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Effects of hydrogen and multiple overloads on the fatigue strength of notched component*

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Abstract

To perform a safety diagnosis on the mechanical components of hydrogen utilization machines suffering from large earthquakes, the effects of multiple overloads and hydrogen on the high-cycle fatigue strength of notched fatigue test specimens were studied. The materials were SUS304 and SUS316L. For SUS304, the fatigue strength was significantly reduced by multiple overloads and the reduction was enhanced by hydrogen. In SUS316L, while the reduction of the fatigue limit due to multiple overloads was similar to the SUS304, there was no effect of hydrogen on further reducing the fatigue strength. The cause of the reduction was small cracks formed by multiple overloads. In SUS304, hydrogen accelerated the propagation of the small cracks during overloading and this resulted in the enhanced reduction. Evaluations of the crack length at the notch root as well as the fatigue limit in relation to the crack length were successfully completed. Based on these evaluations, a method to predict the reduction in the fatigue limit due to multiple overloads including the effect of hydrogen was proposed.

Key words: Fatigue, Overload, Hydrogen, Notched specimen, Austenitic stainless steels, Prediction

1. Introduction

Hydrogen is one of the important factors in fatigue strength design because it is well known that decreased fatigue strength is caused when metal materials are used under hydrogen uptake conditions. Besides hydrogen, there are many factors that influence the fatigue strength such as a notch, variable stress, etc. Therefore, the studies on the effects resulting from combination of hydrogen and other factors on the fatigue strength are required to ensure the safe use of hydrogen utilization machines.

The objective of this study is to establish safety diagnosis criteria which assesses whether the mechanical components of hydrogen utilization machines can be continuously used after large earthquakes. To achieve this objective, a high-cycle fatigue test following multiple overloads was done. This study focused on the fatigue strength of notched

components because most mechanical components contain notches, and in many cases, fatigue failure occurs at the notch [1].

In our previous study [2], multiple overloads reduced the fatigue strength of notched fatigue test specimen. The reduction was enhanced by hydrogen. The cause of the reduced fatigue strength was small cracks which were formed by the multiple overloads.

Although the mechanism for the reduced fatigue strength due to overload and hydrogen is understood, it is difficult to apply the results of the previous study to the design and safety diagnosis since the experiment was done under limited conditions considering that there are various notches in hydrogen utilization machines and the overloading conditions are also different.

In this study, the prediction method for the reduction of the fatigue strength in notched components due to overloading and hydrogen is discussed. The prediction method consisted of the following two steps: (1) evaluation of crack growth resulting from overloading, and (2) evaluation of fatigue strength in relation to the crack length. In this paper, the results of the previous study will also be briefly explained in order to enhance the reader's understanding.

2. Experimental procedure

The materials used in the experiment were SUS304 and SUS316L austenitic stainless steels. The heat treatment was solution heat treatment. The chemical composition and the mechanical properties are given in the previous paper [2].

The configuration of the fatigue test specimen is shown in Figure 1. The specimen has a circumferential notch which has a 2.5mm depth and 60-degree notch angle. Three kinds of notch root radii ρ , which were 0.2, 0.5 and 1.0mm, were used. The surface of the notch part was polished by #400 Emery paper to remove the machined layer and to keep the surface roughness constant.

Figure 2 shows the loading pattern. A high-cycle fatigue test with a pulsating tension load ($R = 0$) at a frequency of 20Hz was performed following multiple overloads with reversed load ($R = -1$) at a frequency of 1Hz. The number of cycles of multiple overloads N_{OL} was 200. N_{OL} is one of the major factors influencing the result of the successive high-cycle fatigue test. In the experiment, N_{OL} was chosen so that the effect of the overload will be clearly observed. The effect of N_{OL} was discussed in the process to create a prediction method of reducing the fatigue strength. The multiple overloads were unloaded from the compression side to create a tensile residual stress at the notch root. This procedure may provide

Fig. 1 Specimen configuration and details of notch (dimensions are in mm).

Fig. 2 Loading pattern.

conservative results. In this study, the nominal stress at the notch root was used.

The test environments were 0.6MPa hydrogen gas and air. The hydrogen gas purity was better than 99.999%. The test temperature was ambient in both environments.

