ELSEVIER

Materials Science and Engineering A 491 (2008) 164–171

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

The effects of atomic hydrogen and flake on mechanical properties of a tyre steel

X.C. Ren [a,b,*], W.Y. Chu [a], Y.J. Su [a], J.X. Li [a], L.J. Qiao [a], B. Jiang [b], M.R. Zhang [b], G. Chen [b]

[a] *School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[b] *Technology Center of Ma'anshan Steel & Iron Corporation, Ma'anshan 243000, China*

Received 23 January 2007; received in revised form 24 January 2008; accepted 1 February 2008

Abstract

The effects of hydrogen and flake on the fracture toughness, hydrogen-induced delayed cracking (HIDC), impact toughness and fatigue properties of a tyre steel have been investigated. The results showed that there was no effect of flake and atomic hydrogen on the fracture toughness K_{IC}. Atomic hydrogen could induce delayed failure under constant displacement. The threshold stress intensity factor of hydrogen-induced delayed cracking, K_{IH}, decreased linearly with diffusible hydrogen concentration C_0, i.e., K_{IH} (MPa m$^{1/2}$) = $K_{IC} - 4.0C_0$ (ppm) ($C_0 > 0.5$ ppm). Atomic hydrogen had no effect on impact toughness and fatigue properties when the C_0 was low ($C_0 \leq 0.5$ ppm). The flakes decreased impact toughness and caused it to fluctuate. Atomic hydrogen increased the fatigue crack growth rate when the diffusible hydrogen concentration was high enough ($C_0 \geq 2.5$ ppm). The flakes increased and undulated the fatigue crack growth rate.

Keywords: Tyre steel; Flake; Hydrogen; Fracture toughness; Fatigue; Hydrogen-induced delayed cracking

1. Introduction

When the concentration of hydrogen in steel exceeds a threshold value, recombination of hydrogen molecules in voids can result in a high pressure of hydrogen molecules, which is sufficient to produce hydrogen blister and/or flake [1]. Internal hairline cracks have been a major problem in large steel forgings and parts since the early part of the 20th century [2]. It is safe to say that these defects are associated with hydrogen, and it is recognized that the best method of avoiding hydrogen flake is to reduce the hydrogen concentration in steel to typically less than 2 ppm [3]. However, with the development of ladle metallurgy, secondary refining and continuous casting, flake in continuous casting clean steels with low hydrogen concentration, e.g., less than 1.5 ppm, again becomes a serious problem [4]. In 1998, delayed failure of a tyre occurred in Britain, and cracks were found in many other tyres, due to flake [5]. In China, flake in tyre and bearing steels is still a major problem. For example, about 10 tyres experienced delayed fracture after being fitted in recent years. So the assessment on the effects of hydrogen and flake on the safety of tyres is very important.

The effects of atomic hydrogen and preexisting hydrogen defects, e.g., flake and hydrogen-induced martensite, on the mechanical properties are different. The effects of hydrogen on mechanical properties strongly depend on the strain rate. The hydrogen-induced reduction in area increases as the strain rate decreases. For example, the elongation of hydrogenated 304 L austenitic stainless steel decreases as the strain rate decreases only when $\dot{\varepsilon} < 0.032\,s^{-1}$, but the decrease of the elongation due to hydrogen-induced martensite in the stainless steel is not so sensitive to the strain rate and can occur at a higher strain rate [6]. The hydrogen can induce delayed cracking though the mechanism of the hydrogen embitterment is open. Whether the flake will affect the hydrogen-induced delayed cracking and fracture toughness is still a question. Tsay et al. [7] observed that the fatigue crack growth rate (FCGR) was enhanced in AISI 304 stainless steel plate and its plasma weld when they were tested in gaseous hydrogen. For precharged 4130 steel heat-treated at different conditions, hydrogen assisted FCGR increased significantly [8]. Little attention has been paid to the effects of flake on mechanical properties. Nong et al. [9] found that the presence of flakes caused significant deterioration in the reduction of area

* Corresponding author at: School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China.
Tel.: +86 10 82376255; fax: +86 10 82376255.
E-mail address: renxchong@163.com (X.C. Ren).

0921-5093/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2008.02.002

values and in the impact toughness in the vertical direction, as well as in the fatigue strength.

The objective of the present research is to investigate the effects of atomic hydrogen and flake on the fracture toughness, hydrogen-induced delayed cracking, impact toughness and fatigue properties of a tyre steel.

2. Experimental procedures

A tyre steel with composition in weight percent of 0.60C, 0.28Si, 0.73Mn 0.012S, 0.015P and 0.18Cr was used. The bloom was processed into tyres at 1300 °C, and was then held at 620 °C for 5 h, after which it was cooled in air. The resulting microstructure was largely pearlite with some pre-eutectoid ferrite. All the samples used in this article were cut from the same tyre. Five hexahedronal samples with dimensions of 4 mm × 8 mm × 12 mm were charged at every current density for 24 h and used for measuring hydrogen concentration. Fig. 1(a) is a U-type impact specimen with a thickness of 10 mm. Fig. 1(b) is a modified WOL (wedge opening loading) sample with a thickness of 30 mm, which is used to measure the fracture toughness, K_{IC}, and the threshold stress intensity factor of hydrogen-induced delayed cracking, K_{IH}. Fig. 1(c) is a compact-tension (CT) specimen for the fatigue crack growth test. The loading direction of the WOL and CT specimen and the maximum normal stress at the tip of impact specimen notch were along the circumference of the tyre.

