JMEPEG (1998) 7:100-103

In Situ Investigation of the Effect of Hydrogen on the Plastic Deformation Ahead of the Crack Tip and the Crack Propagation for 0.15C-1.5Mn-0.17V-0.012N Steel

B. Liao, Y. Nan, Y. Hu, and D.T. Kang

(Submitted 14 June 1997; in revised form 2 September 1997)

The influence of hydrogen on the deformation ahead of the crack tip and the crack propagation were observed and studied in situ under transmission electron microscopy with dynamic tensile deformation for bridge steel. The results show that hydrogen can promote local plastic deformation ahead of the crack tip and change the mode of crack propagation so that the crack will propagate in a zigzag path.

Keywords crack growth, hydrogen, steel, type III crack

1. Introduction

The toughness-embrittlement transformation and fracture of materials is a complex dynamic microprocess, especially if hydrogen is present in the material. For the fracture process, plastic deformation ahead of the crack tip is a main factor (Ref 1-3), and the propagation behavior of the crack is the important failure form (Ref 4, 5). In the present work, the effect of the dissolved hydrogen in the materials on the behavior of plastic deformation and the crack propagation ahead of the crack tip was studied by means of in situ transmission electron microscopy (TEM).

2. Experimental Procedure

The test material was 0.15C-1.5Mn-0.17V-0.012N bridge steel. The specimens were made by rolling to a thickness of 50 μm. They were then heat treated in a manner similar to the treatment of the original bulk material (austenitized at 950 °C for 4 h followed by air cooling, then stress relieved at 650 °C for 4 h). The original material had a fine pearlite microstructure. Annealed thin film specimens were thinned by hand, followed by jet polishing using a solution of perchloric acid and acetic acid (1:10) at room temperature until a hole formed in the middle of the tensile specimens (specimens were 3 by 6 mm). The specimens were divided into two groups: those in the original condition (hydrogen content equal to 0.8 ppm) and those with hydrogen content equal to 5.0 ppm. In situ tensile testing and microstructure observation were carried out with Philips EM420 TEM. The strain rate of the slow tensile test was $\dot{\varepsilon} = 3 \times 10^{-5} s^{-1}$.

B. Liao, Y. Nan, Y. Hu, and **D.T. Kang,** Institute of Materials Engineering, Yanshan University, Qinhuangdao 066004, China.

3. Results and Discussion

3.1 *Analysis of the Dislocation Condition Ahead of the Crack Tip*

In the stress field of a type III crack, the crack force ($d\mathbf{F}_1$) for the unit screw dislocation length ($d\mathbf{L}$) is (Ref 3):

$$d\mathbf{F}_1 = (\sigma \cdot \mathbf{b}) \times d\mathbf{L} \qquad \text{(Eq 1)}$$

where σ is the applied stress and **b** is Burger's vector.

The stress tensor of a type III crack tip is:

$$\sigma = \begin{vmatrix} 0 & 0 & \sigma_{xz\vec{i}\vec{k}} \\ 0 & 0 & \sigma_{yz\vec{j}\vec{k}} \\ \sigma_{zx\vec{k}\vec{i}} & \sigma_{zy\vec{k}\vec{j}} & 0 \end{vmatrix} \qquad \text{(Eq 2)}$$

where

$$\sigma_{xz} = \sigma_{zx} = K_{III}(2\pi r)^{-1/2} \cdot \cos\theta/2$$
$$\sigma_{yz} = \sigma_{zy} = K_{III}(2\pi r)^{-1/2} \cdot \sin\theta/2 \qquad \text{(Eq 3)}$$

and r is the radial length of the crack tip.

For the screw dislocation emitted from a type III crack tip, then:

$$\mathbf{b} = (0 \;\; 0 \;\; b_z k) \qquad \text{(Eq 4)}$$

$$d\mathbf{L} = (0 \;\; 0 \;\; dL_z k) \qquad \text{(Eq 5)}$$

Now introducing Eq 2 to 5 into Eq 1, the crack driving force to emit the screw dislocation in the stress field of type III crack tip is obtained:

$$\mathbf{F}_1 = \mathbf{b}\sigma_{yz} \cdot \mathbf{i} - \mathbf{b}\sigma_{xz} \cdot \mathbf{j} \qquad \text{(Eq 6)}$$

The driving force $\mathbf{F}_1$ can be written in the following form using the polar coordinate:

$$\mathbf{F}_{r1} = K_{III}(2\pi r)^{-1/2} \cos\theta/2 \cdot (\mathbf{r})$$
$$\mathbf{F}_{\theta 1} = K_{III}(2\pi r)^{-1/2} \sin\theta/2 \cdot (\theta) \quad \text{(Eq 7)}$$

The crack force $\mathbf{F}_1$ for the unit length screw dislocation in the stress field of a type III crack tip is the driving force to emit the dislocation.

