Materials Research Proceedings 34 (2023) 62-67 https://doi.org/10.21741/9781644902691-8

The Influence of Hydrogen Embrittlement on Mechanical Properties of Advanced High-Strength Structural Steel S960MC

DRÍMALOVÁ Petra [1,a*], NOVÝ František [1,b], MEDVECKÁ Denisa [1,c] and VÁŇOVÁ Petra [2,d]

[1]University of Žilina, Faculty of Mechanical Engineering, Department of Materials Engineering Univerzitná 8215/1, 010 26 Žilina, Slovak Republic

[2]VŠB Technical University Ostrava, Faculty of Materials and Technologies, Department of Materials Engineering and Recycling, 17. listopadu 2172/15, 708 00 Ostrava – Poruba, Czech Republic

[a]petra.drimalova@fstroj.uniza.sk, [b]frantisek.novy@fstroj.uniza.sk, [c]denisa.medvecka@fstroj.uniza.sk, [d]petra.vanova@vsb.cz

Keywords: Hydrogen Embrittlement, High-Strength Steels, Safety, S960MC, Material Degradation

Abstract. A lot of emphasis is currently being paid to research into how hydrogen affects the mechanical properties of advanced high-strength (AHS) steels. The use of AHS steels in the chemical industry and nuclear technology is heavily influenced by the mechanical properties that result from the impact of hydrogen. Hydrogen, an interstitial element, alters fracture behavior and causes the material to fail earlier than it should. The greatest danger occurs after hydrogen has been absorbed when it diffuses and accumulates into defects such grain boundaries, dislocations, and phase boundaries. The crystal structure of the steel enlarges due to tensile stresses, which increases hydrogen diffusion. Cold forming creates a multitude of components, and even a small amount of hydrogen absorption could result in significant residual stresses in the material. The steel can experience a significant reduction in mechanical properties, strength, and ductility up to fracture at a critical hydrogen concentration level. It is impossible to preventively remove components that have been harmed by hydrogen before they are utilized, which is the primary issue with hydrogen embrittlement from a safety perspective.

Introduction

Hydrogen embrittlement is a phenomenon that occurs in high strength structural steels, when atomic hydrogen is introduced into the material. Numerous procedures, such as electroplating, welding, and hydrogen gas exposure, might cause this. The hydrogen atoms can diffuse into the steel and become trapped at defects in the microstructure, such as dislocations and grain boundaries. After becoming trapped, the hydrogen atoms can make the steel brittle and susceptible to cracking. This can lead to catastrophic failure of the structure and is a major concern in the design of construction of high strength steels [1,2]. The susceptibility to hydrogen embrittlement can be influenced by various factors such as the chemical composition, microstructure, and mechanical properties of the steel, as well as the environmental conditions to which the steel is exposed. Therefore, the material selection, manufacturing processes, and post-treatment procedures such as hydrogen bake-out and stress relief are critical in reducing the risk of hydrogen embrittlement [3,4].

Despite the efforts to reduce the effects of hydrogen embrittlement, it remains a complex and not fully understood phenomenon. There are several theories that attempt to explain the mechanisms of hydrogen embrittlement, such as the decohesion theory, the hydrogen-induced dislocation emission theory and the hydrogen-induced cracking theory, but none of them provide a complete explanation [5-7].

Furthermore, the susceptibility to hydrogen embrittlement can vary depending on the type of steel and the specific application. For example, high strength steels like S960MC are more susceptible to hydrogen embrittlement than lower strength steels due to their high strength-to-weight ratio and high hardness.

Experimental Material

The material used for this research was thermomechanically rolled advanced high-strength steel S960MC in the form of sheet with a thickness of 3 mm. The chemical composition and mechanical properties are presented in tables Table 1 and 2.

The microstructure of steel was studied in polished and etched condition using Olympus IX70 inversion metallographic light microscope (LM). The investigated material was microalloyed steel with a low carbon content and an increased chromium contend. Grain refinement was also caused by thermomechanical treatment, which resulted in tensile strength values up to 1150 MPa. As a result, a fine martensitic microstructure was created (Fig. 1 and 2).

