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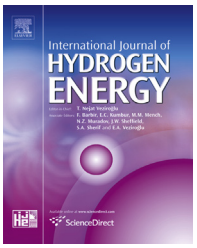

The effect of nanosized NbC precipitates on electrochemical corrosion behavior of high-strength low-alloy steel in 3.5%NaCl solution

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ABSTRACT

The effect of nanosized NbC precipitates on electrochemical corrosion behavior of high-strength low-alloy (HSLA) steels in 3.5%NaCl solution has been investigated by the means of precipitate modulation, microstructure observation, electrochemical and immersion tests. The results showed that NbC precipitates markedly enhance the corrosion resistance of the H-contained steel, and the mechanism is that the plentiful and highly dispersed nanosized NbC particles acting as massive and effective hydrogen traps play a decisive role in the resistance to hydrogen activated corrosion. Moreover, it is evident that the inhibiting effect is related with the amount, size and distribution of the precipitates, and the optimized microstructures and precipitated phases improve the mechanical properties and resistance to hydrogen activated corrosion of HSLA steel.

Introduction

Over the recent years, Nb as a micro-alloying element in high-strength low alloy steels, has been widely exploited and utilized. The effects and mechanisms of Nb-contained precipitation on microstructures and mechanical properties of HSLA steels have been intensively studied [1]. Undoubtedly, nanosized niobium nitride and/or carbide precipitates are markedly beneficial to the strength and ductility of HSLA steels by refining grain and dispersion strengthening [2]. However, when HSLA steels, such as X80 pipeline steel, service in harsh corrosion environment, especially expose to hydrogen sulfide (H_2S), H_2 or cathodic overprotection in seawater, and hydrogen potentially permeate into the steel, the effect of NbC precipitates on electrochemical corrosion behavior is still devoid or indetermination [3,4].

Hydrogen accelerates anodic dissolution by decreasing the activation energy of metals, and induce SCC by the mechanism of HIC [5]. It has been revealed that cathode hydrogen evolution aggravates corrosion severely in X80 pipeline steel, especially in the seawater environment, and the resistance to hydrogen activated corrosion can be improved by preventing diffusion and aggregation of

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hydrogen [6]. On the other hand, recent study shows that the diffusion of hydrogen in steels has been evidently impeded by niobium, and the reason is that nano-sized NbC precipitates trap hydrogen effectively [7–9]. So it is very significant and prospective to understand the effects of precipitated NbC nanoparticles on hydrogen activated corrosion behavior of HSLA steel, and the most effective type of NbC precipitates and hydrogen traps.

In the present study, we focus on the quantity, size and distribution of the nano-sized precipitation to elucidate the structure – property (especially the electrochemical corrosion) relationship in HSLA steel. NbC precipitates formed during the heat treatment are characterized by TEM, and the resistance to hydrogen activated corrosion was investigated in detail by electrochemical test. The results are beneficial to the development of HSLA steel, such as X80 and so on, with excellent resistant to hydrogen activated corrosion and superior mechanical properties.

Experimental

Experimental materials

The experimental steel was micro-alloyed with Nb, and chemical composition of the steel is in weight percent: 0.06 C – 0.27 Si – 1.84 Mn - 0.25 Mo – 0.26 Ni – 0.26 Cu – 0.055 Nb – 0.015 Ti. The steel was prepared by vacuum melting and cast into small ingot with diameter of 120 mm, and then forged into brick with thickness of 50 mm. The brick was homogenized at 1200 °C for 2 h, and then was hot rolled to 15 mm thick strip. To regulate the state of precipitations, the strip specimens were experienced four different heat treatments, and four kinds of states of precipitations were obtained. Specific process is as follows: Firstly, reheated the steels up to 1300 °C which is the entire solution temperature and held for 10 min to make the precipitates dissolve entirely in the steel matrix. Secondly, the compared specimen (N1) quenched immediately to the room temperature to avoid Nb precipitates. Before quenching, the other specimens cooled with furnace to different precipitating temperature of 1000 °C (N2), 920 °C (N3) and 850 °C (N4) respectively, and held for 1 h. The heat treatment process is illustrated in Fig. 1.

