Effects of Earthquake Loads and Absorbed Hydrogen on the Fatigue Strength Reduction of Notched Component

Y. Kondo[1] and T. Yamanouchi[2]
[1] *Kyushu University, Fukuoka, Japan;* [2] *Kyushu Polytechnic College, Kitakyushu, Japan*

1. Introduction

Safety is one of the most important issues in hydrogen economy. Earthquake sometimes gives damages to steel structures and machineries[1,2]. The components which had not been seriously damaged would still be used after the earthquake. The residual fatigue strength of those components, however, might have been decreased. The objective of this work is to clarify the effect of relatively small number of overloads and hydrogen on the residual fatigue strength of a notched component.

2. Test method

2.1 Test material and test specimen

Low alloy steel designated as SCM435H in Japanese Industrial Standard was used. The chemical composition and mechanical properties are shown in Table 1 and 2, respectively. The configuration of test specimen is shown in Fig.1. It has a through-thickness single edge notch. The notch depth was 0.5mm and the root radius was 0.2mm. Test specimen was used as machined.

Table 1 Chemical composition of test material (mass %)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.38	0.18	0.78	0.15	0.19	0.08	1.04	0.15	0.12

Table 2 Mechanical properties of test material

Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)	HV
955	1048	19	344

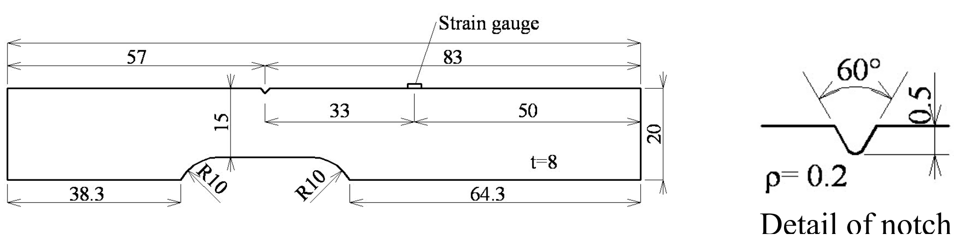


Fig.1 Test specimen

2.2 Fatigue test

Cyclic bending moment was applied to the specimen. Tests were done in air at ambient temperature. Constant amplitude test and multiple overload tests were done. The loading history of multiple overloads is shown in Fig.2. The multiple overloads simulating earthquake were applied for n_1 cycles at stress ratio R=-1 prior to high cycle fatigue. The frequency of the overload cycle was 1Hz. The overload was unloaded from compressive stress side to generate tensile residual stress at the notch root. The number of overload cycles was changed as 10,20,50,100, 200 and 600. After the application of overloads, high cycle fatigue stress was applied until specimen failure. The test frequency of high cycle loading was 28Hz.

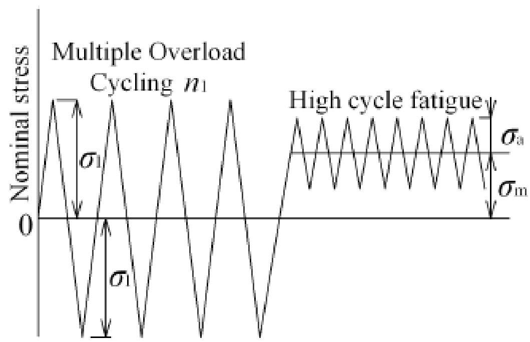


Fig.2 Multiple overloads history

3. Effect of multiple overloads on residual fatigue strength

3.1 Constant stress amplitude fatigue test

Constant stress amplitude fatigue test was done at various mean stress conditions to obtain reference *S-N* curves. Based on the *S-N* curves, the fatigue limit diagram was drawn as shown in Fig.3.