The attracting force of the crack interface also affects the dislocations emitted because the dislocations close to the crack surface are freed. This attracting force, as image force, is $\mathbf{F}_2$.

$$\mathbf{F}_2 = -\mu\mathbf{b}/4\pi r \quad \text{(Eq 8)}$$

The blunting of the crack tip is achieved by emitting dislocations and this leads to the surface free energy increase. The change of energy produces a force for the dislocations emission at the crack tip, $\mathbf{F}_3$:

$$\mathbf{F}_3 = -2\gamma\alpha \sin\theta/\pi(r^2 + \alpha^2) \quad \text{(Eq 9)}$$

where $\alpha = r_0 e^{3/2}$, r_0 is the half width of the dislocation core, and γ is the surface free energy of the crack tip. When the type III crack tip emits the dislocations, the dislocations are in an identical plane with the crack tip; therefore, all the forces acting on the dislocations can be described:

$$\mathbf{F}_1 = K_{III}\mathbf{b} \cdot (2\pi r)^{-1/2} \cdot \cos\theta/2$$
$$\mathbf{F}_2 = -\mu\mathbf{b}/4\pi r$$
$$\mathbf{F}_3 = 0 \quad \text{(Eq 10)}$$

When dissolved hydrogen exists in steel, hydrogen atoms react with the screw dislocations emitted from the crack tip, leading to a new force, $\mathbf{F}_4$:

$$\mathbf{F_4} = N \cdot dW/dr \quad \text{(Eq 11)}$$

where N is the number of hydrogen atoms carried by the emitted dislocation (Ref 6) and W is the elastic action energy between the shear strain field of the type III crack and the hydrogen atom strain field of nonspherical symmetry:

$$W = K_{III} \frac{\alpha^3}{4} \frac{\varepsilon_{33}}{\sqrt{2\pi r}} \cos\frac{\theta}{2} \quad \text{(Eq 12)}$$

Therefore:

$$\mathbf{F}_4 = -B \cdot K_{III} \cdot (2\pi)^{-1/2} r^{-3/2} \quad \text{(Eq 13)}$$

where

$$B = (N \cdot a^3 \cdot \varepsilon_{33} \cdot \cos\theta/2)/8$$

Obviously, hydrogen atoms can produce the additional attractive force for the screw dislocation emitted. The more hydrogen atoms carried by the dislocation, the greater $\mathbf{F}_4$ is.

In the common condition (no hydrogen), the critical stress strength factor (K_{IIIe}) for emitting dislocations from the crack tip and the length of the dislocation-free zone (DFZ) ahead of the crack tip can be represented as:

$$K_{IIIe} = \frac{\mu b}{\sqrt{8\pi r_0}} + \sqrt{2\pi r_0}\,\sigma_f \quad \text{(Eq 14)}$$

$$X_{DFZ} = K^2_{IIIe}/(\sqrt{8\pi}\,\sigma_f)^2 \quad \text{(Eq 15)}$$

where σ_f is the lattice resistance to the dislocation movement.

According to Eq 13 and 14, K_{IIIe} and σ_f not only possess a strict relationship, but also affect the plastic deformation of the crack tip by combining action. Without hydrogen:

$$\sigma_f = \mathbf{F}_1 + \mathbf{F}_2 = K_{III}(2\pi r)^{-1/2} - \mu b(4\pi r)^{-1} \quad \text{(Eq 16)}$$

With hydrogen:

$$\sigma_{f,H} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_4 = K_{III}(2\pi r)^{-1/2} - \mu b(4\pi r)^{-1} - K_{III}(2\pi)^{-1/2} r^{-3/2} \mathrm{B} \quad \text{(Eq 17)}$$

