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HYDROGEN AND PLASTIC INSTABILITY IN DEFORMED, SPHEROIDIZED 1090 STEEL

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INTRODUCTION

While hydrogen is known to degrade the fracture properties of steels in several general ways [1], the detailed mechanism of hydrogen embrittlement remains controversial. For example it has been suggested that hydrogen promotes ductile fracture by decreasing the friction stress for dislocation motion [2] but observations show cases where hydrogen either decreases [3] or increases [4, 5] the flow stress of iron. The present work following a suggestion by Rice [6], is a portion of a programme undertaken to study effects of hydrogen charging on the plastic flow and fracture in blunt U-notched bend specimens of various materials. Results are presented which show that hydrogen promotes weak plastic instability [7] in spheroidized AISI 1090 steel. The results are pertinent to the possible role of hydrogen in one mode of ductile fracture of steels, which has been shown [8, 9] to proceed by cracking along planes of plastic instability following characteristic slip lines [8, 10, 11]. Also relevant to the present work, extensive studies of deformation bands in various notched specimens of mild steel were found to agree with the pattern predicted by slip line theory [12].

Earlier studies had shown that hydrogen greatly influences plastic properties such as the yield point [13 - 16], ductility [17 - 19], hardness and strength of steel. Following Rogers [13] discovery of the change in the yield point phenomenon, there have been many investigations of yield point and Lüders band effects in low and medium carbon steels with and without hydrogen charging, including the possibility of complete removal of the yield point [15, 16], but the mechanisms of these effects have not been established.

EXPERIMENTAL PROCEDURE

Hot-rolled, commercial grade AISI 1090 steel bars were austenitized at 750° C for 1.5 hours, held at 705°C for 20 hours, and air cooled to develop spheroidized cementite structures. Three-point slow bend tests and tensile tests were performed at room temperature on an Instron machine at 8.3×10^{-6}m/s and 1.7×10^{-5}m/s crosshead speeds, respectively. For the bend tests 2.38 and 1.19mm diameter U-notches in specimens of 10 x 10 x 55mm were prepared while tensile tests were made on flat and round 6.35mm diameter bars.

Hydrogen was charged electrolytically at a current density of 10^2 A/m^2 for 2.5 hours. The solution used was 1N sulfuric acid with 1g/ℓ of thiourea as a poison. In the case of notched specimens hydrogen was charged through the well-polished notch surface by insulating the rest of surface with non-conductive paint. After optical study of the surface

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deformation pattern, bent specimens were cut longitudinally and ground to remove the disturbed layer. Then specimens were etched with a solution of 30g $CuCl_2$, 30ml H_2O, 35ml HCl and 120ml C_2H_5OH.

RESULTS AND DISCUSSION

Figure 1(a) shows sharp bands of weak plastic instability at the surface of 2.38mm diameter hydrogen-charged notched specimen after loading to 7.35 x 10^3 N. The band pattern follows the prediction of slip line field theory as in the work of Green and Hundy [12]. An abrupt transition to complete plastic deformation of this specimen was detected at 8.33 x 10^3 N. The plastic zone size measured by interference microscopy of the deformation at the notch was slightly larger than the extent of the instability bands. However, as shown in Figure 1(b), the same size notch specimens without hydrogen charging revealed only short and very vague band markings at the same load. The increased load did not change these patterns up to general yielding. The surface strain markings developed after yielding were nearly the same in both types of specimen except that much sharper elastic-plastic boundaries and clearer instability bands were observed in the hydrogen-charged specimens, Figures 2(a) and 2(b). It was noticed that the elastic-plastic boundaries in both specimens follow the same pattern predicted by slip line theory.

