ABSTRACT

A number of inspections have been performed to evaluate the structural integrity of components in Kashiwazaki-Kariwa Nuclear Power Plants after the Chuetsu-Oki Earthquake in Niigata, Japan. Those inspections include the evaluation of experienced plastic strain using the hardness tester. Structural materials are generally hardened by plastic strain, which means high cycle fatigue life increases with application of plastic strain, while reduces low cycle fatigue life. Since the earthquake causes larger applied stress, it is worthwhile to clarify the allowable plastic strain level which usage factor stands for low cycle fatigue life. Such investigations are also very important for determining the accuracy of detecting plastic strain levels.

Hardness tests and low cycle fatigue tests were performed to clarify the allowable strain level at which the low cycle fatigue life of pre-strained materials is not affected. The hardness of ferrite steel and austenitic stainless steel increased when the plastic strain was greater than 2-4%, while the low cycle fatigue life based on usage factor was not affected when the plastic pre-strain was less than 8%. These results suggest that the estimation of plastic strain from the materials hardness is sufficiently accurate for assessing the remaining fatigue life of the components in nuclear power plants.

INTRODUCTION

Numerous inspections following the Chuetsu-Oki Earthquake that struck Niigata Prefecture, Japan, in 2007 showed that the structural integrity of the nuclear components in the Kashiwazaki-Kariwa Nuclear Power Plant were not severely damaged. Nevertheless, the equipments and components, which designed to be seismic resistant were possibly subjected to excessive seismic load due to the unexpected high seismic acceleration. Residual plastic strain may have been introduced into the local part of the components even though deformation and failure were not detected by the visual inspections.

Structural materials are generally hardened by plastic strain, which means that high cycle fatigue life increases with the application of plastic strain. An increase in plastic pre-strain, however, reduces low cycle fatigue life. Appropriate inspection methods are thus needed for estimating plastic strain, and the allowable plastic strain level at which the low cycle fatigue life of pre-strained materials is not affected must be clarified. Such investigations are also very important for determining the accuracy of detecting plastic strain.

This study focused on the hardness of a component's material as a parameter for detecting plastic pre-strain. Hardness tests using austenitic stainless steel and ferrite steel were carried out by many kinds of hardness tester, and the optimal hardness inspection method was identified on the basis of the hardness test results and the operating conditions in actual nuclear power plants.

The material tests for austenitic stainless steel and ferrite steel were performed to clarify the effect of cyclic pre-strain on the mechanical properties and low cycle fatigue strength. Cyclic plastic pre-strain, which can be detected using a hardness inspection method, were introduced into the specimens prior to the tests. The accumulated damage caused by the cyclic pre-strain and fatigue test were estimated in terms of the usage factor, UF. This factor was shown by investigation to be a valid metric for cyclic pre-strained materials in the low-cycle fatigue region. The usage factor was found to be useful for estimating the residual fatigue life of cyclic pre-strained materials and thus useful for determining whether the components in a nuclear power plant can continue to be used after being subjected to an excessive load caused by an earthquake.
METHODS FOR DETECTING PLASTIC STRAIN

Preliminary examinations

There are several in situ non-destructive methods for plastic strain in the nuclear power plants field that do not moving the components.

- Those based on the hardness of the material surface.
- Those based on the metallographic change of the material surface. (e.g., micrographic observation of Luders band or slip band)
- Those based on the phase transformation of the material surface. (e.g., eddy current examination, x-ray diffraction method, ferrite measurement)
- Those based on stress state of the material surface. (e.g., x-ray diffraction method, magnetic anisotropy method, Barkhausen noise analysis, velocity ratio method)

Preliminary examinations of these methods showed that the hardness of a material correlate most closely with the plastic strain. More detailed examinations of three hardness measurement methods were then conducted.

Detailed examination of hardness measurement methods

Test material and hardness tester

Hardness tests using pre-strained ferrite steel and austenitic stainless steel were carried out to determine the most accurate hardness measurement method. The test materials were a) carbon steel SS400, b) low alloy steel SFVQ1A, and c) Type SUS316L austenitic stainless steel. All are commonly used in the nuclear power plants. The hardness measurements were done using a) a portable Vickers hardness tester, b) an ultrasonic hardness tester, and c) an impact-type (Equotip) hardness tester. Images of the testers are shown in Fig. 1.

