Development of a micromechanics based damage law for the hydrogen induced ductile failure of notched components in high-strength low alloy steel

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MOTIVATION

Global warming is an omnipresent threat and not cutting back on our carbon emissions will have detrimental consequences for society and nature. The European Green Deal strives to make the EU climate neutral by 2050 and explicitly mentions hydrogen as a key element in the energy transition, because of its potential as a clean and versatile energy carrier. Companies are looking into the possibility of creating hydrogen gas using electrolysis from excess energy originating from clean sources such as wind and solar farms. Pipeline systems could be used as an economical means for buffering and transporting energy, in the form of hydrogen gas. In particular, (part of) the existing pipeline network designed for natural gas is considered for hydrogen transport, hereby drastically reducing the cost required for developing a devoted hydrogen gas pipeline network.

However, there are some concerns regarding the safety of welded steel structures subjected to hydrogen. A major challenge in using hydrogen gas is the well-recognized hydrogen assisted mechanical degradation of structural steels. Hydrogen build-up in steel causes degradation in ductility, toughness and fatigue resistance. Figure 1 compares the results of tensile tests performed on a hydrogen-charged specimen and an uncharged ('air') specimen, both taken from the same steel. A significant ductility loss due to hydrogen can be observed. When steel structures are subjected to hydrogen, a structural integrity assessment is required, that takes into account the potentially degraded mechanical properties of the pipeline steel.

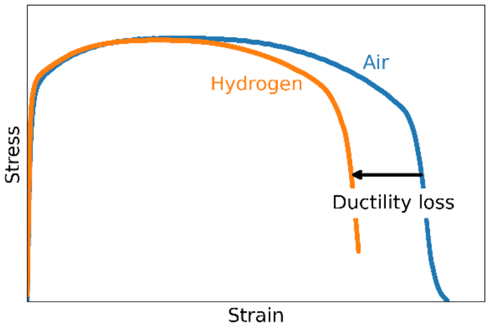

Figure 1 Hydrogen induced ductility loss in steel

Furthermore, even though the phenomenon of hydrogen assisted degradation has been known for a long time, it is still not well understood. Fundamental knowledge lacks on how to link microstructural effects to hydrogen assisted damage at the continuum scale. A mechanistic interpretation describing the effect of hydrogen on failure is disputed and incomplete.

OBJECTIVES

In the context above, a four-year project was kicked off in 2019 where research groups Soete Laboratory and Sustainable Materials Science combine their expertise. The ultimate goal of this combined project is to **improve the understanding of the effect of microstructural and mechanical features on the degradation of hydrogen charged high-strength low alloy steels.** "Degradation" refers to the reduction of ductility and especially fracture toughness. Focus is given to ductile failure.

In order to achieve this goal, two objectives are defined, associated with experimental and numerical work.

1. Investigate the reduction in ductility and fracture toughness of high-strength low alloy steel by means of **tensile and fracture toughness testing with both non-hydrogen and hydrogen charged specimens.**
2. Development of a **numerical micromechanics based continuum damage model accounting for ductile failure in the presence of hydrogen.** Such a model should include the dynamics of hydrogen diffusion and the physics of hydrogen assisted degradation. It will enable to simulate the macromechanical response of a defected structure, loaded in the presence of hydrogen.

APPROACH

To realize the project objectives**, a synergetic experimental and numeric study** is carried out. By combining the findings from both studies, new insight in the degradation of hydrogen charged high-strength low alloy steels will be obtained.

In the project, a “vintage” steel will be compared to a contemporarily used pipeline steel. Evolutions in manufacturing methods and steelmaking practices are reflected in strong differences in terms of microstructure and mechanical characteristics. It is expected that this will also result in significant differences in hydrogen uptake capacity and mechanistic effect of hydrogen.

A micromechanical and microstructural material characterisation is carried out for both steels.

Regarding the first objective, the Single Edge Notched Tension (SENT) fracture toughness test is chosen for its resemblance in loading conditions of thin walled structures (such as pipelines). During an SENT test, a specimen with a crack is quasi-statically loaded in tension, and crack growth is monitored. To perform such tests on hydrogen charged specimens, a chamber is developed allowing for simultaneously (in-situ) charging and mechanically loading the test specimens. The results will be evaluated in terms of both the (reduced) tearing resistance curve, and the appearance of the fracture surfaces.

In the context of the second objective, a finite element based numerical framework is developed that includes crack growth, hydrogen diffusion and the acceleration of damage due to the presence of hydrogen. Hydrogen diffusion towards a loaded crack tip, simulated using a finite element (FE) model is displayed in Figure 2.

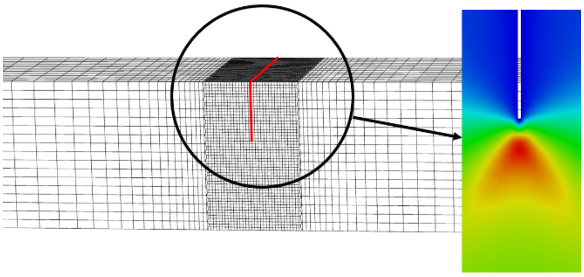

Figure 2 Hydrogen concentration near crack tip in a mechanically loaded SENT specimen (red colour corresponds to a high concentration of Hydrogen)

Crack growth is modelled using a Gurson-type continuum damage model, describing ductile damage in the form of void nucleation, void growth and void coalescence. To determine adequate damage model parameters, experimental input is obtained from tensile tests on (notched) round bar specimens showing different multiaxial stress states.

A mechanistic formulation should be identified capturing the effect of hydrogen on the damage phenomena. For this purpose, experimental tensile tests on hydrogen charged (notched) round bar specimens are performed. Parallel to this PhD work, in-depth microstructural investigations are carried out by the UGent SMS research group to feed the model with observed physics of degradation. Assisting in the analysis of the effect of hydrogen on microvoid and microcrack development, X-ray CT scanning will be performed and will allow the quantification of void distribution.

The numerical framework will eventually be validated with experimental fracture toughness tests, thus paving the path to simulate the structural response of hydrogenated structures.

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