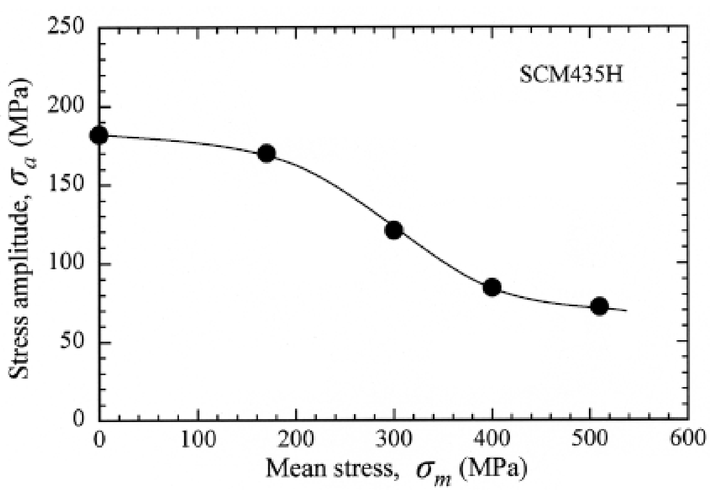


Fig.3 Fatigue limit diagram of constant stress amplitude test

3.2 Overload test results

3.2.1 Effect of overload stress level

The effect of overload stress level on the reduction of fatigue strength was examined. The critical overload that causes a reduction in residual fatigue strength was surveyed. In this test, the overload stress σ_{OL} was chosen as 510,400,300and 250MPa. In this test, the mean stress of high cycle fatigue σ_m was set equal to each overload σ_{OL}, i.e. $\sigma_m=\sigma_{OL}$, in order to simulate the severest condition. This corresponds to a condition that the displacement of component is constrained at the maximum displacement in earthquake.

The fatigue limit diagram of overload test is shown in Fig.4. Fatigue limits of constant stress amplitude without overloads are plotted using solid symbols. The residual strength after overloads are plotted by open symbols. The residual strength after overloads was substantially reduced by overloads. Higher overload stress and larger number of cycles of overloads resulted in more reduction. When the number of overloads were less than 200cycles, overload stress amplitude less than 250MPa would not be detrimental to residual fatigue strength. The major cause of fatigue stength reduction is the formation of short crack by overloads. Examples of short cracks observed in fatigue limit specimens are shown in Fig.5. Short cracks were observed. Larger number of overload cycles generated deeper crack which acted as a trigger for high cycle fatigue crack propagation, which resulted in more reduction of fatigue limit.

The linear accumulation fatigue damage is shown in Fig.6. Fatigue damage as small as 0.002 caused the reduction of residual fatigue strength.

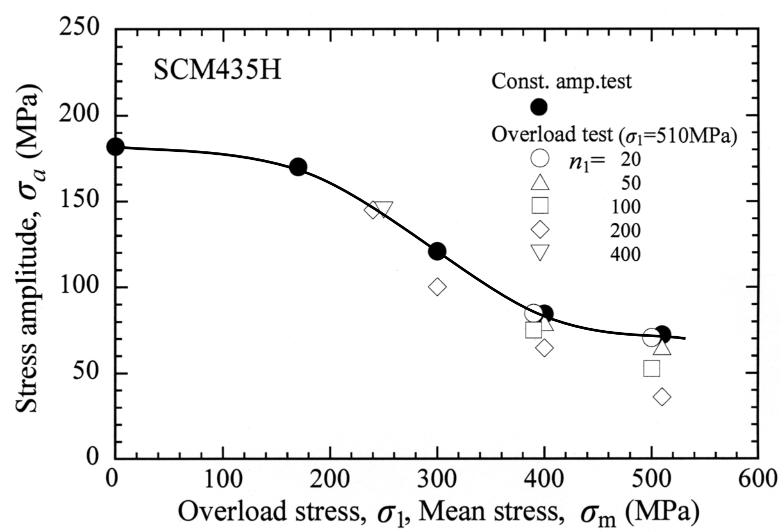
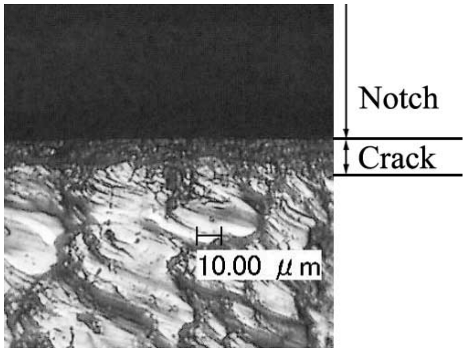
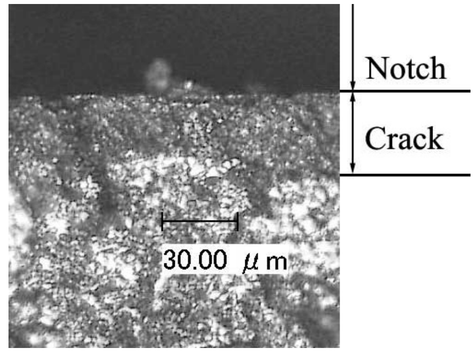