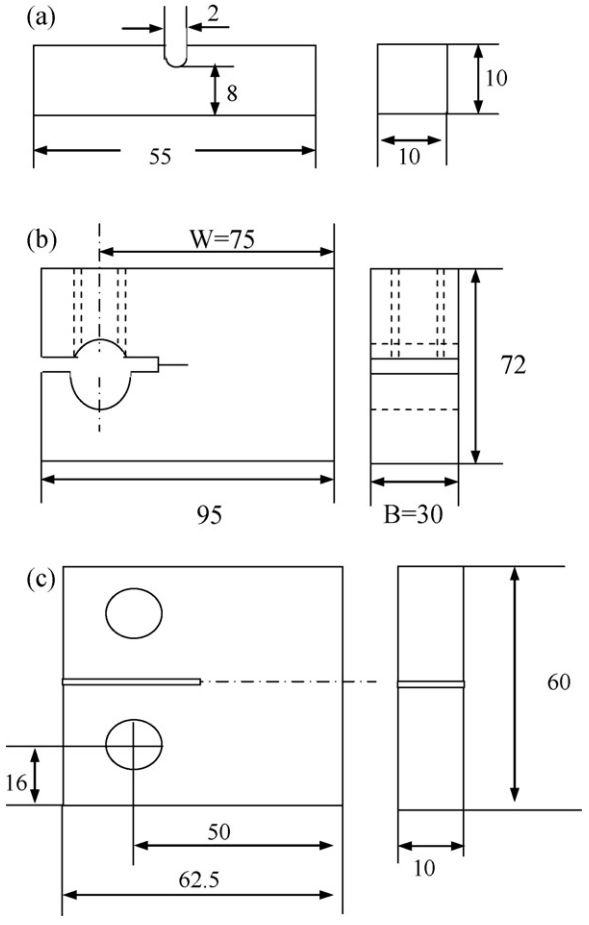

Fig. 1. Samples used in the experiments: (a) wedge opening loading (WOL) sample, (b) impact sample and (c) compact-tension sample (mm).

Charging was carried out in a 0.5 mol/L H_2SO_4 + 0.25 g/L As_2O_3 solution with various current densities i at room temperature. The charged hexahedral samples were placed into a glass tube filled with silicone oil and the hydrogen evolved at room temperature, V (cm^3), was measured. The diffusible hydrogen concentration C_0 (ppm) = $2 \times 10^6 V/82.6mT$, where m (g) is the weight of the sample, T (K) the temperature and V (cm^3) is the volume of hydrogen gas, evolved at T [10]. To gauge the hydrogen concentration in the traps, from where it could not escape at room temperature, C_t, hydrogen was measured by the hot-extraction method, using a mass spectrometry Hydrogen Analyzer H_2A2002. The total hydrogen concentration was $C_T = C_0 + C_t$. Hydrogen blisters on the surfaces of hexahedral samples were studied using polarized optical microscopy. The density of blister on the surfaces was measured.

Some impact specimens were charged in the solution with $i = 0.1$ mA/cm^2 and 2 mA/cm^2 for 100 h, respectively. The specimens charged with $i = 0.1$ mA/cm^2 and some uncharged specimens were tested at room temperature. The specimens charged with $i = 2$ mA/cm^2 were outgassed at 200 °C for 24 h and cooled to room temperature to eliminate the ambient temperature diffusible hydrogen and were then tested.

Prefatigued WOL samples were loaded using a screw to induce cracking. The arrested fracture toughness K_{IC} was then calculated based on the following equation [11]:

$$K_I = \frac{Y(a/w)V_0E}{\sqrt{a}}$$
$$Y\left(\frac{a}{w}\right) = \exp[10.5 - 115.6\,(a/w) + 408.4\,(a/w)^2 - 708.3\,(a/w)^3 + 602.1\,(a/w)^4 - 200.8\,(a/w)^5] \quad (1)$$

where V_0 is the displacement caused by the application of the screw, E is the Young's modulus, a is the crack length, and w is the width of the sample. Three samples were unloaded and charged with $i = 2.0$ mA/cm^2 for 170 h, and then loaded again immediately to cracking. Substituting the new V_0 and a into Eq. (1), the fracture toughness of the hydrogenated sample K_{IC}(H) was obtained. Three other samples were charged simultaneously without unloading at the current density $i = 0.1$, 0.2, 0.5, 1.0 and 2.0 mA/cm^2 for 170 h, respectively, under the constant displacement. Hydrogen-induced delayed cracking occurred. Substituting the constant displacement V_0 and the length of arrested hydrogen-induced crack into Eq. (1), the threshold stress intensity factor of hydrogen-induced delayed cracking, K_{IH}, was obtained.

Compact-tension (CT) specimens were charged in solution with $i = 0.1$, 0.5 and 2 mA/cm^2 for 100 h, respectively. One of the CT specimens charged with $i = 2$ mA/cm^2 was outgassed at 200 °C for 48 h. Fatigue tests were conducted on an Amsler dynamic system at room temperature and the experimental procedures followed the standard of ASTM E647-91. The loading frequency was about 90 Hz with a constant amplitude sinusoidal waveform of applied load and the stress ratio was 0.1. The calcu-