THE EFFECT OF HYDROGEN AND DEFORMATION ON THE MECHANICAL PROPERTIES OF TRIP 780 STEEL

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Abstract

This work deals with the influence of hydrogen on the mechanical properties of TRIP 780 type C-Mn-Si steel. Tensile test bars were hydrogenated in 0.1N sulfuric acid solution with the addition of KSCN during the slow strain rate tensile tests (SSRT). Due to the presence of hydrogen in the steel microstructure, there was a significant decrease of elongation at fracture from 33 % to 3 % and a decrease of tensile strength from 868 MPa to 642 MPa, respectively 658 MPa at current density 5 or 1 mA·cm^{-2}. The yield strength slightly increased from 505 MPa to approximately 517 MPa after hydrogenation. The relative change of elongation at fracture due to hydrogen was expressed by the index of hydrogen embrittlement F, which exceeded 95 %. The fracture surfaces of the tensile test bars were subjected to fractographic analysis. The presence of hydrogen during the tensile test influenced the failure mechanism and manifested itself by the occurrence of the quasi-cleavage fracture at the fracture surface.

Keywords: Hydrogen embrittlement, TRIP steel, deformation, slow strain rate test (SSRT)

1. INTRODUCTION

TRIP steels are the new generation of multi-phase low-alloy materials that show increased values in ductility and strength and by that meet requirements of high- strength, well formable materials in automotive industry. The individual components in cars can be produced from this type of material relatively thin, because TRIP steels report sufficient ductility necessary for high deformation processes like pressing, while preserving strength and properties characterising ability to absorb impact energy. After heat processing, it is possible to obtain three-phase structure formed by ferrite (50 - 60 vol. %), bainite (25 - 40 vol. %) and retained austenite (5 - 15 vol. %), which transforms during plastic deformation under certain conditions to deformation-induced martensite. This transformation is called TRIP effect (transformation induced plasticity). For the TRIP effect to occur, the microstructure has to contain 10 - 15 % austenite. This may be reached by chemical composition which must contain elements that prevent carbide formation and stabilize austenitic matrix, e. g. silicon, manganese, carbon or aluminium. These steels achieve very high strength thanks to TRIP effect, but simultaneously the keep good formability and high energy absorption at deformation. That is why they find wide application in various industries. In the automotive industry, they are used for side rails, dashboards, roof racks, seat frames, longitudinal beams, bumpers, etc. They found an application also in aviation on aircraft cladding or in medical services for surgical needles [1-7].

As with other steels, also with TRIP steels the mechanical properties depend mainly on the chemical composition and processing conditions. TRIP steels can achieve the tensile strength in the range of 590 to 900 MPa with good plastic properties. The ductility ranges from 21 to 30 %. Fatigue properties are similar to martensitic high strength steels. TRIP steels achieve good fatigue properties mainly due to the presence of retained austenite in the structure and deformation-induced austenite transformation during loading. The disadvantage of TRIP steels is relatively low yield strength due to the increasing density of dislocations in the ferrite and near the interface with martensite. The yield strength can be increased by the proportion of bainite in the structure. The ferritic phase has the greatest influence on the mechanical properties because it is represented in the structure the most. The yield strength is influenced by the content of alloying elements, then by grain refinement and hardening of the solid solution. Bainite also has an influence on the tensile strength, due to the fact, that higher bainite fraction are generated during higher cooling rates after inter-critical annealing, thereby increasing the tensile strength [1-2].

The most important barrier is their surface finish by galvanic zinc coating. Zinc coating is a relatively simple, cheap and efficient surface treatment process. It is used in large quantities for steels in automotive industry. The original TRIP steels contained a high content of silicon as an alloying element, which serves primarily to inhibit cementite phase formation. This relatively high silicon content causes the oxide formation before the zinc coating process of the steel surface and thus degrades the properties of the zinc protective layer. These problems are suppressed by adding aluminium as a substitute for silicon [2]. The main sources of hydrogen leading to IHE (Internal Hydrogen Embrittlement) for high-strength steels are solutions that are used for electrolytic plating or pickling [8]. The influence of hydrogen on the degradation of TRIP steel properties is discussed in this article.