Etched free surfaces of specimens loaded to 7.35 x 10^3 N demonstrated the same difference between the charged and uncharged specimens as the unetched surfaces, Figures 3(a) and 3(b), with plastic deformation patterns in the interior sections which were similar but somewhat reduced in extent, Figures 3(c) and 3(d). At a given load, the charged samples exhibited consistently larger plastic zone sizes. The specimens loaded beyond the general yielding, however, showed exactly the same shape of plastic zone in both charged and uncharged specimens. These observations suggested that hydrogen influenced nucleation or propagation, or both nucleation or propagation of instability bands near the free surface. To confirm this postulate tests on charged and uncharged flat tensile specimens were performed. In the charged specimen a Lüders band was formed at a fillet accompanying an initial sharp load drop and this band front advanced slowly until it covered the whole specimen, Figure 4(a). In the charged specimen, however, a new band formed just in front of the first band and then both bands slowly spread until they joined one another. This process continued resulting in numerous bands in the specimen, Figure 4(b). The result indicates that hydrogen mainly influences nucleation of Lüders bands rather than propagation. This role of hydrogen is consistent with the postulates of Spretnak and coworkers [8, 10] that instability bands in general initiate at free surface and suggests a possible similar surface role of hydrogen in ductile fracture.

Studies on round bar tensile specimens showed that the yield strength was lowered and the yield elongation decreased with increased charging time and current density, consistent with the results of Rogers [15] and others [16], but, unlike their work on lower carbon steels, complete removal of the yield point phenomenon was not possible even with more severe charging for 48 hours at a current density of 5 x 10^3 A/m^2. This decrease in yield strength is consistent with the larger plastic zone at a given load in the hydrogen-charged bend specimens.

Easy nucleation of Lüders bands in the hydrogen charged tensile specimens could be attributed to local inhomogenous stress originating from high pressure voids formed on charging. However, scanning electron microscopic examination of specimen charged at 10^2 A/m^2 for 10 hours showed no evidence of void formation in either the bulk or near the surface. More severely charged specimens 1.5 x 10^2 A/m^2 for 10 hours) started to reveal surface blistering and some void formation only at interfaces of metal and slag inclusions near the surface. Those specimens with surface blistering exhibited only minimal instability bands. These results suggested that hydrogen induced voids of detectable size do not contribute to the nucleation of Lüders bands but rather tend to suppress them.

Thus, the overall results support the phenomenological suggestion of Spretnak and coworkers [8, 10] that instability bands are nucleated at the surface and show that hydrogen influences the nucleation. The mechanism by which hydrogen influences this nucleation was not revealed.

At much larger plastic deformation of U-notched specimens, preliminary results show that hydrogen enhanced the formation of deformation induced voids at inclusions, also relevant to the mechanism of ductile fracture and consistent with other observations [20]. These phenomena are being studied further in continuing research.

ACKNOWLEDGEMENT

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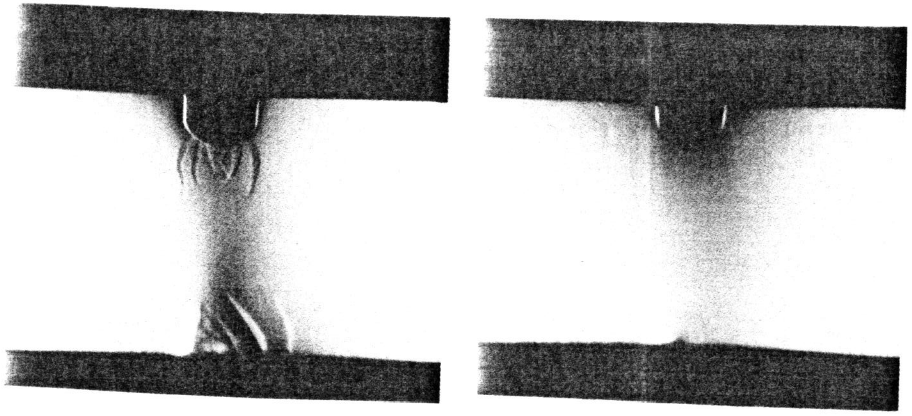
REFERENCES

