Fatigue Crack Tip Plasticity in Hydrogen Charged Reactor Steels

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Abstract.
Hydrogen is known to embrittle metals and shorten their fatigue life. Previous optical microscopy observations also indicate that the fatigue crack path becomes straighter when hydrogen is introduced. In this study, 316LN grade compact tension specimens were fatigue tested in a virgin and hydrogen charged state and the development of plasticity of the crack tips observed. Fatigue tests were monitored with an infrared camera and thermoelastic stress analysis was used to measure plastic zone size and crack length. The results show that hydrogen charging caused crack growth with a steady increase in plastic zone size that appeared to inhibit secondary cracks, thus producing a straight crack. Virgin specimens had a more erratic and tortuous crack path with secondary cracks present.

Introduction

Hydrogen in steels causes deterioration of material properties, such as embrittlement, as well as a reduction in fatigue life and yield strength. While high nickel, low carbon austenitic steels of the 300-alloy range are known for their resistance to hydrogen embrittlement, a degradation in mechanical properties is nevertheless observed[1]. Hydrogen has been found to reduce the number of cycles to failure in low cycle fatigue in 316LN stainless steels [2]**.** Additionally, the crack path was observed to be straighter in hydrogen charged specimens as compared to non-charged ones[2].

Many mechanisms have been proposed to describe the cause of hydrogen embrittlement. Hydrogen enhanced localised plasticity (HELP) is one mechanism that has been widely studied in a variety of metals including 316LN steel [3]. Here, hydrogen that is weakly trapped ahead of dislocations is thought to increase dislocation mobility[3]. Ahead of crack tips stress gradients lead to a greater number of dislocations and higher hydrogen concentrations. Therefore, increased plasticity ahead of crack tips is to be expected [3].

Thermoelastic stress analysis (TSA) is a far-field technique which has been used to quantify and visualise stress distributions around a crack tip during cyclic loading [4]. Therefore, this technique could be of use to identify changes in plasticity caused by hydrogen. When a specimen is cyclically loaded, temperature changes within a specimen are in-phase with the load signal in adiabatic and reversible conditions. Lock-in amplification can be used to correlate the known load signal with temperature data, producing maps of stress following a calibration procedure. Additionally, a map of the phase difference between the load signal and local temperature variation can also be produced. Plastic deformation occurring ahead of the crack tip is an irreversible process that will generate a temperature signal out-of-phase with the load signal and hence will be illuminated in the phase difference map. Therefore, plastic zone shape and size can be evaluated during fatigue testing using TSA.

Fatigue crack propagation in hydrogen-charged compact tension (CT) specimens was monitored using TSA. Crack length and plastic zone area were calculated to observe differences in crack propagation characteristics between hydrogen-charged and virgin specimens.

Experimental Methods

Compact tension specimens with dimensions of 25x24x0.8mm were manufactured from nuclear grade 316LN stainless steel. A 1 mm crack was grown prior to testing to ensure that measurements were not influenced by the proximity of the notch. Fatigue tests were carried out at 450 ± 150N at a test frequency of 20Hz until the crack reached a nominal length of 6mm as measured from the notch tip. Fatigue tests were monitored by an infrared camera (FLIR SC700) and collected 15s of data in two-minute intervals. Lock-in amplification was used to process the data and generate TSA maps after testing.

Crack length and plastic zone area were calculated with a MATLAB script using a procedure similar to that described by Patki and Patterson [4]. Phase difference maps (Y-image) were segmented with a K-means filter and then binarized. From the binarized image, plastic zone size and crack length were computed.

Specimens were electrolytically hydrogen charged for 48 hours in a 1M NaCl solution at 50°C. Under these conditions the hydrogen penetration depth was expected be 10µm. A custom-made electrolysis cell was built consisting of a platinum mesh counter electrode, the specimen as a working electrode, and an Ag/AgCl reference electrode. To ensure that significant amounts of hydrogen were present during testing, no more than thirty minutes elapsed between the hydrogen charging and the starting of fatigue loading.

