**Effect of Hydrogen Absorption on the Fatigue Strength Reduction Caused by Multiple Overloads in Notched Component**

Masanobu KUBOTA**, Toru SAKUMA***, Junichiro YAMAGUCHI**** and Yoshiyuki KONDO**

**Department of Mechanical Engineering, Kyushu University, And National Institute of Advanced Industrial Science and Technology**
744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan
E-mail:kubota@mech.kyushu-u.ac.jp

*** Graduate School of Kyushu University,
744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan

**** Sumitomo Metal Industries, Ltd.,
1 Nishino-cho, Higashi-Mukojima, Amagasaki, 660-0856, Japan

Abstract

Effects of multiple overloads and hydrogen on high cycle fatigue limit was examined to establish a criterion which assesses whether hydrogen utilization machines can be used after large earthquakes. Test materials were SUS304 and SUS316L. The test environments were 0.6MPa hydrogen gas and air. Hydrogen pre-charged specimen was used for in-hydrogen gas test. The reduction of fatigue strength was caused by overloads in both materials. The cause of the reduction was small cracks formed by overloads. In SUS304, the reduction of fatigue limit was enhanced by hydrogen since propagation of small cracks during overloads was accelerated due to hydrogen. In SUS316L, there was no reduction of fatigue limit due to hydrogen. Maximum overload amplitude which caused no reduction of fatigue limit was 0.5σ0.2 for SUS304 and 0.75σ0.2 for SUS316L. These values were regarded as the upper limits of overload amplitude below which the continuous use of components are allowed after earthquakes.

Key words: Fatigue, Overload, Hydrogen, Crack Propagation, Earthquake

1. Introduction

There are many factors which cause the reduction of fatigue strength in service condition. For example, variable stress and notch are major factors. Simultaneous effects of variable stress and notch on fatigue strength were also investigated comprehensively [1][2]. Nowadays, hydrogen can be another important factor in design, since use of hydrogen is steadily increasing. And hydrogen can have influence to reduce fatigue strength as seen in the reports that hydrogen accelerates crack propagation [3]-[5] and reduces crack propagation threshold [5]. Therefore, concurrent effect of hydrogen and other factors on fatigue strength should be carefully examined to establish the design criterion and maintenance program of hydrogen utilization machines.

The objective of this study is to establish safety diagnosis criterion which assesses whether mechanical components of hydrogen utilization machines can be continuously used after large earthquakes. In this paper, the effect of multiple overloads and hydrogen on fatigue strength of notched specimens made of austenitic stainless steels were examined.
2. Experimental procedure

2.1 Materials and fatigue test specimen

The materials were austenitic stainless steels which are designated as SUS304 and SUS316L in Japanese Industrial Standards. The heat treatment was solution treatment. The chemical compositions and the mechanical properties are shown in Tables 1 and 2, respectively.

Figure 1 shows the shape and size of fatigue test specimen. The specimen has a circumferential notch. The notch root radii $\rho$ were 0.2, 0.5 and 1.0mm. The depth of notch was kept constant. The stress concentration factors were 4.75, 3.13 and 2.35 for each notch. The notched part of the specimen was polished by #400 Emery paper.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304</td>
<td>0.05</td>
<td>0.26</td>
<td>1.32</td>
<td>0.036</td>
<td>0.028</td>
<td>8.03</td>
<td>18.32</td>
<td></td>
</tr>
<tr>
<td>SUS316L</td>
<td>0.02</td>
<td>0.21</td>
<td>1.65</td>
<td>0.03</td>
<td>0.014</td>
<td>12.0</td>
<td>16.55</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Condition</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>$\sigma_{B}$ (MPa)</th>
<th>$\delta$ (%)</th>
<th>$\phi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304</td>
<td>Solution heat treated</td>
<td>224</td>
<td>582</td>
<td>64</td>
<td>76</td>
</tr>
<tr>
<td>SUS316L</td>
<td>Solution heat treated</td>
<td>171</td>
<td>496</td>
<td>66</td>
<td>79</td>
</tr>
</tbody>
</table>

2.2 Hydrogen charge and hydrogen concentration in materials

In this study, hydrogen charge was done by exposing specimens to high-pressurized hydrogen gas at elevated temperature. The hydrogen gas pressure was 75MPa and the temperature was 378K. The charging time was 100h. Several small chips having different thickness ($5 \times 5 \times t$ mm) were also exposed to the same hydrogen gas to prepare specimens for the measurement of hydrogen concentration.

