

Measurements and Modeling of Temperature Dependent Hydrogen Embrittlement of Cr-Mo Steel to Enable Fitness-for-Service Life Prediction

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Abstract

Thick-wall vessels in petrochemical applications, fabricated from 2.25Cr-1Mo steel, operate in pressurized H₂ at elevated temperatures for more than 20 years. There is a concern regarding the interactive effects of temper-embrittlement and H-embrittlement on the fitness-for-service (FFS) of this equipment, since the database of the degraded material properties is inadequate to enable accurate assessment. The present study focuses on the internal hydrogen embrittlement (IHE) of the weld metal. Previous data from base metal show that H loss from small fracture mechanics specimens was substantial during either long-term testing or experiments conducted at elevated temperatures. One primary objective of this research is to design and develop a novel laboratory method to retain H in small fracture mechanics specimens over a range of time and temperature pertinent to equipment operation. Other objectives include experimental characterization of the temperature dependent IHE of Cr-Mo weld metal using the developed method, as well as micro-scale modeling of the H distribution near a crack tip to fundamentally understand IHE.

For retaining H in the specimens, the active H supply approach was proposed and developed to provide a H flux source to the microstructure while keeping the test under IHE, instead of hydrogen environment embrittlement (HEE). This has been accomplished using a modified “slotted” specimen, where an electrolyte is pumped continually through the slots and H is charged through the slot surfaces by cathodic polarization. To assure functionality of the active H approach, several major tasks were carried out. The first task was to identify a manageable electrolyte and calibrate H concentrations as a function of electrochemical charging conditions and temperature. The second was to conduct experiments to support and verify the results from finite element stress modeling, and to obtain the necessary relationship for crack length monitoring during IHE cracking. The final task was to extend 2D and perform 3D finite element diffusion modeling of H in the slotted specimen using ABAQUS. The effects of temperature and stress in the crack tip region was emphasized for both standard and slotted specimens. An IHE experiment at ambient temperature with the active H source was successfully conducted.

For the remaining work, additional IHE experiments need to be conducted, particularly at elevated temperatures, to determine the temperature dependence of H cracking. More H diffusion modeling work, using 3D analysis, will be performed to refine the results of H distribution in the specimens. To fundamentally understand the temperature dependence of IHE, the H transport model by Sofronis-McMeeking and Krom et al will be developed first to include the H enrichment in microstructural trap sites located in the stressed region of crack tip. The effect of temperature on H distribution in lattice and trap sites will then be modeled. It is expected that the results of the micro-scale modeling will facilitate interpretation of experimental data and provide guidance on the maximum temperature above which no IHE cracking is expected in Cr-Mo steel.