Fig.4 Effect of overload level on the reduction of fatigue strength





(a)100 cycles (b)200 cycles

Fig.5 Non-propagating crack in fatigue limit specimen after overload σ_{OL}=510MPa

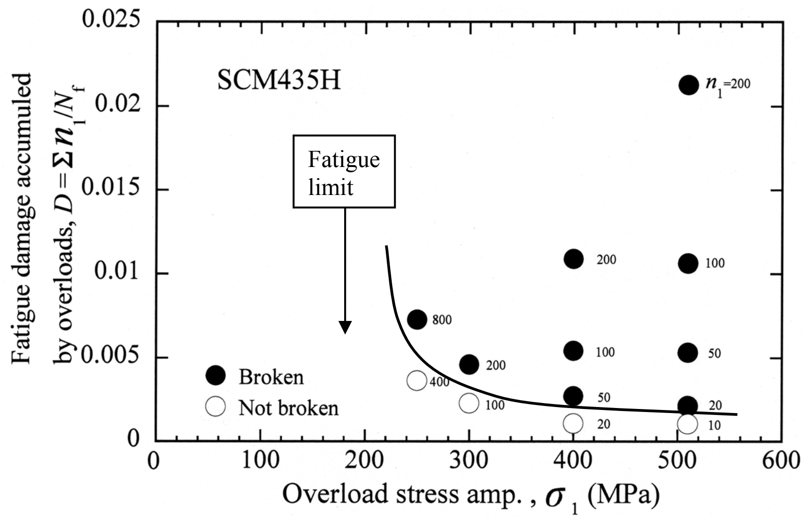


Fig.6 Linear accumulation fatigue damage that caused reduction

3.2.2 Effect of mean stress σ_m on the reduction of fatigue strength after overload

After an earthquake, the displacement of a component is not necessarily completely recovered but often some incomplete constraint remains. Tensile residual stresses caused by incomplete constraint was simulated by adding external mean stress. In these tests, the overload condition was as follows; the overload stress amplitude σ_{OL} was 510MPa and the number of overloads n_1 was 200. Fatigue tests were done under three kinds of external mean stresses of 0, 70, 150MPa. *S-N* curves for each mean stress are shown in Figs.7,8 and 9, respectively.

