Crack Propagation Behavior of SCM440H Low Alloy Steel Enhanced by Hydrogen under Long-term Varying Load and Static Load

Yoshiyuki KONDO, Masanobu KUBOTA and Katsuya SHIMADA

Kyushu University, Department of Mechanical Engineering,
744 Moto-oka, Nishi-ku, Fukuoka-shi, Fukuoka, 819-0395 Japan

ABSTRACT.

Crack propagation behavior of SCM440H low alloy steel enhanced by absorbed hydrogen was investigated. A continuous hydrogen charging method was designed, in which the crack tip was isolated from the electrolyte and kept dry. Six materials which were tempered at different temperatures were used. Effects of stress ratio, loading frequency, hold time and material hardness on the crack propagation rate were examined under long term varying load and static load. An acceleration of crack propagation rate about six times compared to the uncharged material was commonly found in all materials. In addition to this, however, unexpected acceleration of crack propagation up to 1000 times was experienced in certain condition. In materials with Vickers hardness higher than 280 tested at low frequency, the marked acceleration was experienced. The crack surface morphology was quasi cleavage. This critical hardness (HV=280) is a little lower than the usually accepted critical hardness for delayed failure (HV=350). In material with Vickers hardness lower than 268, however, such a marked acceleration was not experienced.

INTRODUCTION

It has been pointed that absorbed hydrogen in metal has detrimental effect such as hydrogen embrittlement [1] and hydrogen enhanced fatigue crack propagation [2,3] and so on. Delayed failure of high strength steel under static loading is a typical example of hydrogen embrittlement. It has been recognized that low alloy steel whose Vickers hardness is higher than 350 is prone to delayed failure. The design of hydrogen utilization machine sometimes requires the use of high strength steels. It is important to prevent the hydrogen embrittlement for the safety in hydrogen economy. Hydrogen utilization machine experiences varying loading as well as static loading in service. Therefore the effect of material hardness on the crack propagation behavior of low alloy steel enhanced by hydrogen under long-term varying load and static load was studied.

TEST METHOD

Test Specimen and Test Equipment

Test material is a low alloy steel designated as SCM440H in Japanese Industrial Standard. The material was quenched at 1143K and tempered at six different temperatures to obtain materials with different strength level. Vickers hardness was ranging from 268 to 587.The chemical composition and mechanical properties are shown in tables 1 and 2, respectively.

The microstructure was tempered martensite.

The test specimen is shown in Fig.1. It has a 2mm deep edge notch and 0.15mm deep fatigue pre-crack was introduced at the notch root in prior to test. The test equipment is shown in Fig.2. A lever is connected to the specimen and cyclic displacement was applied at the end of the lever which produced cyclic bending moment. The computerized stepping motor enabled the application of programmed loading.

Table 1 Chemical composition (mass%)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.42	0.22	0.80	0.017	0.02	0.03	1.04	0.16	0.02

Table 2 Mechanical properties

Tempering Temp. (K)	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	δ (%)	ϕ (%)	HV1
443	1450	2033	13	38	587
803	1046	1151	17.	63	368
843	917	1036	18	67	325
873	857	983	21	67	314
903	773	898	21	70	280
923	714	841	23	70	268

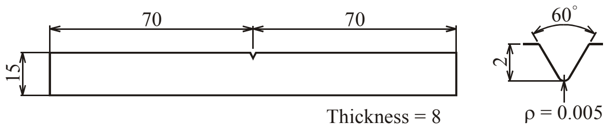


Fig.1 Test specimen

Continuous Hydrogen Charge

Hydrogen charge was done electrochemically as shown in Fig.3. The notched portion was enclosed in a chamber to isolate the crack from electrolyte. The chamber was sealed 7mm away from the crack. The setup has another chamber to hold the electrolyte and perform the cathodic

