FRACTURE TOUGHNESS CHARACTERIZATION OF HIGH STRENGH MARTENSITIC STEELS SUBJECTED TO HYDROGEN

Armin E. Halilović*, Jonas Faleskog, and Pål Efsing

Solid Mechanics, Department of Engineering Mechanics, KTH Royal Institute of Technology, Teknikringen 8D, SE-100 44 Stockholm, Sweden.
** Presenting Author email: arminh@kth.se*

Abstract
High strength steels that are subjected to hydrogen may experience environmentally assisted degradation. These types of steels exhibit a loss of load bearing capacity. This paper presents a numerical-experimental method for screening materials' susceptibility subjected to hydrogen. In this work it is found that hydrogen needs time to diffuse into the material and time to cause degradation.

1. Introduction

Hydrogen Embrittlement (HE) is a phenomenon that reduces the mechanical properties of high strength steels. Although HE has been a known phenomenon for over 150 years as discovered by Johnsson (1875), it is still not evident what causes the degradation. One reason for this is that HE manifests itself in different ways for different high strength steels. Another reason for this misconception is that a standard testing procedure does not exist. A commonly used experimental method employed is *slow strain rate testing* (SSRT). In SSRT a tensile test is performed in a hydrogen rich environment. The testing can provide hydrogens influence on the maximum stress, yield stress, elongation to failure and ductility reduction. SSRT is a method that is easy to perform, it is inexpensive and gives a good indication of a material's susceptibility to HE. However, the results conducted from these experiments are difficult to reproduce and to utilize in a predictive manner. For this reason, a fracture mechanics approach is studied in this work. Here a single-edge notch bend specimen is utilized, which is subjected to a constant displacement rate and cathodic polarization. A fractography study is conducted to further assist in the interpretation of the results obtained from the experiments.

2. Results

The material investigated was a high-strength, low hardening martensitic steel with ultimate tensile stress of 1.5 GPa. The tests are subjected to hydrogen-charging in a 3.5% NaCl electrolyte with a platina mesh as the auxiliary electrode. Nitrogen purging is present throughout the whole experiment. All electrochemical experiments are performed in a simplified autoclave made of hard plastic with ceramic rolling supports to ensure no metal-metal contact in the environment. Several parameters were investigated that may influence the fracture mechanical properties. These include current density, pre-charging time and loading rate. A method based on FEM-solutions was developed to continuously evaluate the J-integral and crack length. It is found that the loading rate has a significant effect on the J-R curves, seen in Figure 1. It should also be mentioned that no significant effect on the fracture toughness is observed by reducing the loading rate in air. The results presented in Figure 1 include the key findings from this study, i.e., the effect of loading rate on the J-R curve for a martensitic steel subjected to a hydrogen rich electrolyte. Here a brief discussion of each individual curve is presented top-down. The loads are defined in terms of the rate of the initial stress intensity factor, $\dot{\chi} = K_{\mathrm{I}}/\left[\mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}\right]$.

The fastest loading rate is performed in air and in accordance with ASTM E1820. From this experiment the fractography shows that dimple failure is the dominating mode of failure. The remaining curves are subject to hydrogen charging and different individual loading rates. By reducing the loading rate by a factor of 100, from $\dot{\chi} = 3.3$ to $\dot{\chi} = 3.3\cdot10^{-2}$, it is seen that the onset of crack growth is reduced from 110 kN/m to 60 kN/m. A fractography examination of this test reveals that failure is still dominated by dimple rupture. However, in these experiments, secondary cracks are also present. The secondary cracks are growing in the middle of the specimen in a direction perpendicular to macroscopic crack front.

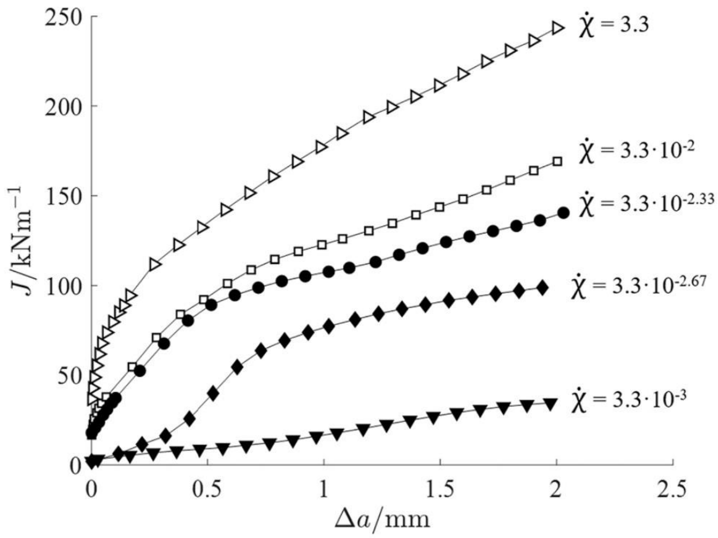

Figure 1: Resistance curves subjected to different loading rates and hydrogen charging.

By further reducing the loading rate to $\dot{\chi}$ = 3.3·10$^{-2.33}$, no significant change in the fracture mechanical properties is observed. The fourth curve from the top pertain to $\dot{\chi}$ = 3.3·10$^{-2.66}$, and here, the J-R curve is initially low and increases rapidly after approximately 0.3mm of crack growth to a plateau at around 60 kN/m. To the author's knowledge, this shape of the J-R curve has not previously been observed in high strength steels. The outcome of this test is interpreted as follows; during charging hydrogen accumulate ahead of the crack tip, and as the loading rate is slow enough, the hydrogen has sufficient time to cause substantial degradation of the material prior to crack initiation. However, as soon as the crack starts to propagate, hydrogen does not have sufficient time to cause degradation of the material in the uncracked ligament. This is further supported by the fractography which shows a region ahead of the crack tip where a mixture of dimple failure and intergranular failure is present in the middle of the specimen, close to the pre-fatigue crack tip. Outside of this region, the intergranular failure is not as intuitively observed. Rather a combination of dimples, secondary cracks and intergranular failure is observed. At the slowest loading rate, $\dot{\chi}$ = 3.3·10^{-3}, a rather flat J-R curve with a slightly increasing tearing modulus ($\mathrm{d}J/\mathrm{d}\Delta a$). Here the fracture toughness is reduced by 90% compared to the experiment in air. The dominating mode of failure is intergranular. However, it should be emphasized that although failure is dominated by intergranular fracture, large regions of dimple rupture is still observed.

3. Conclusions

It is seen in this work that experimental fracture mechanics combined with cathodic polarization is an excellent choice to obtain reproducible results as well as a screening method of materials sensitivity to hydrogen embrittlement. An environmentally driven transition from high to low toughness was observed in a rather narrow range of loading rates. In this range, it was also observed that the hydrogen degradation may be mitigated by crack growth leaving less time for the degradation process to occur and a rise in toughness.

Acknowledgements

The work was carried out within the Strategic Innovation Program Metallic materials and STRIM, a collective venture by Vinnova, Formas and the Swedish Energy Agency. The material used is provided by SSAB Special Steels.