HYDROGEN INDUCED CRACK GROWTH RATE IN STEEL PLATES UNDER UNIAXIAL STRESS

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ABSTRACT

The purpose of this work was to determine in a quantitative manner the effect of an external uniaxial stress on the kinetics of the hydrogen induced cracking. In this study, the hydrogen induced cracking was done by cathodic charging of API–5L–X52 steel plates. The growth of the induced cracks was recorded at increasing inspection times by ultrasonic inspection. The external uniaxial stress affected the number of initial cracks in the HIC tests, having more initial cracks as the stress increases. This effect is related with the stress fields interaction from the internal pressure produced by the molecular hydrogen and the applied external stress, which weakens the interface between the matrix and the non-metallic inclusions, thus facilitating the nucleation of cracks by the pressure mechanism. A greater number of individual cracks causes that the number of cracks interconnections to increase, thus affecting the crack shape and growth. The external uniaxial stress, however did not show a significant effect on the hydrogen induced crack growth rate, at least in the interval of the applied stresses used in this work.

KEYWORDS: API-5L-X52 steel, hydrogen induced cracking, crack growth, pipelines

1. INTRODUCTION

There have been a number of failures of line-pipe steels due to the presence of delaminations and blisters which are formed when atomic hydrogen resulting from the corrosion reaction of the steel pipe in the presence of sour gas (H_2S). Although the actual trend in industry is to continue developing and evaluating new steels resistant to hydrogen induced cracking (HIC), there are thousands of kilometers of installed sour gas pipelines that still experience HIC. This facts justifies a need to be able to predict the life span of these pipelines in terms of the extension of HIC. The HIC is due to the absorption of the atomic hydrogen generated by the corrosion reaction between the sour gas and steel, which diffuses towards some internal discontinuities, such as non-metallic inclusions and pre-existing cracks, where it recombines to form molecular hydrogen. The internal pressure in the cavity increases until that the stress intensity in the edge overcomes the toughness of the material and a crack propagates (1). The cracks usually are formed parallel to the surface of the pipe; when they are located approximately at the half thickness, are called delaminations, and when they are located near a free surface, deforming the pipe wall, they are called blisters (1-4). The HIC is possible even in the absence of an external stress, because the stress concentration at the crack tip provides the driving force for the growth (1-4).

Iino (5) found that the manner of extension of the hydrogen induced cracks is considerably influenced by the presence of external stress (pipe hoop stress): in absence of the external stress, cracks extension develops by stepwise linking the hydrogen induced cracks, founding considerable plastic deformation accompanies the stepwise linking. In the presence of an external stress, cracks extension develops by linking the cracks formed in stacked arrays out of a plane approximately perpendicular to the stress axis. The linking between cracks, in this case, is characterized by the absence of plastic deformation. However, recently Zakaria (6) mentions that external stress did not significantly affect the manner of formation and extension of the hydrogen induced cracks. In his investigation, Zakaria found that in the absence of external stress the cracks still form in a stacked array.

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Therefore the main aim of the present paper is to determine in a quantitative manner the effect of the external uniaxial stress in the range from zero to σ/σ_o = 0.5 on the kinetics of hydrogen induced cracking.

2. EXPERIMENTAL PROCEDURES

The material used in the experimentation was a carbon steel, type API-5L-X52, from a pipe of 91.4 cm diameter and 2.0 cm thickness. The chemical composition was: 0.14 C, 0.25 Si, 0.99 Mn, 0.01 P and 0.03 S (wt.%). At first, the pipe was inspected with an ultrasonic flaw detector to verify the absence of pre existing cracks and internal defects. Plates of 7.6 cm wide and 17.8 cm long, were cut out from the pipe and ground to get parallel faces and a thickness of 0.9 cm. The greater length of the test plates was parallel to the rolling direction of the pipe. The plate faces were finished with grade 400 SiC grit-paper and cleaned by immersion in an ultrasonic bath for 10 minutes. using a commercial cleaning solution (Ultramet). The plates were stressed using a loading frame as shown in Figure 1. The stress was measured with a strain gauge placed on the face of the plate. Finite element stress field calculation showed that plate exposed test area was under a uniform stress. The applied stress were 15.3, 68.3 and 165.9 MPa, which correspond to a σ/σ_o ratio of 0.05, 0.2 and 0.5 respectively (σ is the applied stress and σ_o is the yield stress of the material).