Therefore:

$$\sigma_f > \sigma_{f,H} \quad \text{(Eq 18)}$$

$$K_{IIIe} > K_{IIIe,H} \quad \text{(Eq 19)}$$

3.2 *Observation and Analysis*

3.2.1 Effects of Hydrogen on Emission of Dislocations and Plastic Deformation Ahead of the Crack Tip

When a film sample was loaded with tension, the crack was initiated at the edge of the center thinner area, with the crack growing into the thicker part of the sample. A plastic deformation zone (PDZ) was formed ahead of the crack tip, along the direction of the crack propagation. There was a DFZ in the PDZ on the side of the crack tip, then a submicrostructure of pile-up of dislocations caused by the emission of the dislocations from

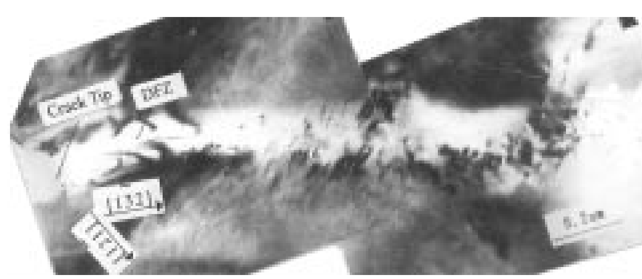

Fig. 1 The microstructure of the plastic zone ahead of the crack tip for the sample without hydrogen

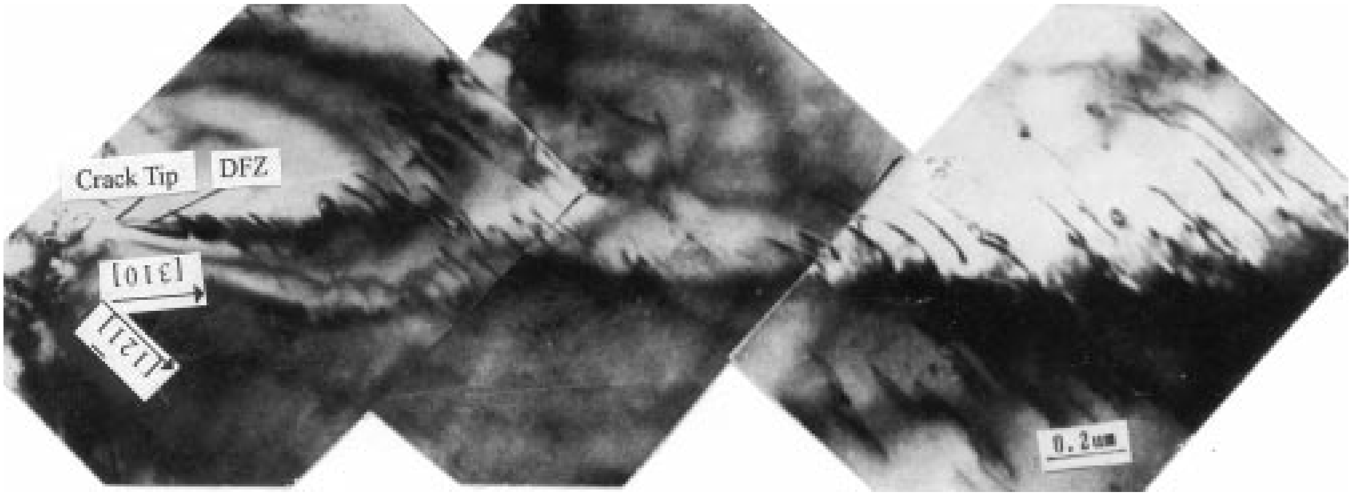

Fig. 2 The microstructure of the plastic zone ahead of the crack tip for the sample with hydrogen

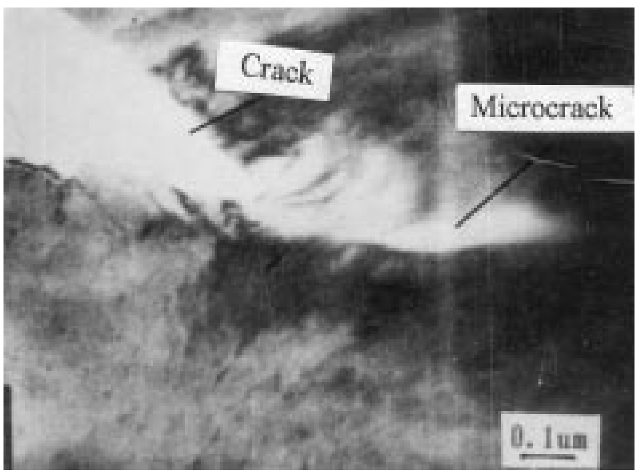

Fig. 3 The microcrack formed during the tensile test for the sample with hydrogen

the crack tip. The dislocations became arranged regularly and were higher density near the DFZ.