Prior to the fatigue test in the hydrogen gas, hydrogen charging of the fatigue test specimen was done by exposing the specimen to 75MPa hydrogen gas at 378K for 100h. The hydrogen concentration of the hydrogen-charged specimen measured at the surface layer was approximately 78mass ppm for SUS304 and 65mass ppm for SUS316L. By comparison, the hydrogen concentration of the uncharged material was 0.13mass ppm for SUS304 and 0.02mass ppm for SUS316L.

3. Results of experiment

3.1 Effects of multiple overloads and hydrogen on high-cycle fatigue strength

Figure 3 shows examples of the S - N diagrams from the previous paper [2]. The S - N data of the uncharged specimen tested in air are shown by the open symbols. In both materials, the multiple overloads reduced the fatigue strength as shown by the symbols $\triangle$, $\square$ and $\diamond$.

The S - N data of the hydrogen-charged specimen tested in hydrogen gas are shown by the solid symbols. In both materials, there was no effect by hydrogen on the fatigue limit when no overload was applied as shown by the comparison between $\circ$ and $\bullet$. However, for SUS304, when multiple overloads were applied, a further reduction in the fatigue strength compared to the uncharged specimen was found as shown by $\blacksquare$ and $\blacklozenge$. That is, hydrogen enhanced the reduction of the fatigue strength due to multiple overloads. In SUS316L, the fatigue strength of the hydrogen-charged specimen was the same as that of the uncharged specimen.

Figure 4 shows the fatigue limit for each notch root radius with respect to the overload amplitude. In SUS304, the effect of hydrogen was significant. In contrast, the fatigue strength of SUS316L was not affected by the hydrogen. The reduction in the fatigue limit was dependent on the overload amplitude σ_{OL} as well as notch root radius ρ .

3.2 Mechanisms causing reduction in fatigue strength by multiple overloads and hydrogen

The fracture surfaces of the run-out specimens were broken open by fatigue after heat tint. Figure 5 shows the fracture surfaces of SUS304 with the experimental conditions. The specimens, which were numbered ①, ② and ③, were uncharged specimens tested in air. Specimen ④ was a hydrogen-charged specimen tested in hydrogen gas.

While specimen ①, which showed no reduction in the fatigue limit by the overloads, had no cracks, specimens ② and ③, which showed a significant reduction in the fatigue limit by the overloads, had small cracks.

Fig. 3 Effects of multiple overloads and hydrogen on fatigue strength of notched specimen.

(a) SUS304 (b) SUS316L
Fig. 4 Effect of overload amplitude and hydrogen on fatigue limit
(Number of cycles of multiple overloads was 200cycles).

(a) Specimen ①
(No crack, uncharged, in air, $\sigma_{OL} = 0.5\sigma_{0.2}$)

(b) Specimen ②
(uncharged, in air, $\sigma_{OL} = 1.0\sigma_{0.2}$)

(c) Specimen ③
(uncharged, in air, $\sigma_{OL} = 1.25\sigma_{0.2}$)

(d) Specimen ④
(H charged, in H_2 , $\sigma_{OL} = 1.25\sigma_{0.2}$)

Fig. 5 Small cracks observed in the run-out specimens of SUS304

Concerning the effect of hydrogen, the size of the small cracks observed in the run-out specimens was obviously larger in specimen ④ than in specimen ③. This is consistent with the experimental fact that the fatigue limit of specimen ④ was significantly lower than that of specimen ③ even though the overload amplitude was the same for both specimens.

A similar observation was noted in SUS316L as shown in Fig. 6. There are small cracks in the specimens in which the fatigue limit was substantially reduced by multiple overloads. As shown in Figs. 3 and 4, the fatigue limit of SUS316L was not reduced by the hydrogen. As can be expected from these figures, there was no difference in the crack length between the hydrogen-charged and uncharged specimens of SUS316L.

These observations revealed the mechanism that reduces the fatigue strength. That is, the reduction of fatigue limit due to overloads was caused by small cracks generated by the

(a) Specimen ①
(uncharge, in air, $\sigma_{OL} = 1.0\sigma_{0.2}$)

(a) Specimen ②
(H charge, in H_2 , $\sigma_{OL} = 1.0\sigma_{0.2}$)

Fig. 6 Small cracks observed in the run-out specimens of SUS316L

multiple overloads. The cause of the enhanced reduction of the fatigue limit due to hydrogen was that the size of the small cracks formed by the multiple overloads was larger in the hydrogen-charged specimen than in the uncharged specimen.