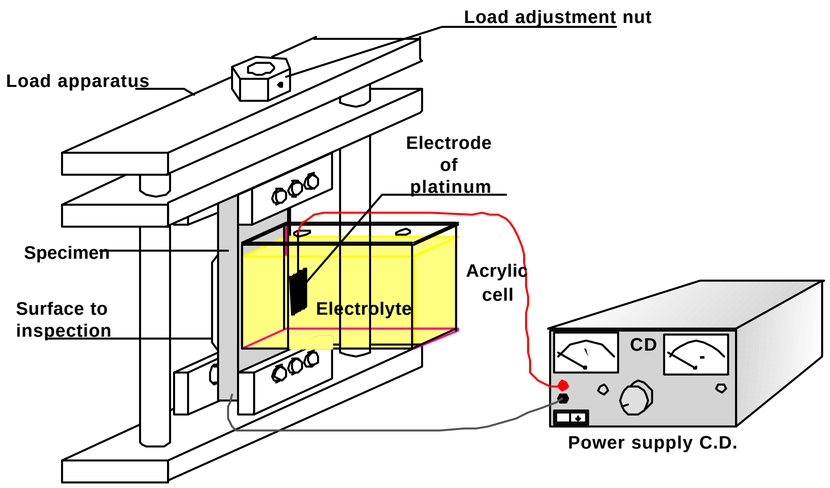


Figure 1. Loading frame and cathodic charging set up.

The cathodic charging set up is shown schematically in Figure 1. This set up, promotes hydrogen absorption through only one face of the plate, just as happens in a pipeline in service. The test solution was 0.4 wt % sulfuric acid in bidistilled water plus five drops of a “poison solution", that consists of 2g of phosphorus dissolved in 40 ml of carbon disulfide. The average pH of the test solution was 2.9. The applied current density was 2.5 mA/cm^2 and the test were ran at ambient temperature (average 22 °C). The solution was changed every six days, adding five drops of the “poison solution” daily. The growth of cracks in the plate was monitored from the free side by ultrasonic inspection. The inspection technique assured a resolution for crack length increments of at least 1 mm. The test were ran until most of the exposed area was cracked.

3. RESULTS AND DISCUSSION

Ultrasonic system used in these studies is a sensitive technique for detecting cracks in samples exposed to hydrogen cathodic charging. Since ultrasonic inspections were conducted before an after to cathodic charging, and those obtained before charging had no defect indications, all defects detected after cathodic charging were due to HIC. Ultrasonic indications were used to identify locations of cracking and quantitative data to characterize the extend of cracking, such as crack length ratios, were obtained. To verify the presence of the cracks, the samples were sectioned for metallographic examination. The cracks observed metallographically were found at the locations indicated from the ultrasonic flaw detector. Figure 2 shows the cracks contours (dashed areas) after the HIC tests at different stresses and inspection times. It is observed that the crack contours are irregular, showing the tendency to be longer in the rolling direction than in the transverse direction of the plate (an average of 1.3 times).

The meallographic observations showed that most of the cracks were initiated at elongated manganese sulfide inclusions (Figure 3); therefore, the longer crack extension in the rolling direction is attributed mainly to the elongated shape of the non-metallic inclusions.

Figure 4 shows that the initial number of cracks increased with the applied external stress. In the absence of an external stress, the atomic hydrogen generated by the corrosion reaction between the sour gas and steel, diffuses towards elongated MnS inclusions, where it recombines to form molecular hydrogen, reducing the bond strength between inclusion and matrix, which produces the HIC. We suppose that effect of external stresses on the hydrogen induced cracks formation is due to the weakening of the interface between the matrix and the non-metallic inclusions by the superposed stress fields of the molecular hydrogen pressure and the applied external stress in the plate. This will promote the formation of cracks. Figure 2 shows that as charging time increases, linking between cracks takes place to form more complex shapes. This crack linking occurred preferentially in the longitudinal direction, due to the fact that the crack growth was greater in that direction. This preferential growing was more evident at the lowest external stress. Figure 2 shows also the profiles of the cracks in the thickness of the test plates. It is seen that the maximum stepwise cracking was of 10 % of the thickness. During the HIC tests, the crack linking occurred preferentially in the longitudinal direction, due to the fact that crack growth was greater in that direction. This also contributes to make the cracks longer in the longitudinal direction, with a final shape close to a rectangle with round corners. Iino(5) found that in the presence of an external stress (sufficiently high compared to zero and sufficiently low compared to the yield strength of the material) cracks linking developed by stacked arrays in a plane approximately perpendicular to the external stress axis, while in absence of an external stress, the cracks link in a stepwise manner. In the present work, it was found that the external stress did not significantly effect the manner of the formation and extension of the cracks at least in the interval of external stresses used in this work, i.e. in the presence of an external stress the cracks still link in a stepwise manner (Figure 5).

