Subcritical Cracking of Modern $2^{1}/_{4}$Cr-1Mo-$^{1}/_{4}$V Steel Due to Dissolved Internal Hydrogen and H_2 Environment, Research Report

API TECHNICAL REPORT 934-F, PART 3
FIRST EDITION, DECEMBER 2017

AMERICAN PETROLEUM INSTITUTE

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EXECUTIVE SUMMARY

A literature review demonstrates the need for an improved laboratory database, as well as basic understanding, to quantitatively characterize the hydrogen-assisted cracking (HAC) resistance of modern 2¼Cr-1Mo-¼V base plate, weld metal, and the weld heat-affected zone. The objectives of this API-sponsored research are to: (a) quantitatively characterize the internal hydrogen-assisted cracking (IHAC) resistance of modern 2¼Cr-1Mo-¼V steel, in both base metal and weld metal product forms and including the effect of stressing temperature, (b) scope the hydrogen environment assisted cracking (HEAC) resistance of 2¼Cr-1Mo-¼V base metal, (c) understand the mechanism(s) for the IHAC and HEAC behaviors of Cr-Mo and Cr-Mo-V steels, centered on hydrogen (H) interactions with microstructure-scale trap sites, and (d) assess application of data and understanding of IHAC and HEAC to determine the role of subcritical H-assisted cracking on a minimum pressurization temperature (MPT) estimate relevant to thick-wall hydrotreating reactor vessels.

This work focused on slow-stable subcritical H cracking and did not examine the effect of H on the fracture toughness for unstable cracking. The temperature dependencies of IHAC of 2¼Cr-1Mo-0.3V base plate and weld metal were characterized using slow-rising displacement loading and elastic-plastic fracture mechanics analysis of crack growth measured through direct current potential difference (DCPD). This test method provides a conservative measure of susceptibility of alloy steels to HAC.

Specific conclusions of this research are as follows.

1) Compared to conventional 2¼Cr-1Mo steel, and consistent with the literature, the solubility of H dissolved in 2¼Cr-1Mo-0.3V base and weld metals increases two-fold due to VC precipitate trapping of H and when exposed to high-pressure H_2 at elevated temperature relevant to thick-wall reactor applications. Consistent with the reversible nature of H trapping at precipitate interfaces, the diffusivity of H in 2¼Cr-1Mo-0.3V decreases by about 100 times compared to H mobility in conventional 2¼Cr-1Mo steel.

2) Without predissolved H, the fracture resistance of high-purity (step-cooled) 2¼Cr-1Mo-0.3V base and weld metals is high at 25 °C and 100 °C, characteristic of upper shelf behavior and a fracture appearance transition temperature (FATT) well below room temperature.

3) Quantitative characterization of IHAC and HEAC in low- to moderate-strength steels is challenged by substantial crack tip plasticity. For 2¼Cr-1Mo-0.3V, the DCPD method, coupled with J-integral elastic-plastic fracture mechanics, effectively characterizes slow-stable H-assisted crack growth during slow-rising stress intensity factor loading. Measurement of the threshold for such cracking, K_{IH}, and the associated crack growth resistance curve as K_J vs Δa, are demonstrated to be conservative when based on DCPD vs crack mouth opening displacement (CMOD) analysis, rather than DCPD vs elastic-plastic J. A validated test protocol is now available at a commercial testing laboratory for use in fitness-for-service and MPT analyses where reactor-steel-specific H cracking properties are required.

4) Cr-Mo-V base and weld metals containing a high concentration of predissolved H, $C_{H\text{-}Total}$ of 6 wppm to 11 wppm from elevated temperature exposure in high-pressure H_2, significantly resist slow-stable IHAC compared to susceptible low-FATT (high-purity) Cr-Mo steel. Nonetheless, 2¼Cr-1Mo-0.3V is susceptible to slow-stable IHAC propagation for severe slow-rising displacement loading in moist air (see Figure 36).

5) 2¼Cr-1Mo-0.3V base metal (BM) and weld metal (WM) compact tension [C(T)] specimens exhibit stable crack extension that yields a rising R-curve, without evidence of the onset of H-stimulated premature fast fracture at K levels below K_{JIC} for H-free specimens. No evidence was obtained to demonstrate that H promotes premature fast fracture in these V-modified steels for the dissolved H concentration, loading rate, and temperatures examined. These results suggest that the H-stimulated fast fracture mechanism may not be operative in V-modified steel with a low FATT. This form of H degradation was reported in the literature to occur in Cr-Mo steel.

