NUCLEATION MECHANISM OF STRESS CORROSION CRACKING FROM NOTCHES

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Crack nucleation mechanism of hydrogen assisted cracking at notched cracks in aqueous solutions is investigated, using the compact type specimens with various notch radius in low-tempered 4340 steel. A detached crack initiates at some distance ahead of the notch root. The crack nucleation at the notched root is determined by the electrical potential method. When the crack initiates, the voltage difference starts to increase. The crack nucleation site is examined by SEM. The time for crack nucleation increases with the notch root radius, ρ, and decreases with the apparent stress intensity factor K_ρ. A linear relationship between the crack nucleation time, t_n, and the parameter $\{2K_\rho/(\pi\rho)^{1/2}-(2K_\rho/(\pi\rho)^{1/2})_{th}\}$ is seen in semi-log diagram, where $(2K_\rho/(\pi\rho)^{1/2})_{th}$ is almost equal to the yield shear strength.

In order to explain these experimental results, a new model of micromechanics is proposed on the basis of stress induced diffusion of hydrogen in the high stress region ahead of the notch root. This model suggests that the detached crack initiates at the elasto-plastic boundary where the hydrogen concentration is from 2 to 5 times higher than that of the notch root surface. The theory agrees with experiments with respect to $\{2K_\rho/(\pi\rho)^{1/2}-(2K_\rho/(\pi\rho)^{1/2})_{th}\}$ vs t_n and t_n vs ρ.

MODEL FOR THE NUCLEATION OF HYDROGEN ASSISTED CRACKING

Hydrogen assisted cracking is closely related to the hydrogen diffusion under the hydrostatic stress condition. To similate the plastic region ahead of a crack tip or a notch root, a dislocation array is considered as shown in Fig. 1.

The hydrostatic pressure, p, for the plain strain is defined by

$$p = -\frac{1}{3}(\sigma_{xx}^D+\sigma_{yy}^D+\sigma_{zz}^D)$$
$$= -\frac{1}{3}(1+\nu)(\sigma_{xx}^D+\sigma_{yy}^D) \quad (1)$$

where ν is the Poisson's ratio and σ_{xx}^D, σ_{yy}^D and $\sigma_{zz}^D=\nu(\sigma_{xx}^D+\sigma_{yy}^D)$ are the principle stress. The stress σ_{xx}^D, σ_{yy}^D and σ_{zz}^D are calculated from the dislocation stress. The dislocation distribution is obtained from the condition that the sum of the shear stress, τ, due to the applied stress and the shear stress due to the dislocations equals to the dislocation motion resistance, k. The dislocation distribution is assumed to be one shown in Fig. 1. For the mathematical simplicity, imaginary dislocations with the opposite sign are assumed in the left side of the notch root, so that the stress condition at the free surface is simulated by that of the center of the distribution. The stress components along the dislocation array are obtained as

$$\sigma_{xx}^D = \frac{2(\tau-k)x}{(a^2-x^2)^{1/2}} \quad (2)$$

$$\sigma_{yy}^D = 0 \quad (3)$$

$$\sigma_{zz}^D = \frac{2\nu(\tau-k)x}{(a^2-x^2)^{1/2}} \quad (4)$$

where a is the dislocation pile up distance. The hydrostatic pressure along the array becomes

$$p = -\frac{2}{3}(1+\nu)(\tau-k)\frac{x}{(a^2-x^2)^{1/2}}\,. \quad (5)$$

The dotted curve in Fig. 2 presents the distribution of −p.

HYDROGEN DIFFUSION CONSIDERATION

The mechano-chemical mechanism of stress corrosion cracking is explained from the fact that hydrogen atoms are generated by the corrosion reaction at the notch root and are absorbed in the material by diffusion. The hydrogen content reaches a saturated value c_1 at the tip of the dislocation array and the saturated region extends to a region of width, d, as shown in Fig. 2. It is assumed that the total number of accumulated hydrogen atoms reaches a critical value, then the saturated region becomes an initial crack. The hydrogen diffusion equation is given by Fick's law as

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} + \frac{AD}{k_b T}\frac{\partial}{\partial x}\left(c\frac{\partial p}{\partial x}\right) \qquad (6)$$

where k_b is the Boltzman constant, A is the interaction constant between the dislocation and a solute atom, T is the absolute temperature and D is the diffusion coefficient. For mathematical simplicity, the above differential equation is solved with the boundary and initial conditions,

$$c(0,t) = c_0 \quad \text{at } x=0 \qquad (7)$$

$$c(b,t) = 0 \quad \text{at } b=0 \qquad (8)$$

$$c(x,0) = 0 \quad \text{at } t=0 \qquad (9)$$

Although b is a function of t and b=0 at t=0, we assume that b is independent of t because of its mathematical difficulty.

