Hydrogen Induced Cracking in Low Strength Steels

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Abstract

This study determines hydrogen induced cracking in low strength steel containing significantly less content of inclusions. The steel was cathodically charged in strong sulfuric acid solution aiming to provide a saturated hydrogen environment since such steel was believed to be immune to hydrogen cracking. The scanning electron microscope showed that there were a lot of microcracks initiated in the band structure at the boundaries between pearite and ferrite layers. The microcracks initiation and subsequent propagation at the ferrite/pearite interface was qualitatively explained by decohesion mechanism and hydrogen pressure theory, respectively. These microcracks were anticipated to reduce the ductility and the modulus of the charged steel. Therefore, if low strength steel is used in a hydrogen environment, there is a need to determine not only the content of inclusions but also the saturated hydrogen condition of the applicable environment.

Keywords: Hydrogen induced cracking, hydrogen cracking mechanism, low strength steels, less inclusion steels, ferritic/pearitic steels.

1. Introduction

While low strength steels have been considered immune to hydrogen embrittlement, the presence of inclusions is known to promote this phenomenon. With or without an externally applied stress, absorbed hydrogen atoms diffuse predominantly to low free energy locations such as inclusions (where the interfaces between the matrix and the defects are bonded weakly), forming hydrogen gas, generating pressure and initiating microcracks at these sites [1-3]. The presence of hydrogen with the applied stress induced the hydrogen assisted cracking phenomena and the condition without the stress gave the phenomena known as hydrogen induced cracking.

In low strength steels, Ribble et al. [4] found that the susceptibilities of hydrogen cracking phenomena depended on the levels of sulfur and phosphorus. Sulfur combines with Mn and high phosphorus promotes the precipitation and the segregation bands, such as phosphate inclusion, acting as crack initiation sites [5]. To minimize these effects, the sulfur content should be lower than 0.002 wt% and phosphorus should be lower than 0.005 wt%. Several works [6-8] studied the effect of microstructure on the hydrogen permeation and found that the hydrogen permeation was retarded in lameallar ferritic/pearlitic microstructure but there is less evidence of hydrogen microcracking in such steel if the inclusion content is very low.

This paper aims to study the hydrogen microcracking in 0.21C steel (used for pressure vessels and having low yield strength) with significantly less content of inclusions. The cracking mechanism and the hydrogen content are determined to identify the condition for this phenomena.

2. Experiment

The steel of interest contains 0.21 wt%C, 0.94 wt%Mn, 0.21 wt%Si, 0.001 wt%S, 0.006 wt%P, and 0.06 wt%Cr. It has a yield strength of 310 MPa, a modulus of 223 GPa and a percent of elongation of 34. Specimens of such steel were prepared as size 1.75x3x1cm and surface polished by sand paper numbers 200, 400, and 600. Then, the polished specimens were cathodically charged by potentiostat/galvanostat model 3600 in 1N

H_2SO_4 + 25mg/l As_2O_3 at a current density of 50 mA/cm^2 for at least 100 hrs. A high concentration of sulfuric acid solution was used to ensure that the specimen was saturated with hydrogen during charging. The saturated hydrogen condition was required since low strength steel with less content of inclusions was believed to be immune to the hydrogen cracking phenomena. Arsenic oxide was added in the solution in order to promote the hydrogen adsorption in steel [10-11]. As the contents of sulfur and phosphorus of this steel is very low (0.001%), it can be assumed that such steel contains mach less content of inclusions. Therefore, the effect of inclusion on hydrogen cracking is less significant. Both uncharged and charged specimens were prepared for microstructure determination using an optical and scanning electron microscope.

3. Result

The microstructure determination of an uncharged specimen showed that there was less evidence of the presentce of inclusions, confirming the assumption that the effect of the inclusion was less significant on the initiation of hydrogen microcracks. After prolonged charging, there were a lot of microcracks initiated on the surface and inside the charged specimen. The cracks were oriented in the rolling direction as shown in Figure 1. For longer charging time, a larger number of microcracks was found. Besides, it was found that most of microcracks were initiated within the peritic/ferritic lamella band in the charged specimen, compared to the uncharged specimen as in Figures 2 and 3.

