Effect of cathodic hydrogen-charging current density on mechanical properties of prestrained high strength steels

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ABSTRACT

The present work investigated the effect of cathodic hydrogen-charging current density on mechanical properties of prestrained high strength steels. This was done by tensile tests on both hydrogen-charged and -uncharged prestrained specimens at a cross-head displacement speed of 0.03 mm/min. The influence of prestrain on hydrogen behavior was also studied using an electrochemical permeation technique. The results show that the relationship between ultimate tensile strength of the hydrogen-charged specimens (UTS-H) and prestrain depends on current density. The UTS-H decreases with increasing current density independent on prestrain. With an increase in prestrain the diffusion coefficient of hydrogen gradually decreases, which is attributed to increasing dislocations density acted as hydrogen traps. SEM fractograph reveals that hydrogen charging causes a change from ductile to brittle failure.

1. Introduction

Due to a combination of high strength and excellent toughness, high strength steels have been widely used. However, hydrogen deteriorates the mechanical properties of steels and gives rise to hydrogen embrittlement (HE). Generally the failures caused by HE are invisible and unpredictable, accompanying by catastrophic consequences [1–3]. Moreover, it is well-established that the sensitivity to HE increases with increasing strength level when the strength is over 1 GPa [4,5]. As a consequence, it is necessary to investigate the interaction between hydrogen and high strength steels.

Previous investigations on hydrogen-induced softening/hardening have been focused on various steels and the results are inconclusive. The effect of hydrogen on dislocations motion was either enhancing dislocations mobility [6–8] or pinning dislocations motion [9–11], corresponding to microscopical hydrogen-induced softening and hardening respectively. A study [12] showed that an increase or decrease in flow stress was determined by the competition between the effect of hydrogen on slip localization and on the dislocation mobility. Matsui et al. [13] suggested that hydrogen-induced softening or hardening of high purity iron depended on the temperature. Below 190 K hydrogen increased flow stress

while hydrogen decreased flow stress above 190 K. Numerical simulation results [14] showed that a loss of strength was dependent on the hydrogen content. Two hydrogen atoms placed in crack tip caused 22% drop in strength while further increase in hydrogen atoms had no significant effect on strength loss. In addition, compared with in air, the tensile strength did not change in high pressure hydrogen for various materials, such as 0.028% C Armco iron, 0.22% C normalized, ASTM A-515 Gr 70, AISI 1020 [15,16].

The effect of hydrogen on mechanical properties of prestrained materials had been studied for dual-phase steels [17], 310S stainless steels [18], 2205 duplex stainless steels [19], 304L stainless steels [20] and pure iron [21]. The purpose of the present study is to investigate the effect of cathodic current density on mechanical properties of prestrained high strength steels. The influence of prestrain on hydrogen bahavior and the role of hydrogen on fracture behavior are analyzed. Furthermore, the effect of cathodic current density on relationship between ultimate tensile strength of hydrogen-charged specimens (UTS-H) and prestrain is discussed.

2. Experimental method

Screw-thread steel bars were used in this study. The chemical composition is shown in Table 1. After hot-rolled, the steel bars underwent air-cooling to room temperature and then tempering

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Table 1
Chemical composition of the high strength steel (wt%).

Element	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Fe
Analyzed	0.25	1.41	2.19	0.014	0.0049	1.07	0.011	0.018	0.015	Balance

at 623 K for 5 h. The smooth cylindrical specimens with dimensions 5 mm diameter × 25 mm length were machined from the bars with axial direction paralleling to the rolling direction. The specimens were subjected to various level of prestrain from 0% to 6% engineering strain. In addition, the plate specimens, as shown in Fig. 1, were machined by wire electrical discharged machining and then tensioned to the different prestrain level (0%, 1%, 2%, 3% and 4%). The hydrogen permeation samples (shaded area in Fig. 1) were cut from the gauge parts of prestrained plate specimens. Subsequently, all specimens were mechanically ground with SiC grinding paper up to 800 grit and rinsed with alcohol.

Some groups of prestrained specimens were electrochemically charged with hydrogen in 0.5 mol/L H_2SO_4 solution at various current densities ranging from 0.05 mA/cm^2 to 0.6 mA/cm^2 for 24 h at room temperature (298 K). The CH_4N_2S (1 g/L) was added in the solution as a hydrogen recombination poison. Platinum was used as an anode and the specimen was used as a cathode. To prevent hydrogen releasing from the charged specimens, cadmium electroplating was carried out immediately after hydrogen-charging, which was performed in an aqueous solution with 98% oil of vitriol (50 g/L), $CdSO_4$ powder (50 g/L), Na_2SO_4 (45 g/L), glutin (6 g/L) and phenol (3 g/L) at the current density of 25 mA/cm^2 for 5 min. The cadmium was used as an anode and the specimen was used as a cathode. Tensile tests were conducted on these prestrained and charged specimens at a crosshead speed 0.03 mm/min, corresponding to a normal strain rate of 2×10^{-5}/s. The prestrained specimens without hydrogen charging was also tensile tested as a reference. After tensile tests, the fracture surfaces of tensile specimens were observed by field emission scanning electron microscope (FESEM).