The plastic pre-strain introduced into the materials up to 7%; the actual pre-strain was calculated from the distance of the gauge length. The surface of the material was finished by buffing to be consistent with condition in the actual power plants. The hardness was measured 30 times in one place. In addition, conventional Vickers hardness tests for a mirror-finish cross section of the each specimen were conducted in order to compare the hardness obtained using these three test methods and a conventional method.

![Images of Vickers hardness tests](image-url)
Test results

As shown in Fig. 2, the hardness derived from each measurement method was strongly correlated with the magnitude of the plastic pre-strain. An increase in the amount of the plastic pre-strain increases the hardness of the materials. The hardness measured with the portable Vickers and ultrasonic hardness testers were almost equal to those measured with a conventional Vickers hardness tester for each test material. The hardness measured with the impact hardness tester were slightly higher than with the conventional tester. The test results for each method varied depending on the type of steels and amounts of pre-strain.

Figure 2 - Relationship between Vickers hardness and pre-strain for each material.
The portable Vickers hardness tester gave the most nearest results to the conventional results. The ultrasonic hardness tester also gave near results to the conventional tester. The tester, however, has to be calibrated beforehand, and the results depend on the thickness of the material. The portable Vickers hardness tester is, therefore, the most appropriate of the three testers evaluated for estimating plastic pre-strain in nuclear power plant. Since an increase in hardness was clearly shown from 2-4% pre-strain, greater than 2-4% can be detected with this hardness tester.

**MECHANICAL AND LOW CYCLE FATIGUE STRENGTH OF CYCLIC PRE-STRAINED MATERIALS**

Manson\(^1\) proposed using the following equation to predict fatigue strength of steel.

\[
\Delta \varepsilon = 0.0266 \epsilon_f^{0.155} \left( \frac{\sigma_B}{E} \right)^{-0.53} N_f^{-0.56} + 1.17 \left( \frac{\sigma_B}{E} \right)^{-0.832} N_f^{-0.09},
\]

where, \(\Delta \varepsilon\) is strain range, \(\epsilon_f\) is true fracture ductility, \(N_f\) is number of cycle to failure, \(\sigma_B\) is tensile strength, \(E\) is Young's modulus. This equation is so-called *Modified Manson's equation*. The first term on the right governs low cycle fatigue life, and second governs high cycle fatigue life. When plastic pre-strain is introduced into the material, tensile strength, \(\sigma_B\) increases, leading to an increase in the high cycle fatigue strength of the material\(^2\)\(^3\). On the other hand, the ductility is reduced by the plastic pre-strain, leading to a decrease in the low cycle fatigue strength.

Mechanical and low cycle fatigue tests were performed to clarify the effect of cyclic pre-strain on the mechanical properties.

**Test materials and specimen**

The test materials here were Type SUS304, SUS316L and SUS316 nuclear-grade austenitic stainless steel and SFVQ1A, STS480, STPT410, SFVC2B and SS400 ferrite steel. All are used extensively in nuclear power plants. The dimensions of the test specimen are shown in Fig. 3. Hourglass-shaped specimens with a minimum diameter of 8 mm were used to prevent buckling due to compression during introducing of cyclic plastic pre-strain. The stress concentration factor, \(K_t\), was 1.05\(^3\).

![Figure 3 - Dimensions of test specimens (mm)](image-url)
Test methodology

The configuration of the machine used for tensile test and fatigue test shown in Fig. 4. Images of the testing are shown in Fig. 5. A hydraulic-servo fatigue-testing machine was used for introducing the cyclic pre-strain and for the tensile strength test and low cycle fatigue test. All tests were carried out using diameter displacement control. The axial true strain, $\varepsilon_{\text{axis}}$, during the tensile and fatigue test was calculated using the change in diameter:

$$\varepsilon_{\text{axis}} = -2 \cdot \ln \left( \frac{d}{d_0} \right) ,$$

where, $d_0$ is initial diameter and $d$ is diameter during the test. The elastic strain was neglected in this translation.

Table 1 and Table 2 show the test matrix for tensile and fatigue tests, and test procedures are illustrated in Fig. 6. The amplitudes of the cyclic pre-strain applied to the specimens were 2, 4 and 8%. The 2% pre-strain was the detection limit with the hardness measurement method. Fatigue tests with strain amplitudes shown in Table 2 were carried out after introducing constant cyclic pre-strain into the specimen in order to ascertain the validity of linear cumulative fatigue damage rule for pre-strained materials. The usage factor, $UF$, was calculated on the basis of the fatigue life for virgin material. The maximum $UF$ due to cyclic pre-strain was set to 0.2.