4. Discussion

4.1 Hydrogen Saturated Condition

Several works [9-10] showed that the hydrogen concentration in steels reaches a saturation level after prolonged charging. The saturation time and hydrogen concentration in the steel depended on the charging procedures and materials. With the presence of arsenic oxide, the saturated level was found after 0.5 to 3 hrs charging [10] depending on the charging current density and the concentration of sulfuric acid. The higher the current density and the higher the concentration, the higher the saturated hydrogen concentration will be. Saturated concentrations from 2 to 8 ppm have been found in cathodically charged specimens [10, 13-14]. Barth and Stringerwald [15] proposed the relationship between the current density and the saturated hydrogen content for specimen charged in sulfuric acid as [H] = 13.3 –2.7 log I. In this case, the saturated hydrogen content in a specimen, prolongly charged at the charging current density of 50 mA/cm^2, can be estimated to be approximately 6 ppm, at which microcracks were found to be induced by hydrogen in low strength steel.

4.2 Hydrogen Microcracks

From the results, the microcracks were found on the surface and inside the specimen lying in the banding microstructure when it was charged in the saturated hydrogen condition. The scanning electron microscope showed that the microcracks were aligned in the rolling direction and were initiated at the ferrite/peralite interface with no evidence of microcracks initiated at the inclusion. This suggested that hydrogen diffused and accumulated at these sites agreeing with Rieckes et al [6] and Tau and Chen [7] who proposed that hydrogen may be trapped in the ferritic/peritic band since the hydrogen diffusion was retarded in these microstructures. The increase of retardation was especially found when the hydrogen entry was through a top surface perpendicular to the rolling direction. The hydrogen concentration of charged band microstructures increases with the amount of pearitic banding [8]. Cracking along the band structure was found in steel having yield strengths below 560 MPa when it contained a large content of inclusions which was normally located in the peritic/ferritic band [16]. For less inclusion steel, this study showed that the hydrogen microcracking was found when it was charged in the saturated hydrogen condition.

4.3 Hydrogen Cracking Mechanism

The initiation and propagation of microcracking, as found in this study, was determined based on the hydrogen embrittlement mechanism. Hirth[17] summarized the embrittlement mechanism including: (1) decohesion, (2) hydrogen pressure, (3) surface energy reduction, and (4) dislocation mobility. The decohesion theory was proposed to determine the reduction of the atomic cohesion forces in a region to which the hydrogen diffuses and accumulates [9, 18-19]. The hydrogen pressure theory, first proposed by Zapffe [20] and later modified by Tetelman [21], was developed for internal hydrogen gas generated in the void during high charging conditions, resulting in high pressure. The surface energy reduction was applicable to the nucleation of new surfaces for hydrogen cracking with the external applied stress [22]. The dislocation mobility explained the hydrogen cracking during a dynamic deformation [23-24]. From the hydrogen mechanism theory, the nucleation and subsequently propagation of microcracks in less inclusion steel charged with the saturated hydrogen condition can be quanlitatively explained by the decohesion mechanism and hydrogen pressure model, as cathodic charging produces a high supersaturation of atomic hydrogen in steels [20, 25-26].

4.4 Hydrogen Microcracks and Steel Properties

The hydrogen had a predominant effect on the ductility of steels. It was found that the ductility of steels was decreased by the hydrogen, especially in high strength steel [27-29]. With and without the external stress, the hydrogen was found to induce the crack/microcracks and promote the rapid crack growth. The higher the strength, the larger the decrease in the ductility will be. Several studies [30-32] showed that the ductility was also found to be markly reduced in low strength steel having the yield stress of approximately 500 MPa whereas the microcracks were found to preferably initiate at the inclusions. The microcracks are believed to link together during the application of an external stress and promote the crack growth resulting in the decrease in the ductility. Therefore, a similar effect could be found in the steel of interest as there were a lot of microcracks initiated on and inside the specimen.

Little research [33-34] has determined the effect of hydrogen on the Young's modulus in 0.1C steels. They have found that the modulus of charged steels was reduced approximately 2%. For the appearance of the microcracks, the modulus was found to be reduced according to the definition [35-36] of $E^m = E\ (1-(f(v^m)\varepsilon))$ where E^m and E are the elastic moduli of the microcracked and uncracked materials, respectively, f is the function of poisson's ratio, v^m, and ε is the crack damage parameter related to the number of cracks per unit volume ($\varepsilon \propto N$). Therefore, it could be predicted that the hydrogen microcracks found in this study could reduce the elastic modulus of this steel.

5. Conclusion

When low strength steel (with significantly less content of inclusions) is cathodically charged in a saturated hydrogen environment, internal cracking by hydrogen is induced. The hydrogen microcracks were found to initiate and subsequently propagate in the ferrite/pearite interface, which can be qualitatively explained by decohesion mechanism and hydrogen pressure model, respectively. The presence of microcracks was anticipated to reduce the ductility and the modulus of charged steel. In this case, to use low strength steel in a hydrogen environment, one needs to determine not only the content of inclusion but also the saturated hydrogen condition of the applicable environment.