As shown in Figs. 5 and 6, there were small cracks in the run-out specimens when the reduced fatigue limit was caused by multiple overloads. This implied that the high-cycle fatigue strength of these specimens is governed by whether the small cracks propagate or not.

There is a report in which the crack propagation threshold ΔK_{th} of a small crack is reduced by absorbed hydrogen [3]. The materials used in that reference are low alloy steels and carbon steels. If the reduction of ΔK_{th} of small cracks due to hydrogen also occurred in SUS304, it would be one of the causes of the reduced fatigue limit.

Figure 7 shows the result of an experiment to determine whether the ΔK_{th} of the small cracks was reduced by hydrogen or not. The experimental procedures were as follows: (1) introduction of pre-crack to uncharged specimen by multiple overloads in air, (2) hydrogen charge to the pre-cracked specimen, and (3) high-cycle fatigue test in hydrogen gas at the stress amplitude equal to the fatigue limit of the uncharged specimen. Two results could be expected depending on the hydrogen effect. If ΔK_{th} of the small cracks was reduced by hydrogen, failure of the specimen would occur. If not, no failure of the specimen would occur. The experiment was done under the conditions of $\rho = 0.2\text{mm}$ and $\sigma_{OL} = 1.25\sigma_w$, at which the effect of hydrogen was the most obvious.

Fig. 7 Effect of hydrogen on the reduction of ΔK_{th}

As shown in Fig. 7, no failure of the specimen occurred in the experiment. Therefore, ΔK_{th} of the small cracks has not been substantially changed by the hydrogen charge. The reduction of ΔK_{th} of the small cracks was within the difference of the stress amplitude between the specimens in the $S-N$ diagram.

4. Prediction of the reduction in fatigue strength for general conditions concerning notch and overload

As shown in Fig. 4, the reduction of the fatigue strength due to multiple overloads as well as hydrogen was affected by the notch root radius and overload amplitude. Besides these factors, the number of cycles of the multiple overloads is also an important influencing factor. Therefore, the method to predict the reduction in the fatigue strength for the general notch and overload conditions is considered.

The results of this described experiment showed that the reduction in the fatigue limit including the effect of hydrogen was governed by the small crack formed at notch root by the multiple overloads. Therefore, a method to evaluate the crack growth occurring at the notch root during the overloading was first discussed.

4.1 Evaluation of crack growth in low-cycle fatigue regime

In this experiment, the stress conditions at the notch root during overloading were considered to be in the low-cycle fatigue. For the low-cycle fatigue, most of the fatigue life is spent during propagation of the crack [4]. Therefore, assuming that the failure of the specimen occurs when the crack attains a certain length, the low-cycle fatigue life N_f in the Manson-Coffin equation ($\Delta \varepsilon_p N_f^{\alpha} = C$) is considered as the number of cycles of fatigue loading at which the fatigue crack grows to a certain length. Also, the coefficient C in the equation is associated with the crack length.

To use the Manson-Coffin rule for the evaluation of the crack propagation at the notch root, cyclic stress-strain curves of the test materials were obtained as shown in Fig. 8. These curves were obtained by multiple steps increasing strain test. The plastic strain range $\Delta \varepsilon_p$ at the notch root was estimated by Neuber's rule [5] based on the cyclic stress-strain curves.

Figure 9 shows the crack propagation curves of the crack at the notch root. The curves were obtained by the crack propagation test based on the following procedure. Several notched fatigue test specimens were prepared and different fatigue cycles with the same stress amplitude were applied to each specimen. The fracture surface of the specimens was then opened after the heat tint. The crack length was measured on the fracture surface.

In SUS304, the crack propagation was significantly accelerated by the hydrogen. On the other hand, in SUS316L, no obvious change in the crack propagation behavior due to hydrogen was found. These results were consistent with the observation of the non-propagating cracks seen in Figs. 5 and 6.