The microstructure of the crack tip for a sample without hydrogen charged is the common micrograph. The length of the PDZ is about 1400 nm and that of the DFZ is about 340 mm (Fig. 1).

In the case of a dead load, the tip still emitted dislocations for a period of time; then a relative equilibrium was reached. When the load was increased, with the crack propagation, the crack tip emitted the dislocations again and the dislocations moved forward continuously, resulting in movement of the PDZ.

For the samples with hydrogen charged, both the PDZ and the submicrostructure changed. The rate of dislocation emission at the crack tip accelerated obviously and the dislocations moved into the PDZ rapidly so that the size of the DFZ ahead of the crack tip was reduced to about 160 nm. However, the phenomenon of DFZ disappearance reported by Robertson (Ref 7) was not observed during our experiment. The PDZ turned narrower and longer, with a length about 3 μm. The dislocation's density in the center of the PDZ was lower than that on the two sides of the PDZ, and cross sliding occurred on one side of the PDZ far away from the crack tip (Fig. 2).

For samples without hydrogen charged, during the process of crack propagation, the piled-up dislocations moved forward, overcoming both the lattice friction σ_f (Ref 1) and the effect shield (Ref 8, 9), which limited movement to only a short distance. Addition of the discontinuous blunting effect of the crack tip resulted in reduction of the PDZ but with higher dislocation density that coincided with the microplastic deformation state at the crack tip during cracking for low-alloy steels with medium strength.

After hydrogen charging, when dissolved hydrogen segregated at a crack tip, the σ_f was reduced effectively (Ref 10) (as seen in Eq 17) and mobility of the screw dislocation was promoted at the same time, which caused the dislocation movement in a way of crossing slip (Ref 11). Then the resistance was smaller, causing a narrower and longer shape of PDZ ahead of the crack tip (Ref 1). Dissolved hydrogen promoted the movement of screw dislocations and plastic deformation of a crack tip; however, it brought about a strong localized tendency for plastic deformation, concentrating the plastic deformation ahead of the crack tip within a narrower area. This phenomenon indicated that the existence of hydrogen decreased the stress required for plastic deformation and promoted localized plastic deformation. Compared with the condition without hydrogen charged, the longer and narrower microplastic deformation state appeared to have a brittle fracture character macroscopically.

3.2.2 Effect of Hydrogen on Mode of Crack Propagation

Under tension, the crack in the film sample without hydrogen charged propagated in a discontinuous way, propagating a little, blunting the crack tip, then propagating again. The crack grew straighter along the direction normal to the main stresses until critical fracture. During the propagation of the crack, when the plastic deformation reached a certain level (a certain amount of dislocations ahead of the crack tip were piled up), the crack propagation was resisted, together with the effect of the dislocation emission. The crack tip was blunt and the crack growth would stop. The continuous loading supported a force