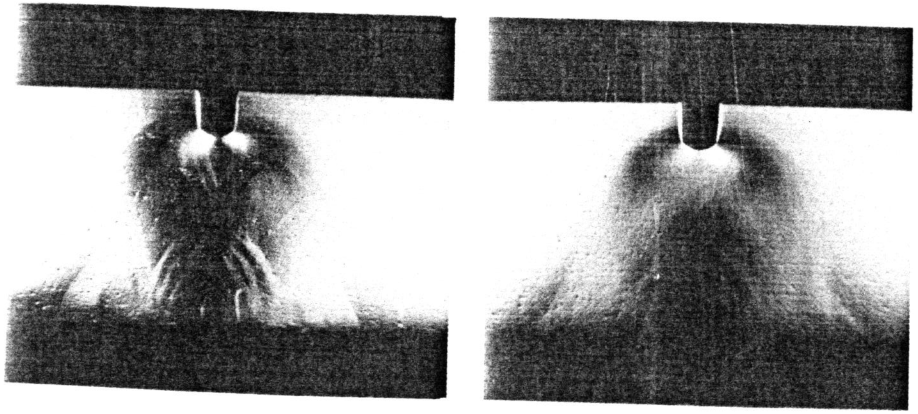
1. HIRTH, J. P. and JOHNSON, H. H., Corrosion, <u>32</u>, 1976, 3.
2. BEACHAM, C. D., Met. Trans., <u>3</u>, 1972, 437.
3. BERNSTEIN, I. M., Scripta Met., <u>8</u>, 1974, 343.
4. LOUTHAN, M. R., Mater. Sci. Eng., <u>10</u>, 1972, 357.
5. WINDLE, R. H. and SMITH, G. C., Met. Sci. J., <u>4</u>, 1970, 136.
6. RICE, J. R., Corrosion, <u>32</u>, 1976, 22.
7. CHAKRABARTI, A. K. and SPRETNAK, J. W., Met. Trans. <u>6A</u>, 1975, 733.
8. GRIFFIS, C. A. and SPRETNAK, J. W., Trans. Iron Steel Inst. Japan, <u>9</u>, 1969, 372.
9. McCLINTOCK, F. A., KAPLAN, S. M. and BERG, C. A., Int. J. Fract. Mech., <u>2</u>, 1966, 615.
10. CHAKRABARTI, A. K. and SPETNAK, J. W., Met. Trans. <u>6A</u>, 1975, 737.
11. COX, T. B. and LOW, J. R., Met. Trans., <u>5</u>, 1974, 1457.
12. GREEN, A. P. and HUNDY, B. B., J. Mech. Phys. Sol., <u>4</u>, 1956, 128.
13. ROGERS, H. C., Acta Met., <u>2</u>, 1954, 167.
14. ADAIR, A. M. and HOOK, R. E., Acta Met. <u>10</u>, 1962, 741.
15. ROGERS, H. C., Acta Met., <u>4</u>, 1956, 114.
16. CRACKNELL, A. and PETCH, N. J., Acta Met., <u>3</u>, 1955, 200.
17. HOUDREMONT, E. and SCHRADIER, H., Arch. Eisenhüttenw., <u>15</u>, 1941, 87.
18. SIMS, C. E., MOORE, G. A. and WILLIAMS, D. C., Trans. AIME, <u>176</u>, 1948, 283.
19. GARBER, R., BERNSTEIN, I. M. and THOMPSON, A. W., Scripta Met. <u>10</u>, 1976, 341.
20. THOMPSON, A. W., Mater. Sci. Eng., <u>14</u>, 1974, 253.