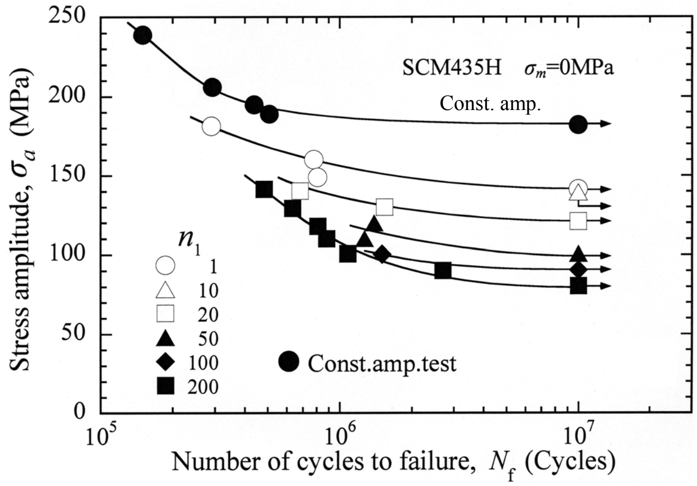


Fig.7 Fatigue strength after overload at external mean stress σ_m=0MPa

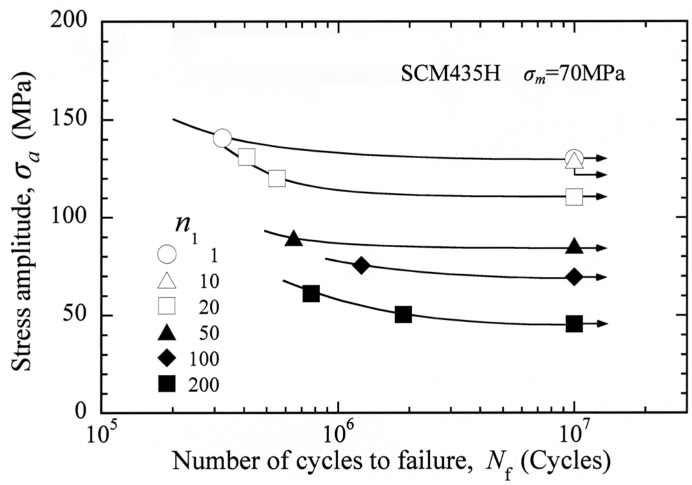


Fig.8 Fatigue strength after overload at external mean stress σ_m=70MPa

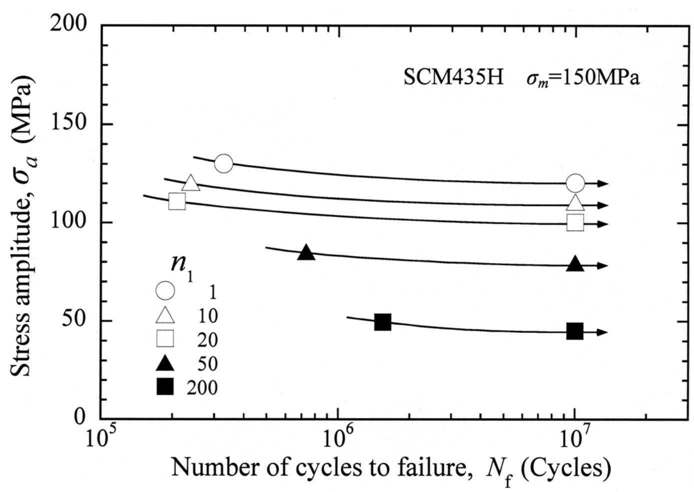


Fig.9 Fatigue strength after overload at external mean stress σ_m=150MPa

Fatigue limits of these tests are shown in fatigue limit diagram as shown in Fig.10. Residual fatigue strength shown by open symbol was substantially reduced compared with the constant amplitude test result shown by solid symbol. Moreover, addition of a little tensile mean stress was quite detrimental to fatigue strength reduction. Application of only 70MPa resulted in a reduction down to about 30% of constant amplitude data in the case of n_1=200.

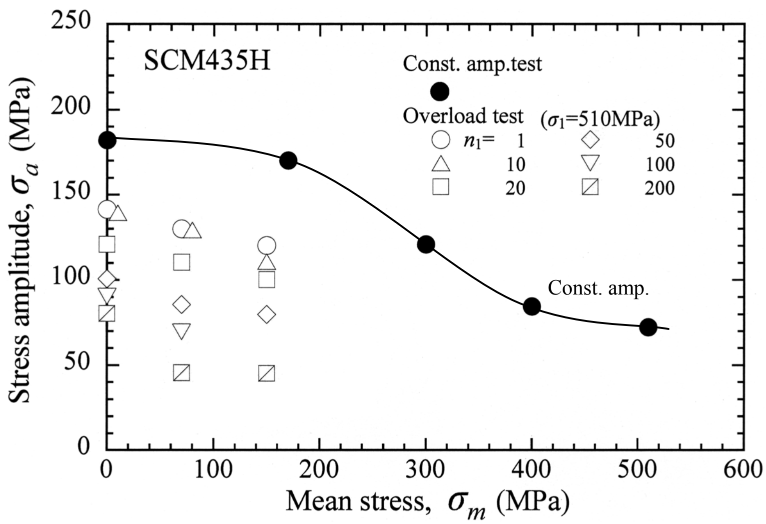


Fig.10 Reduction of residual fatigue strength after overloads shown in fatigue limit diagram

4. Effect of absorbed hydrogen on the reduction of residual fatigue strength after overloads

It is known that absorbed hydrogen in metal is detrimental also in fatigue. The effect of hydrogen should be carefully considered in the integrity assessment of hydrogen utilization machine. The effect of absorbed hydrogen on the reduction of residual fatigue strength after overloads was investigated.