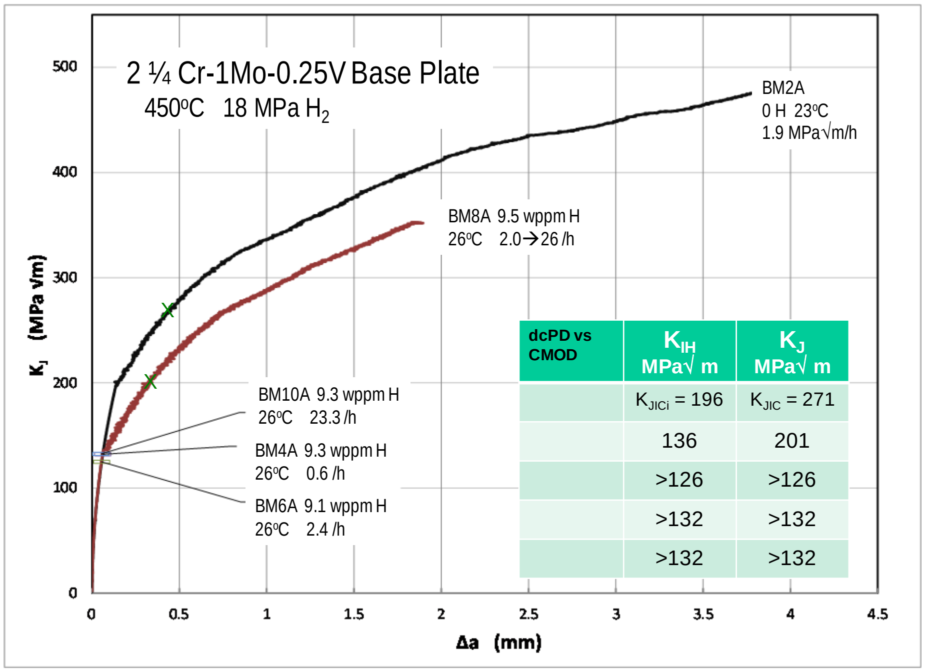

Figure 36—Crack growth resistance curves, plotted as the elastic-plastic stress intensity factor vs crack extension from DCPD, for H-precharged 2¼Cr-1Mo-0.3V base metal stressed under slow-rising K at 26 °C. Values of the 0.2 mm offset K_{JIH} and K_{JIC} are indicated by "X" on each resistance curve.

6) 2¼Cr-1Mo-0.27V weld metal is more susceptible to IHAC than 2¼Cr-1Mo-0.30V base metal, with the potential for variability in K_{IH} and K_J–Δa (see Figure 81, as well as Figures 82 and 83).

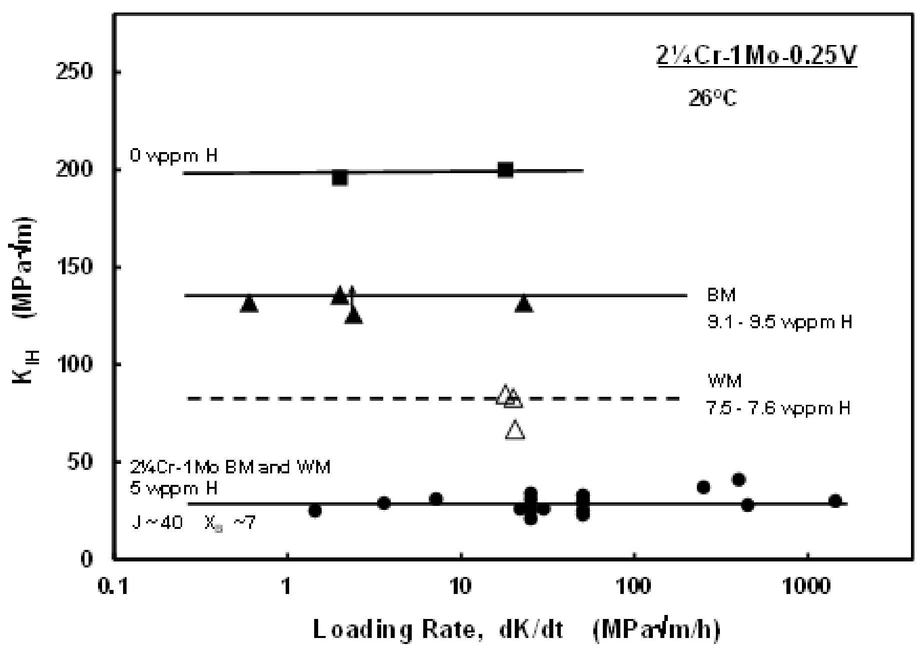

Figure 81—The loading rate dependence of K_{IH} for IHAC in 2¼Cr-1Mo-0.3V BM at 26 °C compared to values measured for 2¼Cr-1Mo BM and WM at 23 °C to 26 °C using the conservatively aggressive slow-rising K test method [2,4,5]. The conditions for the Cr-Mo steel experiments are reported in Bibliographic Item [2]. The dK/dt is the value of elastic K increase up to K_{IH}, above which this rate rises due to the onset of stable crack growth and/or plasticity.