HYDROGEN EMBRITTLEMENT IN HIGH STRENGTH STEELS

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Summary Hydrogen ingress in high strength steels cause a dramatic decrease in ductility resulting with mechanical reliability issues in structural applications. Hydrogen present in the steel is either accommodated in lattice or trapped at microstructural defects. By way of analysing experimental data from literature, we demonstrate that lattice hydrogen increases the susceptibility to hydrogen embrittlement whereas trapped hydrogen has no significant effect.

INTRODUCTION AND THEORY

High strength steels, when exposed to hydrogen, suffer from a loss of ductility which may lead to sudden premature failure. When hydrogen is absorbed into steel, it is either accommodated in lattice or trapped at microstructural defects such as dislocations and grain boundaries. The concentration of lattice hydrogen is given as $C_L = \theta_L \beta N_L$, where θ_L is the fraction of occupied interstitial sites, β is the number of interstitial sites per lattice atom and N_L is the number of lattice atoms per unit volume. Similarly concentration of trapped hydrogen is given as $C_T = \theta_T \alpha N_T$. This time θ_T is the fraction of occupied trapping sites, α is the number of atom sites per trap and N_T is the number of traps per unit volume. At equilibrium Oriani's equation gives the relation between the occupancy ratio of sites as,

$$\frac{\theta_T}{1-\theta_T} = K\frac{\theta_L}{1-\theta_L}, \qquad (1)$$

where K is the equilibrium constant. When dislocation traps are considered, N_T is related to the number of dislocations and increases in the course of plastic deformation as a function of equivalent plastic strain $\varepsilon^{\mathrm{p}}_{\mathrm{e}}$. Therefore C_T depends on in total of three parameters K, C_L, and $\varepsilon^{\mathrm{p}}_{\mathrm{e}}$. Moreover the hydrostatic stress σ_h creates chemical potential gradients that drives lattice hydrogen from compressive regions to regions under tension. The equilibrium C_L level in the presence of a hydrostatic stress is then given as $C_L(\sigma_h) = C_L^0 \exp((\sigma_h \bar{V}_H)/(RT))$, where C_L^0 is the lattice hydrogen concentration in the absence of any hydrostatic stress and $\bar{V}_H$ is the partial molar volume of hydrogen in solid solution.

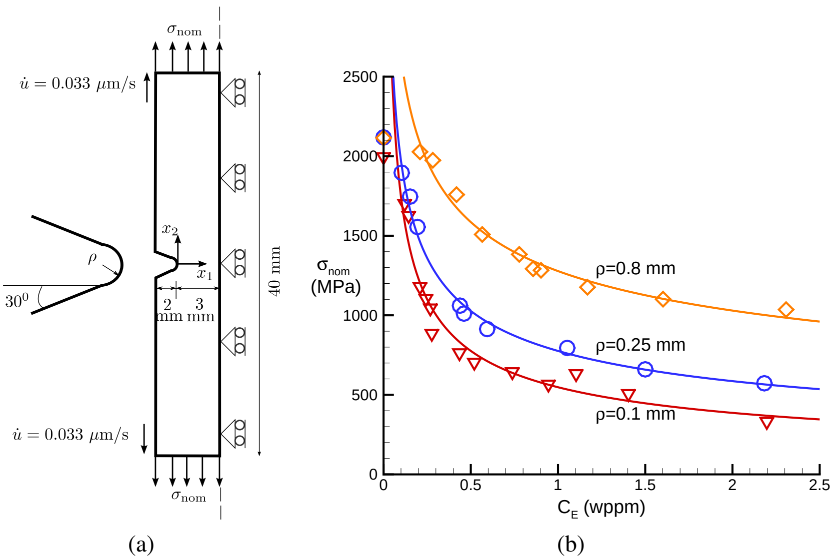

Figure 1. In (a) illustration of the notched tensile bars used in [1]. In (b) net section failure stress, σ_{nom} at the instant of failure as a function of C_E for various values of ρ [1].

LITERATURE REVIEW

We aim to identify the effect of hydrogen located at different sites on mechanical degradation by way of analysing the experimental data from literature. Wang et al. carried out slow strain rate tensile tests on tempered martensitic AISI 4135 steel with different hydrogen charging conditions [1]. In these experiments specimens circumferentially notched with a notch radius of $\rho = 0.1, 0.25, 0.8$ mm were used as shown in Fig. 1(a). Hydrogen was introduced into the specimens by electrochemical charging at various current densities prior to the tensile test. Thus a uniform lattice concentration equal

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to the environmental concentration, C_E is attained before the test starts. The nominal tensile strength σ_{nom} defined as the maximum tensile load during the test divided by the net cross section area and is given in Fig. 1(b) as a function of environmental hydrogen concentration C_E.