From the crack contours at different inspection times, the crack length and crack growth rates were calculated. Figures 6 and 7 show the average crack growth rate and crack length in the longitudinal direction of the test plates as a function of the exposure time. Figure 6 shows that the crack growth rate decreases with the exposure time and that there is not a significant effect of the external stress on the crack growth rate; however, figure 7 shows that the presence of an external stress increases the final average crack length. This is associated with the effect of the external stress on the crack initiation. and not with the effect of the external stress on the crack growth rate. As the number of initial cracks increases, the interconnection of individual cracks is more frequent and the final crack size is larger.

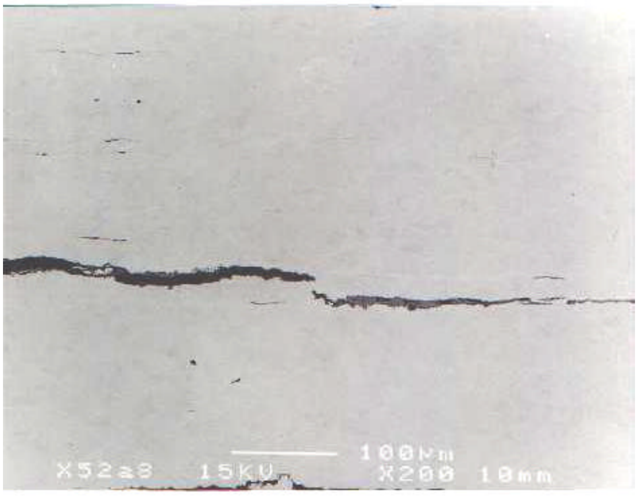
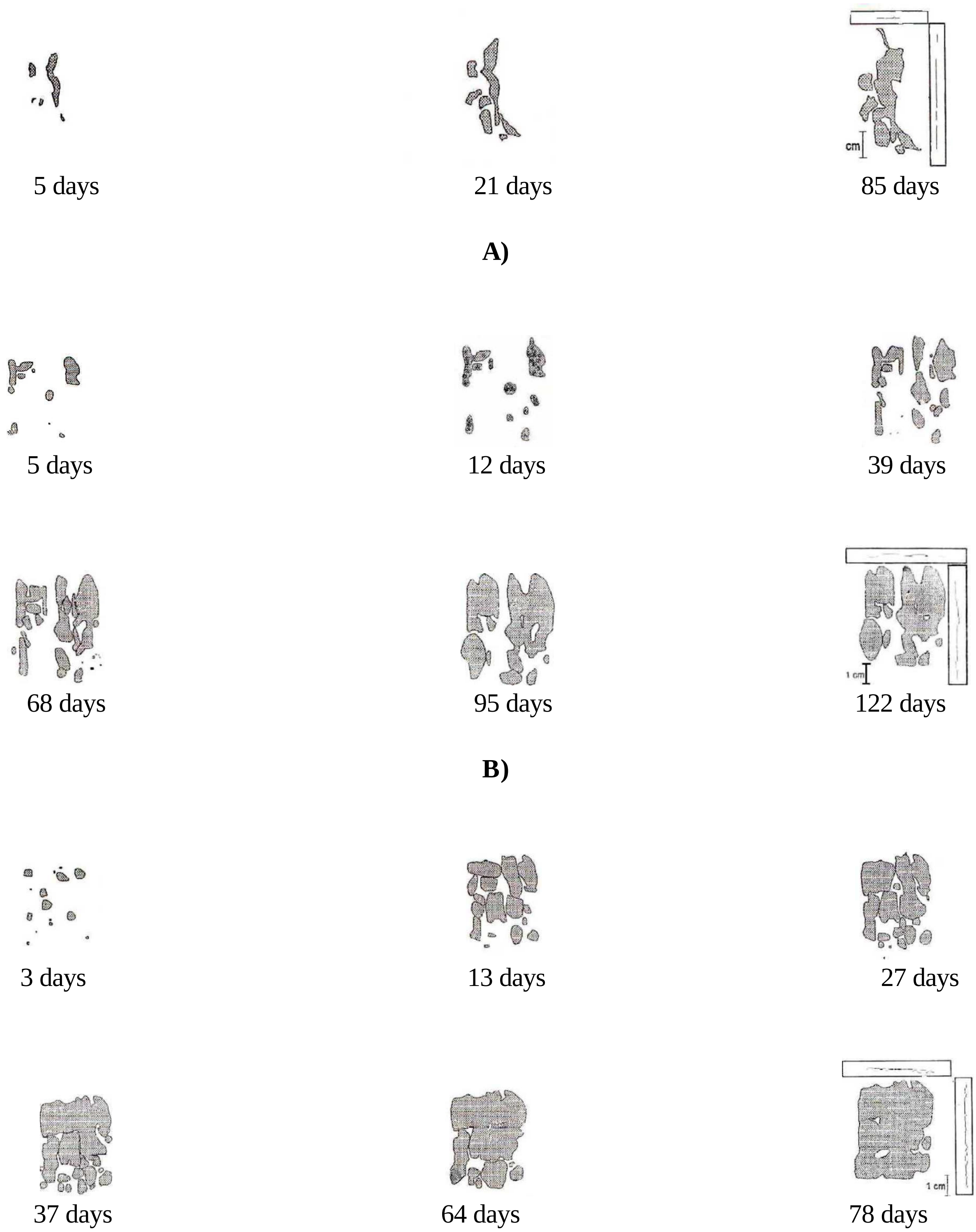