4.1 Hydrogen absorption method

Cathodic polarization method was used for hydrogen absorption. Usually, pre-charge by cathodic polarization is done before fatigue test and cathodic charge is not done during fatigue test. In ferritic metal, however, the diffusivity of hydrogen is quite high and hydrogen in the specimen quickly dissipates. The hydrogen concentration becomes lower in 10h. Since fatigue test needs about 100h for fatigue limit test, a method which enables continuous polarization is desirable. In addition to this, the isolation of crack from the solution is important to avoid additional damage. A continuous charging method was tried as shown in Fig.11. The notched portion of the test specimen was coated using water resistant adhesive. A solution chamber was attached to the specimen in which counter electrode made of platinum plate was arranged. The specimen and the counter electrode were connected to a galvanostat. The solution was dilute sulfuric acid whose pH was 2.0. The temperature was ambient and the cathodic current was 130A/m^2. Material surface 2mm away from the notch was continuously polarized during fatigue test. The absorbed hydrogen was diffused in the specimen and hydrogen reached the notch. Fatigue tests were started after 48hours pre-charging. By this method, the continuous hydrogen supply to the crack without touching the solution was realized.

Test results are shown in Figs.12 and 13. Fig.12 shows *S-N* curves. Open symbols show data for uncharged specimens and solid symbols show those of hydrogen-charged specimens. The absorbed hydrogen gave additional reduction of fatigue strength.

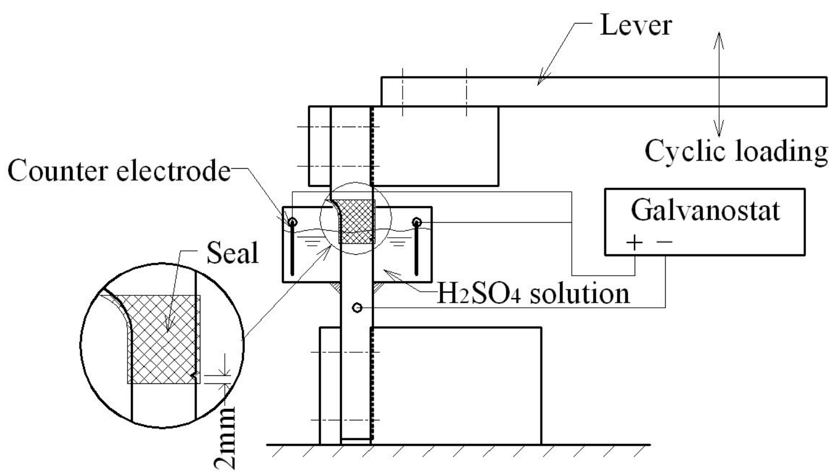


Fig.11 Continuous cathodic polarization method

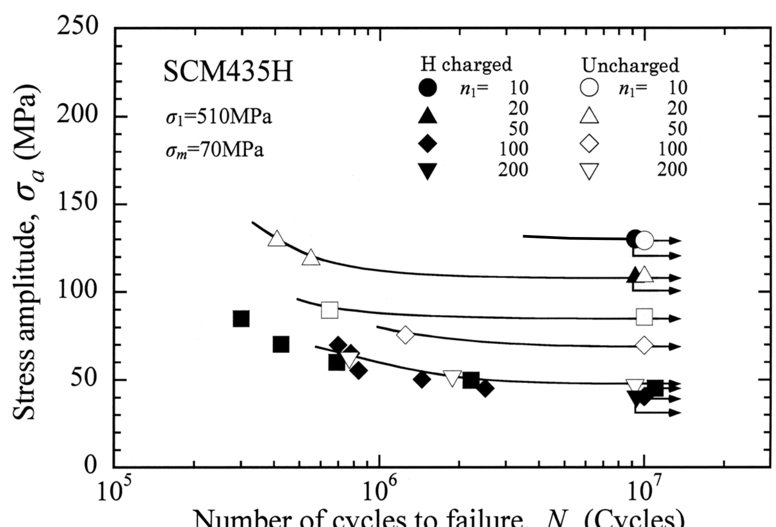


Fig.12 Effect of absorbed hydrogen on the reduction of fatigue strength after overloads

The relation between the number of overload cycles and the fatigue limit is shown in Fig.14. Overloads n_1 more than 50cycles gave significant reduction of residual fatigue strength after overloads.