2. EXPERIMENTAL PART

2.1. Material description and microstructure

Steel TRIP 780 of a type C-Mn-Si was delivered after two-stage cold rolling and after one-stage hot rolling. The surface of this steel is usually treated by hot dip galvanizing or by galvanic plating. Tensile strength of this steel is in range of 780 to 900 MPa, yield strength 450 to 550 MPa and ductility should be higher than 23 %. According to the fact that this steel has excellent plastic properties and good energy absorbing ability, it is used for safety features of bodywork in automotive industry, specifically for the production of safety reinforcements, bumpers, beams and B pillars [1].

A sheet metal of 1,17 mm thickness without surface treatment was delivered for experimental purposes. The chemical composition of commercially produced sheet metal, from which samples were taken, was determined by glow discharge optical emission spectrometry GDOES method on the device GDA 750 of the company Spectruma and is shown in **Table 1**.

Table 1 The chemical composition of steel TRIP 780 in wt. %.

C	Mn	Si	P	S	Cr	Ni	Mo
0.203	1.57	1.65	0.015	<0.001	<0.001	<0.001	<0.001
Cu	**Ti**	**Co**	**B**	**Pb**	**V**	**W**	**Al**
0.007	0.002	0.003	<0.001	<0.001	0.001	<0.001	0.058

As mentioned above, the microstructure of TRIP steel is formed by ferrite (α), bainite, (α_B) and by retained austenite (M/A). Metallographic samples of default samples were observed in polished and etched condition. Etching was carried out in 2% Nital. Samples were observed by an optical metallographic microscope Olympus IX70 (zk. OM, **Figure 1**) and by a scanning electron microscope JEOL 6490LV in mode of secondary electrons (abbrev. SEM, **Figure 2**). The material showed high metallurgic cleanliness. Complex inclusions based on aluminium oxide and calcium sulphide, inclusions based on aluminium oxide organised in the direction of rolling and sharp-edged inclusions of titanium nitride occurred in the microstructure. The size of individual inclusions was appx. 10 μm.

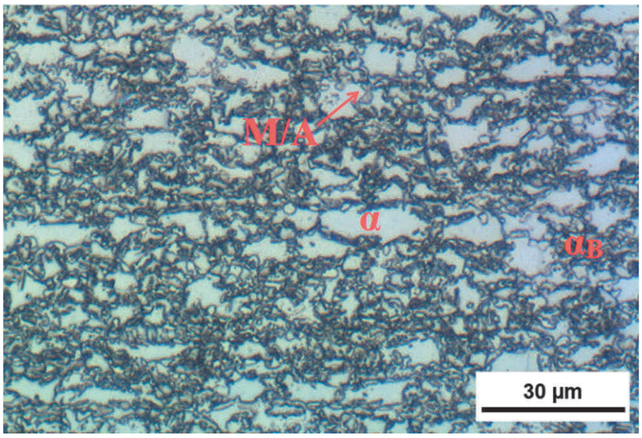

Figure 1 Microstructure of steel TRIP 780, longitudinal direction, etched in Nital (OM)

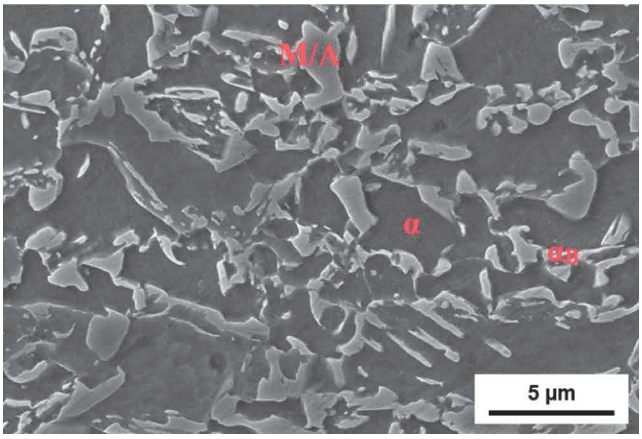

Figure 2 Microstructure of steel TRIP 780, longitudinal direction, etched in Nital (SEM)