Table 1. Chemical composition of advanced high-strength steel S960MC [wt. %]

C	Si	Mn	P	S	Al	Nb	V	Ti	Mo	B
0.085	0.205	1.09	0.011	0.009	0.028	<0.004	0.014	0.018	0.122	0.002

Cu	Cr	Ni	N
0.019	1.17	0.055	0.014

Table 2. Mechanical properties of advanced high-strength steel S960MC

Yield Strength [MPa]	Tensile Strength [MPa]	Ductility [%]
1014	1162	4

Fig.1. *Microstructure of S960MC steel (LM, 100x, Nital etch.).*

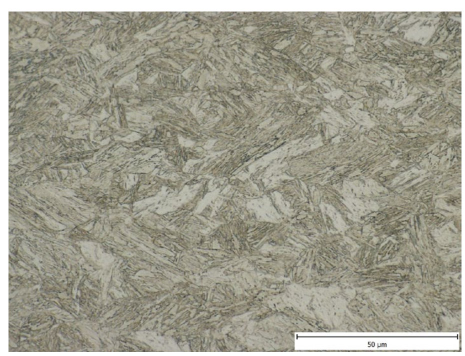


Fig.2. *Microstructure of S960MC steel (LM, 1000x, Nital etch.).*

Hydrogen Charging

The samples from experimental material were electrolytically hydrogen charged in their as received state (AR) with the oxide layer, after grinding the oxide layer (G) and with a blasted surface (B). The sample was connected as a cathode, platinum-plated wolfram mesh as an anode. The electrolyte was a solution of 0.05 M sulfuric acid (H_2SO_4) with the addition of 1 g of potassium thiocyanate (KSCN) per one liter. The hydrogenation process was carried out for 4 hours at a current density of 1mA·cm^{-2} at the temperature 20±2°C. After hydrogenation, the samples were dried and quickly transferred to the tensile testing machine. The tensile tests were performed using a multifunctional LFV 100 kN servo-hydraulic test machine. The mechanical properties of the samples in the initial state and in the state after hydrogen charging are shown in Table 3 and Figs. 3, 4 and 5.

Results and Discussion

Due to the diffusion and recombination of hydrogen atoms into experimental steel, there was a significant decrease of ductility and tensile strength (Table 3). The effect of hydrogen on the yield strength was different for the different state of surface condition. The highest decrease of yield strength was measured for samples G, while the lowest decrease was measured for samples B. However, changes in mechanical properties are very well evident from the tensile diagrams of each state of samples surface (Figs. 3, 4 and 5).

Table 3. Results of mechanical properties in the initial state and after hydrogen charging of samples with every surface condition

Sample	Test conditions	Yield Strength [MPa]	Tensile Strength [MPa]	Ductility [%]
AR	Initial state	988.05	1157.32	4.11
	After hydrogen charging	936.11	928.97	0.19
G	Initial state	1398.90	1570.73	5.07
	After hydrogen charging	1038.71	1056.39	0.92
B	Initial state	976.72	1056.84	9.31
	After hydrogen charging	975.85	985.18	1.89

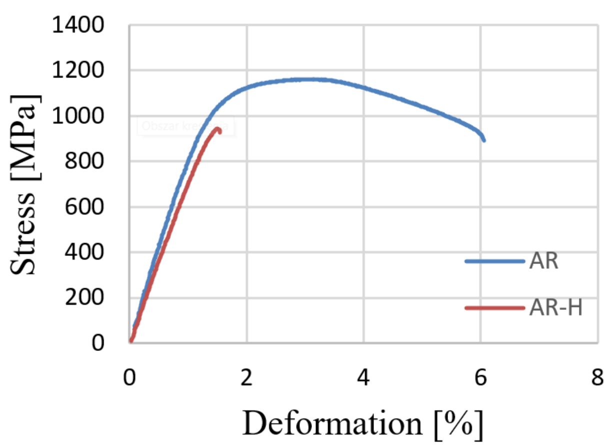


Fig. 3. *Tensile diagrams of samples in their as received state (AR) in initial state and after hydrogen charging (AR-H).*