Fig. 8 Estimation of plastic strain range at notch root using Neuber's rule

Fig. 9 Crack propagation curves of small crack at notch root in low-cycle fatigue regime

The data points plotted in Fig. 9 were linearly interpolated and the crack propagation lives N_i at which the crack length reached $a_i = 20, 40, 60, 80$ and $100\mu\text{m}$ were obtained. Figure 10 shows the relationship between $\Delta\epsilon_p$ and N_i . Each line which belongs to the same experimental conditions (material and with or without hydrogen) had almost the same slope.

Similar to Fig. 9, the effect of hydrogen on the propagation of a small crack in SUS304 was also clearly shown in Fig. 10. The lines of the hydrogen-charged specimen were located on the short-life side compared to the uncharged specimen. In SUS316L, there is little difference between the hydrogen-charged and uncharged specimens. The coefficients α and C in the Manson-Coffin equation were obtained from these lines and are listed in Table 1.

The crack propagation curves shown in Fig. 9 that became the basis of Fig. 10 were obtained by the specimen that had just one notch root radius ($\rho = 0.2\text{mm}$). Therefore, to confirm whether the relationship is applicable to other notched specimens, an additional experiment was run using a notched specimen having notch root radius of $\rho = 0.5\text{mm}$.

N_i for $a_i=20\mu\text{m}$ was obtained and it was indicated by ★ in Fig. 10. The result of the additional experiment was on the original line for $a_i=20\mu\text{m}$. Thus, the evaluation method of the crack propagation in the notched specimen by plastic strain at the notch root was experimentally validated.

Figure 11 shows the relationship between the crack length a and $C (= \Delta\epsilon_p N_i^\alpha)$. The crack propagation behavior of the small crack under the respective test conditions was represented by one line. The figure can provide the crack length for various loading conditions including the overload amplitude, number of cycles of the multiple overloads and shape of the notch.

Fig.10 Crack propagation behavior of small crack at notch root represented by Manson-Coffin-like correlation

Table 1 Coefficient in Manson-Coffin rule's equation
applied to the evaluation of crack propagation life of the small crack at notch root

Material	Conditions	a_i (μm)	α	C	Material	Conditions	a_i (μm)	α	C
SUS304	Uncharged, in Air	20	0.200	1.824	SUS316L	Uncharged, in Air	20	0.277	2.654
		40		2.183			40		3.308
		60		2.425			60		3.762
		80		2.613			80		4.122
		100		2.768			100		4.425
	H charged, in H_2	20	0.146	1.082		H charged, in H_2	20	0.264	2.456
		40		1.233			40		3.03
		60		1.332			60		3.426
		80		1.407			80		3.737
		100		1.468			100		3.999

(a) SUS304

(b) SUS316L

Fig.11 Evaluation of propagation behavior of small crack at notch root

The crack length measured on the fracture surface of the run-out specimens is also indicated by ★ and ☆ in Fig. 11. These data were plotted very close to the prediction lines.

4.2 Evaluation of high-cycle fatigue limit

The reduced fatigue limit due to multiple overloads including the effect of hydrogen was governed by whether the small crack propagates or not. Therefore, it is reasonable that the small cracks in the run-out specimens are regarded as non-propagating cracks. If so, the stress intensity factor range ΔK of these cracks was considered to be the threshold stress intensity factor range for crack propagation ΔK_{th} . The stress intensity factor was calculated by the equation shown in Fig. 12 [6][7]. The aspect ratio of the crack required for the calculation was measured on the fracture surface.

Figure 13 shows ΔK_{th} with respect to the crack length. The value of ΔK_{th} decreased with a decrease in the crack length. Since the slope was approximately 1/3 on the log-log graph, this trend was derived from the small crack behavior [8]. The fatigue limit for the various crack lengths can be obtained from this graph.

4.3 Prediction of fatigue limit and verification

In the previous subsections, the method to estimate the crack length of the small crack at the notch root and the relationship between the fatigue limit and crack length were discussed. Prediction of the fatigue limit was now done using the conditions specified for the fatigue test to verify the effectiveness of the prediction method.

