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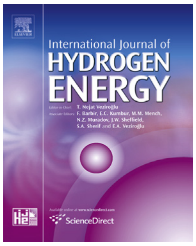

Characterization of hydrogen induced cracking in TRIP-assisted steels

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ABSTRACT

The present work evaluates hydrogen induced cracking in a TRIP-assisted steel with a multiphase microstructure, containing ferrite, bainite, retained austenite, and some martensite. When deformed, the retained austenite transforms to martensite, which changes the phase balance in the alloy. Each microstructural constituent demonstrates a different behavior in the presence of hydrogen. The goal of this work is to understand the response of the hydrogen saturated multiphase structure to a mechanical load. Tensile tests on notched samples combined with in-situ electrochemical hydrogen charging were conducted. The test was interrupted at specific points, before the macroscopic failure of the material. Hydrogen induced crack initiation and propagation were examined by studying the microstructure at several intermediate elongations. Characteristic hydrogen induced cracks were only observed after reaching tensile strength and were located at the surface in a specific pattern. Finite element simulations indicated that the observed crack pattern coincides with the increased stress regions induced by the notch presence. This indicates that hydrogen induced crack formation is dominantly stress induced for this steel.

Introduction

The presence of hydrogen in steels is often correlated to a degradation of mechanical properties, i.e. a significant decrease in ductility and unpredictable failure may occur, which is prejudicial to the performance of a material in a specific application [1]. This phenomenon is referred to as hydrogen embrittlement. Hydrogen Induced Cracking (HIC) refers to fracture of the material at subcritical stress levels (e.g. before reaching the ultimate tensile stress of the material) due to embrittlement of highly stressed regions ahead of cracks or notches caused by an, although still rather low, increased hydrogen concentration [2].

Nowadays, there is an increased interest in numerous applications where hydrogen embrittlement may occur. A current topic concerns the use of hydrogen gas as an energy carrier for both transportation and energy sectors. It is

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considered an environmentally friendly solution for the problem of the diminishing fossil fuels [3]. However, the applications require transportation (e.g. pipelines [4]) and stocking facilities (e.g. storage tanks [5]) able to resist hydrogen induced cracking and embrittlement. For cost reduction purpose High Strength Steels (HSS) are considered as good candidates. However, the industrial applicability of HSS, which are more prone to hydrogen related failure than other steel grades, is claimed to be limited due to hydrogen embrittlement [6–8]. This is also a concern in the automotive industry and multiple structural applications, for which such steels are very interesting due to their high strength/stiffness vs. weight ratio. For instance, the use of these steels in the automotive industry results in a reduction of fuel consumption and emissions, while delivering an improved crashworthiness [7]. A detailed evaluation of the interaction between hydrogen and these steels is necessary to understand and predict potential hydrogen damage.

Low carbon steels with TRIP (Transformation Induced Plasticity) effect are advanced HSS with a microstructure of ferrite, bainite, and retained austenite. The latter transforms fully or partially under mechanical load to martensite (TRIP effect) and contributes to improved strain hardening and postponed necking. In literature these kinds of steel are frequently referred to as TRIP steels. The above microstructure determines a "composite" like deformation behavior of the steel which results in an excellent combination of properties, such as high tensile strength, high ductility, large uniform elongation, and good work hardening capacity [9,10]. These specific properties make these steels perfect for impact-absorbing structural parts of car bodies [11].

