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A fracture criterion for the notch strength of high strength steels in the presence of hydrogen

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ABSTRACT

High strength steels can suffer from a loss of ductility when exposed to hydrogen, and this may lead to sudden failure. The hydrogen is either accommodated in the lattice or is trapped at defects, such as dislocations, grain boundaries and carbides. The challenge is to identify the effect of hydrogen located at different sites upon the drop in tensile strength of a high strength steel. For this purpose, literature data on the failure stress of notched and un-notched steel bars are re-analysed; the bars were tested over a wide range of strain rates and hydrogen concentrations. The local stress state at failure has been determined by the finite element (FE) method, and the concentration of both lattice and trapped hydrogen is predicted using Oriani's theory along with the stress-driven diffusion equation. The experimental data are rationalised in terms of a postulated failure locus of peak maximum principal stress versus lattice hydrogen concentration. This failure locus is treated as a unique material property for the given steel and heat treatment condition. We conclude that the presence of lattice hydrogen increases the susceptibility to hydrogen embrittlement whereas trapped hydrogen has only a negligible effect. It is also found that the observed failure strength of hydrogen charged un-notched bars is less than the peak local stress within the notched geometries. Weakest link statistics are used to account for this stressed volume effect.

1. Introduction

Steels, when exposed to hydrogen, suffer from a loss of ductility and toughness and this may lead to sudden, premature failure. Consequently, the adverse effects of hydrogen embrittlement must be included in engineering design for applications such as pipelines and nuclear power plants that come into contact with water, hydrocarbons or hydrogen gas. Hydrogen embrittlement is also critical for welded joints since hydrogen take-up can arise from the use of damp electrodes in electric welding operations.

The atomistic mechanism of hydrogen embrittlement remains a controversial issue: at least two major mechanisms have been proposed. According to the Hydrogen Induced Decohesion (HID) mechanism, hydrogen which has accumulated at a crack tip reduces the cohesive strength giving rise to a reduced fracture toughness (Troiano, 1960; Oriani, 1972). In contrast, the Hydrogen Enhanced Localised Plasticity (HELP) mechanism (see for example Birnbaum and Sofronis, 1994), assumes that hydrogen redistribution occurs around dislocations, reduces the elastic interaction energy between dislocations and thereby decreases the Peierls stress. Material softening then ensues.

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Gangloff (2003) argued that HID is the dominant mechanism in high strength alloys on the basis that a wide range of micromechanical fracture toughness models of HID are able to predict (i) the threshold stress intensity factor K_{ISCC} and (ii) the crack growth rate da/dt versus K response for hydrogen exposed alloys; see, for example, Gerberich et al. (1991) for a model based on crack tip dislocation mechanics. Serebrinsky et al. (2004) support Gangloff's (2003) view by developing a quantitative HID based model: they assumed that a cohesive zone exists at a crack tip and the strength of the cohesive zone drops with increasing local hydrogen concentration. By suitable adjustment of material parameters, this model was able to predict the observed incubation time for crack initiation, the effect of hydrogen concentration upon K_{ISCC} and the effect of temperature upon da/dt. The HID mechanism is also supported by first principles calculations; see for example Jiang and Carter (2004) who demonstrated that the surface energy decreases sharply with increasing hydrogen concentration. Recently, Novak et al. (2010) proposed a synergetic effect of the HID and HELP mechanisms. They argued that the HELP mechanism reduces the length of dislocation pile-ups on carbides situated at the grain boundaries. Simultaneously, the presence of hydrogen reduces the cohesive toughness of the grain boundaries (HID), giving rise to premature intergranular fracture. In their analysis, Novak et al. (2010) assumed that hydrogen trapped at dislocations are the only source of embrittlement by HID: their analysis reveals that hydrogen trapped at grain boundaries, carbides, and at lattice sites has a negligible role in embrittlement.