The amount of hydrogen absorbed in the material was measured by thermal desorption spectroscopy. Hydrogen absorbed in metallic material is classified into diffusible and non-diffusible hydrogen. There is a report in which the effects of diffusible and non-diffusible hydrogen on fatigue properties were examined separately [6]. In this study, however, the hydrogen concentration was defined by total hydrogen.

Figure 2 shows the relationship between hydrogen concentration and thickness of each chip. The hydrogen concentration was constant in thinner chips and then decreased with increase of the thickness of chip. This shows that the hydrogen concentration in thinner chips achieved the saturated value in the hydrogen charge condition used in this test. Since
hydrogen penetrates through both surfaces of the chip, it is presumed that high hydrogen concentration is established approximately 0.1mm deep beneath the specimen surface. The hydrogen concentration of uncharged material was 0.13ppm for SUS304 and 1.2ppm for SUS316L, respectively.

![Graph showing hydrogen concentration vs. thickness of chip, with data points for SUS304 and SUS316L.]

**Fig. 2** Average hydrogen concentration of chips having different thickness (hydrogen charge condition: exposure to 75MPa hydrogen gas at 378K for 100h, specimen size: $5 \times 5 \times t$ mm).

### 2.3 High-cycle fatigue test following multiple overloads

In this study, application of multiple overloads in large earthquake was assumed. Therefore, the effect of a small number of overloads with large amplitude was examined. The loading pattern is shown in Fig. 3. High-cycle fatigue test with 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 overload was 200cycle. The number of cycles of overload is one of the major factors influencing high-cycle fatigue strength after the application of overloads. As the first step of this study to know what will happen due to overloads and hydrogen, the number of cycles of overloads was chosen so that the effect of overloads will be clearly shown. The multiple overloads were unloaded from the compression side to create a tensile residual stress at the notch root. This procedure may provide conservative results.

The hydrogen charged specimen was used for in-hydrogen gas test and the uncharged specimen was used for in-air test. The pressure of hydrogen gas was 0.6MPa in gage pressure. The purity of hydrogen gas was better than 99.999%. The test temperature was ambient in both environments.

![Diagram showing loading pattern with multiple overload and high-cycle fatigue test.]

**Fig. 3** Loading pattern used to evaluate the effect of seismic load.
3. Results of fatigue test

Figure 4 shows the effects of overloads and hydrogen on the fatigue strength of SUS304. Figure 4(a) is the S-N curves of $\rho = 0.2\text{mm}$ notched specimen. In the in-air test of uncharged specimen (solid symbols), the application of multiple overloads reduced fatigue strength. The amount of reduction of fatigue limit was dependent on the overload amplitude.

When the effect of hydrogen was added to that of overloads (open symbols), the fatigue strength reduced even further. As shown by the comparison between ◆ and ◇, the effect of hydrogen was significant when the overload amplitude was relatively large. Here again, hydrogen enhanced the reduction of fatigue strength by overloads in some cases.

Figure 4 (b) and (c) are the S-N curves of $\rho = 0.5$ and 1.0mm notched specimens, respectively. First, focusing on the results of in-air test, the fatigue strength increased with increase of notch root radius. The effect of overloads diminished with increase of notch root radius. That is, larger amplitude of overloads was necessary to cause the reduction of fatigue strength and the amount of reduction became smaller with increase of notch root radius.

The effect of hydrogen was significant in the case of $\rho = 0.2\text{mm}$ as well as $\rho = 0.5\text{mm}$, but it was not so in the case of $\rho = 1.0\text{mm}$. The effect of hydrogen had a dependency on notch root radius.