2.2. Mechanical properties

Samples for the tensile test were taken by a method of electrical discharge cutting in longitudinal direction to the direction of rolling. All samples were before the tensile test treated by hand grinding with a grinding paper of 800 grain size. The initial cross-section of the tensile test specimen S_0 was 11.70 mm^2, initial measured length L_0 = 50 mm. Tensile tests were run on testing machine ZD10 with the deformation speed of $2{,}7{\cdot}10^{-5}$ s^{-1}. The values of yield strength $Rp_{0,2}$, tensile strength R_m and ductility A_{50} of tested samples in initial state are shown in **Table 2**.

Electrolytic hydrogen charging was carried on simultaneously with ductility test. Test samples were put into a special cell. The sample was connected as a cathode, platinum-plated wolfram mesh as an anode. The electrolytic hydrogen saturation was carried out in 0.1N solution of H_2SO_4 with an addition of 1 gram of KSCN to 1 litre of solution with the current density of 1 or 5 mA·cm^{-2} (with voltage 28,9 V).

For evaluation of hydrogen embrittlement of individual samples, so called index of hydrogen embrittlement was used [9]. This index marked as F (eq. 1) describes the change in ductility between not hydrogenated and hydrogenated test samples related to the ductility of samples in initial condition without hydrogen.

$$F = \frac{A_0 - A_H}{A_0} \cdot 100 \quad (1)$$

where

F - index of hydrogen embrittlement [%]

A_0 - ductility of tested initial samples without hydrogen [%],

A_H - ductility of tested samples with hydrogen [%].

When comparing mechanical properties of samples that were hydrogenated during tensile test with current density at 5 mA·cm^{-2} with samples in initial condition without hydrogen, it can be stated that hydrogen had only insignificant influence on the yield strength, but tensile strength significantly decreased by 226 MPa and ductility by 29 %. The index of hydrogen embrittlement was 95 %.

Samples that were submitted to hydrogen saturation during the tensile test with current density at 1 mA·cm^{-2} showed similar trend of mechanical properties. When comparing to samples in initial condition without hydrogen, a little increase of yield strength occurred, but tensile strength decreased by 210 MPa and ductility again decreased by 30 %. The index of hydrogen embrittlement was 93 %. Little increase of yield strength and tensile strength decrease compared to samples in initial condition can be attributed to lower current density at which hydrogen penetrates to steel and therefore probably lower hydrogen content in steel.

For samples that were hydrogenated in solution without KSCN with current density at 5 mA·cm^{-2}, it was confirmed that KSCN helps easier diffusion of hydrogen into steel. Samples showed slightly lower yield strength compared to samples in initial condition, then a decrease in tensile strength only by 91 MPa occurred and ductility lowered by 22 %, where these samples showed lower index of hydrogen embrittlement F, and that was 80 %.

Tension diagrams of selected samples are summarized in **Figure 3**.

