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EFFECTS OF TESTING RATE ON HYDROGEN-ASSISTED FRACTURE OF FERRITIC STEELS

Joseph Ronevich[1*], Milan Agnani[1], Chris San Marchi[1]

[1]Sandia National Laboratories, Livermore, CA, USA
[*]Presenting Author email: jaronev@sandia.gov

Abstract

Conventional wisdom suggests hydrogen-assisted fracture occurs principally at slow testing rates as hydrogen requires time to diffuse to the region of elevated stress, such as the crack tip. The effects of testing rate were examined on ferritic-based steels by performing fast rate fracture tests in gaseous hydrogen at testing rates spanning four orders of magnitude.

1. Introduction

When evaluating environmental effects on mechanical properties, fracture tests are conventionally performed at slow testing rates to provide sufficient time for environmental effects to manifest. In this study, we evaluate fracture performance of ferritic steels at faster testing rates to understand if there is a rate above which hydrogen-assisted fracture would substantially diminish or approach the fracture response in air. For example, when considering a fast-moving crack in a pipeline transporting gaseous hydrogen, should one base the fracture arrest on fracture resistance measurements in air or in gaseous hydrogen. To this end, elastic-plastic fracture tests were conducted in gaseous hydrogen at pressure of 210 bar at rates spanning four orders of magnitude. For the purposes of this study, the rate is characterized as dK/dt; the change in K as a function of time in the elastic loading part of the J-R curve. The results were compared to tests in air tested over a similar dK/dt range.

2. Results

Fracture tests were performed using arc-type fracture specimens extracted from X100 pipeline steel. Samples were tested in the C-L orientation where the load was applied in the circumferential direction (e.g. hoop stress orientation) and the crack extended in the longitudinal direction. The applied displacement rates ranged from 5 to 0.005 mm/min. Tests were performed in gaseous hydrogen at pressure of 210 bar to develop J-R curves according to ASTM E1820. The fracture resistance, K_{JQ}, values were determined by the intersection of the 0.2 mm construction line and the J-R curve. Figure 1 shows the fracture resistance values in both air and 210 bar hydrogen gas. The tests in 210 bar gaseous hydrogen exhibit an increasing fracture resistance with increasing testing rate (dK/dt) with K_{JQH} values ranging from 40 to 79 MPa $m^{1/2}$. Consistent K_{JQH} values were measured among duplicate tests at each of the testing rates. For reference, the fastest test in gaseous hydrogen reached the K_{JQH} value (i.e. intersection of 0.2 mm construction line with J-R curve) at around 2 seconds whereas the slowest test required approximately 2000 seconds. The air data exhibit an upward trend of fracture resistance as well with testing rate, albeit the fracture toughness values were significantly greater, e.g. above 200 MPa $m^{1/2}$. Limited diffusion can occur during the fast-testing rates. If the diffusivity of hydrogen is assumed to be 10^{-7} cm^2/s for pipeline steels [1,2], then one can estimate diffusion distance (x) by using $x = \sqrt{2Dt}$, where t is time. In 2 seconds, the hydrogen diffusion distance is limited to less than 10 μm, which suggests that hydrogen-assisted fracture occurs without the need for significant redistribution of hydrogen to the crack tip region.

Figure 2 shows scanning electron microscope (SEM) images of the fracture surfaces of select fracture tests. Figure 2a shows the fracture surface for the test conducted in air, which exhibits ductile voids throughout the surface. Figure 2b and 2c represent fracture surfaces for the slowest and fastest tests, respectively, performed in 210 bar gaseous hydrogen. The fracture features in hydrogen are quasi-cleavage and look distinctly different than the test in air. The overall appearance of the two fracture surfaces for tests in gaseous hydrogen are similar and the presence of quasi-cleavage fracture is consistent with lower measured fracture resistance.

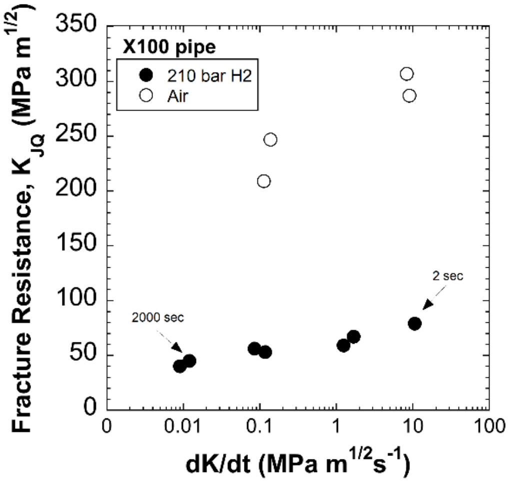

Figure 1: Fracture resistance (K_{JQ}) as a function of testing rate (dK/dt) for X100 pipeline steels tested in 210 bar gaseous hydrogen and air.

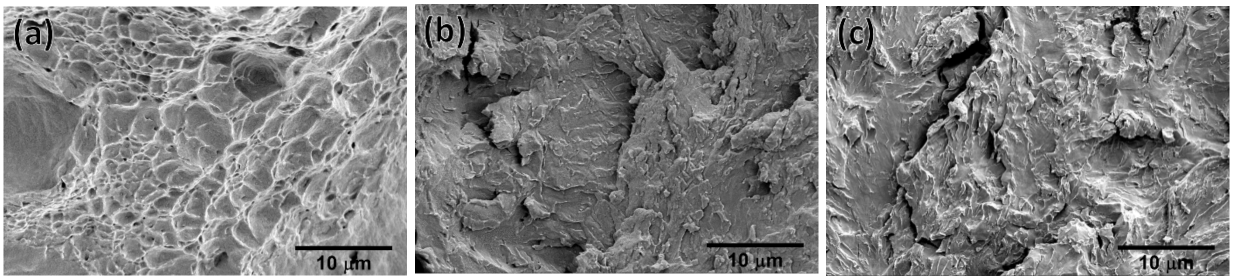

Figure 2: Fracture surfaces of X100 tested: (a) in air at dK/dt = 0.1 MPa $m^{1/2}s^{-1}$, (b) in 210 bar at dK/dt = 0.01 MPa $m^{1/2}s^{-1}$, (c) in in 210 bar at dK/dt = 10 MPa $m^{1/2}s^{-1}$.

3. Conclusions

Fracture tests were performed in air and gaseous hydrogen at different testing rates to evaluate if hydrogen effects would diminish at faster testing rates. Fracture tests conducted on X100 pipeline steel suggest that while there is clearly an influence of testing rate, e.g. faster rates result in increased fracture resistance in gaseous hydrogen, hydrogen-assisted fracture still manifests over all the testing rates explored in this study and hydrogen effects should not be ignored in this regime. For all tested rates, the fracture surfaces generated in gaseous hydrogen display quasi-cleavage features as compared to ductile voids observed on fracture surfaces generated in air.

4. References

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