![Figure 4](image_url)

**Fig. 4** Effect of multiple overloads and hydrogen on fatigue strength of notched specimen of SUS304
Figure 5 shows the $S-N$ curves of SUS316L. The fatigue strength was reduced by overloads. The amount of reduction depended on overload amplitude as well as notch root radius. These trends were the same as those seen in SUS304. However, no reduction of fatigue strength due to hydrogen was seen in SUS316L. Rather, the fatigue strength was somewhat increased in hydrogen gas.

The relationship between fatigue limit and notch root radius is shown in Fig. 6 to summarize the effect of overloads and hydrogen on the fatigue limit. In both materials, the fatigue limit decreased with decrease of notch root radius. The amount of reduction of fatigue limit due to overloads became larger with increase of overload amplitude. SUS304 was susceptible to hydrogen, but SUS316L was insusceptible.

(a) $\rho = 0.2\text{mm}$

(b) $\rho = 0.5\text{mm}$

Fig. 5  Effect of multiple overloads and hydrogen on fatigue strength of notched specimen of SUS316L

(a) SUS304

(b) SUS316L

Fig. 6  Reduction of fatigue limit due to overloading and hydrogen

4. Discussions

4.1 Mechanisms causing reduction of fatigue strength by overloads and hydrogen

Fracture surfaces of run-out specimens were broken open by fatigue after heat tint. Figure 7 shows photographs of small cracks observed on the fracture surfaces of SUS304. The experimental condition of the observed specimens was also included in the figure. The specimens which were numbered ①, ② and ③ were uncharged specimen tested in air.
The specimen ④ was hydrogen charged specimen tested in hydrogen gas. While the specimen ① which had no reduction of fatigue limit by overloads had no cracks, the specimens ② and ③ which showed significant reduction of fatigue limit by overloads had small cracks. The overload amplitude was the same for the specimens ③ and ④, however, the fatigue limit of specimen ④ was more lowered than specimen ③. The size of small cracks was obviously larger in the specimen ④ than in the specimen ③.

Figure 8 shows a part of the results of the same observation on SUS316L. Similar to the results of SUS304, there are small cracks in the specimens in which the fatigue limit was substantially reduced by the application of overloads. As shown in Fig. 5, the fatigue limit
of SUS316L was not reduced by hydrogen. In the case of SUS316L there was no difference in crack size between hydrogen charged and uncharged specimens, while in the case of SUS304 hydrogen charged specimens had larger cracks than uncharged specimens. These observations led to the following conclusions. The reduction of fatigue limit due to overloads was caused by small cracks generated by overloads. The cause of lowered fatigue limit due to hydrogen was that the size of small cracks formed by overloads was larger in hydrogen charged specimen than in uncharged specimen.

The reduction of high-cycle fatigue strength has close relation to the length of small cracks. There are a lot of notches which have various shapes in hydrogen utilization machines. And there are wide variety of loading conditions such as overload amplitude and number of cycles of overloads depending on the earthquake as well as the shape of mechanical component. It is considered that comprehensive evaluation of crack growth at notch root during overloading is necessary.

As shown in Figs. 7 and 8, there were non-propagating cracks in some specimens. This implies that the high-cycle fatigue strength of those specimens is governed by whether small cracks propagate or not. On the other hand, there is a report in which the crack propagation threshold $\Delta K_{th}$ of small crack is reduced by absorbed hydrogen in cases of low alloy steels and carbon steels [7]. Therefore, there is a possibility that the reduction of $\Delta K_{th}$ of small cracks due to hydrogen would be one of the causes of the reduction of fatigue limit.

Figure 9 shows threshold stress intensity factor for crack propagation $\Delta K_{th}$ of the small cracks with respect to the crack length. In this figure, $\Delta K_{th}$ is $\Delta K$ of the non-propagating cracks as a consequence of the fact that the non-propagating cracks were found in the run-out specimens. As shown in the figure, there was no obvious difference in $\Delta K_{th}$ between hydrogen charged and uncharged specimens. In consequence, it can be presumed that the effect of hydrogen on $\Delta K_{th}$ is negligibly small in this study.

