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Entitled: Research on Hydrogen Effects on Phase
Distribution Ahead of Propagating Cracks in
Stainless Steel

Submitted by: Carl Altstetter
Dept. of Materials Science and Engineering
University of Illinois at Urbana-Champaign

Submitted to: University Contract Administrator
c/o R.N. Tokay
Los Alamos National Laboratory
Box 990, mail stop P274
Los Alamos NM 87545
telephone 505-667-5931

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Abstract

This research was performed in support of computations to determine the distribution of hydrogen at a crack tip in an unstable stainless steel. It involved metallographic observations of the distribution of martensite at a stressed crack tip.

Objectives

1. introduce a sharp crack at a notch in a stainless steel strip and propagate the crack in the presence of gaseous hydrogen
2. prepare metallographic specimens of the crack tip material at mid-thickness
3. observe the specimen using optical and scanning electron microscopic observations in order to determine the distribution of phases at the crack tip
4. communicate the results of the experiments to Los Alamos National Laboratory personnel in order to incorporate the information into a finite element method (FEM) computer model of hydrogen embrittlement

Experimental Procedure

This research was performed with the assistance of two undergraduate students, David Prasso and Ronald Jaracz, in collaboration with Daniel Weinacht, on leave from Los Alamos National Laboratory to the University of Illinois for the purpose of satisfying the PhD requirements in the Mechanical and Industrial Engineering Department. Carl Altstetter supervised the experimental work and was a thesis advisor of Mr. Weinacht. Tensile test specimens of an unstable austenitic stainless steel, AISI 301, were prepared as 25 by 250 mm by 1 mm thick strips which contained a 6 mm deep saw cut at the midpoint of one edge. A sharp crack was propagated at the blunt notch by about 1 mm of fatigue crack growth. The load during the fatigue cycles did not exceed 60% of the subsequent constant load. The specimen was then loaded at a constant load in hydrogen gas at one atmosphere, conditions that are known to cause hydrogen embrittlement of this alloy. After propagation of the crack a distance of the order of 1 mm, the test was stopped and the specimen was sacrificed. After cutting a section of material that included the crack tip and the region ahead of it, the

specimen was mounted in plastic. After grinding to mid-thickness and polishing, the specimen was etched for enhancing the contrast of the stress-induced martensitic phase. Some specimens were tested to failure at a constant rate of elongation (0.02 in/min). In order to preserve the fracture surfaces from damage during grinding, polishing and etching, these specimens received a thick coating of hard nickel from an electroless nickel plating solution.

Results

For two reasons, the principle means of observation was the optical microscope. The scanning electron microscope (SEM) was used, but there was insufficient contrast between the martensitic and matrix phases to be able to distinguish the two. Secondly, the mesh size for the numerical finite element method computation was closer to distances seen at optical microscope resolution than at SEM resolutions. Figure 1 shows the general distribution of martensite ahead of the crack tip. The dark, rough-textured regions in this micrograph are the alpha prime (body-centered cubic crystal structure) martensite phase which was induced by the stress at the crack tip. Typically, this phase is mixed with epsilon phase (hexagonal close packed crystal structure), and the two phases cannot be clearly distinguished at this magnification. The two martensitic phases form roughly simultaneously with the onset of plastic deformation by slip. Figure 2 shows a magnified view of the martensite within the grains of the austenite (face centered cubic crystal structure). In the center of this figure the austenite grain orientation is such that the martensite is clearly seen as individual plate-like regions, however in the surrounding grains the martensite appears only as a general roughening of the surface, due to the fineness of the transformation. Figure 3 includes the crack tip. It can be seen that the crack has propagated in a transgranular mode. This can be seen at higher magnification in figure 4, however in this field of view there is a secondary crack which has begun to propagate in an intergranular mode.

These results have been compared to a more extensive study of this alloy by Gary Schuster as part of his PhD thesis on the effects of martensitic transformation on fatigue crack propagation in hydrogen. It was verified that the general features of the distribution of the martensitic transformation at the crack tip are quite similar in the present and the previous experiments. Considering the spatial resolution of FEM, the photographs of Schuster represent the current situation adequately.

Conclusions

It is concluded that the martensite phase distribution is much too fine to model realistically by the finite element method when far-field stress effects must be included. The mesh size would have to be less than 50 micrometers in order to include the effects of non-uniform distribution of martensite within a single grain. This would lead to unrealistic computation times. A reasonable compromise is to assume that a finite element will be considered to change from the hydrogen diffusivity of the austenite to that of the bcc martensitic phase when the yield stress of the austenite has been reached. This should give a significantly different hydrogen distribution from the case of untransforming austenite and allow the FEM computations to verify or disprove the kinetic model of hydrogen embrittlement of unstable austenitic stainless steels.

Figures

- Figure 1 Phase transformation in AISI 301 stainless steel ahead of a crack propagated in a hydrogen gas atmosphere at 1 atm pressure.
- Figure 2 Stress-induced martensitic transformation of AISI 301.
- Figure 3 Crack tip region. Constant extension rate test of AISI 301 in hydrogen gas.
- Figure 4 View of nickel-plated fracture surface (top).

Figure 1 Phase transformation in AISI 301 stainless steel ahead of a crack propagated in a hydrogen gas atmosphere at 1 atm pressure.

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Figure 4 View of nickel-plated fracture surface (top).