6. Reference

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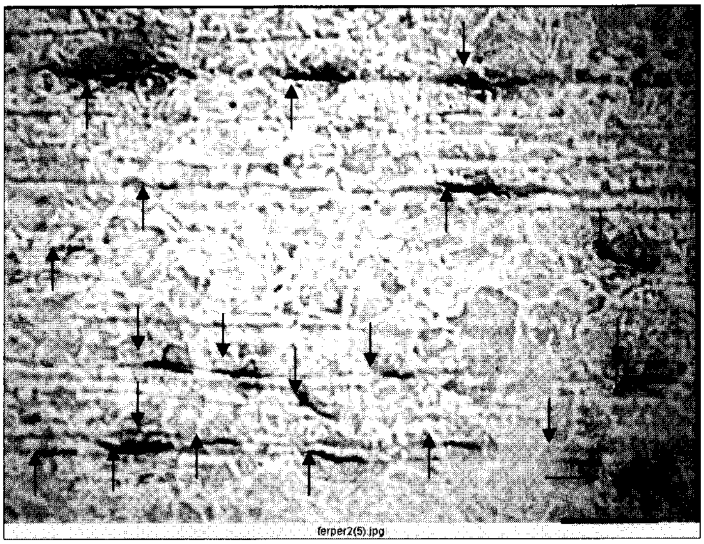

Figure 1. Optical Micrograph of 0.21C Steel Hydrogen Charged Specimen Etched in 3% Nital (Arrows Indicates Cracks Passing through Pearlitic Regions)

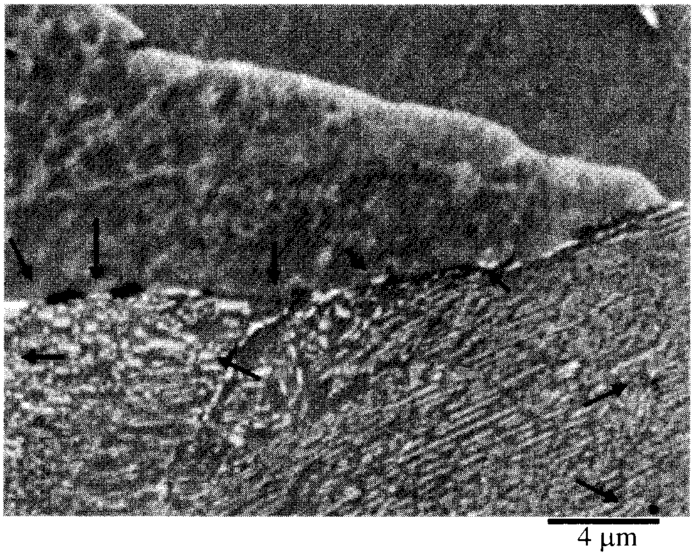

Figure 2. Scanning Electron Micrograph of Microcracks Initiated at Pearlite Colony in 0.21C Hydrogen Charged Steel

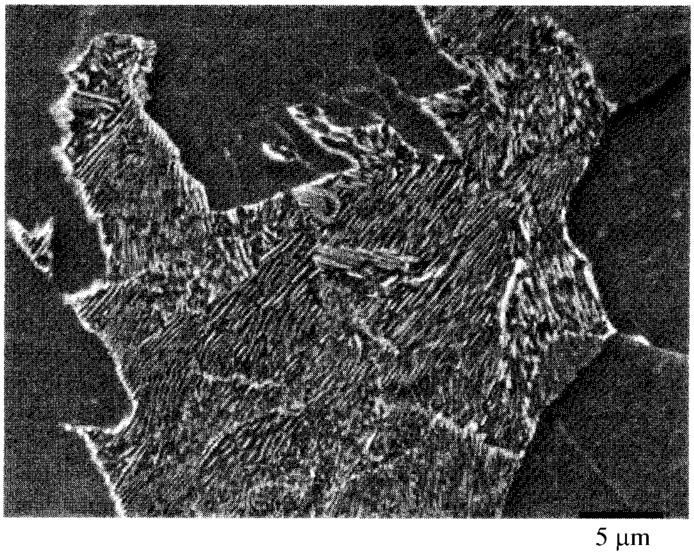

Figure 3. Scanning Electron Micrograph of 0.21C Uncharged Steel, Etched with 3% Nital