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# Hydrogen embrittlement of a bimaterial

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ABSTRACT

Commonly, within the energy industry, the corrosion resistance of pressure vessel steels is increased by the addition of an overlay coating comprising a nickel-based alloy or a stainless steel. However, the interface between the two alloys is prone to hydrogen-assisted cracking, due to for example carbide precipitation near the interface. In the present study, the sensitivity of the tensile strength of the interface to hydrogen concentration is measured for both notched and un-notched specimens made from the overlay welding of 690 nickel alloy on a low alloy steel A533B. An elastic–plastic finite element analysis is used to determine the stress and strain state near the notch root, and thereby to calculate the local distribution of hydrogen within the lattice and at traps. The observed strength of the notched specimens is best rationalised by assuming that the local cohesive strength of the interface is a function of the lattice hydrogen concentration, with a negligible influence of the trapped hydrogen. The scatter in specimen strength, and the relative strength of the notched and un-notched specimens, are adequately described by Weibull statistics, with a low value of Weibull modulus equal to 3.4.

## 1. Introduction

Weld cladding is the deposition of a relatively thick (3 mm or more) metal layer onto a metallic substrate in order to improve the corrosion or wear resistance of the material. It is widely used in nuclear and fossil-fuel power plants, petrochemical applications and in pipelines (Rao et al., 2011). An example is the overlay of stainless steel on the surface of a low alloy steel for improved corrosion resistance.

Usually, the clad and the base material are metals of dissimilar composition and properties, and it is challenging to produce a dissimilar welding interface that is of sufficient strength and ductility that the component will not fail from the weld (Satyanarayana et al., 2005). Intermetallic compounds may form at the weld interface between the dissimilar metals that deteriorate ductility, or increase susceptibility to corrosion or hydrogen embrittlement (Sireesha et al., 2000). The weld strength can also be significantly degraded by the presence of residual stress. For example, Lee and Chang (2012) have presented a three-dimensional FE simulation of bimaterial welding to identify the temperature and residual stress fields in butt-welded joints between plain carbon steels and stainless steels.

Hydrogen embrittlement is a recognised threat for welded joints since hydrogen take-up can arise during the welding operation. Recently, Blach et al. (2011) have investigated the influence of hydrogen charging upon the room temperature tensile properties and fracture behaviour of dissimilar welded joints. They conjectured that hydrogen charging has a detrimental effect upon the strength of a ferritic/ferritic weld, but only a small influence on the strength of a ferritic/austenitic weld.

In our previous work (Ayas et al., 2014) we investigated the hydrogen embrittlement of monolithic, high strength low alloy AISI 4135 steel; we concluded that strength of

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notched and un-notched specimens correlate with the concentration of lattice (diffusible) hydrogen while the trapped hydrogen at dislocations, grain boundaries and carbides have a negligible effect on the failure strength. A fracture locus for notched specimens was established in terms of peak maximum principal stress versus concentration of diffusible hydrogen. A similar fracture locus, but displaced to lower strength levels, was obtained for un-notched specimens. Weibull theory was used to account for the reduction in strength with increasing stressed-volume.

In the current paper, we measure and analyse the loss in strength of a dissimilar weld, comprising 690 Nickel alloy and A533B low alloy steel (LAS) for pressure vessel applications, due to dissolved hydrogen. A failure locus in terms of strength versus hydrogen content is constructed for both notched and un-notched specimens, and Weibull theory is invoked in order to account for the observed statistical scatter in strength and for an observed size effect.

## 2. A brief summary of Oriani theory

We begin our study by summarising the relative distribution of hydrogen in the lattice and at traps, in accordance with Oriani's theory (Oriani, 1970; Sofronis and McMeeking, 1989). Hydrogen is stored either at normal interstitial lattice sites (NILS) or is trapped at microstructural defects such as dislocations, grain boundaries, interfaces and carbides. The concentration of hydrogen at NILS, also called the lattice hydrogen concentration, is given by

$$C_L = \theta_L \beta N_L, \tag{1}$$

where $\theta_L$ is the fraction of occupied interstitial lattice sites, $\beta$ is the number of NILS per lattice atom and $N_L$ is the number of lattice atoms per unit volume. Similarly, the concentration of hydrogen trapped at any given site is