Another group of prestrained specimens were mechanically polished and etched in 4% Nital solution to observe the microstructure using an optical microscope. In addition, discs were cut from the some prestrained samples perpendicular to the axial direction. By mechanical thinning, the discs foils were created and further prepared by twin-jet electropolishing in a solution of 10% perchloric acid and 90% alcohol at 243 K. Through using JEM-200CX transmission electron microscopy (TEM), variation of dislocation structures at different prestrain was investigated.
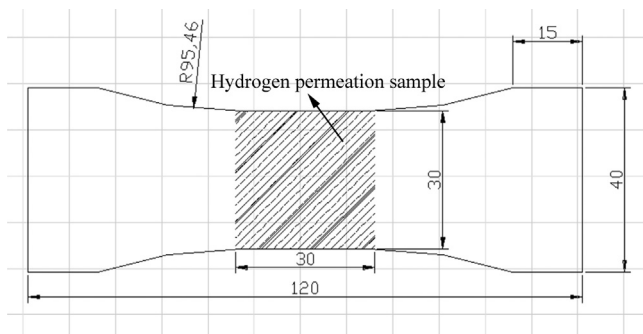
3. Results

3.1. Hydrogen permeation tests

Electrochemical permeation technique originally developed by Devabathan and Stachurski was employed to study the hydrogen permeation behavior of prestrained steels [22]. The hydrogen permeation instrumentations were composed of an electrolytic cell with two compartments (cathodic and anodic sides), a reference electrode (Hg/HgO/NaOH 0.1 M NaOH), two auxiliary electrodes (Pt plate) and two potentiostat/galvanostat. The specimen with an exposed surface area of 2.27 cm^2 on each side was clamped between the compartments. One side of the specimen acted as hydrogen entry side. It was galvanostatically polarized at a constant charging current density (20 mA/cm^2) in 0.5 M H_2SO_4 with 0.824 g/L $Na_4P_2O_7$. Prior to hydrogen charging, the specimens were depleted of residual hydrogen until the current lowered to 1.13 μA. The hydrogen exit side of the cell was potentiostatically maintained at a constant potential of -200 mV versus reference electrode. Fig. 2 shows the transient hydrogen permeation current density curves for various prestrain specimens.

We used the following equations to calculate permeability coefficient ($J_\infty L$) and effective hydrogen diffusivity (D_{eff}):

$$J_\infty L = \frac{I_P^\infty L}{nF} \tag{1}$$

$$D_{eff} = \frac{L^2}{6t_L} \tag{2}$$

In the equations listed above, I_P^∞ (A/m^2) was the steady-state permeation current density, n the number of electrons transferred, F (C/mol) the Faraday's constant, L (m) the specimen thickness, t_L (s) was the lag time, defined as 0.63 times the steady-state value. The experimental hydrogen permeability data of prestrained specimens are shown in Table 2. With an increase in prestrain, the diffusion coefficient of hydrogen decreases.
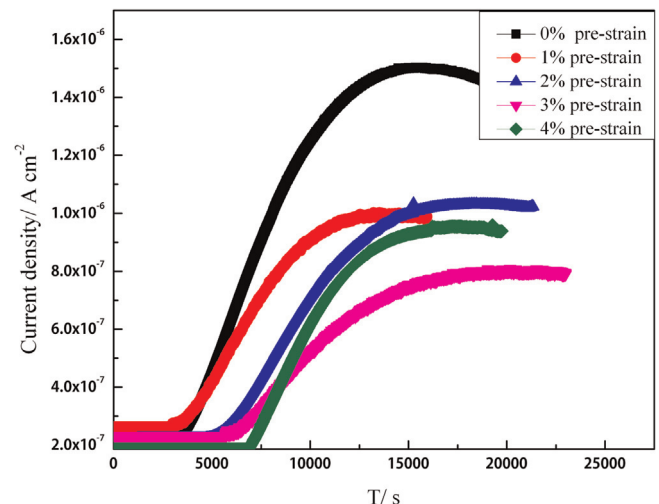

Fig. 1. Dimensions (in mm) of the plate specimen for hydrogen permeation tests. Note the thickness 1.5 mm.

Fig. 2. The transient hydrogen permeation current density curves for various prestrain specimens.