In-Situ Neutron Imaging and Modeling of Hydrogen Embrittlement in High Strength Steels

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Abstract

A new experimental method to investigate hydrogen assisted cracking is presented in this paper. By combining electrochemical pre-charging, fracture mechanics and neutron imaging it is possible to get large experimental data which can give insight into the local fracture process zone. Furthermore, it can be used to calibrate FEM-models which considers crack propagation, embrittlement, and H diffusion from a moving stress field.

1. Introduction

Hydrogen is becoming increasingly important in today's economy in quest for a sustainable future, where its potential has been discussed as possible alternative to fossil fuels and natural gas to mitigate CO2 emissions. However, storing and using hydrogen under long operating conditions is non-trivial since it can dissolve into most metals during manufacturing or service causing a detrimental reduction in strength and fracture toughness of engineering alloys, this is a phenomenon commonly referred to as hydrogen embrittlement (HE). Several theoretical suggestions, covering a wide range of length scales, from atomistics to continuum mechanics, have tried to elucidate the effects of hydrogen in metals. However, there is yet no experimental evidence how the accumulated H-concentration can lead to premature failure of engineering structures or how and where the concentration evolves over time. A reason for this debate has to do with the difficulty to measure hydrogen content. In this project the aim is to combine well established fracture mechanics testing and neutron imaging, which is one of the few experimental techniques which in theory can get a spatial and temporal resolution of hydrogen diffusivity in metals. The testing was performed on a single-edge-notch bend specimen and subsequently imaged with time series of neutron radiographs under in-situ conditions at NeXT, Grenoble.

2. Results

The specimen was charged for 4 hours while simultaneously increasing the mechanical load up to 10kN. Thereafter the displacement was kept constant. The environment was removed and once the drying was completed (in 3-4 minutes) we started taking radiographs using a 10mm pinhole and 10s exposures. Image acquisition proceeded over 10 hours to ensure good statistics. We managed to capture a related phenomenon called delayed hydrogen cracking whereby H accumulated to the crack tip, the crack advances a distance and arrests when it has passed through the embrittled region, then the procedure is repeated. Data and examples of the analysis from the experiment can be seen in Fig 1. In numerous computational studies, the maximum hydrogen concentration appears immediately ahead of the crack tip due to its strong dependence on the gradient of the hydrostatic stress. The crack growth obtained from the radiographs, and the recorded force- displacement data was used to calibrate a FEM-model. Here, a node-release model was deployed to simulate the fracture process, and to investigate how the hydrostatic stress state changes with a moving crack tip since this will influence the hydrogen redistribution. The material is assumed to follow small strain J2-plasticity and the hardening is described by Voce’s model. Some preliminary modeling results can be seen in Fig 2.

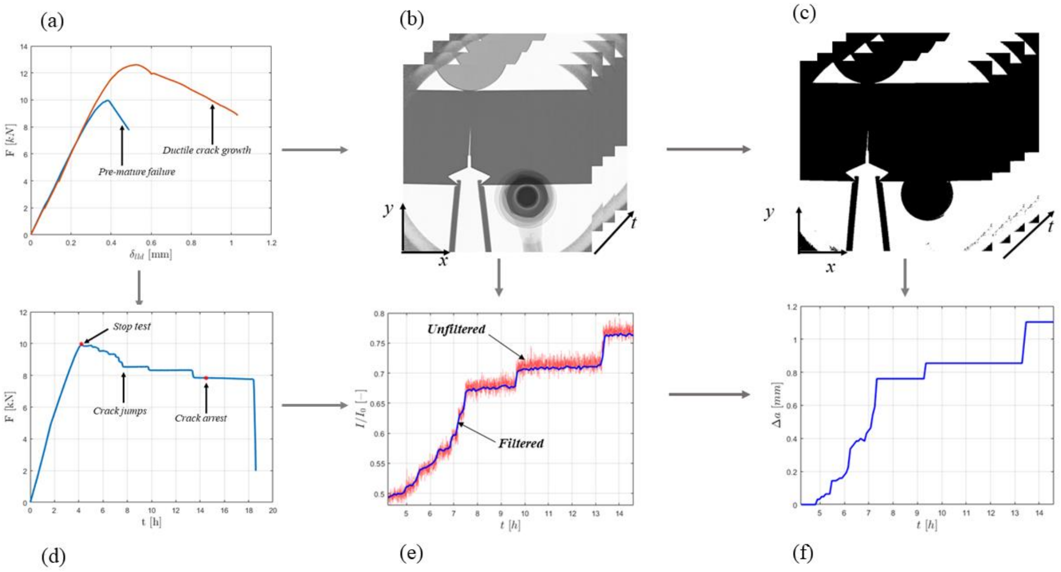

Fig.1 – Data from experiment showing (a) failure at 10kN (blue line) compared to reference sample (red), (b) imaging crack propagation over 10 hours, (c) image thresholding to automatically determine crack tip position, (d) force vs time showing load drop events correlated with (e) transmission profile of the crack propagation and (f) the obtained crack growth increments from the thresholding analysis.

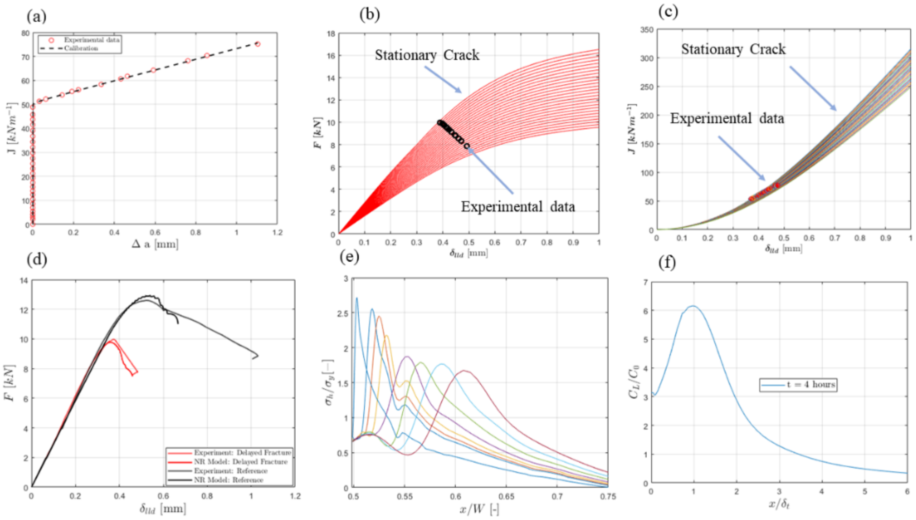

Fig.2 – Modeling results showing (a) J-integral versus crack growth from experiments (b) stationary FEM-solutions compared with failure initiation (c) J-integral for stationary crack compared with failure initiation (d) force vs load line displacement from the calibrated FEM-model and experiments (e) hydrostatic stress state (f) lattice hydrogen concentration after 4 hours.

3. Conclusions

This work has the potential to gain insight into the complex interaction between hydrogen and steels, which can be utilized in future experimental and modelling endeavors**.**

Acknowledgements

The authors would like to thank the researchers at ILL, Grenoble for the cooperation as well as the Swedish research council for financial support