Corrosion Science 82 (2014) 380–391

Contents lists available at ScienceDirect

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Effects of tungsten on the hydrogen embrittlement behaviour of microalloyed steels

Jingwei Zhao [a], Zhengyi Jiang [a], Chong Soo Lee [b,*]

[a] School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, NSW 2522, Australia
[b] Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

ARTICLE INFO

Article history:
Received 30 September 2013
Accepted 28 January 2014
Available online 4 February 2014

Keywords:
A. Low alloy steel
B. Hydrogen permeation
C. Hydrogen absorption
C. Hydrogen embrittlement

ABSTRACT

The effects of tungsten (W) additions (0, 0.1, 0.5 and 1 wt.%) on the hydrogen embrittlement behaviour of microalloyed steels were systematically investigated by means of slow strain rate tests on circumferentially notched cylindrical specimens, and the mechanism of hydrogen-induced embrittlement was discussed. W addition is found to increase the activation energy of hydrogen desorption. Microstructural features affect the hydrogen embrittlement behaviour and fracture modes of microalloyed steels. It is suggested that the hydrogen-induced embrittlement in the studied microalloyed steels with different W additions is caused by the combined effects of decohesion and internal pressure in the presence of hydrogen.

1. Introduction

Microalloyed steel, which is also called high-strength low-alloy (HSLA) steel, is a category of alloy steel that contains small amounts of alloying elements such as titanium (Ti), niobium (Nb) and vanadium (V). The addition of alloying elements in microalloyed steels plays a key role in the grain size refining and precipitation hardening [1]. Microalloyed steels offer increased excellent mechanical properties at a moderate increase in price over carbon steels, and they are economical for a variety of applications such as cars, trucks, bridges, oil and gas extraction, construction equipment, off-highway vehicles, mining equipment and other heavy-duty structures [2,3]. Microalloyed steels have been developing rapidly over the past several years, and extensive investigations have been conducted with a view of improving the toughness and strength in order to meet the requirement of excellent mechanical properties for various practical applications [4–7]. Tungsten (W) is a strong ferrite former, and is effective for precipitate refining and solid solution strengthening. W is usually added to steels as an alloying element to improve their mechanical properties, and several attempts have been made to achieve this goal in tool steels, high speed steels, heat resisting steels and stainless steels, and steels used in power-generation and chemical industries [8–13]. For microalloyed steels however, only limited published work is available with regard to W alloying in them. Our previous studies have indicated that W addition in microalloyed steels changes the phase transformation characteristics [2] and influences the microstructural evolution behaviour [3,14]. The addition of proper amount of W is beneficial for the improvement of room/low temperature tensile strength and ductility of microalloyed steels [15]. W alloying in microalloyed steels is becoming a rear and fruitful research field.

One of the significant challenges in the development of high strength steels is the so-called hydrogen embrittlement (HE) when these steels are applied in a hydrogen environment. It has been found that high strength steels are susceptible to HE, and the susceptibility to HE increases with enhancing the strength level [16,17]. The ductility will decrease and an unpredictable failure may occur in the presence of hydrogen in steels [18,19]. Numerous studies on the HE of high strength steels have been carried out in various environments such as stress corrosion cracking in an aqueous or H_2S and charging in H_2 gas or an aqueous solution in order to understand well the mechanism of hydrogen induced failure of these steels [20–29]. It is generally accepted that HE of steels correlates closely with the attractive interactions between hydrogen atoms and structural imperfections in crystals, i.e. the hydrogen trapping phenomena at various structural imperfections in steels affect the susceptibility of hydrogen-induced embrittlement [30]. The presence of hydrogen in solution in steels is mainly related to the small diameter of hydrogen atom and its capacity to diffuse and/or trap under a certain condition in solid state. Different factors such as environment, temperature, chemical composition,

* Corresponding author. Tel.: +82 54 279 2141; fax: +82 54 279 2399.
E-mail addresses: jwzhaocn@gmail.com (J. Zhao), jiang@uow.edu.au (Z. Jiang), cslee@postech.ac.kr (C.S. Lee).

http://dx.doi.org/10.1016/j.corsci.2014.01.042
0010-938X/

stress status and microstructural constituents can affect the hydrogen diffusion and strapping behaviour in steels [31]. It has been found that almost all kinds of defects in steels including vacancies, dislocations, interfaces, micro-voids and grain boundaries can act as hydrogen trapping sites [30,32]. The trapped hydrogen may diffuse to the stress-concentrated zone and microcracks that occurred at the tips of defects during loading, and an early failure is expected as the loading proceeds. There are generally two kinds of hydrogen trapping sites in iron and steels based on the trapping activation energy that is needed to escape from the trapping site to the normal lattice site. Table 1 presents the values of trapping activation energies for a number of trapping sites in iron and steels. It can be seen that the trapping activation energies of hydrogen for defects like iron lattice, grain boundary, austenite/martensite interface, dislocation, austenite/dislocation boundary, microvoid and Fe oxide interface are low, while those for ferrite/cementite interface and various non-metallic inclusions such as Cr carbide, Y_2O_3, MnS, Al_2O_3, Fe_3C and a precipitate, TiC are high. The ferrite/cementite interface and interfaces of non-metallic inclusions with high trapping activation energy of hydrogen are usually called irreversible trapping sites, whereas those with lower energies are termed as reversible or diffusible trapping sites [17,30].