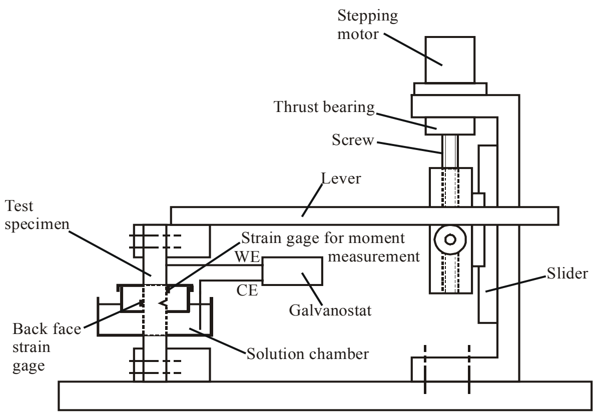


Fig.2 Test machine

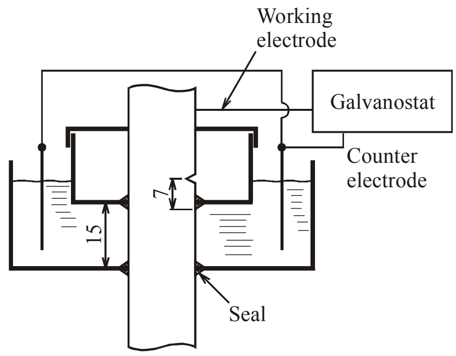


Fig.3 Apparatus for continuous charge

polarization. The absorbed hydrogen diffuses in the specimen and reaches the crack. The concentration of diffusible hydrogen was 1.32ppm at the polarized location and 0.21ppm at crack location. This arrangement enabled the continuous hydrogen charge keeping the isolation of crack from electrolyte. Sulfuric acid whose pH was 2.0 was used as the electrolyte. Cathodic polarization was done at current density of 174A/m^2. Crack propagation test was done in air at ambient temperature. The crack length was measured by back face unloading elastic compliance method [4].

TEST RESULTS

Crack Propagation under Triangular Stress Pattern

Crack propagation tests on material tempered at 843K which has medium strength and is popularly used in engineering application were done using triangular stress pattern shown in Fig.4. Loading period t was chosen as 1800s. Crack propagation rate is shown against stress intensity factor range ΔK in Fig.5. The crack propagation rate was accelerated by hydrogen absorption. At stress ratio lower than 0.4, moderate acceleration about six times occurred as shown by open symbols. At stress ratio

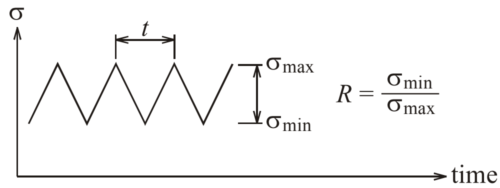


Fig.4 Triangular stress pattern

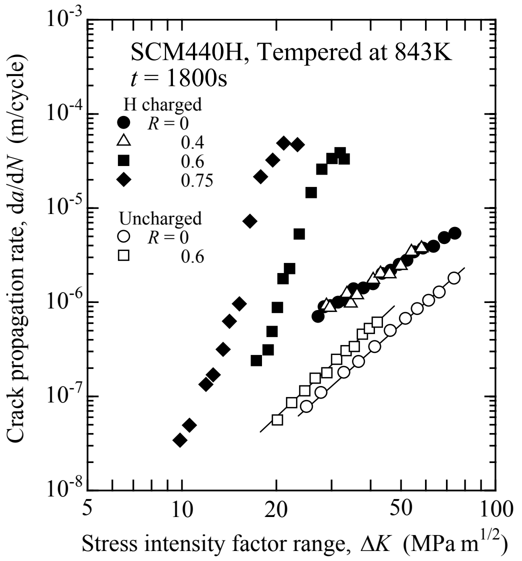


Fig.5 Effect of stress ratio on crack propagation rate under triangular stress shown against ΔK