(a) (b)

Figure 1 Surface Instability Bands of 2.38 mm diameter U-notched Specimens Loaded to 7.35 x 10^3 Newton by Slow Bending 4.5X

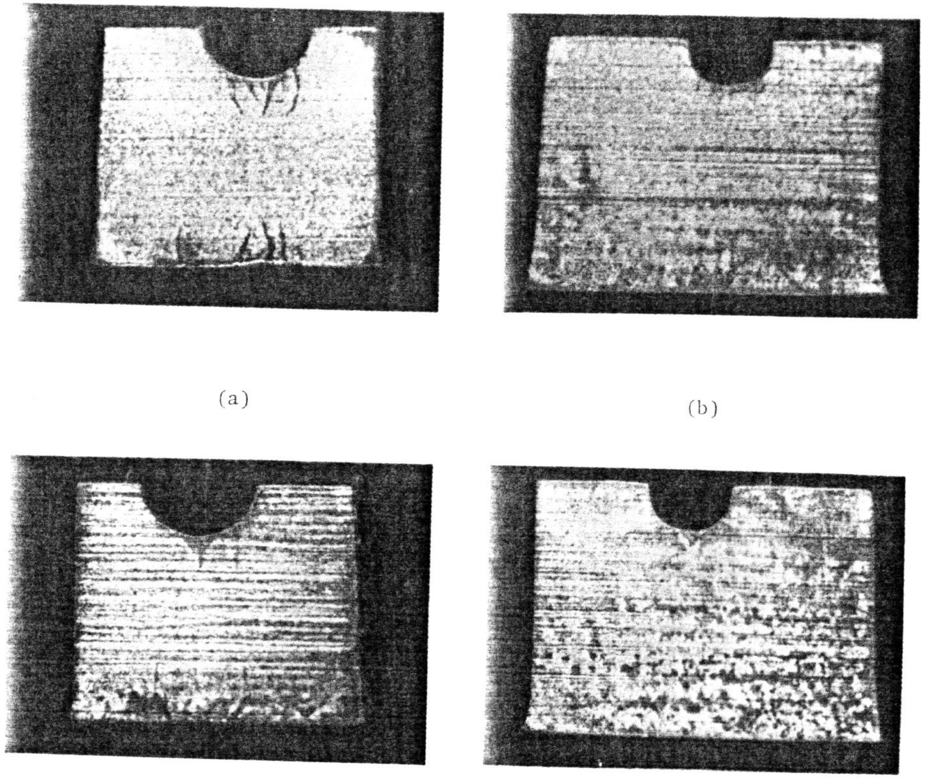
(a) Hydrogen-Charged Specimen
(b) Uncharged Specimen



(a) (b)

Figure 2 Surface Instability Bands of 1.19 mm diameter U-notched Specimens Loaded to 1.08 x 10^4 Newton by Slow Bending 4.5X

(a) Hydrogen-Charged Specimen
(b) Uncharged Specimen



(a) (b) (c) (d)

Figure 3 Instability Bands of 2.38 mm diameter U-notched Specimens Loaded to 7.35 x 10^3 Newton by Slow Bending Followed by Etching 4.5X

(a) Surface of Hydrogen-Charged Specimen
(b) Surface of Uncharged Specimen
(c) Hydrogen-Charged Specimen, Sectioned 3 mm from Surface
(d) Uncharged Specimen, Sectioned 3 mm from Surface

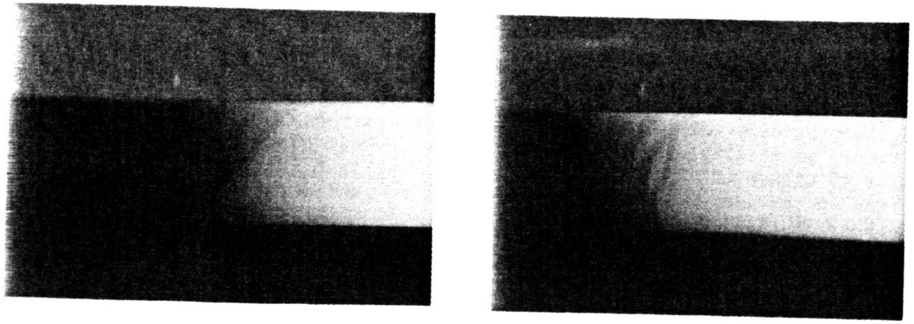

(a) (b)

Figure 4 Lüders Bands in Flat Tensile Specimens 5X

(a) Uncharged Specimen
(b) Hydrogen-Charged Specimen