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COMPARISON OF LINEAR-ELASTIC FRACTURE AND ELASTIC-PLASTIC FRACTURE OF FERRITIC STEELS IN GASEOUS HYDROGEN

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Abstract

There is a common misperception that exposure to gaseous hydrogen makes construction steels brittle. Reality, however, is more nuanced. Whereas very high-strength steels can display characteristics of brittle fracture, low- to medium-strength steels remain ductile in gaseous hydrogen. Typical pressure vessel steels (e.g., quench and tempered Cr-Mo and Ni-Cr-Mo steels) and line-pipe steels (e.g., low-carbon steels) remain sufficiently ductile that fracture measurements do not satisfy the requirements of standardized linear elastic fracture mechanics. Generally, for steels with tensile strength <900 MPa, an elastic-plastic fracture analysis is necessary to characterize hydrogen-assisted fracture, even in gaseous hydrogen at pressure of >1,000 bar. This presentation reviews the requirements of linear elastic and elastic plastic fracture testing in the context of fracture tests in gaseous hydrogen that have been reported in the literature.

1. Introduction

The constant displacement test methodology from ASTM E1681 is, by definition, a linear elastic fracture mechanics (LEFM) methodology. This method is referenced in the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3, Article KD-10 for the determination of the threshold stress intensity factor for hydrogen-assisted cracking of steels for high-pressure hydrogen vessels; this quantity is referred to as K_{IH}. Article KD-10 is also referenced by ASME B31.12 (Hydrogen Piping and Pipelines) for qualifying the fracture resistance of line-pipe steels in gaseous hydrogen. However, most low- to medium-strength steels, such as those used in construction of pressure structures, cannot satisfy the requirements of LEFM for the largest specimens that can be extracted from typical product forms, inclusive of fracture tests in gaseous hydrogen environments. In contrast, elastic-plastic fracture mechanics (EPFM) characterizes fracture when the assumption of linear elasticity cannot be realized. While there are several methods for the evaluation of elastic-plastic fracture, for the purposes of this comparison, we use the J-integral method of ASTM E1820, specifically the plane-strain fracture toughness, commonly noted as J_{IC}. For comparison, the measured J_{IC} (or J_Q) value is converted to a stress intensity factor (K), which is referred to here as K_{JQH} when measured in gaseous hydrogen. ‘Q’ is used to emphasize the qualified nature of the measurement as the straightness of the crack front is often not satisfied in gaseous hydrogen (although generally requirements for specimen thickness and remaining ligament are satisfied). In this presentation, K_{IH} and K_{JQH} measurements are compared and the requirements of the two methods are evaluated.

2. Results

In general, the objective of fracture testing is to measure a specimen size-independent value of a material’s fracture resistance for use in materials qualification or structural design. ASTM E1681 requires that the remaining ligament (b_o) be sufficiently large that plasticity does not influence the measurement:

$$b_o > \frac{4}{\pi}\left(\frac{K_{IH}}{\sigma_Y}\right)^2$$

where K_{IH} is the determined threshold stress intensity factor and σ_Y is the yield strength (or flow stress for strain hardening materials). More restrictive requirements also exist in ASTM E1681 for size-independence and specimen thickness, but here we focus on this (least restrictive) requirement. In comparison, the analogous requirement for the determination of K_{JQH} is

$$b_o > 10\frac{J_{QH}}{\sigma_Y} = 10\frac{\sigma_Y}{E'}\left(\frac{K_{JQH}}{\sigma_Y}\right)^2$$

where J_{QH} is the elastic-plastic fracture resistance measured in gaseous hydrogen (determined by the intersection of the J-R curve with the 0.2 mm construction line) and E' is the plane-strain elastic modulus. For the purposes of this analysis, we assume $K_{IH} = K_{JQH} = 110$ MPa $m^{1/2}$ (the minimum required loading configuration for line-pipe steels from ASME B31.12) and E' = 225 GPa. The curves in Figure 1 represent the minimum ligament required for these two criteria (LEFM and EPFM, respectively) as a function of σ_Y. Literature values of K_{IH} for low-strength steels (X80 and lower strength) are 110 MPa $m^{1/2}$ or greater; however, to our knowledge these measurements never satisfy the requirements of LEFM. Typically, for constant displacement tests, the $b_o < 40$ mm due to constraint of the product forms and testing apparatus. In contrast, lower bound K_{JQH} measurements are in the range of 25 to 75 MPa $m^{1/2}$ (over the given strength range in gaseous hydrogen at pressure of 210 bar).

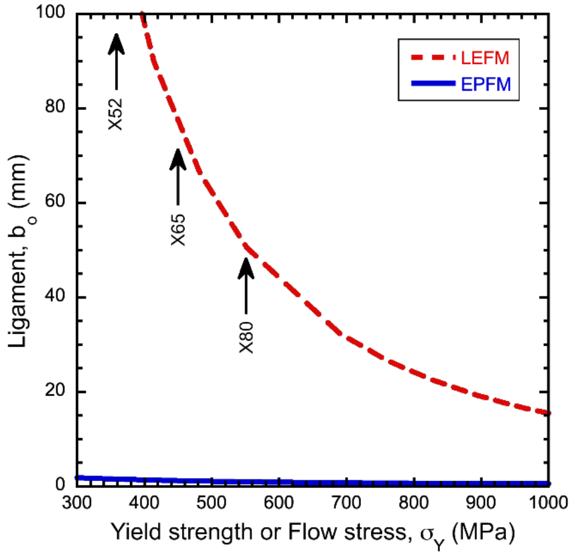

Figure 1. Minimum ligament size for validity of LEFM and EPFM test methods. Specified minimum yield strength (SMYS) is indicated for several API grade line-pipe steels for context.

3. Conclusions

Line-pipe steels generally do not show hydrogen-assisted cracking in LEFM measurements and testing suggests $K_{IH} > 100$ MPa $m^{1/2}$. In contrast, K_{JQH} values for line-pipe steels are generally lower. The difference between these measurements reflects the ductile nature of the fracture process and the invalidity of the LEFM measurements. A similar outcome was reached when comparing LEFM and EPFM methods for measuring fracture resistance of pressure vessel steels (Nibur, 2010): K_{JQH} is lower than K_{IH} for materials with tensile strength less than about 900 MPa. In short, LEFM test methods are generally inadequate to characterize gaseous hydrogen-assisted fracture of pressure vessel and line-pipe steels.

Reference

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