Due to the harmful effect of HE in high strength steels, an insight in the interaction between hydrogen and failure behaviour is of crucial importance. Extensive investigations have been performed to understand the causes of HE occurring in various high strength steels, such as twining-induced plasticity (TWIP) steel [46], transformation induced plasticity (TRIP) steel [47], dual phase (DP) steel [48], high Mn steel [36], tempered martensitic steel [31], ferrite-martensite steel [49], stainless steel [50], maraging steel [50] and ODS RAF steel [17]. With regard to the HE occurred in microalloyed steels, Michler and Naumann [19] performed heat treatments on some microalloyed steels with different chemical compositions in order to obtain a variety of microstructural combinations of ferrite/pearlite, bainite and martensite. Tensile tests on smooth specimens of these steels were then conducted in a gaseous hydrogen environment at room temperature. They found that hydrogen assisted crack propagation, and hydrogen enhanced localised plasticity was the primary failure mechanism. Increased acicular ferrite content in the microstructure improved the resistance of hydrogen-induced cracking in the welded API 5L-X70 microalloyed pipeline steels, and the precipitated titanium carbonitrides could act as beneficial hydrogen traps and delay cracking in hydrogen sulphide environment [51]. The work of Kim et al. [52] indicated that hydrogen induced cracking in microalloyed steels primarily nucleated at inclusion and/or clusters containing the Al and Ca oxides. Kim et al. [53] concluded that in acicular ferrite, Fe_3C particles acting as reversible trapping sites for hydrogen atoms were newly precipitated along the grain boundary of microalloyed steel by the post-weld heat treatment at 620 °C. This led to an increase in diffusible hydrogen content in the steel that made it more susceptible to hydrogen-induced cracking. Nanninga et al. [54] studied three microalloyed pipeline steels by tensile tests in a high-pressure hydrogen gas environment. The results indicated that hydrogen absorption occurred prior to reaching the yield point for these steels, but after yielding, the rate of absorption and diffusion became much more rapid due to dislocation assisted mobility. They concluded that this initial hydrogen probably led to the formation of the hydrogen-induced surface cracks, and the tensile specimens tested in hydrogen failed through a mechanism of surface crack initiation and growth that occurred during the necking of the tested specimens. The micro-mechanism of hydrogen cracking was quasi-cleavage fracture of ferrite grains. Alp et al. [55] found that the susceptibility to HE in microalloyed steel was closely related to the microstructural state. Hydrogenated specimens with martensite islands in a ferrite matrix basically exhibited quasi-cleavage fracture with some ductile dimpling. The mode of fracture in charged specimens quenched from higher intercritical annealing temperatures was predominantly intergranular fracture along prior austenite grain boundaries and cracking of martensite laths. Although HE of microalloyed steels has been investigated extensively, there is still no relevant publication available that addresses HE behaviour in W-containing microalloyed steels, let alone a systematic investigation on the quantitative relationships among hydrogen concentration, W content and HE behaviour. As an alloying element with growing scientific and industrial interests, W has attracted an increasing attention due to its positive effect in microalloyed steels. It is therefore worthwhile to conduct an in-depth research with the purpose of understanding the effects of W on the HE behaviour of microalloyed steels. The research has practical applications, and the outcomes will be helpful in the development of W-containing microalloyed steels.

In the current study, several microalloyed forging steels with varying W contents were produced by a controlled forging process. This work aims to systematically investigate the HE behaviour of microalloyed steels with different W additions. The trapping activation energies of hydrogen in the W-containing microalloyed steels were quantified. The relationship between hydrogen concentration and tensile properties was investigated, and the effects of hydrogen on the fracture behaviour were analysed. In addition, the mechanism of hydrogen-induced embrittlement in the microalloyed steels with different W contents was discussed.

Table 1
Trapping activation energies for various trapping sites in iron and steels.

Trapping sites	Trapping activation energy (kJ/mol)	References
Reversible trapping sites		
Iron lattice	5.4–7.1	[33]
Grain boundary	17.2–18.6	[34,35]
Austenite/martensite interface	22	[36]
Dislocation	26.4–26.8	[34,37]
Austenite/dislocation boundary	37	[36]
Microvoid	35.2–40	[34,38]
Fe oxide interface	47	[17,39]
Irreversible trapping sites		
Ferrite/cementite interface	66.3–68.4	[16,31]
Cr carbide interface	67	[40]
Y_2O_3 interface	70	[39]
MnS interface	72	[41,42]
Al_2O_3 interface	79–86.2	[41,43]
Fe_3C interface	84	[39]
TiC interface	68–137	[44,45]

2. Experimental procedure

2.1. Materials

Four microalloyed forging steels with different W contents were adopted in this study. The chemical compositions are summarised in Table 2. The addition of W was intended to modify the microstructure and improve the mechanical properties of microalloyed forging steels. Room temperature tensile tests were carried out at a strain rate of 5×10^{-3} s^{-1} on the specimens with a gauge length of 30 mm and gauge diameter of 6 mm according to ASTM E 8M. The values of hardness were measured with a Vickers hardness tester using 2 kg load and 10 s dwell time, and 8 indentations for every specimen were made randomly on its surface. The mechanical properties are listed in Table 3. Since the fabrication of these microalloyed steels, and the microstructural evolution and mechanical properties variation after W addition have been