$$C_T = \theta_T \alpha N_T, \tag{2}$$

where $\theta_T$ is the fraction of occupied trapping sites, $\alpha$ is the number of atom sites per trap and $N_T$ is the number of traps per unit volume. Oriani's equation relates the equilibrium value of occupancy ratio of sites, in terms of an equilibrium constant $K$, as

$$\frac{\theta_T}{1-\theta_T} = K\frac{\theta_L}{1-\theta_L}. \tag{3}$$

In turn, $K$ is related to the trap binding energy $\Delta H$, the gas constant $R = 8.314$ J/(mol K) and the absolute temperature $T$ according to

$$K = \exp\left(\frac{-\Delta H}{RT}\right). \tag{4}$$

Upon examining Eq. (4) we recognise that the value of $\theta_T$ is much more sensitive to $\Delta H$ than to $\theta_L$ since the equilibrium constant $K$ has an exponential dependence upon $\Delta H$.

### 2.1. Dislocation traps

Now consider dislocation traps. The concentration of hydrogen $C_T^{(\mathrm{d})}$ trapped at dislocation cores is given by Eq. (2), with $\alpha = 1$, and $\theta_T$ given by Eqs. (3) and (4). However, the number of dislocation traps per unit volume $N_T^{(d)}$ increases with the von Mises plastic strain $\varepsilon^{\mathrm{p}}$ in contrast to the fixed number of carbide traps $N_T^{(c)}$ and grain boundary traps $N_T^{(\mathrm{gb})}$. Following Novak et al. (2010) we can relate $N_T^{(d)}$ to the dislocation density $\rho_d$ and to the lattice parameter $a$ of the crystal structure of host atoms according to

$$N_T^{(\mathrm{d})} = \sqrt{2}\rho_{\mathrm{d}}/a. \tag{5}$$

In turn, $\rho_d$ scales with $\varepsilon^{\mathrm{p}}$ according to

$$\rho_d = \begin{cases} \rho_0 + k\varepsilon^{\mathrm{p}} & \varepsilon^{\mathrm{p}} \leqslant 0.5 \\ 10^{16}\mathrm{m}^{-2} & \varepsilon^{\mathrm{p}} > 0.5 \end{cases} \tag{6}$$

where $\rho_0 = 10^{10}\ \mathrm{m}^{-2}$ is the dislocation density of the material at zero plastic strain and $k = 2\times10^{16}\ \mathrm{m}^{-2}$ (Novak et al., 2010). The set of Eqs. (1)–(6) gives the concentration of hydrogen $C_T^{(\mathrm{d})}$ that is trapped at dislocations. In order to specify the value of $C_T^{(\mathrm{d})}$, the values of $(\varepsilon^{\mathrm{p}}, C_L)$ and the binding energy for dislocation traps $\Delta H^{(\mathrm{d})}$ need to be determined. In general, $\varepsilon^{\mathrm{p}}$ is known as function of loading history and position. For example, it is known immediately for an un-notched specimen under uniaxial tension, and its spatial distribution can be deduced from an elastic–plastic FE analysis for a notched specimen. The lattice concentration $C_L$ is generally determined experimentally by thermal desorption spectroscopy (TDS), along with a knowledge of the local hydrostatic stress distribution $\sigma_h$, as discussed below. However, the value for $\Delta H^{(\mathrm{d})}$ is problematic as the values quoted in the literature range from $\Delta H^{(\mathrm{d})} = -18$ kJ/mol (Novak et al., 2010) to $\Delta H^{(\mathrm{d})} = -36.4$ kJ/mol (Oriani, 1970). In order to bound the predicted behaviour, we shall calculate the dislocation-trapped hydrogen concentration $C_T^{(\mathrm{d})}$ using two extreme values of $\Delta H^{(\mathrm{d})}$, namely $-18$ kJ/mol and $-36.4$ kJ/mol.

## 3. Lattice hydrogen concentration in a notched specimen

Commonly, the sensitivity of a material to hydrogen embrittlement is determined by performing notched/un-notched tensile tests on specimens that have been either pre-charged or are continuously charged with hydrogen during the test. In this section, we outline a simple scheme for determining the distribution of hydrogen in a notched specimen that is charged continuously under remote tension. First, consider a sample under zero applied stress that is in contact with a charging environment such that the hydrogen equilibrium has been established. Thermodynamic equilibrium dictates that the chemical potential of hydrogen remains spatially uniform within the specimen. Consequently, the chemical potential of hydrogen in the specimen can be written as

$$\mu = \mu_0 + RT\ln C_L^0, \tag{7}$$