International Journal of Fatigue 59 (2014) 14–22

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Anomalies in hydrogen enhanced fatigue of a high strength steel

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ARTICLE INFO

Article history:
Received 16 March 2013
Received in revised form 19 August 2013
Accepted 9 October 2013
Available online 17 October 2013

Keywords:
Fatigue crack growth
Hydrogen embrittlement
Stress gradient
Loading protocol
Hydrogen diffusion

ABSTRACT

Fatigue crack growth for an HSLA steel was studied with in situ hydrogen charging. The hydrogen effect was highest at low ΔK values. The anomalies in hydrogen effect were found in the relative insensitivity of the crack growth rates to ΔK in a decreasing ΔK test protocol, and in the distinct differences of the crack growth rates for different loading protocols. These anomalies are explained by the hydrogen availability at the crack tip as a function of the test parameters. A "t" and "ΔK" based parameter was found to be universally applicable for hydrogen enhanced fatigue irrespective of loading protocol.

1. Introduction

The presence of hydrogen is known to accelerate fracture in metals and alloys [1–4]. This phenomenon of hydrogen embrittlement (HE) can cause changes in the fracture response of the material and therefore in the cracking mechanism during fatigue. Concerns for HE effect in structural and industrial components have resulted in studies of hydrogen enhanced fatigue in the corresponding materials [5–18].

The most popular definition of the fatigue process is due to the Paris' Law [19] which provides a relation between fatigue crack growth rate (da/dN) and the driving force, ΔK ($=K_{max} - K_{min}$), (where N is the number of cycles, and K is the stress intensity factor at the crack tip). Over the years, there has been an increasing acceptance of multi-parameter definitions for fatigue crack growth rates (FCGR), where, in addition to ΔK one or more operational parameters (usually a stress or stress intensity parameter) are used [20–22], especially for situations where extraneous conditions may affect the mechanism of crack growth. This is a recognition of the fact that issues which are important in crack propagation, like crack closure, crack-tip stress distribution, crack-tip blunting, and others, cannot be adequately represented by a single parameter formalism.

The two important observations which are reported in literature for hydrogen-enhanced fatigue are the inverse dependency of fatigue crack growth rate (FCGR) on the frequency of loading [11,12,15,16,23,24] and the pronounced influence of hydrogen at low ΔK values [15,17,23,25]. The frequency effect has been attributed to the time needed for hydrogen diffusion ahead of the crack tip. One of the arguments provided for the low ΔK effect is that due to the lower FCGR at low ΔK, the hydrogen diffusing ahead of the crack tip has enough time to keep up with the crack growth and the availability of hydrogen at the crack tip is enhanced [15]. Another reason put forth [9] is that at low ΔK, there is less diffusional egress of hydrogen in the unloading part of the cycle and thus more residual hydrogen is available for embrittlement. Added to that is the fact that at high ΔK the conventional mechanistic fatigue mechanisms are dominant, suppressing the hydrogen effects. In spite of the recent interest in hydrogen enhanced fatigue, there has been little attempt to isolate the hydrogen effect from the normal fatigue response of the material. This article reports the anomalies of fatigue crack growth with regards to its relation to ΔK, and the mode of loading, when hydrogen is present, as demonstrated in a high strength steel. The reported anomaly is significant with relation to remaining life estimation and life prediction of cyclically loaded components under hydrogen service apart from its apparent contradiction of the well established material behavior in fatigue.

2. Experimental procedures

The material used in this study was a Cu strengthened HSLA-80 steel with a chemical composition [In wt%: C-0.05, Mn-1.00,

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0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.10.002

P-0.009, S-0.001, N-0.01, Si-0.34, Cr-0.61, Mo-0.51, Al-0.025, Nb-0.037, Ni-1.77, Cu-1.23, Fe-balance]. It was obtained in the form of rolled plates 2″ (50 mm) thick. The steel had an acicular ferrite microstructure, a tensile strength of 740 MPa, an uniaxial yield strength (σ_{ys}) of 650 MPa, and a hardness of 280 VPN. Fatigue tests were conducted using notched three point bend (TPB) specimens with nominal dimensions of 100 × 20 × 10 mm. Prior to the fatigue tests all the specimens were pre cracked up to 2 mm in air. Suitable precautions were taken during pre-cracking to avoid overload effects. The fatigue tests were conducted at room temperature using the procedure laid down in ASTM standard E 647. Crack closure was monitored based on the procedure proposed by ASTM Task Group E24.04.04 [ASTM2404]. Due to crack closure, the crack faces were in contact below K_{op} (K_{op} = stress intensity at which the crack opens) during cyclic loading; the K_{op} could be determined by the latter procedure. The effective stress intensity range ΔK_{eff} is defined as follows $\Delta K_{eff} = K_{max} - K_{op}$. The fatigue crack growth rate (FCGR) tests were conducted using a decreasing as well as increasing ΔK protocol with constant stress ratio, $R(=K_{min}/K_{max})$ at a frequency of 1 Hz. Tests were conducted with different samples for the decreasing and increasing ΔK tests. In ΔK decreasing tests, the ΔK applied at any instant was calculated using $\Delta K = \Delta K_0 e^{-0.08(a-a_0)}$ and in ΔK increasing test the ΔK applied at any instant was calculated using $\Delta K = \Delta K_0 e^{+0.08(a-a_0)}$ where, ΔK_0 and a_0 refer to initial ΔK and the initial crack length with which a test was initiated.