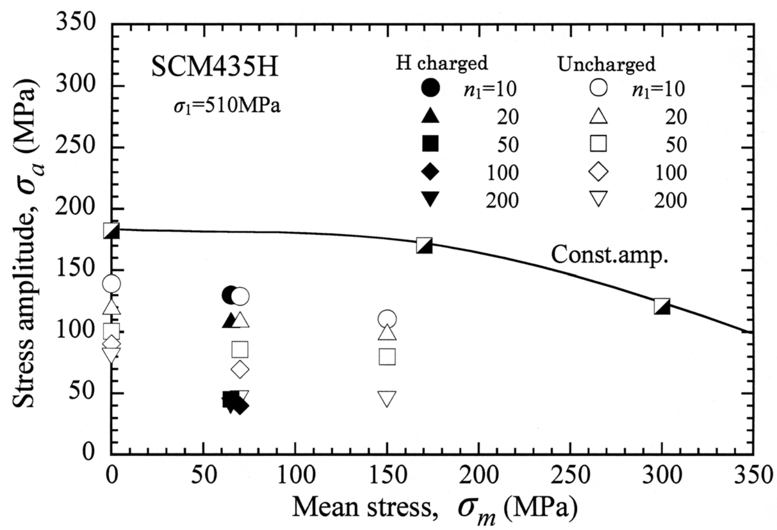


Fig.13 Effect of absorbed hydrogen on the reduction of fatigue limit after overloads shown in fatigue limit diagram

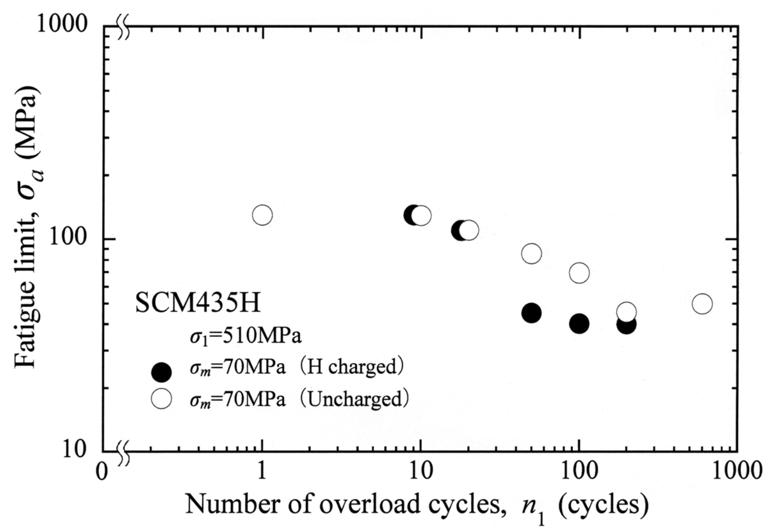


Fig.14 Effect of overload cycle and hydrogen on the reduction of fatigue limit

The cause of larger reduction in hydrogen charged material was examined. Two possible causes could be considered. The first possibility is the acceleration of crack growth in low cycle fatigue in overloads. The test specimens which ran out at fatigue limits were opened after fatigue tests. The depth of non-propagating crack was measured on the crack surface. Crack depth is shown in Fig.15. Non-