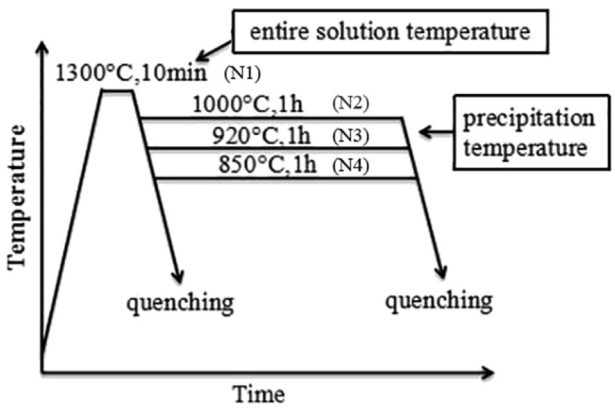

Fig. 1 – Schematic diagram of the heat treatment.

Experimental procedures

The electrochemical test solution was 3.5%NaCl. The electrochemical experiments included potentiodynamic polarization scan test and electrochemical impedance test.

A three-electrode system was used for polarization curve measurements. The working electrode was the experimental steel electrode surface exposed to the electrochemical test solution, the counter electrode was a platinum plate, and the reference electrode was a saturated calomel electrode (SCE). All potentials were measured and quoted against SCE if not specially mentioned. Potentiodynamic polarization curves were measured by using an Autolab electrochemical work station. Before measuring, galvanostatic cathodic hydrogen charging had operated at the constant current density of 10 mA/cm^2 for 1 h. Potentiodynamic polarization curves were measured at a sweep rate of 0.33 mV/s. One of the test was designed for the steel specimens without hydrogen-charging, and the other test was designed for the 1 h hydrogen-charged steel. Hydrogen charging at 10 mA/cm^2 and 0 (non-charging) are presented in follow figures as H-10 and H-0 respectively.

Dynamic electrochemical hydrogen charging and the electrochemical impedance measurements were performed with a Devanathan-Stachurski dual cell, as Fig. 2. The dual cell consisted of a hydrogen input cell and an electrochemical test cell. The solution for hydrogen charging was 0.2 mol/L NaOH with 0.25 g/L thiourea. The solution for testing the electrochemical behavior was 3.5%NaCl solution as above. The working electrodes used for electrochemical measurements were about 1.7 cm^2 with a thickness of 2 mm. Both surfaces were polished up to 2000-grit SiC paper and then rinsed in ethanol and in acetone prior to the electrochemical measurements. All tests were carried out in naturally aerated aqueous solutions at room temperature of about 25 °C. All solutions used in the tests were prepared with deionized water and analytical reagents. Before the electrochemical impedance spectroscopy (EIS) testing, the working electrodes had been charged at the constant current density of 10 mA/cm^2 for 1 h, and at the testing, the charging was continuing. During the EIS measurement, the scanning frequency ranged from 0.01 to 10,000 Hz with an applied AC amplitude of 10 mV.

In immersion test, the control and experimental specimens which had been charged at the constant current density of 10 mA/cm^2 for 1 h were immersed for 200 h in 3.5%NaCl solution. The corrosion morphology was investigated by

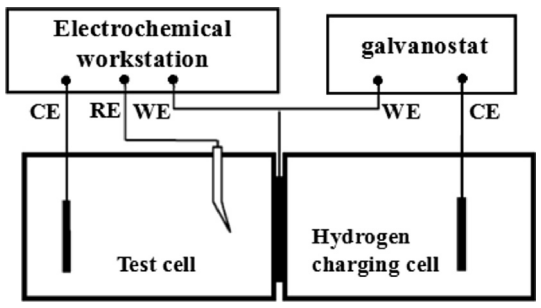

Fig. 2 – Schematic illustration of double electrolytic-cell and testing configuration.

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