RESULTS & DISCUSSION

We have calculated the stress and strain distribution of specimens at failure using an elastic/plastic finite element model. We assume stress controlled brittle fracture initiates at the location where the maximum σ_{22} is reached. The steady state hydrogen concentrations are attained at every instant during the tensile tests due to low strain rate imposed. We have calculated the lattice hydrogen concentration, C_L from C_E and σ_h and also the hydrogen concentration at dislocation traps, C_T from ε_e^p and also using the Oriani theory (see eq. (1)). In Fig. 2(a), the σ_{22} trajectories as a function of lattice hydrogen concentration C_L are plotted whereas in Fig. 2(b), trajectories are given for the total hydrogen concentration, $C_L + C_T$ along the thinnest section of the specimen for $\rho = 0.1$ mm. The only possible way to rationalize the experimental data is constructing a failure locus from the trajectories of σ_{22} as a function of C_L only. No failure locus can be drawn for trajectories calculated for $C_L + C_T$. Therefore we have concluded that C_L increases the susceptibility to hydrogen embrittlement whereas C_T has no effect.

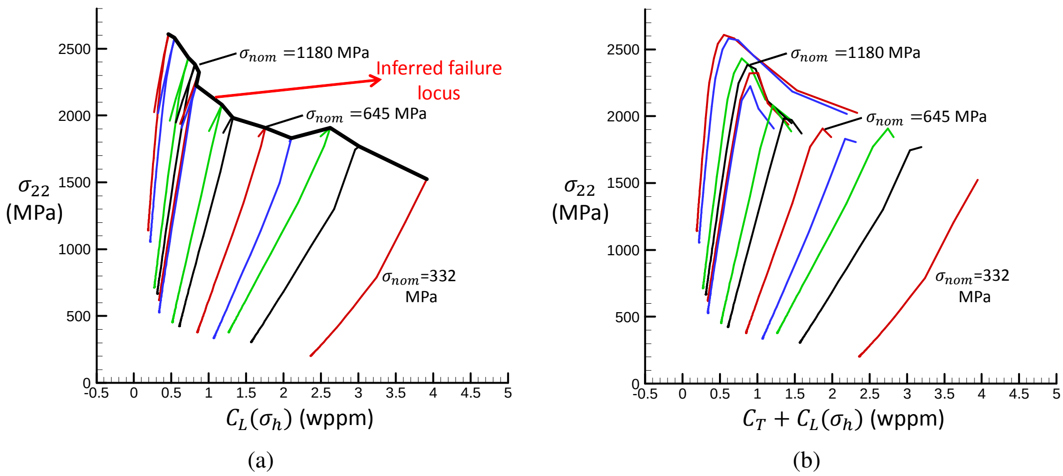

Figure 2. In (a) failure locus constructed from the σ_{22} vs. C_L trajectories and in (b) trajectories of σ_{22} vs. C_T with no failure locus.

It is important to note that the fracture loci for different geometries coincide to a unique failure locus which is shown in Fig. 3. Thus the proposed failure locus is a material property which can be a useful tool for predicting failure and design of components susceptible to hydrogen embrittlement.

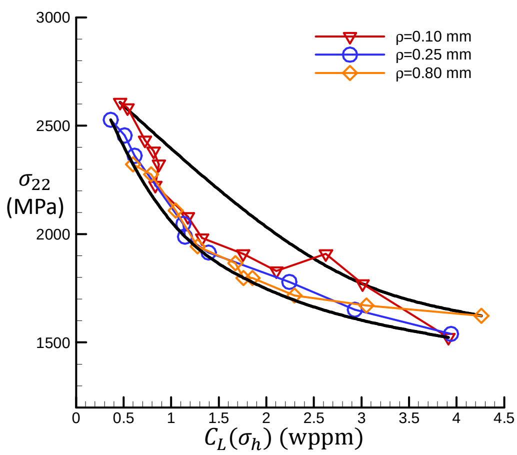

Figure 3. Failure loci calculated for notched tensile bars with various notch radii ρ.

References

[1] Wang M., Akiyama E., Tsuzaki K.: Effect of hydrogen and stress concentration on the notch tensile strength of AISI 4135 steel. *Materials Science and Engineering A* **398**:37–46, 2005.