Each microstructural component in multiphase TRIP-assisted steels exhibits a different behavior when exposed to hydrogen [12], which makes the hydrogen related behavior in TRIP steels hard to assess. The hydrogen embrittlement susceptibility of the phases present in TRIP steel increases in following order: retained austenite, ferrite, bainite and martensite [13]. Especially the interaction between hydrogen and austenite and martensite is of interest for TRIP steels, since the ductility of TRIP steels is partially based on the stress and strain induced transformation of retained austenite to martensite. Due to the low hydrogen diffusivity and high hydrogen solubility in austenite, it acts as a hydrogen reservoir [14]. Pérez Escobar et al. [15] found that the retained austenite in TRIP700 steel contains hydrogen at ambient temperature, even before hydrogen charging of the material. Additionally, this amount of hydrogen in austenite did not increase by additional electrochemical hydrogen charging. Seemingly, the hydrogen is introduced into the retained austenite during the intercritical annealing process, which is a step in the fabrication process of the material. Rozenak and Bergman [16] reported that the presence of hydrogen in austenitic stainless steels affects the stability of the austenite and can induce a phase transformation of austenite to martensite. However, most observations of the hydrogen induced transformation were obtained by charging the samples at high cathodic current densities, which results in hydrogen concentrations higher than 300 wppm. In the case of TRIP steels, a much smaller amount of hydrogen is enough to cause severe mechanical degradation of the steel [17]. Other studies [18,19] illustrated that for such a low amount of hydrogen, the stability of retained austenite is not affected under the applied conditions. Chan [13] illustrated that a fresh martensitic structure is the one most susceptible to hydrogen embrittlement. The lath martensite has a large density of dislocations (10^{11} to 10^{12} cm^{-2}) and residual micro-stresses and thus displays a large hydrogen trapping capacity. Luppo and Ovejero-Garcia [20] found that the quantity of hydrogen desorbed is maximal for an as-quenched martensitic structure, which implies that martensitic transformations introduce reversible trapping sites (potential sources for diffusible hydrogen) in the material, which explains why this structure possesses the lowest hydrogen embrittlement resistance. So, when the deformation induced transformation of hydrogen charged austenite occurs, the hydrogen will be inherited by newly formed martensite, which is very susceptible to hydrogen embrittlement. Since the hydrogen solubility is higher in austenite than in martensite, a hydrogen supersaturated, brittle phase forms. TRIP steels show a stronger loss of ductility due to hydrogen embrittlement in comparison to steels that do not transform as a function of plastic strain [21]. This was clearly illustrated by Depover [6] by performing similar tensile tests for multiple high strength steels. Lovicu et al. [22] stated that the high sensitivity of TRIP steel to hydrogen is attributed to the strong embrittlement of the stress or strain induced martensite. Under stress, the hydrogen supersaturated martensite quickly cracks, inducing the failure of the specimen. Lacroix et al. [23] investigated the fracture behavior of TRIP steels in an inert environment and found that crack initiation was always related to the presence of martensite. Ronevich et al. [24] observed that crack initiation occurs at martensitic regions and further propagation into ferrite takes place in TRIP steel charged with hydrogen, while in uncharged TRIP steel microcracks were found in martensite without further propagation into the ferrite. Similar observations were made by Koyama et al. [25] for dual-phase steel. Thus, martensite seems to be the crack initiation location for both hydrogen charged and non-charged samples.

Hilditch et al. [26] studied the influence of hydrogen on the mechanical deformation behavior of TRIP780 and found that the yield strength did not undergo discernible changes due to hydrogen charging. The hydrogen did not appear to affect strain hardening behavior of TRIP780. Liu et al. [27] stated that at smaller elongations than the elongation associated with the yield strength, no hydrogen effect is observed in 3.5NiCrMoV steel when tensile tested. Brass and Chêne [28] stated that this is a result of the enhanced hydrogen transport after the start of plastic yielding, due to hydrogen transport by dislocations. Additionally, cracking was only observed after the onset of necking. Marchetti et al. [29] studied 9%Cr–1%Mo steel and equally found that no hydrogen influence occurred for stresses less than the yield strength and cracking occurred in the necked part of the tensile sample. This hydrogen effect was associated with localized plastic deformation of the necked region.

The deformation mechanism of TRIP-assisted steels involves a displacive transformation which not only transforms a phase with high hydrogen solubility to a phase highly susceptible to hydrogen embrittlement, but additionally generates crystallographic defects and internal stresses, which also