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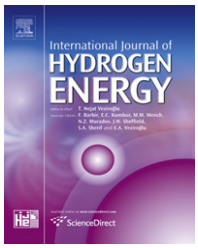

Effects of hydrogen-charging on the susceptibility of X100 pipeline steel to hydrogen-induced cracking

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ARTICLE INFO

Article history:
Received 4 August 2009
Received in revised form
24 September 2009
Accepted 26 September 2009
Available online 28 October 2009

Keywords:
Hydrogen-induced cracking
X100 pipeline steel
Hydrogen-charging
Inclusions

ABSTRACT

In this work, the hydrogen-induced cracking (HIC) behavior of X100 pipeline steel was investigated by a combination of tensile test, electrochemical hydrogen permeation measurement and surface characterization techniques. The effect of inclusions in the steel on the crack initiation was analyzed. Results demonstrated that the amount of hydrogen-charging into the X100 steel specimen increases with the charging time and charging current density. Hydrogen-charging will enhance the susceptibility of the steel to HIC. The cracks initiate primarily at inclusions, such as aluminum oxides, titanium oxides and ferric carbides, in the steel. The diffusivity of hydrogen at room temperature in X100 steel is determined to be 1.04×10^{-8} cm^2/s.

1. Introduction

In the recent years, with the continuously growing demand in energy consumption, extensive attentions have been paid to supply oil and natural oil in a more economic and safer way. Development of high-strength steel pipelines has enabled the energy industry to realize significant savings in the total cost of long-distance oil/gas transmission in view of the pipeline wall thickness and operating pressure [1–3]. Thus, the primary interest in the design and manufacture of pipeline steels meeting the American Petroleum Institute (API) grades is to obtain the best possible combination of strength, toughness and corrosion resistance through improving metallurgical and material processing techniques [4,5].

Hydrogen-induced cracking (HIC) is one of the predominant failures occurring in high-strength steels, including API X100 steel [6–12]. HIC results from the entry of atomic hydrogen into the steel [13]. The penetrated hydrogen atoms diffuse towards the tri-axial stress zones, and are trapped and precipitated at sensitive metallurgical defects, such as hardening phases, non-metallic inclusions or micro-cracks to reduce the local ductility, resulting in HIC [14,15]. It is generally acknowledged that an elevated strength level tends to decrease the resistance of the steel to HIC. Hardie et al. [7] compared the susceptibility of three API grade pipeline steels, X60, X80 and X100 steels, to HIC. It was found that the loss of ductility upon hydrogen-charging becomes greater while the strength level of the steel increases. Almonsour [16] investigated the sulfide SCC of X100 steel in a H_2S environment, and found that HIC cracks nucleated at banded martensite-ferrite interfaces and propagated along the rolling direction parallel to the applied tensile stress through the softer ferrite phase.

To date, research on X100 steel has generally focused on the mechanical and metallurgical aspects in order to improve

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doi:10.1016/j.ijhydene.2009.09.090

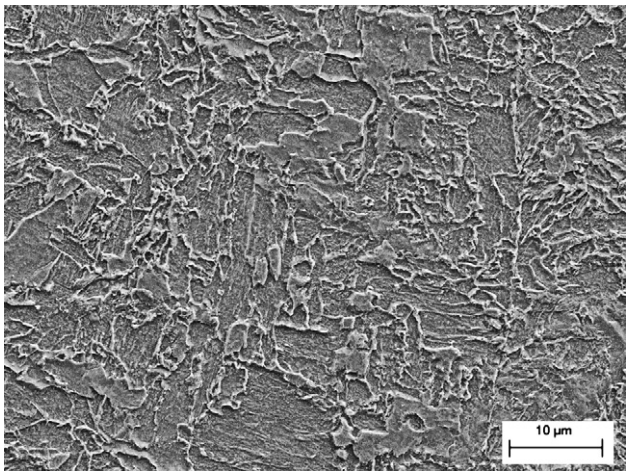

Fig. 1 – Micrograph of the microstructure of X100 pipeline steel.