$$\Delta K = \frac{1.1215\alpha}{\sqrt{1+(4.5\lambda)}} \cdot \frac{\Delta\sigma\sqrt{\pi a}}{\left[1+1.464\left(\frac{b}{a}\right)^{1.65}\right]^{\frac{1}{2}}} \dots (1)$$

$$\lambda = \frac{a}{\rho}$$

α : stress concentration factor

Fig.12 Calculation of ΔK

Fig.13 Relationship between ΔK_{th} and length of the non-propagating cracks

The procedure to predict the reduction in the fatigue limit due to multiple overloads and hydrogen is as follows. When the overload amplitude σ_{OL} and notch root radius ρ are determined, the plastic strain range $\Delta\epsilon_p$ can be obtained from Fig. 8 using Neuber's rule. The value of α in the Mason-Coffin equation can be obtained from Table 3 depending on the material with or without the effect of hydrogen. When the number of cycles of the multiple overloads N_{OL} is then determined, the value of C can be calculated from the Manson-Coffin equation $\Delta\epsilon_p N_f^\alpha = C$ (N_{OL} is regarded as N_f). C can provide the crack length a from Fig. 11. Eventually, when ΔK_{th} for a is obtained from Fig. 13, the fatigue limit can be obtained by the equation (1).

Figure 14 shows a comparison of the results between the experiment and prediction. The results of the prediction, which are represented by ☆ or ★ in the figure, were almost in agreement with the experimental results. Although there was error within approximately 10%, if it was high, the prediction is useful when some designers who want to evaluate the

Fig.14 Validation of the prediction method

effect of multiple overloads and hydrogen in the basic design stage when no experiment has been done.

5. Conclusions

The effects of the multiple overloads and hydrogen on the high-cycle fatigue strength of the SUS304 and SUS316L austenitic stainless steels were investigated using three kinds of notched specimens. The results are as follows.

- (1) Reduction of fatigue strength due to overloads occurred in both materials. The cause of the reduction was the small cracks introduced by the multiple overloads.
- (2) In SUS304, hydrogen enhanced the reduction of the fatigue limit due to the overloads. The primary cause of the enhancement was that larger cracks were formed by the overloading as hydrogen accelerated the crack propagation.
- (3) In SUS316L, no reduction in the fatigue limit due to hydrogen was found.
- (4) The crack propagation was evaluated using the Manson-Coffin relationship and Neuber's rule. The fatigue limit under general conditions concerning the number of cycles of multiple overloads, overload amplitude and notch root radius was then predicted by the relationship between the estimated crack length and threshold stress intensity factor range for the crack propagation ΔK_{th} .

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References

- [1] N. E. Frost, K. J. Marsh and L. P. Pook, "Metal fatigue", Dover Publications, Inc., pp.130 (1999).
- [2] M. Kubota, T. Sakuma, J. Yamaguchi and Y. Kondo, Effect of Hydrogen Absorption on the Fatigue Strength Reduction Caused by Multiple Overloads in Notched Component, Journal of Solid Mechanics and Materials Engineering, Vol. 4, No. 11, pp.1627-1635 (2010).
- [3] Y. Kondo, M. Kubota, K. Shishime and J. Yamaguchi, Effect of Absorbed Hydrogen on the Near Threshold Fatigue Crack Growth Behavior of Short Crack: Examination of Low Alloy Steel, Carbon Steel and Heat Resistant Alloy A286, Transactions of the Japan Society of Mechanical Engineers, Part A, Vol. 74, No. 746, pp. pp. 1366-1372 (2008).
- [4] Y. Murakami, S. Harada, H. Taniishi, Y. Fukushima, Correlations among Propagation Law of Small Cracks, Manson-Coffin Law and Miner Rule under Low-Cycle Fatigue, Transactions of the Japan Society of Mechanical Engineers, Part A, Vol. 49, No. 447, pp. 1411-1419 (1983).
- [5] H. Neuber, "Theory of Stress Concentration for Shear-Strained Prismatic Bodies with Arbitrary Nonlinear Stress-Strain Laws", Transactions of the ASME, Journal of Applied Mechanics, Vol. 28(1961), pp.544-551.
- [6] Y. Murakami, *Stress Intensity Factors Handbook*, vol. 1 (1986), p.249, Pergamon Press.
- [7] Y. Murakami, *Stress Intensity Factors Handbook*, vol. 2 (1986), p.712, Pergamon Press.
- [8] Y. Murakami, M. Shimizu, Effects of Nonmetallic Inclusions, Small Defects and Small Cracks on Fatigue Strength of Metals, Transactions of the Japan Society of Mechanical Engineers, Part A, Vol. 54, No. 499, pp. 413-425 (1988).