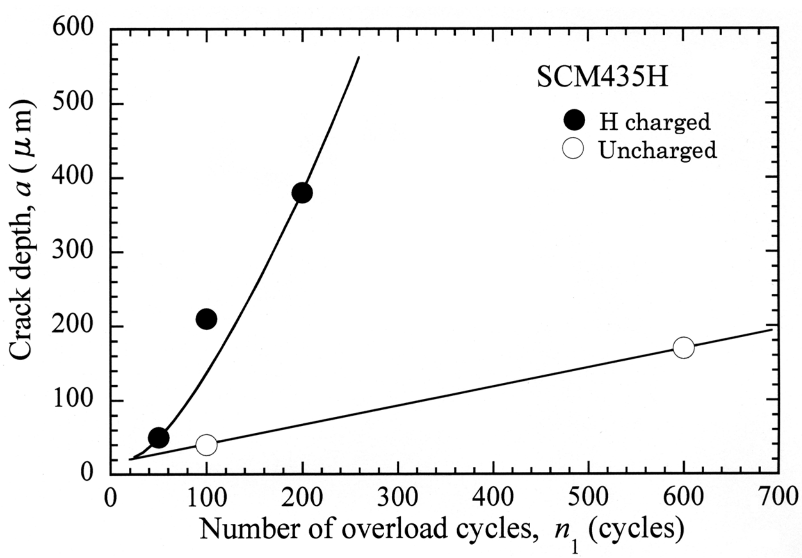


Fig.15 Depth of non-propagating crack in fatigue limit specimen after overload

propagating crack of hydrogen charged specimen shown by solid symbol was substantially deeper than those of uncharged specimen. It was about four times longer. This seems to be the primary cause of the reduction.

The second possibility is the reduction of ΔK_{th} of short crack for high cycle fatigue propagation in hydrogen charged material. The relation between the crack depth formed by overloads and the residual fatigue strength is shown in Fig.16. The slope of the diagram was not 0.5 as in the Kitagawa-Takahashi diagram[3]. This is because the tensile residual stress formed by overloads was released as crack grew deeper. The effective stress ration became lower for deeper crack. The reduction of fatigue limit of material by hydrogen absorption was about 20%, which is a similar result to the previous result[4].

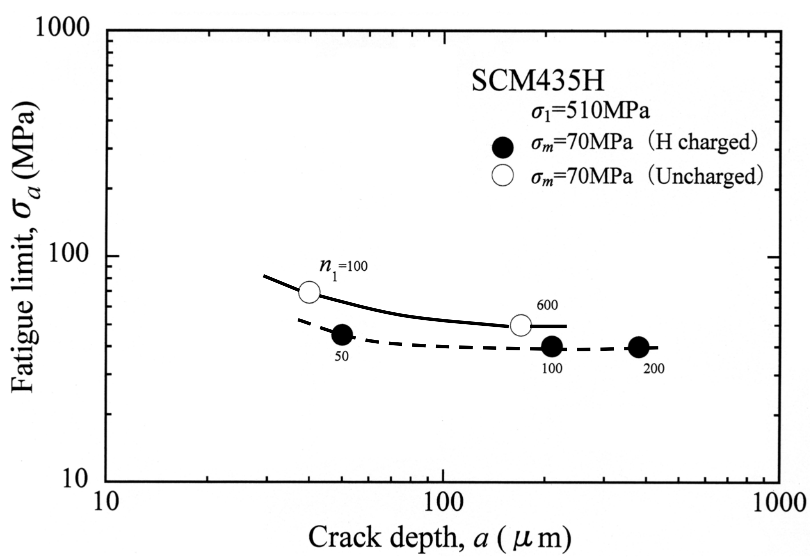


Fig.16 Effect of crack depth on the reduction of residual fatigue limit

Considering these two possible causes, the acceleration of low cycle fatigue crack growth by overloads plays a major role and the reduction of ΔK_{th} gives secondary contribution.

5. Conclusion

The reduction of residual fatigue strength after overloads of low alloy steel SCM435H was investigated. The effect of absorbed hydrogen was also investigated.

(1) The formation of small crack and the residual tensile stress introduced by overloads caused substantial decrease of residual fatigue limit.

(2) The crack depth formed by overloads was about four times deeper in hydrogen charged material. The acceleration of low cycle fatigue crack growth by overloads played a major role. The reduction of ΔK_{th} also occurred. It gave secondary contribution for the reduction of residual fatigue limit.

(3) This phenomenon should be considered in the design, maintenance program and failure analysis of hydrogen utilization machineries.

Reference

[1] K.Okuya and Y.Kondo,The Effect of Large Strain Cycling on the Fatigue Strength of Welded Joint, Journal of ASTM International, Vol.3, No.4, Paper ID JAI 13232, 2006,1-11.

[2] Y.Kondo and K.Okuya, The Effect of Seismic Loading on the Fatigue Strength of Welded Joint, Materials Science and Engineering A, 468-470 2007, 223-229.

[3] H.Kitagawa and S.Takahashi, Applicability of fracture mechanics to very small cracks or the cracks in the early stage, Proc. of 2nd ICM, Cleveland, 1976, 627-631.

[4] 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, 409-412.