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Hydrogen trapping in some advanced high strength steels

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ABSTRACT

Permeability experiments were used to study hydrogen diffusion and trapping in dual phase (DP), quenched and partitioned (Q&P), advanced high strength steels. The measured reversible hydrogen trap densities indicated that (i) trapping was less significant at a more negative potential, and (ii) the lattice diffusion coefficient of hydrogen could be measured from the partial transients at the most negative potentials. The densities of reversible hydrogen traps evaluated from complete decays from $-1.700\,V_{Hg/HgO}$ were ~ 2×10^{18} sites cm^{-3}, and were a factor of two higher than those from partial decay transients between $-1.700\,V_{Hg/HgO}$ and $-1.100\,V_{Hg/HgO}$.

1. Introduction

1.1. Advanced high strength steels (AHSS)

Advanced high strength steels (AHSS) were developed, and have been adopted, for auto components to reduce vehicle weight and to increase vehicle safety [1–4]. This paper characterises hydrogen trapping in some AHSS and thereby adds to the knowledge base regarding AHSS.

The AHSS includes Dual Phase (DP) steels, Complex-Phase (CP) steels, Ferritic-Bainitic (FB) steels, Martensitic (MS) steels, Transformation-Induced Plasticity (TRIP) steels, Hot-Formed (HF) steels, and Twinning-Induced Plasticity (TWIP) steels [3].

DP steels have a microstructure of ferrite and martensite. The soft, continuous, ferrite matrix produces good formability. The hard martensitic phase is dispersed in the ferrite matrix and contributes to the high strength, and high strain hardening. As a result, vehicle components made from DP steels have a high capacity to absorb energy [5]. DP steel components may be galvanised for corrosion protection in service.

Transformation induced plasticity (TRIP) steels have a microstructure of a ferrite matrix, islands of retained austenite, and dispersed bainite. Martensite is also commonly present. Transformation of retained austenite to martensite causes the transformation induced plasticity, and also causes an increased strain hardening rate at higher strain levels [6]. TRIP steel components also have a good ability to absorb energy [5].

Quenching and partitioning (Q&P) is a new heat treatment to produce TRIP steel. The microstructure [7] contains more retained austenite at room temperature [8,9], resulting in a greater TRIP effect. As a result, their ductility, formability and strain-hardening rate are greater than other steels with comparable strength. Q&P steels are thus third generation AHSS with high strength and high-ductility [10].

1.2. Hydrogen sources in service

Hydrogen embrittlement (HE) can occur in AHSS [11,12]. The hydrogen can be liberated by corrosion of the steel of the car body in service. In neutral and alkaline solutions, the hydrogen evolution occurs by the following cathodic partial reaction [13]:

$$H_2O + M + e \rightarrow MH_{ads} + OH^- \quad (1)$$

where M represents the metal surface and MH_{ads} represents hydrogen adsorbed on the metal surface. The atomic hydrogen may be desorbed by the desorption reaction given by Eq. (2), through which two adsorbed hydrogen atoms combine to a molecule of hydrogen that leaves the metal surface, or by the electrochemical desorption reaction given by Eq. (3).

$$2MH_{ads} \leftrightarrow H_2 + 2M \quad (2)$$

$$MH_{ads} + H_2O + e \rightarrow H_2 + OH^- + M \quad (3)$$

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Some of the adsorbed hydrogen enters the metal, MH_{abs}, by the following equilibrium reaction:

$$MH_{ads} \leftrightarrow MH_{abs} \quad (4)$$

The hydrogen in the steel, in combination with an applied stress, can cause hydrogen embrittlement (HE), which is of particular concern for high-strength steels [14], such as the AHSS.

1.3. Hydrogen trapping

Hydrogen diffusion is often studied using the permeation technique of Devanathan and Stachurski [15]. This permeation method can provide quantitative information, such as the effective hydrogen diffusion coefficient, D_{eff}, the hydrogen concentration, C_H, and the hydrogen trapping site density. This permeation technique was used in the present research to study hydrogen diffusion and trapping in DP and Q&P AHSS.

Hydrogen atoms are located in interstitial sites and are trapped by microstructure features such as voids, dislocations, grain boundaries, carbide interfaces, and impurities [16–18]. These hydrogen traps play an important role in the transportation and distribution of hydrogen in the steel [18]. Hydrogen traps are characterized as irreversible traps and reversible traps [19–21]. Irreversible traps are sites with a high trap activation energy, and thus the trapped hydrogen is considered as non-diffusible. Examples of irreversible traps are carbide interfaces, incoherent precipitates, and high-angle grain boundaries. In contrast, hydrogen de-trapping is easier from trap sites with lower activation energy. These sites are characterized as reversible traps. Examples are dislocations, low-angle grain boundaries, coherent precipitates and twin boundaries. Hydrogen trapped in reversible hydrogen trap sites is diffusible. These reversible hydrogen traps influence hydrogen diffusion and have an influence on the hydrogen embrittlement of the steel [22].

