FE analysis of hydrogen diffusion around a crack tip in an austenitic stainless steel

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ABSTRACT

Hydrogen-assisted cracking (HAC) is a coupled phenomenon between crack growth rate and hydrogen diffusion to the region ahead of crack tip. To understand the cracking mechanism and to control or predict the HAC rate, knowledge of hydrogen diffusion around a crack tip is essential. Metastable austenitic stainless steels can be severely embrittled by hydrogen due to strain-induced α′ martensite transformation around crack tip, as the hydrogen diffusivity in α′ martensite is much higher than in γ austenite while the solubility is lower. However, the effect of induced α′ martensite on local diffusion of hydrogen around a loaded crack tip has not been intuitively demonstrated. This study first reveals the quantitative relations of hydrogen diffusivity and solubility with induced α′ martensite amount, and then performs FE analysis of hydrogen diffusion around a crack tip in a 304L ASS cylinder storing high pressure gaseous hydrogen with considering the combined effect of α′ martensite transformation and hydrostatic stress on diffusion. The hydrostatic stress exhibits a peak value at a distance away from crack tip, while the peak α′ martensite volume fraction locates at the crack tip. Compared to the analysis only considering stress effect, the presence of induced α′ martensite can not only significantly accelerate the hydrogen transport to the critical region ahead of crack tip, but also markedly elevate the level that the peak hydrogen concentration reaches. The peak hydrogen concentration doesn’t locate at the peak hydrostatic stress site as generally expected, but at the site in the γ austenite-rich region abutting the α′ martensite-rich region at crack tip vicinity, because this site possesses very high hydrogen solubility and close to the high hydrogen diffusivity region, consequently accommodating the hydrogen getting off the α′ martensite diffusion “highway”.

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Introduction

Hydrogen can accelerate crack initiation and growth in metals under both static and cyclic loading conditions. This is known as hydrogen-assisted cracking (HAC). It has been established that the hydrogen diffusion ahead of a crack tip existing in a metal plays a key role in HAC of the metal. In static loading cases, according to hydrogen-enhanced decohesion (HEDE) mechanism [1,2], it is believed that when the hydrogen concentration at a critical site (potential crack initiation site) ahead of crack tip, e.g. the elastic-plastic boundary, accumulates to exceed a critical value [3,4] by stress-assisted diffusion, a new crack initiates at the critical site, and then the new crack coalesces with the old crack resulting in crack growth (in the absence of hydrogen, crack initiation and growth will not occur). Continuous crack growth with the aid of hydrogen finally causes the complete fracture of metal. In cyclic loading (fatigue) cases, besides HEDE, hydrogen-enhanced localized plasticity (HELP) mechanism [1,2,5], which presumes that the solute hydrogen can reduce the stress for plastic deformation hence leads to a localization of deformation process, also operates through affecting the opening and closing behaviour of fatigue crack tip [6,7]. And the hydrogen-accelerated fatigue crack growth is assumed to be coupled to hydrogen diffusion and increased hydrogen concentration near the crack tip [6–9]. Thus, for both cases, it has been concluded that the acceleration in crack initiation and growth due to hydrogen depends on the rate at which the hydrogen is provided to the critical region ahead of crack tip as well as the level that the hydrogen concentration can reach.

It is clear that analysing the hydrogen diffusion ahead of a crack tip is critical to understand the HAC process in a metal. Also it has the potential to derive the crack initiation and growth kinetics and hence predict the HAC based on the evolution of hydrogen concentration in time and space ahead of crack tip [10,11]. Thus, over the years, many authors have made great efforts to analyse the hydrogen diffusion around a crack tip. Yokobori et al. [12] built a physical model and preformed analyses on the time- and space-dependent hydrogen concentration around a crack tip considering the assistance effect of stress on diffusion. Sofronis et al. [13] and Krom et al. [14] added the effect of plastic strain to the model as the plastic strain affects the number of hydrogen trapping sites, hence affects the hydrogen populations in trapping sites. According to HELP, Sofronis et al. [15] further proposed a model considering the hydrogen-induced softening effect (the initial yield stress of metal decreases due to hydrogen absorption). Liang et al. [16] then performed diffusion analyses taking account of the combined effect of stress, plastic strain and hydrogen-induced softening. Kotake et al. [17] performed diffusion analyses around a crack tip under cyclic loading. Takayama et al. [18] conducted analyses around a crack tip in a steel pipe under internal hydrogen pressure. Takakura et al. [19] performed simulations demonstrating the residual stress effect on diffusion and concentration of hydrogen around a crack tip.

Due to good HAC resistance, austenitic stainless steels (ASSs) have been widely used in hydrogen environments in petrochemical industry. However, the metastable ASSs, e.g. 304L, can be severely embrittled by hydrogen, due to the occurrence of strain-induced γ austenite to α‘ martensite transformation [20–23] around crack tip, as the hydrogen diffusivity in α‘ martensite is much higher (about five orders of magnitude higher) than that in γ austenite, whereas the solubility in it is much lower (about two orders of magnitude lower) [2,24,25]. Note that the stable ASSs, e.g. 310, in which no α‘ martensite forms upon deformation, can also be embrittled by hydrogen although with much less severity. Thus, it has been pointed out [6,26] that austenitic stability is a key factor affecting the acceleration of crack growth due to hydrogen. Many studies [7,23,27,28] have shown that a large amount of α‘ martensite formed in the vicinity of fatigue crack tip in hydrogenated ASSs, and believed that this α‘ martensite acted as a “highway” for rapid hydrogen diffusion and accumulation, thus enhanced the transport of hydrogen to the critical region ahead of crack tip, consequently increased the crack growth rate. In addition, some authors have demonstrated that the pre-existing strain-induced α‘ martensite, acting as hydrogen diffusion “highway”, can lead to an increased hydrogen amount into the steels during exposure to hydrogen [28–30].

Nowadays, ASSs are further regarded as the primary materials for vessels and pipes storing hydrogen, especially high pressure gaseous hydrogen, in the future hydrogen energy industry. For instance, the vessels or pipes are designed to endure the internal pressure of hydrogen gas more than 35 MPa [31]. Clearly, under such high pressure, HAC should be a threat to the structural integrity of these structures [24]. For a crack existing in a metastable ASS structure, e.g. a vessel or pipe storing high pressure hydrogen gas, besides the high local stress due to static or cyclic loading, severe plastic deformation and α‘ martensite transformation should also occur around the crack tip. As the diffusivity of hydrogen in α‘ martensite is high while solubility is low, the formed local α‘ martensite should have an influence on local diffusion of hydrogen around the crack tip. However, such influence is not analysed detailedly and demonstrated intuitively in the open literatures. Thus the objective of this study is to analyse the diffusion and concentration evolution of hydrogen around a crack tip in a 304L cylinder (i.e. a vessel or pipe) containing high pressure hydrogen gas by FE method considering the combined effect of stress and induced α‘ martensite on diffusion.

Dependence of hydrogen diffusivity and solubility on α‘ martensite

Quantitative relations describing the dependence among the plastic strain level, the amount of α‘ martensite induced by the plastic strain and the hydrogen transport parameters, i.e. diffusivity and solubility, are needed for the FE analysis. For the 304L steel, our previous study [30] has reported the hydrogen diffusivity at room temperature as a function of plastic pre-strain level up to 0.25 and the volume fraction of α‘ martensite induced by the pre-strain. Table 1 reproduces the data. In brief, plate specimens were tested in Ref. [30] by sequential tensile pre-straining, cathodically hydrogen pre-charging in 0.5 mol/l H2SO4 solution at a current density of 50 mA/cm² and tensile testing. The data were calculated based
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