Figure 3. HIC initiating at the MnS inclusions.



C)

Figure 2. Figure 2. Crack contours in the steel plates exposed to cathodic charging with uniaxial stress. / $_o$ = 0.052; b) / $_o$ = 0.2 and c) / $_o$ = 0.5

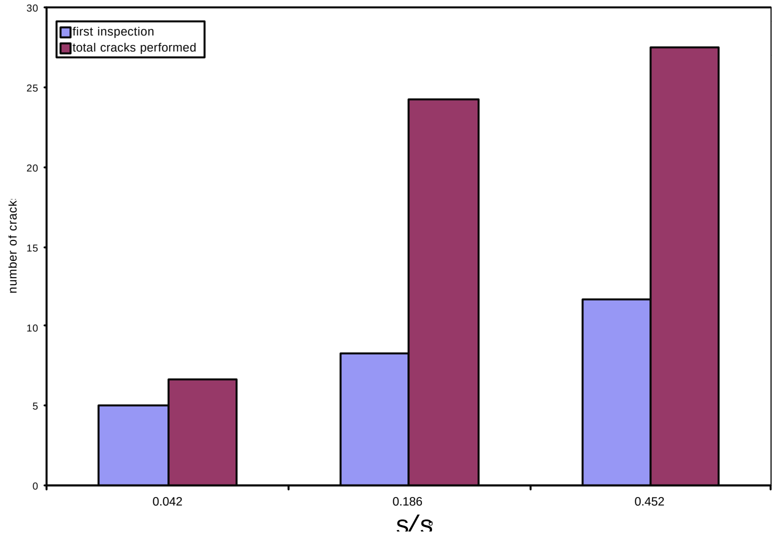


Figure 4. Number of detected cracks during the HIC test.

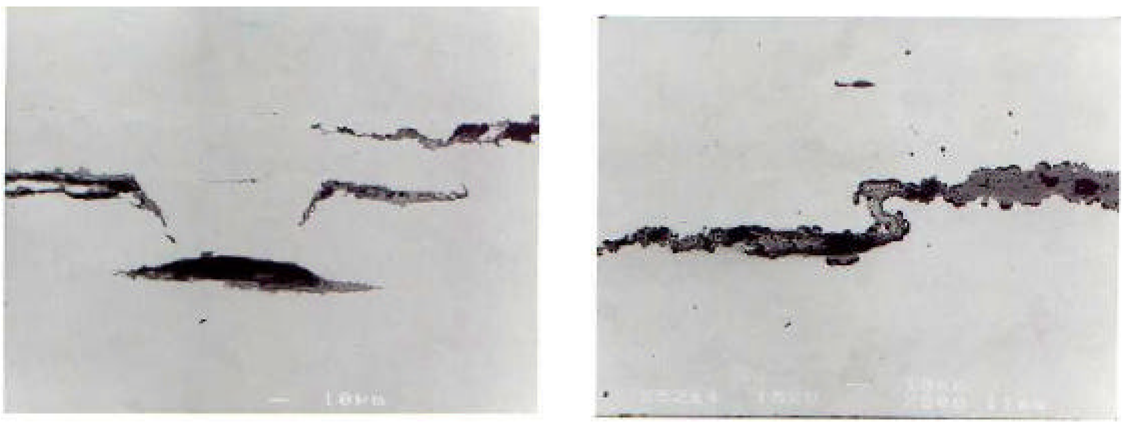


Figure 5. Examples cracks linking in a stepwise manner, observed in the loaded plates.

