# Hydrogen embrittlement of twinning-induced plasticity (TWIP) steel in a viewpoint of practical issues

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https://doi.org/10.15017/2534451

出版情報：Kyushu University, 2019, 博士（工学）, 課程博士
バージョン：

（様式２）

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論 文 名　：Hydrogen embrittlement of twinning-induced plasticity (TWIP) steel in a viewpoint of practical issues
（実問題の観点からの TWIP 鋼の水素脆性）

区　　分　：甲

論　文　内　容　の　要　旨

Generally, practical problems in structures are related to two parts of material microstructure and structure geometry. The motivation of this research is based on these two practical issues in the presence of hydrogen to understand the mechanisms of hydrogen-assisted crack initiation and propagation and related factors to these mechanisms.

Practical consideration for light-weight manufacturing requires the material with high strength and reasonable ductility. The exceptional combination of these two material properties provides high quality and low cost for industries. Furthermore, there is an interest in numerous application where hydrogen embrittlement may occur, such as use of hydrogen gas as an energy carrier for both transportation and energy sectors. Therefore, material microstructures play an important role to resist the hydrogen embrittlement. On the other hand, most structure members always contain the geometric discontinuities, such as notch or crack-like defects from the manufacturing and machining as well as servicing processes. The main difficulty in designing against fracture in materials particularly in high-strength steels is that the presence of notches or cracks can change the local stresses at the crack or notch tip. This stress concentration makes hydrogen more aggressive as a hydrogen embrittlement agent.

Regarding these concepts, this dissertation is focused on the practical material which has been received attention from the automotive industry, namely: twinning-induced plasticity (TWIP) steel to underlie the mechanisms of hydrogen-assisted crack initiation and propagation in the applicable geometries such as notch and crack-like defects under electrochemical hydrogen charging. One of the important issue that should be considered in the crack propagation is hydrogen kinetic. This issue is also studied to the viewpoints of local and global strain rates by introducing different precrack lengths and various applied strain rates, respectively.

This dissertation consists of six chapters. All chapters are arranged in order to achieve the main theme and objectives of the research work as explained briefly as a purpose of this study.

Chapter 1 describes a general introduction of this work. A newly-developed high-strength steel called TWIP steel shows an exceptional combination of strength and elongation. Unlike general high-strength steels such as low carbon steels, martenstic steels and dual-phase steels, TWIP steels present high resistance to hydrogen embrittlement. Therefore, what has launched TWIP steel into the limelight of practical steel in a design of light-weight structures particularly automotive industries and hydrogen-based applications is a focus on the extraordinary balance between strength and elongation and also high resistance against hydrogen embrittlement.

Chapter 2 illustrates the mechanisms of hydrogen-assisted crack initiation and propagation in the one type of interesting microstructure of TWIP steel, namely, bimodal-grained TWIP steel. In case of smooth specimen, the crack initiation and propagation mechanisms of equi-axed TWIP steel have been studied under hydrogen environment, but the practical one contains a bit peculiar microstructure, i.e., bimodal-grained has not been fully understood. However, no systematic work has been reported on the effects of the bimodal grain size distribution on hydrogen embrittlement in TWIP steel. Hydrogen was introduced to the smooth specimen by electrochemical charging under slow strain rate tensile test. Results indicated that crack initiation sites showed transgranular and intergranulr cracking. In addition, the observed fracture surface exhibited quasi-cleavage fracture features combination with ductile delamination cracking. In this chapter, we confirmed that the bimodal grain size distribution of TWIP steel plays a major role in hydrogen-assisted cracking and the evolution of delamination-related damage.

Chapter 3 illustrates the behavior of the hydrogen-assisted crack growth of pre-strained twinning-induced plasticity (TWIP) steel with an artificial defect (micro-drill hole/s) as an artificial crack initiation site. Hydrogen was introduced to the specimens by electrochemical hydrogen charging during the slow strain rate tensile test. The observed fracture surface exhibited quasi-cleavage fracture features. The quasi-cleavage crack propagation was caused by repetition of crack initiation near a crack tip and subsequent coalescence. The crack initiation near the crack tip occurs after crack-tip plastic deformation. An effect of the pre-strain facilitates the plasticity-driven crack initiation. An early stage of the plasticity-driven crack growth was sensitive to crack length and remote stress, accordingly, the crack growth rate in the early stage increased with increasing initial defect size. On one hand, in a late stage of the crack growth, the crack propagation rate did not show simple trend against the crack length, which is perhaps due to stress field around the crack tip that depends on initial defect size. In this chapter, we confirmed that the structure strength of very ductile, slightly hydrogen susceptible steels, i.e. TWIP steels is mainly determined by the stable crack propagation properties which is not influenced by the specific feature of the bimodal microstructure.

Chapter 4 focuses on the effect of the different precrack length introduced by fatigue on the hydrogen-assisted cracking in the uniform-grained TWIP steel. Hydrogen was introduced to the specimens by electrochemical hydrogen charging during the slow strain rate of $10^{-4}$ $s^{-1}$ under tension. The use of precracked in slow strain rate testing has important advantages, the main one being the localization of the hydrogen and stress in the vicinity of the crack tip. Different crack lengths can induce different local strain rates in front of the crack tip. The results showed that there is a critical precrack length which hydrogen does not have any effect larger than that. There is, however, an important interpretation of results that the local strain rate at the crack tip, and not the externally applied strain rate, is the variable that controls the hydrogen-assisted cracking in the cracked specimens and should be considered as an effective variable even in the slow strain rate tensile test.

Chapter 5 describes the effect of very slow strain rate of $10^{-5}$ $s^{-1}$ in precracked TWIP steel specimens. The reduction in strain rate did not have any influence in uncharged specimens. By contrast, the susceptibility of hydrogen embrittlement increased dramatically by reducing the strain rate in the cracked specimens. Particularly, specimens which have not shown any effect of hydrogen on mechanical properties in the chapter 4 showed sensitivity to hydrogen embrittlement at lower strain rate.

Chapter 6 summarized the results and proposed the outlook.