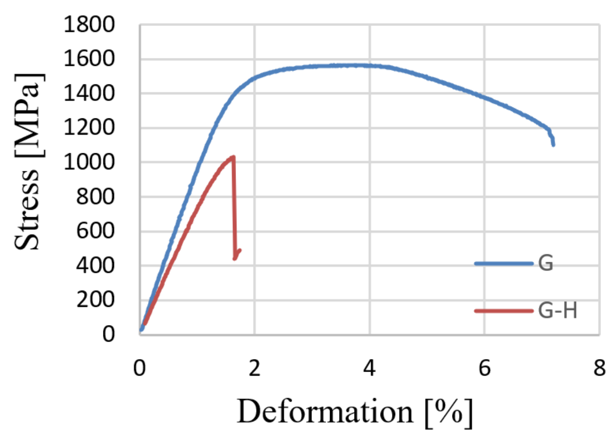


Fig.4. *Tensile diagrams of samples after grinding the oxide layer (G) in initial state and after hydrogen charging (G-H).*

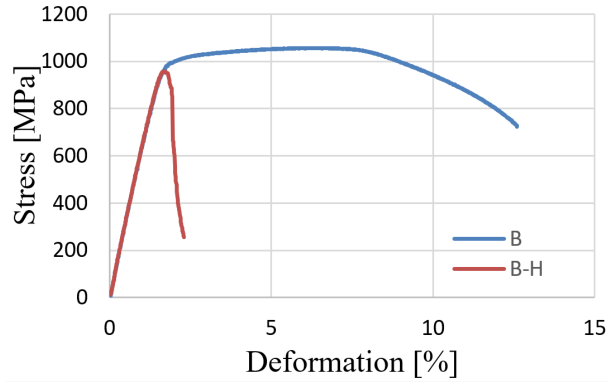


Fig. 5. *Tensile diagrams of samples with a blasted surface (B) in initial state and after hydrogen charging (B-H).*

Similar results were obtained by Váňová and her coworkers [8], for TRIP 800 and TRIP 780 steels, which were also exposed to hydrogen in the same way and in the same environment as in our case.

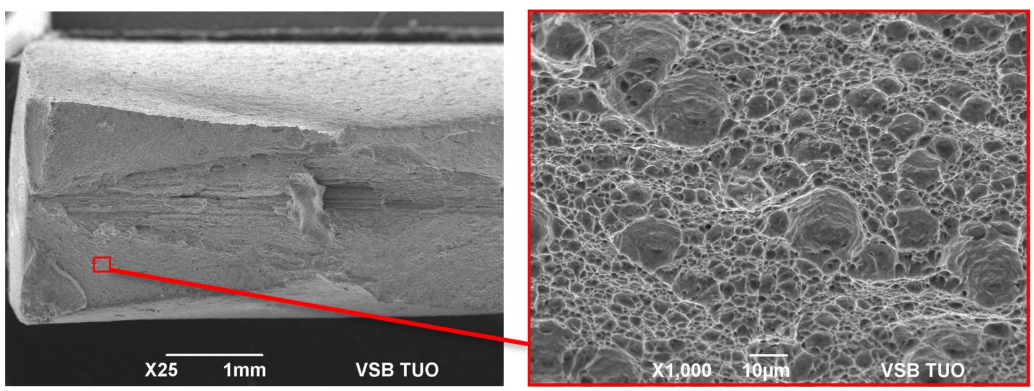
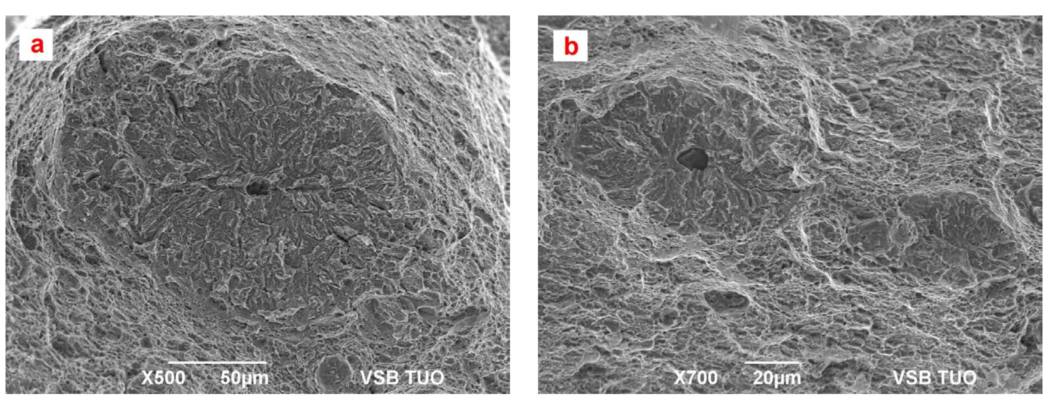