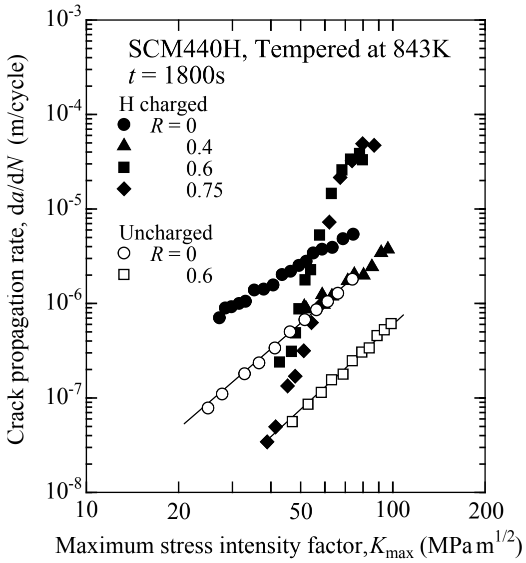
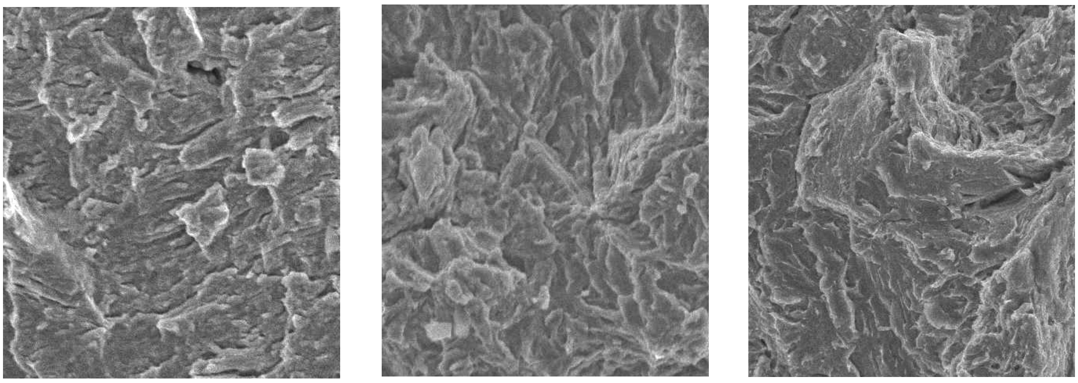


Fig.6 Crack propagation rate under triangular stress shown against K_{max}

higher than 0.6, however, sudden acceleration appeared. The acceleration was about thousand times. The data were re-plotted against maximum stress intensity factor K_{max} in Fig.6. The remarkably accelerated propagation rate data fell in a unique data band. The sudden acceleration was governed by K_{max}, which indicates that the time-dependent crack growth mechanism is involved. The Vickers hardness of 843K tempered material was 325 which was lower than the usually accepted critical hardness for delayed failure.

The fracture surface is shown in Fig.7. The morphology of uncharged material (Fig.a)



K_{max}=79MPam$^{1/2}$ (a) Uncharged, t=60s | K_{max}=50MPam$^{1/2}$ (b) Charged, t=1800s | K_{max}=73MPam$^{1/2}$ (c) Charged, t=1800s

Fig.7 Fracture surface of 843K tempered material tested at R=0.6 10μm

was striation mode. On the contrary, the morphology of hydrogen charged material which showed medium acceleration (Fig.b) as well as sudden acceleration (Fig.c) was quasi cleavage.

The effect of material hardness on the occurrence of sudden acceleration was examined using materials tempered at different temperatures. Test were done at R=0.6. Test results are shown in Fig.8. In all materials except 923K tempered material, sudden acceleration was observed. The fracture surfaces are shown in Fig.9. In the case of 403K tempered material