Results

The crack length with elapsed cycles for the hydrogen-charged and non-charged specimens is shown in fig. 1a. A reduction in fatigue life can be seen in the hydrogen-charged specimen. The plastic zone areas measured from TSA data for both specimens can be seen in fig. 1b and are comparable up to a crack length of about 4.5mm. At greater crack length the hydrogen-charged specimen showed a steady increase in plastic zone area with crack length with little scatter in the data, while the non-charged specimen exhibited scatter around a constant value of slightly less than 0.45mm^2. At a crack length of 3.5 mm, a peak can be seen for the hydrogen-charge specimen, which could be attributed to the formation of secondary cracks. Conversely, the non-charged specimen experienced several peaks in size of the plastic zone area. This is indicative of irregular crack growth and the formation of multiple secondary cracks.

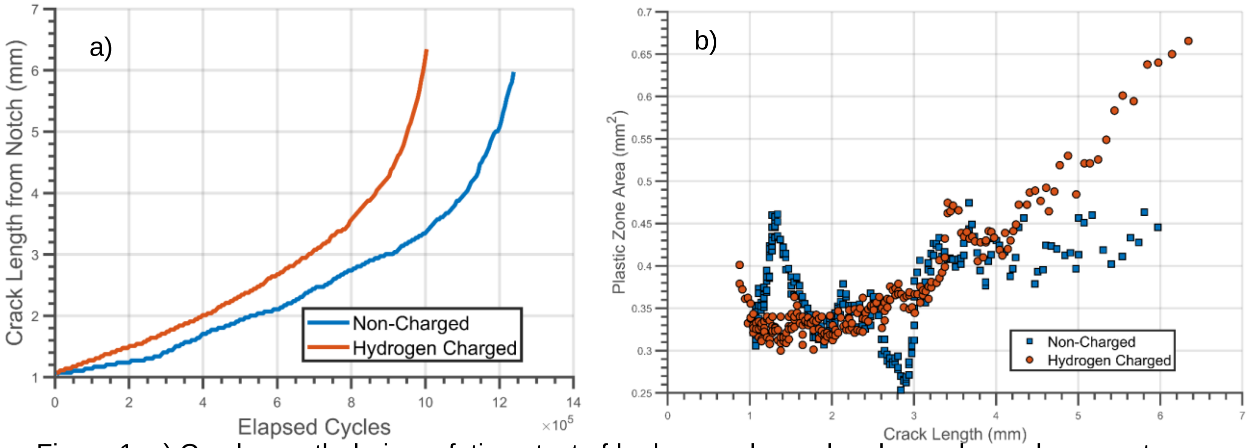

Figure 1: a) Crack growth during a fatigue test of hydrogen-charged and non-charged compact tension specimens; and b) Plastic zone areas for a non-hydrogen charged and hydrogen-charged specimen .

Discussion

Fatigue tests showed that hydrogen accelerated the crack growth rate and reduced the fatigue life of the compact-tension specimens as compared to their virgin state. Additionally, the plastic zone size increased steadily in the hydrogen-charged specimen. Previous investigations have shown that local peaks and jumps in the area of the plastic zone can be attributed to the formation of secondary cracks and changes in the crack path direction. The smooth increase in plastic zone area in the hydrogen-charged specimen therefore indicates straight crack growth with no, or little, secondary crack formation. On the other hand, the plastic zone area of the uncharged specimen had many local peaks. Therefore, suggesting that secondary cracks formed during crack propagation and that the crack followed a less straight path. As more energy was expanded in forming secondary cracks and the longer non-straight path, this could explain the lower crack growth rate in the non-hydrogen charged specimen. These results agree with previous observations of straighter cracks forming in hydrogen pre-charged specimens.

Conclusion

Compact tension specimens were fatigue tested in virgin and hydrogen-charged states. The presence of hydrogen reduced the number of cycles to failure and accelerated the crack growth rate. Data showed that plastic zone area grew steadily with crack length in hydrogen-charged specimens. The opposite was seen in the non-charged specimen where the crack path was more erratic. This indicates that fewer secondary cracks formed in the hydrogen-charged specimens and agrees with optical microscopy observations from literature.

References

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