Fig. 6. *The sample fracture surface in the initial state without hydrogen charging, transgranular ductile fracture with dimple morphology.*



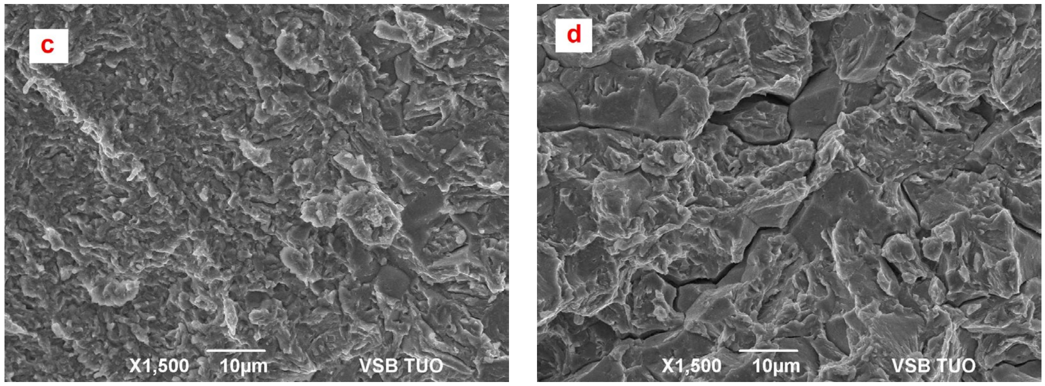


Fig. 7. *The sample fracture surface in the state after hydrogen charging; a) and b) fish-eyes accompanied by quasi-cleavage fracture around inclusions, c) quasi-cleavage fracture, d) intergranular ductile fracture.*

The fracture surfaces of the samples after tensile test were subjected to fractographic analysis. The fractographic analysis was carried out using the JEOL 6490LV scanning electron microscope (SEM) in secondary electron mode. Samples that were not subjected to hydrogen charging shows signs of transgranular ductile fracture with a dimple morphology.

From Fig. 6 and 7 it is possible to see how the presence of hydrogen in microstructure influenced the fracture mechanism during the tensile test. Hydrogen embrittlement typically manifest itself by the occurrence of the quasi-cleavage fracture and by large secondary cracks at the fracture surface for materials with a bcc crystal lattice [9-11]. In our case, hydrogen embrittlement was manifested by the formation of fish-eyes (Fig. 7a and b). Each of these fish-eyes were represented by the area of quasi-cleavage failure, which initiates on a non-metallic inclusion [12]. The inclusions observed in the center of the fish-eyes were identified as elongated sulphide inclusions or as complex globular oxysulphide inclusions. Quasi-cleavage facets are visible on the edge of the samples and around elongated non-metallic inclusions (Fig. 7c). Locally, especially on the edge of the samples, is also possible to see the intergranular ductile fracture (Fig. 7d).

Summary

The study of hydrogen embrittlement of advanced high-strength steel S960MC using tensile tests after hydrogenation confirmed the significant tendency of this steel to hydrogen embrittlement. Even though the electrolytic method of hydrogenation took place at a low current density, compared to structural steels of usual quality, embrittlement due to hydrogen in the S960MC steel during the tensile test was manifested by a more significant reduction in ductility [13]. Therefore, in production processes in which S960MC steel is processed (especially galvanic surface treatments, etc.), where there is a potentially high risk of interaction of atomic hydrogen with the material, it is necessary to pay extra attention to the ingress of hydrogen into the material in order to avoid hydrogen embrittlement.