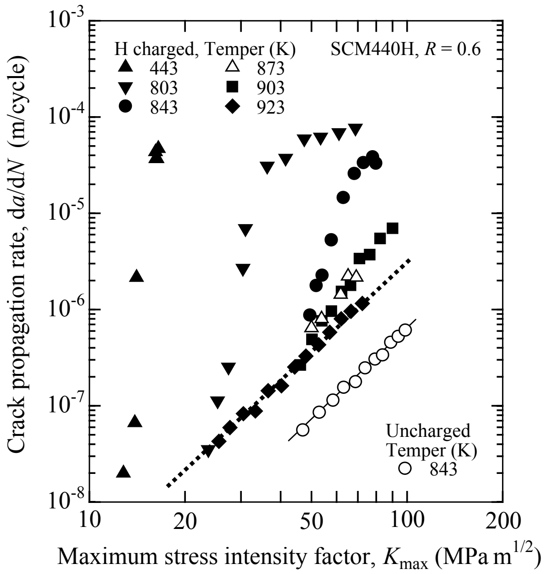
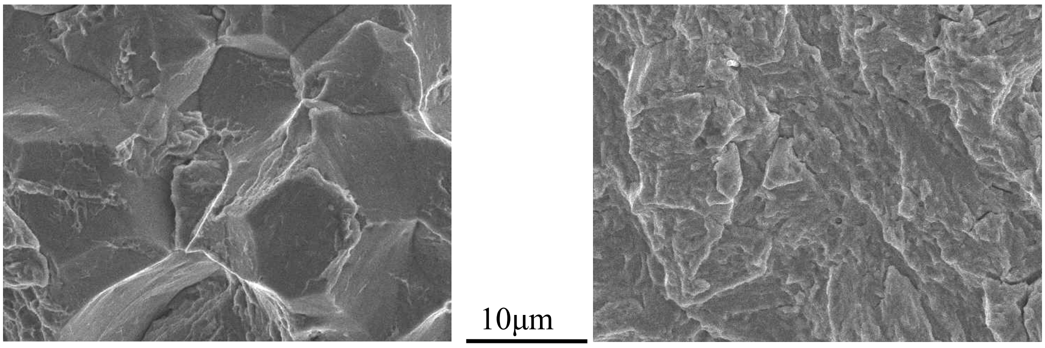


Fig.8 Effect of tempering temperature on acceleration of crack propagation at high stress ratio (triangular stress, R=0.6)



(a)443K,K_{max}=16MPam$^{1/2}$ (b)803K, K_{max}=53MPam$^{1/2}$

Fig.9 Effect of tempering temperature on fracture surface for triangular stress R=0.6, t=1800s

which is a very hard material, the morphology was intergranular. On the contrary, the morphology in other materials was quasi cleavage.

In the case of 843k tempered material which has medium strength, the sudden acceleration was experienced only at high stress ratio as shown above. This kind of acceleration is expected even at lower stress ratio in harder materials. Therefore, tests at various stress ratios including low stress ratio were done using 443K and 803K tempered materials. Test results are shown in Fig.10 and 11. Sudden acceleration was experienced at all stress ratios including R=0. The acceleration ratio compared to the

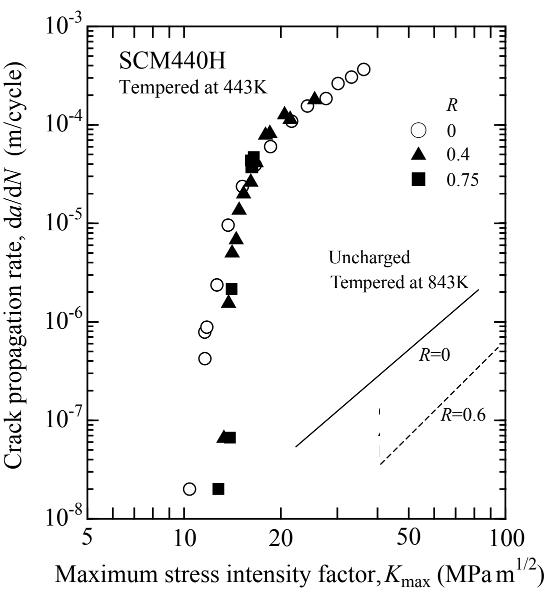


Fig.10 Effect of stress ratio on crack propagation of material tempered at 443K (triangular stress, t=60s)

