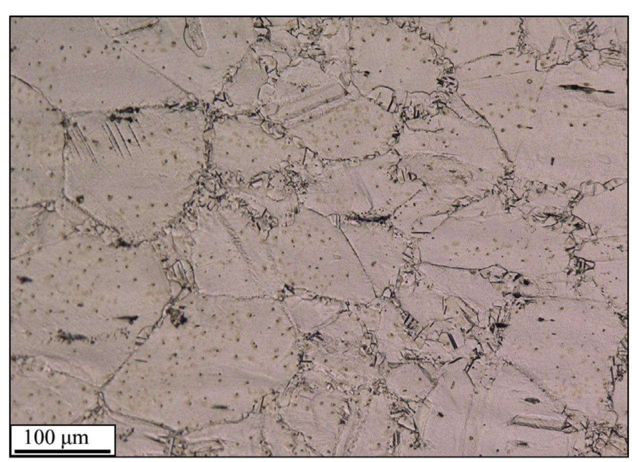

Fig. 1 – Optical micrograph of the initial microstructure of the etched specimen showing the bimodal microstructure featuring fine grains along the boundaries of the coarse ones.