NUMERICAL ANALYSIS OF HYDROGEN DIFFUSION AROUND THE NOTCH UNDER CYCLIC LOADING WITH AN OVERLOAD

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Abstract

Hydrogen embrittlement is known to be induced by a local increase in hydrogen concentration in materials. Therefore, it is important to elucidate the mechanism of hydrogen concentration behavior, which is the cause of hydrogen embrittlement, to prevent hydrogen embrittlement. One of authors proposed a numerical analysis method that couples stress analysis using the finite element method and hydrogen diffusion analysis using the finite difference method. This analysis has clarified that there is the effect of loading waveforms on hydrogen concentration behavior. In this study, hydrogen diffusion concentration behavior analysis under fatigue conditions with an overload was performed, and it was shown that hydrogen concentration may be enhanced by an overload.

1. Introduction

Since hydrogen diffusion in materials is non-stationary, it is difficult to observe experimentally. Therefore, many studies have been conducted to predict hydrogen concentration and distribution by numerical analysis. It is important to consider the effect of hydrostatic stress because hydrogen in a material diffuses and accumulates due to the diffusion driving force caused by hydrostatic stress gradient. Furthermore, it is also important to consider the plastic deformation history under fatigue conditions because this maximum hydrostatic stress exists at the elastic-plastic boundary. In the case of an overloading history, work hardening may result in a small yield zone, which is expected to increase the hydrostatic stress gradient and promote hydrogen accumulation. In this study, the hydrogen diffusion behavior around a notch tip was numerically analyzed under fatigue conditions with an overloading history.

2. Basic equation and model of analysis

The basic equation of hydrogen diffusion is written by Eq. 1 taking account for the term of stress induced diffusion.

$$\frac{\partial C}{\partial t} = D\nabla\left(\nabla C - \alpha\frac{C\Delta V}{RT}\nabla\sigma_p\right) \qquad (1),$$

where C is hydrogen concentration, D is diffusion constant, R is universal gas constant, T is absolute temperature, t is time, ΔV is volume change when hydrogen enters the interstitial lattice space, σ_p is hydrostatic stress. α is the multiplication parameter of stress gradient term which related to the interaction factor shown in the general formulation of transportation theory. The physical model of the analysis is shown in Fig. 1. The boundary conditions for the hydrogen diffusion analysis are shown in Fig. 2. Hydrogen diffusion analysis around a notch tip was performed in polar coordinate form. The elastic-plastic finite element method was used for stress analysis, and cyclic loading of 9 cycles was applied. The analytical model of the finite element method is shown in Fig. 3. The stress ratio is R=0. Von Mises yield criterion is adopted as the yield condition of each element. The characteristic of work hardening during the plastic deformation is approximated by Eq. 2.

$$\bar{\sigma} = H\left(a + \bar{\varepsilon}_p\right)^n \qquad (2),$$

where H is work hardening factor, a and n are constants, $\bar{\sigma}$ is equivalent stress, $\bar{\varepsilon}_p$ is equivalent plastic strain. The overload was applied in the 5th cycle. The value of the overload was 1 to 1.5 times the applied fatigue load, and this magnitude was defined as OL. 6 analyses with OL = 1.0~1.5 were compared to see if the maximum hydrogen concentration increased. Under cyclic conditions, the notch tip is under compressive stress during unloading and work hardening progresses. Therefore, the effect of OL is assumed to be different for each material. In this study, analyses were performed under various Young's modulus E and work hardening factor H conditions to check the increase in hydrogen concentration.

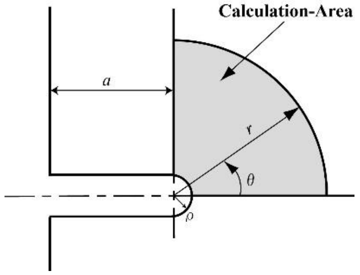

Fig.1 A model of analysis of hydrogen diffusion by FDM analysis

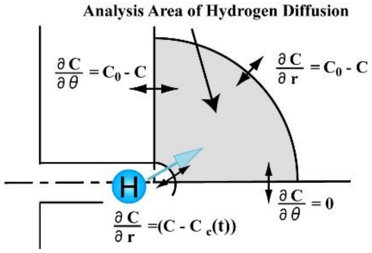

Fig.2 Boundary conditions of hydrogen diffusion by FDM analysis

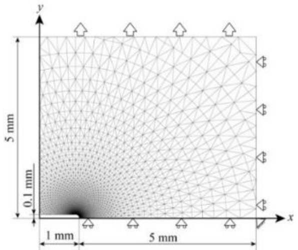

Fig.3 FEM model

3. Results

The hydrogen concentration distribution for the fifth cycle when an excessive load is added is shown in Fig. 4. The result is a one-dimensional hydrogen concentration distribution in a notch extension direction. The maximum hydrogen concentration is almost four times higher when an overload of 1.5 times the fatigue load is applied ($OL = 1.5$) than when no overload is applied ($OL = 1.0$). Under this analytical condition, the higher an overload, the higher the maximum hydrogen concentration. A similar analysis was conducted under several conditions, and the conditions under which the hydrogen concentration increased are shown in Fig. 5. The results suggest the existence of conditions under which hydrogen concentration increases due to overloading, i.e., conditions under which hydrogen accumulation is promoted.

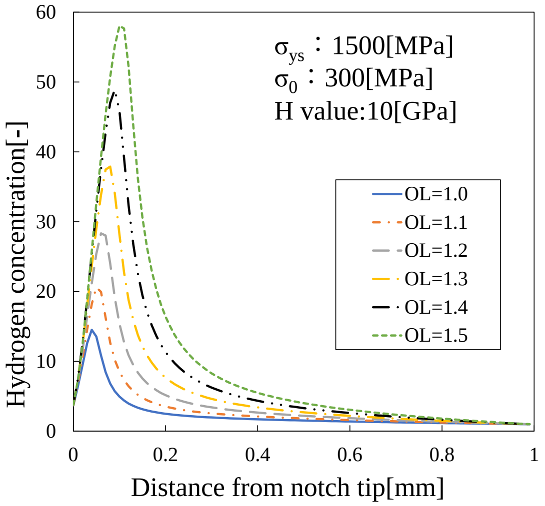

Fig.4 Distribution of hydrogen concentration along the θ=0 rad. from a notch tip

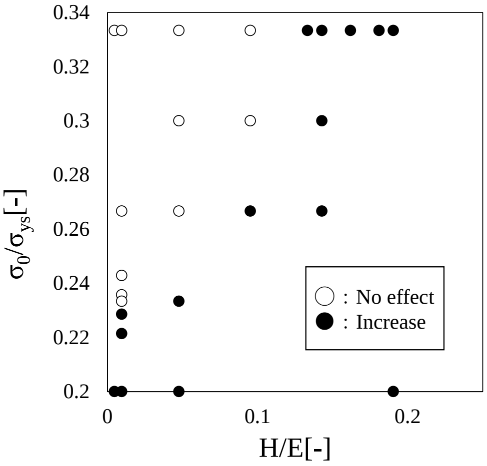

Fig.5 Mapping of overload effect on maximum hydrogen concentration

4. Conclusions

In this study, numerical analysis indicates that hydrogen accumulation may or may not be accelerated by overloading during fatigue. It was also shown that hydrogen embrittlement can be predicted by mapping an overloading effect.

Acknowledgements

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