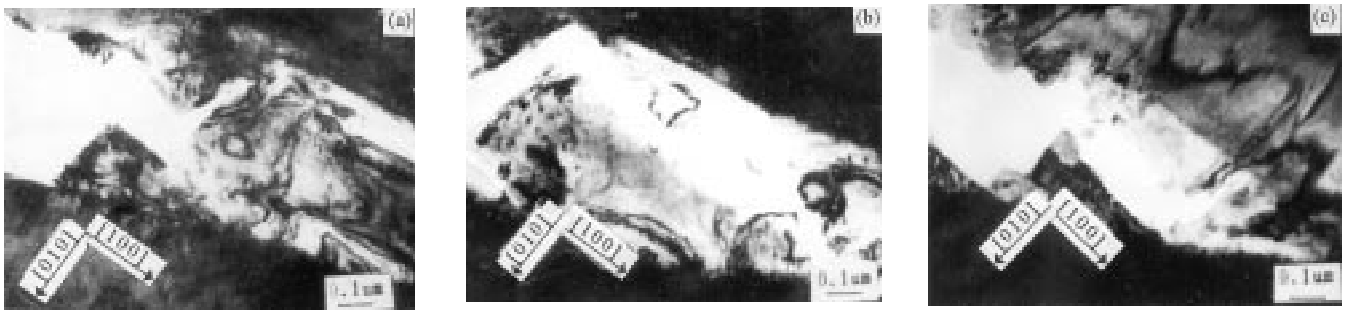

Fig. 4 The zigzag crack propagation for the sample with hydrogen. (a) 10 s. (b) 20 s. (c) 35 s

for the moving of the piled-up dislocation and the propagating of the crack, starting a new process of crack growth. The growth path of the crack can be seen in Fig. 2.

For the film samples with hydrogen charging, the microstructure state ahead of a crack tip would change due to the existence of the dissolved hydrogen, which caused the brittleness of the steel and influenced the growth process of the crack. The plastic deformation was resisted in front of a crack in the film propagated to a certain degree. Increasing load promoted the crack growth; however, it was different for the sample without hydrogen charged. The microcracks were initiated at a higher dislocation density area near the DFZ in the PDZ. The initial microcracks were at 45° and along the direction of main stress (seen in Fig. 3). With the growth of the microcracks, they also propagated when the main crack grew under loading. The main crack would meet these microcracks at a certain angle, which changed the crack growth direction, resulting in a "zigzag" shape until final fracture. It was a continuous crack growth process, as shown in Fig. 4.

4. Conclusions

- The existence of dissolved hydrogen in 0.15C-1.5Mn-0.17V-0.012N steel decreases the critical stress field strength factor (K_{IIIe}) effectively for the dislocation emission and reduces the lattice friction (σ_f) for dislocation movement and critical stress for the plastic deformation at the crack tip.
- Dissolved hydrogen can reduce the size of the DFZ and increase the size of the PDZ ahead of the crack tip. However, it causes a localized tendency for plastic deformation.
- Dissolved hydrogen promotes the initiation of microcracks in the PDZ, which affects the crack growth process in the steel. The microcracks in the PDZ grow and intersect with the main crack, resulting in a zigzag growth of the main crack.

References

1. S.M. Ohr, An Electron Microscope Study of Crack Tip Deformation and Its Impact on the Dislocation Theory of Fracture, *Mater. Sci. Eng.*, Vol 72, 1985, p 1
2. K.F. Yao, Q.Y. Tang, and N.P. Chen, TEM Observation on the Deformation Band of the Crack Tip Localization, *Acta Metall. Sinica*, Vol A27, 1991, p 395
3. J.R. Rice, Ductile versus Brittle Behavior of Crystals, *Philos. Mag.*, Vol 29, 1974, p 73
4. S.M. Ohr, Electron Microscope Study of Dislocation Emission from Cracks, *Scr. Metall.*, Vol 20, 1986, p 151
5. H.E. Hanninen, T.C. Lee, I.M. Robertson, and H.K. Birnbaum, In-situ Observation on Effects of Hydrogen on Deformation and Fracture of A533B Pressure Vessel Steel, *J. Mater. Eng. Perform.*, Vol 2, 1993, p 806
6. J.P. Hirth and B. Caranahan, *Acta Metall.*, Vol 26, 1978, p 1795
7. I.M. Robertson and H.K. Birnbaum, *Acta Metall.*, Vol 34, 1986, p 353
8. R. Thompson, Dislocation Crack Interactions, *Scr. Metall.*, Vol 29, 1986, p 1473
9. I.H. Lin and R. Thompson, Cleavage, Dislocation Emission and Shielding for Crack under General Loading, *Acta Metall.*, Vol 34, 1986, p 187
10. B. Liao, D.T. Kang, T.Q. Lei, and S.J. Song, *Chin. J. Mech. Eng.*, Vol 30, 1994, p 50
11. H. Kimura and H. Matsui, Mechanism of Hydrogen Induced Softening and Hardening in Iron, *Scr. Metall.*, Vol 21, 1987, p 319