Hydrogen trapping can be characterised by the parameters: the hydrogen-trap binding energy, E_b, and the density of trap sites, N_t. Hydrogen trapping was incorporated into a kinetic diffusion model by McNabb and Foster [23]. This model was reformulated by Oriani [24] using the assumption that there is a local equilibrium between trapped hydrogen atoms and mobile hydrogen. Based on the Oriani [24] model, Dong et al. [25] proposed that the number of hydrogen-trap sites per unit volume, N_t, could be evaluated from:

$$\ln\left(\frac{D_L}{D_{eff}} - 1\right) = \ln\frac{N_t}{N_L} + \frac{E_b}{RT} \quad (5)$$

where D_L is the lattice diffusion coefficient for hydrogen, D_{eff} is the effective diffusion coefficient for hydrogen in the presence of traps, N_L is the density of the interstitial sites in the steel, E_b is the hydrogen-trap binding energy, R is the gas constant, and T is the absolute temperature. This model is designated as the Oriani-Dong model in this paper.

Hydrogen trapping can be minimized by successive partial permeation rise transients after which the following permeation rise transients are controlled by lattice diffusion, because all the hydrogen traps are full [26,27].

Permeation decay transients, in contrast, are sensitive to the de-trapping of hydrogen, and can be used to evaluate the amount of reversibly trapped hydrogen [27–29], as illustrated in Fig. 1, adapted from Liu and Atrens [29]. The area under the experimental desorption permeation curve corresponds to the total amount of diffusible and trapped hydrogen. The area under the corresponding theoretical permeation decay curve, evaluated using the lattice diffusion coefficient, D_L, corresponds to the amount of diffusible hydrogen. By subtraction, the area difference between the two curves, as illustrated by the shaded part in Fig. 1, represents the amount of reversible trapped hydrogen. This method is called the permeation curve method herein.

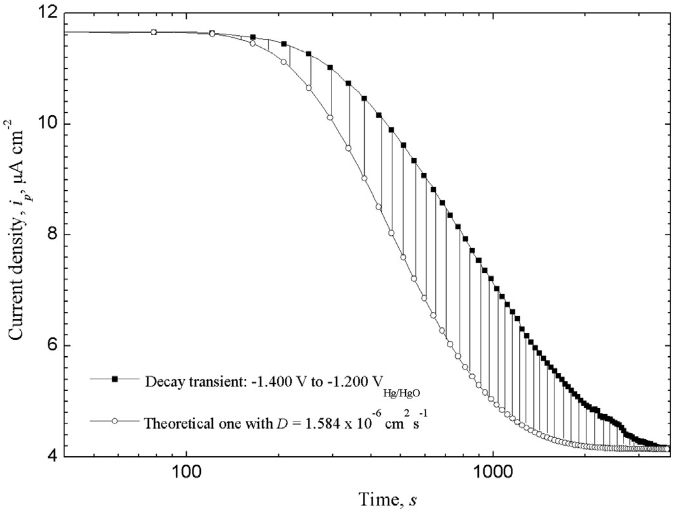

Fig. 1. The typical area difference (shaded part) between the integration of the permeation curve and the theoretical one for a decay transient for a 980 DP-GI (650 MPa YS) steel hydrogen charged in 0.1 M NaOH solution.

The permeation curve method indicates that the density of reversible hydrogen traps, designated as N_t^*, is given by [27,29]:

$$N_t^* = \frac{12.5 \times 10^{18} s}{L} \quad (6)$$

where s is the difference in area between the experimental decay curve and the theoretical decay curve evaluated using the lattice diffusion coefficient, D_L, and L is the thickness of the specimen. Eq. (6) assumes that there is only one type of reversible trap for hydrogen, and that each trap holds one hydrogen atom.

The concentration of the trapped hydrogen is given by [29]:

$$C_t^* = \frac{N_t^*}{N_A} \quad (7)$$

where N_A is the Avogadro constant with value of 6.02×10^{23} mol^{-1}.

This permeation curve method was applied by Zakroczymski [27] to Armco iron. Complete decay transients, where complete discharge was allowed, indicated that the reversibly trapped hydrogen corresponded to 98% of the total amount of absorbed hydrogen. This method was also used to measure the density of reversible hydrogen traps influencing hydrogen diffusion between cathodic charging potentials of $-1.700\,V_{Ag/AgCl}$ and $-1.100\,V_{Ag/AgCl}$ for a 3.5NiCrMoV medium strength steel [29]. The density of reversible traps was $\sim 10^{18}$ sites cm^{-3}. In this case the total amount of trapped hydrogen was not measured.

These techniques have not been applied to advanced high strength steels (AHSS) to measure the density of hydrogen traps.

1.4. Scope of current research

The current work (i) studies hydrogen diffusion in DP and Q&P grades of AHSS using permeability experiments, (ii) evaluates the density of reversible hydrogen traps that influence the hydrogen diffusion under these charging conditions using (a) the Oriani-Dong model and (b) the permeation curve method, and (iii) evaluates the total density of reversible hydrogen trap sites from complete permeation decay curves.