The sample details and experimental set-up are provided in Fig. 1. A stress ratio (R) of 0.1 was used for the tests. The compliance crack length relation was used for the on-line crack length measurements using a 5-mm crack opening displacement (COD) gauge. Fatigue crack growth rates (da/dN) were computed on-line by the 7-point incremental polynomial method. Tests were conducted in a stainless steel tank attached to the lower ram of the loading frame. All tests were conducted open to atmosphere in a 0.1 N NaOH solution (approximately 4 l). No external stirring was applied. The pH at the start of the experiment was measured to be 12.2 and decreased to 12 by the end of the longest duration experiments. The crack tip pH was not monitored. To introduce hydrogen into the samples cathodic charging was used which entailed making the samples cathodic and using a galvanostat to pump in hydrogen. A platinum wire was used as a counter electrode for hydrogen charging. The charging current density (I_c) was kept constant for the duration of a test. The I_c used for such experiments served as an indirect measure of the extent of hydrogen entry into the samples. Tests in air were also carried out for comparison and for normalization of the tests carried out in hydrogen environments.

Fractographic examinations were carried out after completion of the fatigue tests using a scanning electron microscope (SEM). The fracture surfaces corresponding to different crack lengths and therefore different ΔKs were examined to find out the changes in cracking mechanism with crack progression.

3. Results

3.1. Effect of hydrogen concentration on FCGR in decreasing ΔK tests

Hydrogen was charged cathodically into the sample and the amount of hydrogen at the sample surface was directly dependent on the charging current density. The fatigue crack growth rates (FCGR) in different hydrogen concentrations are shown in Fig. 2a. The tests were conducted using a decreasing ΔK protocol, where the driving force for fatigue crack growth (ΔK) was programmed to monotonically decrease. The crack growth rate was observed to increase with increase in hydrogen presence (higher hydrogen charging current density), indicating hydrogen aiding the cracking process. For a hydrogen charging current density of 0.1 mA/cm^2, the crack growth rate increased by a small amount over that in air. However, on correcting for closure by plotting crack growth rate (da/dN) against ΔK_{eff} (as shown in Fig. 2b), the crack growth rate was found to be the same as in air. Interestingly, while the crack growth rate continuously decreased with a decrease in ΔK for the specimen charged at the lowest current density (0.1 mA/cm^2), the crack growth rates were found to be relatively constant for the higher charging current densities (0.5, 1 and 3.5 mA/cm^2) with slight gradual decrease with decreasing ΔK. The hydrogen current density of 1 mA/cm^2 corresponds to a sub-surface hydrogen concentration of ~2×10^{-6} mol/cm^3 [26]. The observation of increased hydrogen influence at low ΔK is not novel; several authors [15,17,23,25] have reported the same. For high hydrogen

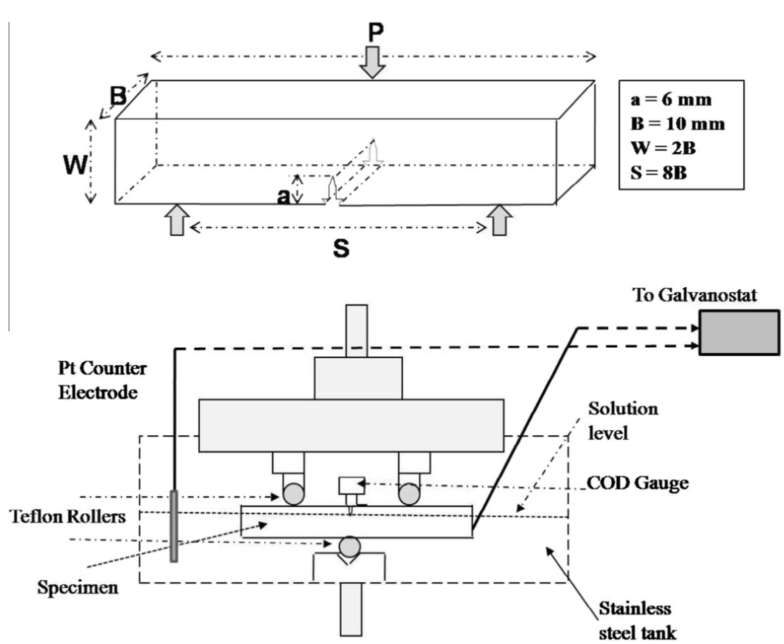

Fig. 1. Sample details (top) and experimental set-up for in situ hydrogen charging with cyclic loading.