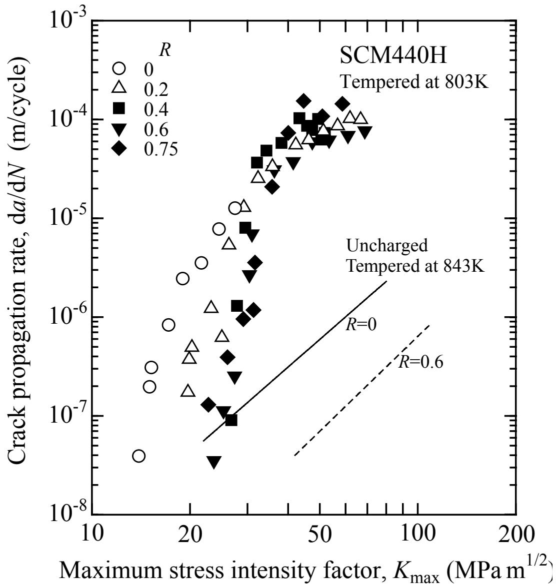


Fig.11 Effect of stress ratio on crack propagation of material tempered at 803K (triangular stress, t=1800s)

uncharged material was about one thousand. The critical condition map that caused sudden acceleration is shown in Fig.12. The acceleration was dependent on tempering temperature and stress ratio. Popularly used medium strength steel as well as hard material was enhanced by hydrogen. Soft material which was tempered at 923K was not enhanced by hydrogen.

Time-dependent Crack Growth

Crack propagation test using trapezoidal stress pattern shown in Fig.13 was done to examine the participation of time-dependent crack growth in the sudden acceleration. Test result is shown in Fig.14 for R=0.6. Hold time was

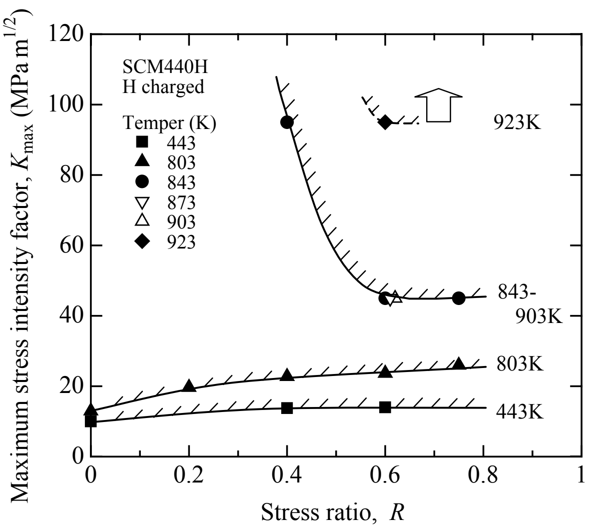


Fig.12 Onset of acceleration of crack propagation under triangular stress

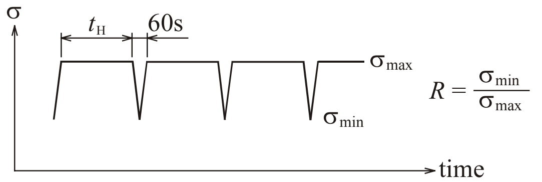


Fig.13 Stress pattern for time-dependent crack propagation

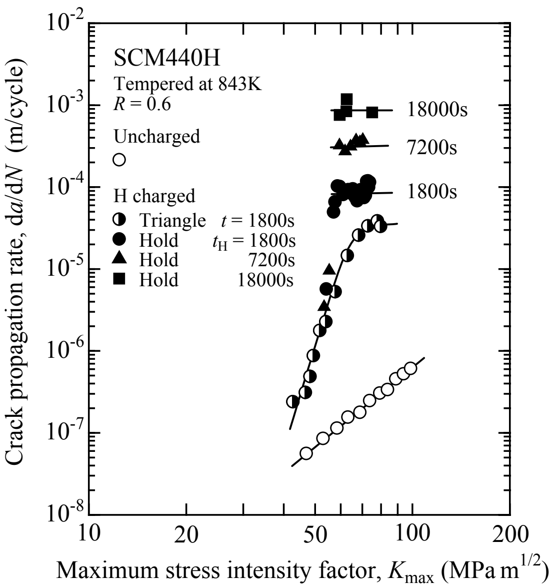


Fig.14 Time-dependent crack propagation in material tempered at 843K under stress hold