The total accumulation of hydrogen atoms, I, that has flowed into the saturated region, d, is calculated as

$$I(b,t) = -D\int_0^t (\partial c/\partial x)_{x=b}\,dt$$

$$= \frac{2c_0 D}{b}\sum_{n=1}^{\infty}(-1)^n\left[-t+\frac{2b^2}{n^2\pi^2 D}\{1-\exp(-n^2\pi^2 Dt/b^2)\}\right] \qquad (10)$$

$$\exp\left[\frac{1}{2}(1+\nu)(\tau-k)\frac{A}{k_b T}\frac{b/a}{\{1-(b/a)^2\}^{\frac{1}{2}}}\right]$$

On the other hand, the accumulation of hydrogen atoms is equal to $c_1 d$. Our criterion for crack initiation is that a crack initiates along the dislocation array when the total number of accumulated hydrogen atoms reaches a critical value. It is assumed that a microcrack with length d initiates along the dislocation array when the total number of accumulated hydrogen atoms reaches a critical value, which is $c_1 d$ as shown in Fig. 2. Therefore, we have an equation

$$I(b,t) = c_1 d = c_1(a-b) \qquad (11)$$

which is used for evaluation of crack nucleation time, t_n.

After numerical calculation, it is found that Eq. (10) is sufficiently approximated by the simple expression,

$$I(b,t) = \frac{c_0 D}{b}\, t \exp\left[\frac{1}{2}(1+\nu)(\tau-k)\frac{A}{k_b T}\frac{b/a}{\{1-(b/a)^2\}^{\frac{1}{2}}}\right] \qquad (12)$$

EXPERIMENTAL RESULTS AND DISCUSSIONS

In Fig. 3 is shown the relation between the time to crack nucleation, t_n, and the apparent stress intensity factor, K_ρ, with a parameter of notch radius, ρ, for 200°C tempered 4340 steels. It is clear that the crack nucleation time, t_n, increases with the notch radius. The figure also shows that these are threshold (apparent) stress intensity factors, $(K_\rho)_{th}$, below which no crack nucleation occurs.

Barsam et al examined the effect of notch radius on fatigue crack nucleation for high strength steel and suggested that crack nucleation lifes in notched specimens can be regulated by parameter $2K_\rho/(\pi\rho)^{\frac{1}{2}}$. The parameter, $2K_\rho/(\pi\rho)^{\frac{1}{2}}$ is maximum stress at the notch tip, σ_{max},

$$\sigma_{max} = 2K_\rho/(\pi\rho)^{\frac{1}{2}} \qquad (13)$$

In order to correlate t_n with $2K_\rho/(\pi\rho)^{\frac{1}{2}}$, we put in Eq. (12)

$$\tau = 2K_\rho/(\pi\rho)^{\frac{1}{2}} \qquad (14)$$

$$k = (2K_\rho/(\pi\rho)^{\frac{1}{2}})_{th} \qquad (15)$$

Then, Eq. (11) leads to

$$\Delta\tau \equiv \frac{2K_\rho}{(\pi\rho)^{\frac{1}{2}}} - \left(\frac{2K_\rho}{(\pi\rho)^{\frac{1}{2}}}\right)_{th} = \frac{6.9k_b T}{(1+\nu)A}\frac{\{1-(b/a)^2\}^{\frac{1}{2}}}{b/a}\left[\log c_1/c_0 + \log(1-b/a) - \log\frac{D}{a\,b}t_n\right] \qquad (16)$$

The experimental data in Fig. 3 are replotted in Fig. 4 to see the relation between $\{2K_\rho/(\pi\rho)^{\frac{1}{2}} - (2K_\rho/(\pi\rho)^{\frac{1}{2}})_{th}\}$ and log t_n, where $(2K_\rho/(\pi\rho)^{\frac{1}{2}})_{th}$ is taken as the mean value of $(2K_\rho/(\pi\rho)^{\frac{1}{2}})$ at $t_n = \infty$ in Fig. 3. This mean value becomes 745 MPa which is almost half of σ_y. This fact justifies the assumption (15) since $k = \sigma_y/2$. Equation (16) predicts that long t_n is a linear function of $\Delta\tau$ as observed experimentally. The slope of the relation agrees with experiments when we take b/a = 0.94 and A/k_bT = 1225 MPa. The last value of A/k_bT is taken from Gerberich's paper, where A/k_bT corresponds to V*/RT in his paper. The positions of these straight lines depend on values of D,c_1/c_0 and ab. When D is taken as 2×10^{-5} mm²/sec from Gerberich et al works,c_1/c_0=2.8 and a≈b≈0.15 mm,Eq (16) provides the solid straight line in Fig. 4. These values of b and c_1/c_0 seem reasonable in view of the other researchers' evaluation.