![Fig. 9 Comparison of $\Delta K_{th}$ between hydrogen charged and uncharged specimens](image)

4.2 Effect of hydrogen on propagation of small crack in low-cycle fatigue regime

According to the comparison between the specimen ③ and ④ shown in Fig. 7, hydrogen can have influence on the propagation of small cracks during overloading. Thus, crack propagation test at the stress level corresponding to the overload amplitude was performed to examine the effect of hydrogen on the propagation of small fatigue crack. Several notched specimens were prepared and different fatigue cycles were applied to each specimen. Small cracks were then observed after heat tint and break open by fatigue.

The comparison of crack propagation behavior between in-hydrogen gas test using hydrogen charged specimens and in-air test using uncharged specimens is shown in Fig. 10. In SUS304, the crack propagation was considerably faster due to the effect of hydrogen. On
the other hand, in SUS316L, no obvious change of crack propagation behavior was found. Therefore, one of the reasons why hydrogen enhanced the reduction of fatigue limit by overloads was the acceleration of crack propagation during overloading. In reference [8], hydrogen has some effect to reduce low-cycle fatigue strength. Extensive investigations concerning the effect of hydrogen on low cycle fatigue properties are required to ensure safety of hydrogen utilization machines.

![Graph](image1)

Fig. 10 Effect of hydrogen on propagation of small crack in low-cycle fatigue regime

### 4.3 Criterion for safety diagnosis of hydrogen utilization machine’s component suffered large earthquake

There are a lot of influencing factors on fatigue strength after multiple overloads in hydrogen gas such as number of cycles of overloads. While further studies are necessary on this subject, the authors tried to propose a criterion which assesses whether hydrogen utilization machines can be used continuously after the earthquake or not within the limited results.

Figure 11 shows the fatigue limit of each notch root radius with respect to overload amplitude. In this figure, the knee points of the lines show critical overload amplitudes that are not detrimental to fatigue strength after the application of overloads. In the case of SUS304, the knee points shifted with change of notch root radius. However, considering that it is difficult to estimate accurate overloading conditions for all components, the adoption of the lowest value as the critical overload amplitude is appropriate for the assessment. Thus, $0.5\sigma_{0.2}$ was appropriate to the criterion to prevent fatigue failure after the earthquake in the case of SUS304. The critical overload amplitude was determined as $0.75\sigma_{0.2}$ in the case of SUS316L.

![Graph](image2)

Fig. 11 Consideration of upper limit to permit continuous use of mechanical components of hydrogen utilization machines suffered large earthquake
5. Conclusions

Effects of multiple overloads and hydrogen on high-cycle fatigue strength of austenitic stainless steels SUS304 and SUS316L were investigated using three kinds of notched specimens. Fatigue strengths were compared between in-0.6MPa hydrogen gas test using hydrogen charged specimen and in-air test using uncharged specimen. The hydrogen concentration of hydrogen charged specimen was more than 60ppm. Reversed multiple overload was applied for 200cycles and high-cycle fatigue test was then performed using pulsating tension load. The results are as follows.

(1) Reduction of fatigue strength due to overloads occurred in both materials. The root cause of reduction was the small cracks introduced by overloads.

(2) In the case of SUS304, hydrogen enhanced the reduction of fatigue limit due to overloads. The primary cause of the enhancement was the formation of larger cracks during overloads by the effect of hydrogen.

(3) In SUS316L, hydrogen had no effect to enhance the reduction of fatigue limit by overloads.

(4) When the overload amplitude was 0.5 times the proof strength of material $\sigma_{0.2}$ or smaller, no reduction of high-cycle fatigue limit was caused by overloads as well as hydrogen in SUS304. The overload amplitude of $0.75\sigma_{0.2}$ or smaller caused no reduction of high-cycle fatigue limit in SUS316L.

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References