In conclusion, hydrogen embrittlement is a significant concern in the design of the construction produced from high-strength structural steels. The proper material selection, manufacturing processes, and post-treatment procedures are critical in reducing the risk of hydrogen embrittlement. Despite of the efforts to understand and mitigate the effects of hydrogen embrittlement, it remains a complex and not fully understood phenomenon. Further research is needed to fully understand and reduce the effects of hydrogen embrittlement on high strength structural steels.

Acknowledgement
The research was funded by Slovak Research and Development Agency under contract No. APVV-20-0427 and the Slovak Ministry of Education, Science, Research, and Sport's Scientific Grant Agency under contract VEGA No. 1/0741/21.

References
[1]M.F. McGuire, R. J. Matway. A Mechanism for Hydrogen Embrittlement in Martensitic Steel Based on Hydrogen Dilation, Preprints.org (2022) art. 2022020275. https://doi.org/10.20944/preprints202202.0275.v1

[2]T. Schaupp et al. Hydrogen-assisted cracking of GMA welded 960 MPa grade high-strength steels. Int. J. Hydrog. Energy 45 (2020) 20080-20093. https://doi.org/10.1016/j.ijhydene.2020.05.077

[3]B.L. Enis et al. The role of aluminium in chemical and phase segregation in a TRIP-assisted dual phase steel. Acta Mater. 115 (2016) 132-142. https://doi.org/10.1016/j.actamat.2016.05.046

[4]J. Sojka. Resistance of steel to hydrogen embrittlement. Ostrava: VŠB – Technical University of Ostrava, 2007 (In Czech).

[5]L. Hyspecká, K. Mazanec. Hydrogen embrittlement of structural steels with higher parameters. Praha: Academia – publishing house of the Czechoslovak Academy of Sciences. 1978 (In Czech).

[6]X. Li et al. Review of Hydrogen Embrittlement in Metals: Hydrogen Diffusion, Hydrogen Characterization, Hydrogen Embrittlement Mechanism and Prevention. Acta Metall. Sin.-Engl. 33 (2020) 759-773. https://doi.org/10.1007/s40195-020-01039-7

[7]S. P. Lynch. Hydrogen embrittlement (HE) phenomena and mechanisms. Corr. Rev. 30 (2011) 90-130. https://doi.org/10.1515/corrrev-2012-0502

[8]P.Váňová et al. Comparison of Behaviour of Different Variants of Hydrogenated TRIP Steels at Slow Strain Rate Tests. Key Eng. Mater. 810 (2019) 70-75. https://doi.org/10.4028/www.scientific.net/KEM.810.70

[9]D. Hardie, E.A. Charles, A.H. Lopez. Hydrogen embrittlement of high strength pipeline steels. Corr. Sci. 48 (2006) 4378-4385. https://doi.org/10.1016/j.corsci.2006.02.011

[10] T. Hojo, et al. Effects of Alloying Elements Addition on Delayed Fracture Properties of Ultra High-Strength TRIP-Aided Martensitic Steels. Metals 10 (2020) art.6. https://doi.org/10.3390/met10010006

[11] Q. Liu, et al. The role of the microstructure on the influence of hydrogen of some advanced high-strength steels. Mater. Sci. Eng. A 715 (2018) 370-378. https://doi.org/10.1016/j.msea.2017.12.079

[12] P. Betakova, J. Sojka, L. Hyspecka. Quantitative assessment of hydrogen embrittlement in structural steels, METAL 2002 11th Int. Conf. on Metall. and Mater. (2002), Hradec nad Moravici, 55-57.

[13] P. Váňová. Hydrogen embrittlement and hydrogen diffusion characteristics in TRIP steels. Habilitation thesis. Ostrava: VŠB – Technical University of Ostrava, 2019 (In Czech).