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In Situ Synchrotron Tomography Investigation of the Effects of Gaseous Hydrogen on Embrittlement in a modern X70 Pipeline Steel

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Abstract

The transition toward low carbon industry has intensified interest in green hydrogen as an energy carrier and storage medium. While hydrogen offers significant advantages, its interaction with structural materials poses major challenges. To choose a material to be used in pipelines requires a thorough understanding of its hydrogen embrittlement mechanisms. In this context, the present study investigates the effects of high-pressure gaseous hydrogen on the mechanical behavior and damage evolution of a modern API 5L X70 pipeline steel. Sub-sized smooth and notched tensile specimens were extracted from a X70 steel pipe. Tensile tests were conducted under a hydrogen gas atmosphere of 240 bar, representative service conditions of offshore pipelines and compared to similar tests in air. In situ synchrotron tomography tests were performed under hydrogen gas environment to visualize the damage evolution during the mechanical test. Two strain rates, 10^{-4} s^{-1} and 10^{-5} s^{-1}, were applied to evaluate the influence of deformation rate on hydrogen diffusion and embrittlement behavior. Edge Tracing (ET) extensometry was employed to accurately measure strain and radial contraction without introducing mechanical components into the pressurized hydrogen environment. Hydrogen exposure led to a pronounced loss of ductility, while the ultimate tensile strength remained largely unaffected. This embrittlement was quantified using normalized radial contraction to calculate the hydrogen embrittlement index (HEI), revealing ductility losses of up to approximately 60% compared to air-tested specimens. Both smooth and notched geometries showed similar embrittlement levels, suggesting that under in situ gaseous hydrogen charging conditions, diffusion may dominate over stress triaxiality alone. Strain rate had a significant influence on both the severity of embrittlement and the reproducibility of the mechanical response. At the higher strain rate (10^{-4} s^{-1}), results showed greater scatter in radial contraction, with values ranging between 18% and 29%, indicating heterogeneous hydrogen interaction and limited diffusion into the bulk material. At the lower strain rate (10^{-5} s^{-1}), deformation times were longer, enabling deeper hydrogen penetration and leading to more repeatable behavior, with radial contraction consistently between 17% and 19% prior to failure. Post-mortem analysis using scanning electron microscopy (SEM) and synchrotron X-ray microtomography provided detailed insight into fracture mechanisms and damage evolution. Specimens tested in air exhibited classical ductile fracture characterized by void nucleation growth. In contrast, hydrogen-charged samples showed surface-initiated cracks with quasi-cleavage features. At 10^{-4} s^{-1}, cracking was primarily confined to the specimen surface, while the core remained largely ductile. At 10^{-5} s^{-1}, extensive embrittlement was observed across the entire cross-section, particularly in notched specimens with higher stress triaxiality. An EBSD was done near the broken surface of the slower strain rate to characterize the damage at a microstructural level where the oblate cracks were observed as cleavage damage. The in situ tomography enabled three-dimensional quantification of crack morphology, orientation, and spatial distribution, revealing anisotropic crack initiation associated to anisotropic plasticity. The brittle surface cracks nucleated normal to the local maximum principal stress in the notched tensile samples, i.e. normal to the notch root surface.

Keywords:

X70 steel Hydrogen embrittlement In situ gas charging Mini specimens Stress triaxiality Synchrotron tomography Damage modeling