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Simulation of hydrogen embrittlement of ferritic steels: application to cracked specimens

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Abstract

Embrittlement may affect the toughness of ferritic steels used to transport or store gaseous hydrogen. This phenomenon results from the interaction between hydrogen diffusion, plastic deformation and stress concentration, and various physical mechanisms may be involved. Hydrogen embrittlement can lead to a strong decrease in the fracture toughness. In this study, this phenomenon was characterized experimentally using sub-size compact tension (CT) specimens, which were extracted from a 'vintage' pipeline steel (grade API X52). The CT specimens have a thickness of 5 mm and a width of 10 mm. They are machined with side grooves to favor straight crack advance. Tests were carried out in air and in gaseous hydrogen (up to 200 bars) at ambient temperature. Various loading rates and hydrogen pressures were considered. The fracture toughness was found to decrease significantly in gaseous hydrogen, the decrease being more pronounced at lower loading rates and higher hydrogen pressures. Some additional tests on smooth specimens were also performed to characterize the plastic behavior of the material. The experimental database was used to identify a coupled mechanical-diffusion model implemented in the finite element code Z-set. The model is based on a Gurson-Tvergaard-Needleman (GTN) framework modified to account for hydrogen effects. The model is designed to provide a framework able to simulate the gradual transition from ductile to brittle fracture as a function of hydrogen concentration, stress triaxiality and plastic strain. The model aims at modeling the Hydrogen Enhanced Decohesion (HEDE) mechanism which results in quasi-cleavage fracture along slip planes. A nonlocal formulation based on the implicit gradient approach was used to avoid pathological mesh sensitivity. The finite element formulation is based on a B-bar technique to alleviate volumetric locking. An additional problem is solved to compute the pressure at nodes and evaluate the pressure gradient, which drives hydrogen diffusion. The model was implemented in a fully coupled manner, where the various fields (displacements, nonlocal variables, hydrogen concentration, pressure) are obtained in a single global system. The model was identified using the experimental results obtained on CT specimens. The numerical simulations were able to capture the trends observed experimentally, in particular the influence of loading rate and hydrogen pressure on the fracture toughness. The model also provided insights into the distribution of hydrogen concentration, damage type (ductile or quasi-cleavage), and stress fields near the crack tip, which are critical for understanding the embrittlement process.

Keywords:

Modeling. Hydrogen embrittlement. Finite Element Simulation