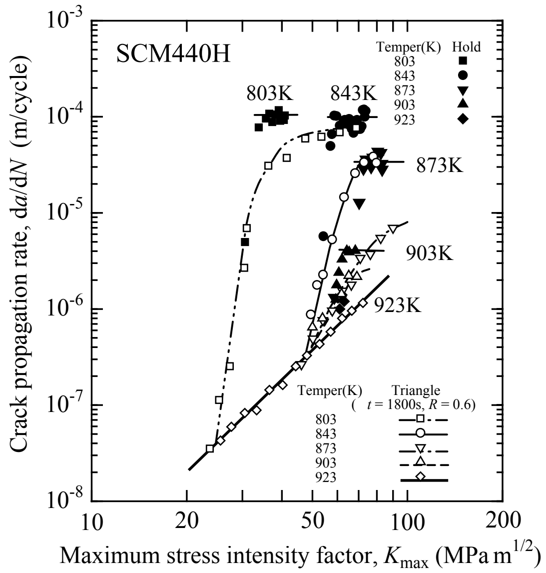
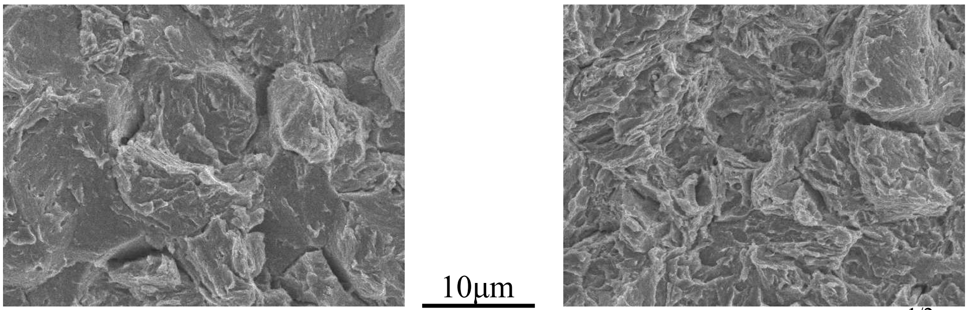


Fig.15 Effect of tempering temperature on time-dependent crack propagation under stress hold (t=1800s, R=0.6)

changed from 1800 to 18000s. The crack propagation rate per cycle showed plateau characteristic and the propagation rate at plateau was increased in proportion to hold time t_H, which suggests the involvement of time-dependent crack growth.

The effect of material strength on time-dependent crack growth was examined. Test result is shown in Fig.15. Stress ratio R=0.6 and hold time of 1800s were chosen. In all materials tested, crack propagation rate was increased by stress hold compared to the triangular stress pattern test shown by open symbols. Especially, materials which were tempered at lower than 873K showed large acceleration. Even in material tempered at 923K, small amount of acceleration was observed. The fracture surfaces are shown in Fig.16. The morphology was quasi cleavage. Harder material looks more brittle.