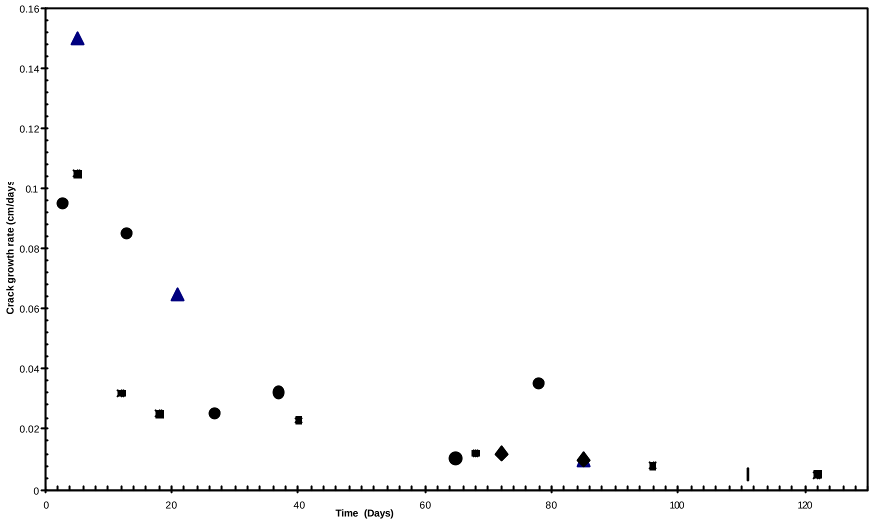


Figure 6. Measured crack growth rates at different external stresses.

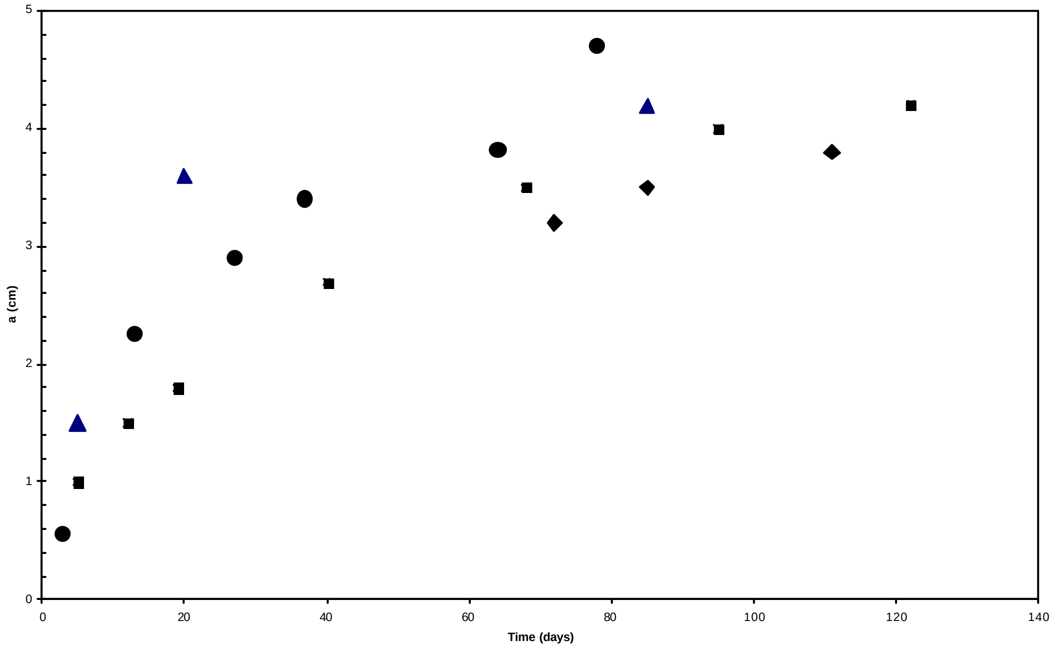


Figure 7. Measured crack lengths at different external stresses.

4. CONCLUSIONS

The effect of a external stress on the hydrogen induced cracking was monitored successfully using an ultrasonic flaw detector.

The presence of an external stress affected the number of initial cracks in the HIC tests, having more initial cracks as the stress increases. This effect is due to the weakening of the interface between the matrix and the non-metallic inclusions by the superposed stress fields of the molecular hydrogen pressure and the applied external stress.

It was found that the total crack length and the number crack interconnections, increased proportionally to the applied uniaxial stress, however little or no effect of the stress was seen on the crack growth rate.

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