EFFECT OF HYDROGENATION ON THE FRACTURE MODE OF A REACTOR PRESSURE-VESSEL STEEL

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The conditions for hydrogen-induced intergranular fracture in an artificially embrittled, low-alloy reactor pressure-vessel steel were investigated by using fracture toughness and stress-corrosion cracking tests. The specimens were taken from two locations: the heat-affected zone beneath the cladding and the base material directly below the heat-affected zone. A hydrogenating system allowed the tests to be carried out on both prehydrogenated specimens and with continuous hydrogenation in the course of the tests. In total, the results demonstrate a detrimental effect of hydrogen on the subcritical crack-growth resistance of both materials. At 120°C (close to the upper shelf), it led to a lower energy ductile fracture mode and isolated events of transgranular fracture. At ambient temperature (in the ductile-to-brittle transition mode) some mixed intergranular and transgranular subcritical crack growth was observed.

Key words: reactor pressure-vessel steel, heat affecting zone under cladding, fracture toughness, subcritical crack growth, hydrogen embrittlement, intergranular fracture.

Hydrogen embrittlement of low-alloy steels typically leads to low-energy fracture modes and, hence, can be a concern for evaluating the stability of actual or postulated defects in pressure-vessel structures. This type of embrittlement can reduce fracture toughness, fatigue resistance, and the stress intensity threshold for subcritical crack growth [1, 2]. The associated fracture mode may take the form of enhanced ductile tearing, transgranular cleavage, or intergranular fracture. The latter, although microscopically ductile, is observed macroscopically as a quasibrittle fracture mode. Kameda [3] and more recently McMahon [4] have reviewed the phenomena and the mechanisms involved. On a more general level, hydrogen embrittlement has been investigated by several researchers in relation to the low-alloy steels used for the reactor pressure vessels (RPV) in light water reactor (LWR) designs with regard for possible synergies with irradiation embrittlement [5, 6]. Although the vessel steel is protected from the reactor-water environment by a relatively thick austenitic overlay cladding on the inner surface with a thickness of about 10 mm, the process of cladding can itself cause hydrogenation of the substrate steel [5, 7]. This leads to the analysis of the possible influence of hydrogen on the behavior of any preexisting flaws, either by subcritical crack growth or during severe shutdown transients, especially those involving thermal shocks with high stresses at the inner surface and/or cold overpressurization. Seifert et al. [8], however, suggest that hydrogen-induced damage mechanisms hardly exist at the LWR operating temperatures due to the high diffusion rate of hydrogen and small trap efficiency.

Against this background, two events of unexplained intergranular cracking were observed in large-scale pressurized thermal-shock simulation tests performed within the framework of the Network for Evaluation of Structural Components (NESC), known as NESC-I [9] and NESC-II [10, 11]. Both involved cylindrical components made of RPV steels treated to produce an artificially embrittled state intended to be a representative of the

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end-of-life conditions. Both contained large subclad defects, which extended after the tests in an unexpected intergranular mode.\(^4\)

Despite extensive investigations, the occurrence of this type of cracking has not been fully explained.

In the present work, we study the role of hydrogen embrittlement in the fracture mode of an embrittled RPV steel in order to support better understanding of this potential cracking mechanism in relation to the accident scenarios for operating plants, as well as for the assessment of its significance (if any) in connection with the above-mentioned large-scale tests. Experimentally this required the simulation of subcritical crack growth under the conditions of hydrogenation by using fracture-mechanics specimens. Two different scenarios were considered: (a) environmental hydrogen penetrating into the material at the crack tip under loading and (b) internal motion of hydrogen to the crack tip (hydrogen stress cracking). Therefore, the tests were performed both in hydrogenated environments and after preliminary hydrogenation (prehydrogenation). In this respect, it is noted that slow rising-displacement fracture tests [12] allow hydrogen transport to the crack tip via dislocations [13] and avoid possible problems of delayed yielding to which constant-load tests might be susceptible even at the ambient temperature [14].

Material and Testing Methods

The material used in the present study was taken from the so-called NESC-I cylinder [9] fabricated from ASTM-A508 Class 3 steel (0.23C, 0.23Si, 1.32Mn, 0.011S, 0.012P, 0.08Cr, 0.50Mo, 0.73Ni) subjected to a nonstandard heat treatment with an aim to simulate embrittlement of the reactor pressure-vessel steel at the end of life. After welding of the cylinder from two shells and insertion of several artificial surface cracks, a two-layer stainless-steel clad (AISI 308/309 SS) with a total thickness of 11 mm was applied to the inner surface creating a distinct heat-affected zone with a depth varying from 5 to 10 mm in the underlying base material. The fractography performed on the broken specimens revealed classical cleavage or ductile failure modes depending on the testing temperature relative to the transition curve.

For the testing program, 0.5CT specimens with a reduced thickness of 10 mm were machined from two locations in the cylinder wall, namely, the heat-affected zone (HAZ) and the base material located just beneath the HAZ (Fig. 1). The reason for considering this particular location of the base material is that it corresponds to the region where extensive intergranular cracking was observed at the large subclad defect in the NESC-I test. The orientation of all the specimens was L–T. All specimens were fatigue precracked to the \(a/W\) ratio equal to 0.5 for the final range of the stress intensity factor (SIF) \(\Delta K = 15\) MPa \((f = 10\) Hz, \(R = 0.1)\). Attention was mainly focused at a temperature level of 120°C corresponding to the time at which the crack driving force at the large subclad defect approached its peak in the NESC-I thermal shock transient. At this point, the test instrumentation also indicated that an event may have taken place, although it cannot be excluded that the intergranular extension occurred prior to testing. To study the effect of hydrogen on the fracture properties in this upper transition mode, we used a specialized test system including a tensile-testing machine equipped with an autoclave to guarantee the possibility of continuous hydrogenation of the specimens in heated solutions in the course of electrochemical processes [15]. The following test environments were used:

- saturated \(\text{CaCl}_2\) solution at 120°C with cathodic charging at current densities of \(10^{-5}\), \(10^{-3}\) and \(10^{-1}\) A/cm\(^2\);

- 0.3% \(\text{NaCl}\) (pH 6.5) + 2 g/liter thiourea at a current density of \(10^{-1}\) A/cm\(^2\);

\(^4\) In the NESC-I spinning-cylinder test, the component contained a large range of types and sizes of defects. During the test transient, cleavage and arrest occurred at the largest of the through clad defects, as planned; however, several under-clad defects unexpectedly produced limited intergranular cracking.