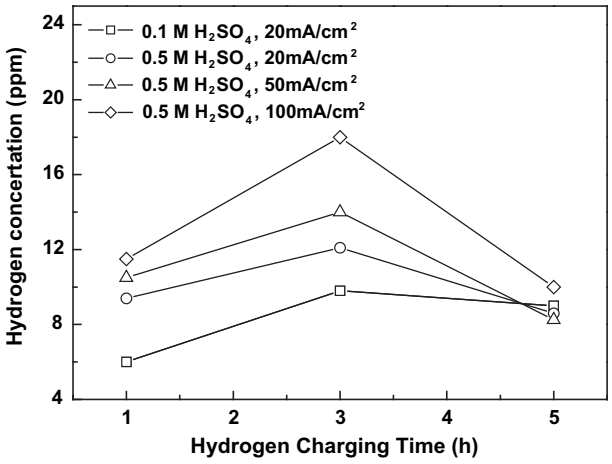

Fig. 3 – Steady state concentrations of hydrogen released from the steel under various charging conditions.

the strength and roughness of the steel [17,18]. In this work, the HIC behavior of X100 steel was investigated to simulate the inside pipeline environmental condition by a combination of tensile test, electrochemical hydrogen permeation measurement and surface characterization techniques. The influences of inclusion and microstructure on the crack initiation and propagation were analyzed, and the cracking mechanism of X100 steel upon hydrogen-charging was determined. A H_2S environment could also be caused due to the microbiological activity outside the pipelines, and the relevant research is still going and not included in this work.

2. Experimental

The material used in this work was cut from a sheet of API X100 steel plate, with the chemical composition (wt%): C 0.064, Si 0.13, Mn 1.56, Cu 0.38, Al 0.030, Nb 0.089, Ti 0.011, Ni 0.54, Mo 0.28, S 0.0024, P 0.024, and Fe balance. The metallographic observation showed that it contained predominantly bainite and ferrite, as shown in Fig. 1.

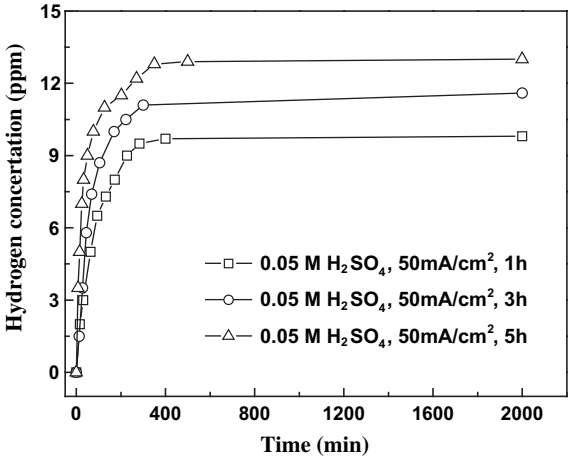

Fig. 2 – The amount of hydrogen released from the steel specimen that was charged at 50 mA/cm^2 in 0.05 M H_2SO_4 + 250 mg/L As_2O_3 solution at various times.

Specimen used for electrochemical hydrogen-charging was machined into a rectangle shape, with a dimension of 1.10 cm × 1.60 cm × 0.05 cm. The specimen was grounded sequentially to 1200 grit emery paper, and then polarized cathodically in 0.05 M and 0.5 M H_2SO_4 solutions at 20 mA/cm^2 and 200 mA/cm^2 cathodic current densities for 1 h, 3 h, and 5 h, respectively. The solutions also contained 250 mg/L arsenic trioxide (As_2O_3). The addition of As_2O_3 was to enhance the hydrogen atom permeation, and avoid their recombination. After charging, the specimen was immersed immediately into a liquid paraffin to measure the release flux of hydrogen.

The electrochemical hydrogen permeation test was performed in a modified double-cell, as described previously [5]. The hydrogen-charging side of the double-cell contained 0.5 M H_2SO_4 + 250 mg/L As_2O_3. The hydrogen ingress into the steel specimen was facilitated by applying a constant cathodic current density of 10 mA/cm^2. The hydrogen-detecting side contained 0.1 M NaOH, and a potentiostatically polarized potential of 300 mV (vs. saturated calomel electrode, SCE) was applied on the specimen. Prior to the hydrogen permeation test, the cell was purged with a high-purity nitrogen (99.99%) to remove the dissolved oxygen in the solution. All electrochemical control and measurement was conducted through a PAR 2273 potentiostat.

The hydrogen flux through the specimen was measured by the steady state hydrogen current density, I_∞, which was converted into hydrogen permeation flux, J_∞, by [9]:

$$J_\infty = \frac{I_\infty}{FA} \quad (1)$$

where A is the specimen area and F is Faraday constant. The effective hydrogen diffusivity, D_{eff}, can be calculated by [19]:

$$D_{eff} = \frac{d^2}{6t_L} \quad (2)$$

where d is the specimen thickness and t_L is the time-lag, corresponding to the point on the hydrogen permeation curve