Table 2 Mechanical properties of samples in initial condition and after hydrogen saturation in different conditions

Sample indication	**I [mA·cm^{-2}]**	**$R_{p0.2}$ [MPa]**	**R_m [MPa]**	**A_{50} [%]**	**F [%]**	**RA [vol. %]**
Initial state without H	-	505 ± 1	868 ± 1	32.5 ± 0.2	-	3.2
State during hydrogen charging 0.1N H_2SO_4+KSCN	5	516 ± 20	642 ± 16	3.3 ± 0.1	94.6 ± 0.1	7.7
State during hydrogen charging 0.1N H_2SO_4+KSCN	1	517 ± 3	658 ± 7	2.7 ± 0.1	93.4 ± 0.3	7.6
State during hydrogen charging 0.1N H_2SO_4	5	496 ± 1	777 ± 3	10.3 ± 0.4	79.5 ± 0.9	-
State **after** hydrogen charging 0.1N H_2SO_4+KSCN, 4 hours [10]	1	559 ± 15	753 ± 28	6.8 ± 0,8	83.3 ± 2.2	6.7

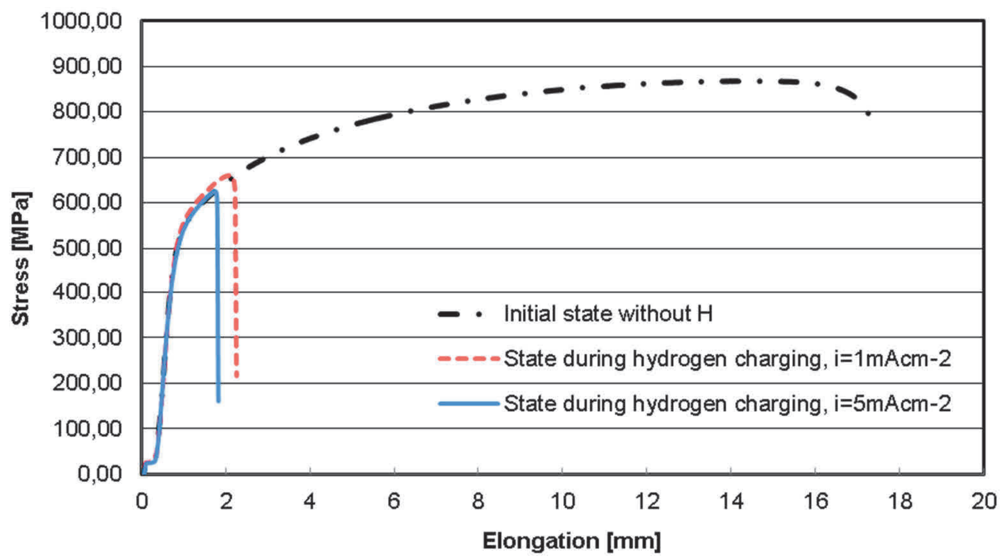

Figure 3 Dependence of the strength on the elongation of selected steel TRIP 780 samples

The volume fraction of retained austenite was observed on four selected samples (**Table 2**) by X-ray diffraction analysis on the machine Bruker-AXS D8 Advance with 2θ/θ measurement geometry and detector LynxEye. The volume fraction of retained austenite depends on the deformation stage at which deformation induced transformation of retained austenite to martensite occurs. The sample in an initial condition of material without hydrogen and without applied deformation contained 14.9 vol. %. After deformation till the damage during the tensile test without hydrogen a decrease in volume fraction of retained austenite to 3.2 vol. % occurred under the influence of TRIP effect. For hydrogenated samples in both current densities only partial transformation of retained austenite to martensite occurred because of lower plasticity, and it was to 7.7 vol. %.

Mechanical properties of steel TRIP 780 samples after 4 hours hydrogen charging and following tensile test without hydrogen can be seen in **Table 2**. These values were measured within the work [10]. When comparing to mechanical properties of samples that were hydrogenated during the tensile test, it can be concluded that sampled that were hydrogen charging for 4 hours and then submitted to the tensile test without hydrogen, have better mechanical properties than samples that were hydrogenated during the tensile test. Samples that were hydrogen charging for 4 hours showed higher yield strength by 42 MPa, then higher tensile strength by 95 MPa and greater ductility by 4.1 %. All these values are also connected to the lower index of hydrogen embrittlement which was for pre-hydrogenated samples in average of 83 % and for samples that were hydrogenated during the ductility test 95 %. Compared values of mechanical properties of hydrogenated samples before and after tensile test confirm that steel TRIP 780 is more subjected to hydrogen embrittlement if there is hydrogen penetrating during the deformation which probably relates to a mechanism of hydrogen atoms transfer during the dislocation movement.