Loading rate also plays an important role upon the fracture mode and the threshold stress intensity factor K_{ISCC} of high strength alloys exposed to hydrogen (Gangloff, 2003). Thomas et al. (2003) measured K_{ISCC} in ultra high strength steel specimens charged with hydrogen, and found that $K_{ISCC} \approx 0.1 K_{IC}$ when the loading rate was below $dK/dt = 0.3\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{s}$, where K_{IC} is the fracture toughness measured in the absence of hydrogen. In contrast, for loading rates greater than $dK/dt = 0.7\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{s}$, the threshold stress intensity factor was found to be $K_{ISCC} \approx 0.4 K_{IC}$. Associated with this increase in K_{ISCC} is a change in fracture mode from cleavage to micro-void coalescence; see Thomas et al. (2003).

The effect of hydrogen *trapping* at microstructural defects upon hydrogen embrittlement remains a controversial issue, see Gangloff (2003). It is unclear whether embrittlement is due to trapped hydrogen (for example at carbide particles and at dislocations) or is mainly due to lattice hydrogen. Li et al. (2004) argued that trapping sites such as martensite interfaces, austenite grain boundaries, and dislocation cores possessing a strong affinity to hydrogen can prevent hydrogen from segregating to crack tip and mitigate against hydrogen embrittlement. Yamasaki and Bhadeshia (2006) shares this view and investigated the peak trapping affinity of carbides to hydrogen in martensitic steels in order to mitigate the detrimental effects of hydrogen upon mechanical performance. In contrast, Novak et al. (2010) conjectured that hydrogen trapped at the dislocations is the dominant source of embrittlement in high strength steels.

In this paper, we shall analyse the sensitivity of the tensile strength of a high strength steel to the presence of hydrogen at lattice interstitial sites and trapped at defects. To achieve this, the experimental data of Wang et al. (2005b, 2007) and Hagihara et al. (2008) are analysed for AISI 4135 steel. Both sets of authors considered notched bars and measured the tensile strength for a wide range of hydrogen charging conditions, and for selected values of notch radius. We shall show below that the test times employed by the Wang et al. (2005b) are sufficiently long for hydrogen diffusion to attain equilibrium. In contrast Hagihara et al. (2008) performed rapid tests in relation to the diffusion time for hydrogen.

It is notoriously difficult to measure accurately the amount of absorbed hydrogen and its relative partitioning between various sites in a steel microstructure. Here, we will calculate the trapped and lattice hydrogen concentrations using Oriani's theory, and the stress-driven diffusion equation; the procedure will be explained in some detail in Section 2. Since this analysis requires a knowledge of the stress and strain state of the solid, an elastic–plastic FE model is used in order to obtain these field quantities.

Sofronis and McMeeking (1989) gave the governing field equations for hydrogen diffusion in a plastically deforming solid. They assumed that the relative concentration of hydrogen in the lattice and at traps is given by thermodynamic equilibrium as first proposed by Oriani (1970). In the present study, it suffices to use a simplified approach by assuming the two limits of zero time for hydrogen diffusion in the conventional strain rate tests of Hagihara et al. (2008) and infinite time for hydrogen diffusion in the slow loading tests of Wang et al. (2005b, 2007).

1.1. Scope of study

First, the ability of various types of trap to bind hydrogen is assessed. The partitioning of hydrogen between the traps and the bulk lattice is analysed as a function of test time. Notched strength data are taken from the literature and used to establish a fracture criterion in the form of a locus of maximum principal tensile stress versus hydrogen concentration. To achieve this, an elastic–plastic FE analysis is performed on the notched geometries and the stress distribution across the net section is determined. Finally, the data of Wang et al. (2007) for un-notched smooth specimens are compared with the results for notched specimens. We shall demonstrate that the fracture criterion as deduced from the notched tests is able to account for un-notched strength as a function of hydrogen concentration, provided due account is made for the stressed volume effect, as quantified by Weibull statistics.

2. A brief summary of Oriani's theory

We begin our study by summarising the relative distribution of hydrogen in the lattice and at traps, in accordance with Oriani's theory. Hydrogen in a metal is either stored at normal interstitial lattice sites (NILS) or is trapped at microstructural