The effect of material hardness on plateau crack propagation rate is shown in Fig.17. The crack propagation rate is shown against material hardness HV. Even in material whose Vickers hardness was lower than the critical value for delayed failure (HV=350)



(a)803K, K_{max}=41MPam$^{1/2}$ (b) 843K, K_{max}=73MPam$^{1/2}$

Fig.16 Effect of tempering temperature on fracture surface of time-dependent crack propagation under stress hold

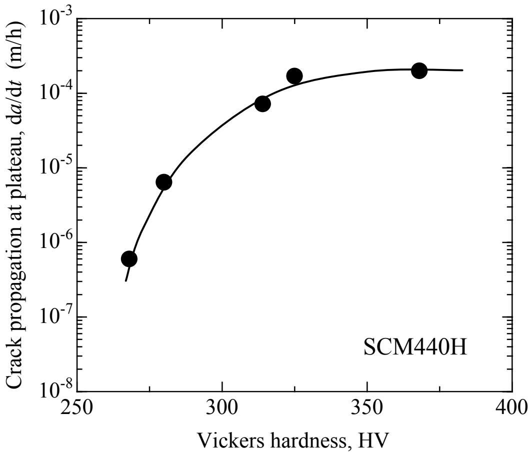


Fig.17 Effect of material hardness on time-dependent crack propagation rate

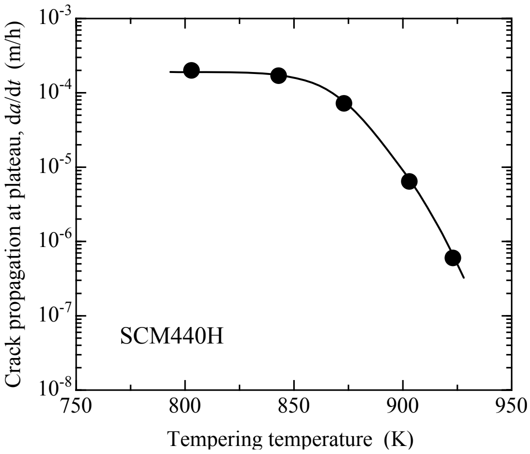


Fig.18 Effect of tempering temperature on time-dependent crack propagation rate

also showed crack propagation in the case of continuous hydrogen charged condition. In material with HV=268, the time-dependent crack growth was negligibly small [5]. The same data are plotted against tempering temperature in Fig.18. Time-dependent crack propagation rate could be substantially reduced by increasing the tempering temperature up to 923K.

CONCLUSION

Crack propagation behavior of SCM440H low alloy steel enhanced by absorbed hydrogen under continuous hydrogen charge was investigated.

(1) A continuous hydrogen charging method was designed, in which the crack was isolated from the electrolyte and kept dry.

(2) Moderate acceleration of crack propagation rate at least six times was commonly found in all materials. In addition to this, sudden acceleration of crack propagation up to thousand times was experienced in materials with HV> 280 tested at low frequency. In material with HV< 268, such a marked acceleration was not experienced. The crack surface morphology was quasi cleavage. Time-dependent crack propagation mode is involved in this acceleration.

(3) The use of low strength material is desirable to prevent the cracking enhanced by hydrogen.

REFERENCE

(1) S. Fukuyama, et al., Tensile properties of SUS304 Stainless Steel in High Pressure Hydrogen at Room Temperature, *Journal of the Japan Institute of Metals*, Vol.67 (2003), pp.157-160.

(2) K.Shishime, M.Kubota and Y.Kondo, Effect of absorbed hydrogen on the near threshold fatigue crack growth behavior of short crack, Materials Science Forum, Vol.567-568 (2008), pp.409-412.

(3) H.Tanaka, et al., Effect of Hydrogen and Frequency on Fatigue Behavior of SCM435 Steel for Storage Cylinder of Hydrogen Station, *Transactions of the Japan Society of Mechanical Engineers*,Vol.73,No.736 (2007), pp.1358-1365.

(4) M.Kikukawa, et al., Measurement of Fatigue Crack Propagation and Crack Closure at Low Stress Intensity Level by Unloading Elastic Compliance Method, *Journal of Materials Science, Japan*, Vol.25 (1976), pp. 899-903.

(5) H.Itoh, et al., SCC Susceptibility of 3.5NiCrMoV Steel in an Actual Low-pressure Turbine Environment, Proc. of 8th Int. Conf. on Nuclear Engineering, ICONE-8113, Baltimore, (2000).