2.3. Fractographic analysis

Fractographic analysis was performed in secondary electron mode on the scanning electron microscope JEOL 6490LV. The fracture area of the sample deformed in the initial state without hydrogen is formed by two types of fracture: a transgranular ductile fracture with dimple morphology at the edge of the fracture surface and a transgranular cleavage fracture at the centre of the fracture area **(Figure 4**).

Due to the presence of hydrogen in the TRIP steel microstructure, the crack propagation mechanism has changed. A mixed fracture consisting of a transgranular ductile fracture with dimple morphology and a transgranular cleavage fracture is evident. Quasi-cleavage fracture, so-called fish eye, occurs in the area of non-metallic inclusions and segregation belts (**Figure 5**).

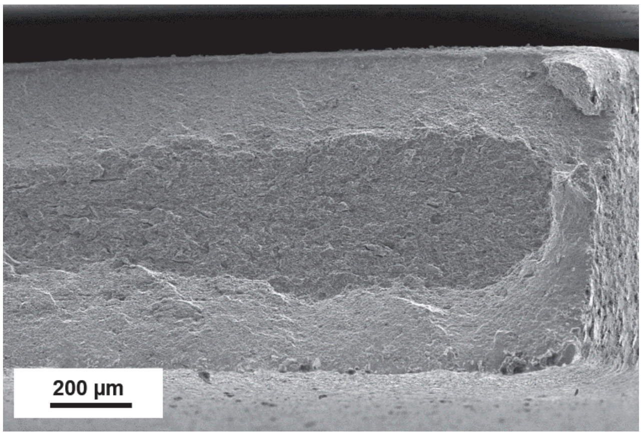

Figure 4 Fracture area of the sample deformed in the initial state without hydrogen (SEM)

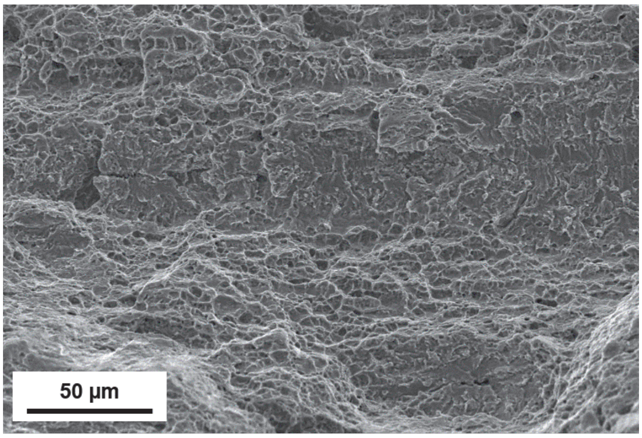

Figure 5 Fracture area of the hydrogenated samples,quasi-cleavage and transgranular ductile fracture, detail (SEM)

3. CONCLUSION

The aim of this paper was to observe concurrent influence of hydrogen and deformation on mechanical properties of steel TRIP 780. Generally, it can be stated that hydrogen embrittlement showed primarily by a decrease in tensile strength of tested steel TRIP 780 and by significant decrease in ductility. Presented results show that the higher current density is, the higher amount of hydrogen penetrates the steel and causes greater loss of utility mechanical properties. For samples that were hydrogenated without KSCN was confirmed that KSCN helps easier diffusion of hydrogen to steel. This paper confirmed strong propensity of TRIP steels to hydrogen embrittlement and it is significant that hydrogen embrittlement occurs more significantly during hydrogen penetration to steel during deformation, and therefore at relatively short saturation times (orderly in units or maximum tens of minutes), rather than in long-term (several hours) effect of hydrogen before deformation itself.

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