In the present model the value of c_1/c_0 = 2~5 is adopted. These values are comparable with the value obtained by VanLeenwen, who investigated notched 4340 with 1372 MPa yield strength level under various initial hydrogen concentrations. Gerberich et al proposed that the value of c_1/c_0 is inversely proportional to the yield strength. They obtained 2~5 for 4340 steel under various conditions; the cathodically charged conditions and the aqueous solution conditions. They also indicated that the value of c_1/c_0 will be in the range 10~100 under the hydrogen gas pressure conditions.

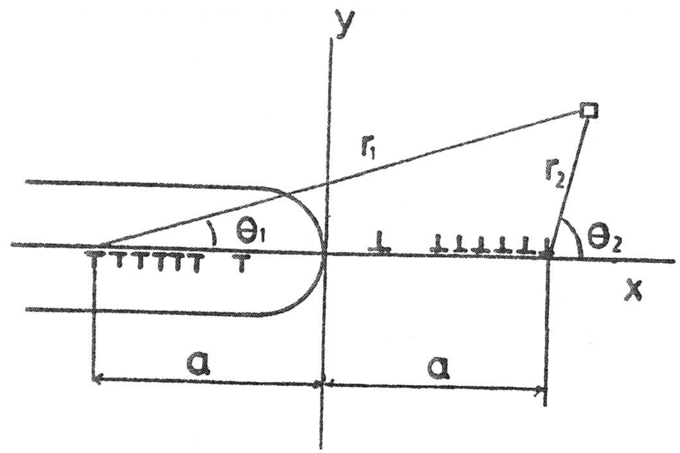

Fig.1

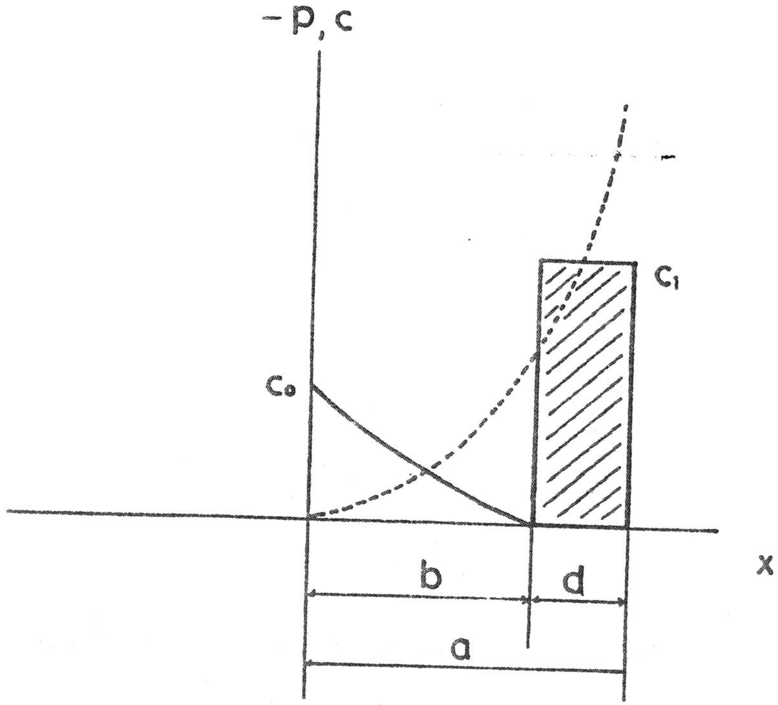

Fig.2

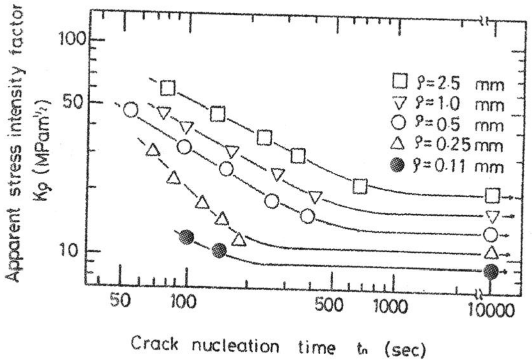

Fig. 3

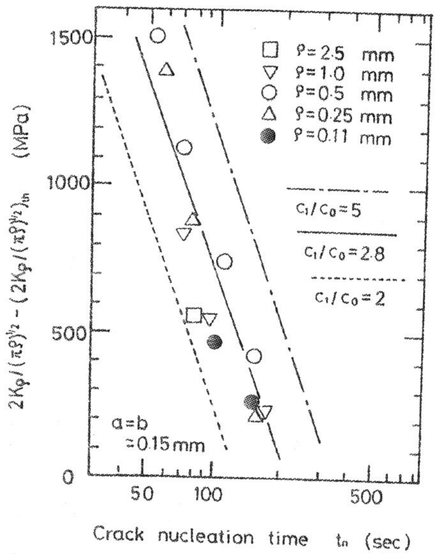

Fig. 4 Relation between crack nucleation time and $(2K\rho/(\pi\rho)^{\frac{1}{2}}-(2K\rho/(\pi\rho)^{\frac{1}{2}})_{th})$