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Effect of hydrogen charging on the mechanical properties of advanced high strength steels

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ABSTRACT

The present work investigates the influence of hydrogen on the mechanical properties of four multiphase high strength steels by means of tensile tests on notched samples. This was done by performing mechanical tests on both hydrogen charged and uncharged specimens at a cross-head displacement speed of 5 mm/min. A considerable hydrogen influence was observed, as the ductility dropped by 8–60%. In order to demonstrate the influence of diffusible hydrogen, some parameters in the experimental set-up were varied. After tensile tests, fractography was performed. It was found that hydrogen charging caused a change from ductile to transgranular cleavage failure near the notch with a transition zone to a fracture surface with ductile features near the centre.

1. Introduction

Hydrogen is often quoted to be the future energy carrier as it might offer an alternative for the scarce fossil fuels. However, the commercialization of hydrogen has proven to be a challenge. A significant difficulty from the steel substrate point of view appears to be the high diffusivity of hydrogen, as this element may give rise to embrittlement in the steel components. Therefore, further investigation of the possibilities to store and transport hydrogen and of the material–hydrogen interactions is inevitable and thus required.

In hydrogen-powered vehicles, gaseous hydrogen has to be stored at a pressure up to 70 MPa to achieve sufficient gravimetric and volumetric energy density [1]. Nowadays, stable nickel-based austenitic stainless steels are commonly used for structural applications such as fittings, pipes and valve housings. Nevertheless, these materials are too expensive for automotive mass production. Aluminum alloys are feasible alternatives for valve housing, resulting in a cost and weight reduction. Unfortunately, parts such as springs, fittings and pipes, cannot be made of aluminum alloys, due to incompatible strength, wear and fatigue characteristics. Therefore, the application of steel in the automotive industry remains unavoidable [2].

In the automotive industry, one of the main goals is weight reduction while retaining the same strength and stiffness level at the lowest possible cost. Aluminum has the drawback of a lower stiffness and a higher cost compared to steels. Therefore, excellent candidates to attain these necessary

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requirements are high strength steels since they combine light weight and high strength. Unfortunately, high strength steels are more sensitive to hydrogen embrittlement [3]. This embrittlement has a substantial influence on the mechanical material characteristics, causing a brittle and unpredictable fracture which can have severe consequences. In order to be able to understand and predict the potential hydrogen damage, detailed research on the effect of the interaction between hydrogen and high strength steels is necessary.

Among the advanced high strength steels, Dual Phase (DP), Transformation Induced Plasticity (TRIP), Complex Phase (CP), Ferritic Bainitic (FB), High Strength Low Alloy (HSLA) and martensitic steels are the most important ones. DP steel consists of a dispersion of martensitic islands in a ferrite matrix and combines low yield strength with high tensile strength. TRIP steel possesses both superior strength and good formability as a result of the transformation of a small volume fraction of metastable retained austenite to martensite during deformation. The microstructure of CP steel consists of very fine ferrite and a higher volume fraction of hard phases which can be further strengthened by fine precipitates obtained by adding small quantities of niobium, titanium and/or vanadium. The FB steel consists of fine ferrite and bainite regions. The HSLA steel used in this research consists of a ferrite/cementite microstructure containing Ti and Nb, which makes precipitation strengthening possible. In martensitic steels, the high temperature austenite almost entirely transforms into martensite during quenching. Furthermore, these steels are often subjected to post-quench tempering to improve ductility.

Although the impact of hydrogen on high strength steel has already been confirmed by many research groups, little data are available about the interaction between hydrogen and TRIP steels, except for the early work of McCoy et al. [4], and the recent studies of Hilditch et al. [3] and Ronevich et al. [5]. Recently, the mechanical properties of four different high strength steels, including TRIP, have been studied by Duprez et al. [6]. They performed, among others, tensile tests on TRIP samples immediately after electrochemical charging and on samples that were atmospherically discharged for one week. Their results showed that the ductility loss after charging is reversible. A large part of the ductility is recovered after discharging the sample for one week. These tests prove that damage that is observed after charging is caused by the intrinsic presence of mobile hydrogen and not due to an irreversible damage mechanism caused by hydrogen charging. Other high strength steels appeared to be less sensitive to the ductility loss immediately after charging, while it was also observed that not all steels recovered their initial ductility by waiting one week in between hydrogen charging and tensile testing due to irreversible damage.

As mentioned before, TRIP steel contains metastable austenite, which transforms to martensite during deformation. The effects of a martensitic microstructure on the hydrogen content and diffusivity have been studied by a number of researchers [2,7–11]. Chan et al. [9] found that the observed variations in hydrogen content and diffusivity did not only depend on the carbon content, but also on the different martensite morphologies and the effects of the presence of retained austenite. Sakamoto and Mantani [10] pointed out that minimum diffusivity and maximum solubility of hydrogen are obtained when the steel has an as-quenched martensitic structure, as opposed to tempered martensite. Other work of Chan et al. [11] shows that a higher amount of hydrogen is present in steels (especially for high carbon steels) which still contain retained austenite.

In the present study, the influence of hydrogen on the mechanical properties of four multiphase steels was investigated by performing tensile tests on in-situ charged samples. Correlations were made with previously published [12] hot extraction and thermal desorption spectroscopy measurements where possible. Some tensile tests were also performed at different cross-head displacement speeds in order to elucidate the impact of the diffusible hydrogen on the embrittlement.

2. Experimental procedure

In this study, the mechanical properties of four multiphase, advanced high strength steels under various conditions were investigated. These industrial materials contained different constituents, such as martensite, bainite, pearlite and retained austenite.

The thickness of the TRIP steel sheets was 0.7 mm, while the FB, DP and HSLA steels had a thickness of 1.1 mm. These thicknesses were reached after hot and cold rolling, followed by subsequent annealing via industrial annealing parameters necessary to obtain the desired microstructure. Chemical compositions are summarized in Table 1. The samples were ground using a Ziersch and Baltrusch surface grinder, rotating at 3342 rpm. After grinding, notched tensile samples were made by spark erosion, the tensile axis being parallel to the rolling direction. Finally, the surface and edges of the samples were sand blasted.

To characterize the material by the optical microscopy, it was ground, polished and etched. For the TRIP steel a 4% Picral solution was used and for the FB, DP and HSLA steel a 2% Nital solution was used as an etchant. The amount of retained austenite was quantified by XRD measurements. The retained austenite volume fraction was determined with the direct comparison method [13] using the integrated intensity of the $(200)_\alpha$, $(112)_\alpha$, $(220)_\gamma$ and $(311)_\gamma$ peaks. The carbon content was determined according to the method of Cullity [13].

In order to study the influence of hydrogen embrittlement, the tensile properties of the four alloys were measured in air (uncharged) and in hydrogen charged conditions. Each test was performed twice in order to get an indication on the reproducibility of the results: two identical test conditions

Table 1 – Chemical compositions in wt%.

Material/element	C	Mn	Si	Other
TRIP	0.17	1.60	0.40	1%–2% Al 0.04%–0.1% P
FB	0.07	1.00	0.10	0.5%–1.0% Cr
DP	0.07	1.50	0.25	0.4%–0.8% Cr + Mo
HSLA	0.07	0.95	0.00	0.08%–0.12% Ti + Nb