Tensile and fatigue test results

Effect of pre-strain on mechanical properties

Figures 7 and 8 show typical results for the cyclic pre-strain introduction and the tensile tests for austenitic stainless steel and ferrite steel. The pre-strain range was 16%
### Table 1 - Tensile test matrix for cyclic pre-strained materials

<table>
<thead>
<tr>
<th>Test material</th>
<th>No</th>
<th>Cyclic pre-strain (∆ε&lt;sub&gt;pre&lt;/sub&gt;(%))</th>
<th>Cycles</th>
<th>Strain rate of tensile test</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS316NG SFVQ1A</td>
<td>1</td>
<td>8</td>
<td>0.5-15</td>
<td>0.4%/s</td>
</tr>
<tr>
<td>SUS304 STPT410 SFVC2B STS480 SS400</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 - Fatigue test matrix for cyclic pre-strained materials

<table>
<thead>
<tr>
<th>Test material</th>
<th>No</th>
<th>Cyclic pre-strain (∆ε&lt;sub&gt;pre&lt;/sub&gt;(%))</th>
<th>Cycles</th>
<th>Strain range of fatigue test (∆ε&lt;sub&gt;fat&lt;/sub&gt;(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS316NG</td>
<td>1</td>
<td>16</td>
<td>0.25-2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>0.25-15</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>5-30</td>
<td>1</td>
</tr>
<tr>
<td>SUS304</td>
<td>1</td>
<td>16</td>
<td>0.75-2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>3.75-15</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>5-70</td>
<td>1</td>
</tr>
<tr>
<td>SUS316L</td>
<td>1</td>
<td>16</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SFVQ1A</td>
<td>1</td>
<td>16</td>
<td>0.25-2.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>0.25-15</td>
<td>2</td>
</tr>
<tr>
<td>STPT410 SFVC2B STS480 SS400</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 6 Test procedures.
Figure 7 - Example of cyclic pre-strain introduction and tensile test result for stainless steel (Type SUS304 stainless steel, $\Delta \varepsilon_{pre} = 16\%$, 2.5 cycles).

Figure 8 - An example of cyclic pre-strain and tensile test result for ferrite steel (STS480 steel, pre-strain range 16\%, 2.5 cycles).

and number of cycles was 2.5. The tensile strength of austenitic stainless steel was increased by the pre-strain, but the true fracture ductility decreased. The tensile strength of ferrite steel was increased slightly by the pre-strain, and the true fracture ductility was almost equal to that for non pre-strained material.

(a) Axial strain, $\varepsilon$ (%) Nominal stress, $\sigma_{nom}$ (MPa)

(b) Axial strain, $\varepsilon$ (%) Nominal stress, $\sigma_{nom}$ (MPa)
The relationships between mechanical properties (tensile strength and true fracture ductility) and usage factor UF for austenitic stainless steel and ferrite steel are summarized in Fig. 9 and 10. The UFs were obtained from a best-fit S-N curve for virgin materials, as described in a later section.

As shown in Fig. 9, the results for the SUS304 stainless steel were no difference from those for the SUS316NG stainless steel. An increase in the UF by introducing pre-strain increased the tensile strength and reduced the true fracture ductility. This is because austenitic stainless steel has remarkable work hardening characteristics. The difference between the results for virgin materials and for pre-strained material was 1.3 times for tensile strength and 0.8 times for true fracture ductility. These differences, however, are not significant in terms of structural strength.

Figure 10 demonstrates that the work hardening for ferrite steels is small compared with that for austenitic stainless steels. The tensile strength remained constant or increased slightly with increasing UF caused by cyclic pre-strain. The true fracture ductility remained constant or decreased slightly with increasing UF. These changes did not significantly affect the structural strength of these materials because the variations in the tensile strength and true fracture ductility of ferrite steels were smaller than those of austenitic stainless steels, as shown above.

**Effect of cyclic pre-strain on fatigue lives**

The fatigue test results for cyclic pre-strained austenitic stainless steels are shown Fig. 11. The results are almost equal to those predicted using Modified Manson’s equation (1) with tensile strength $\sigma_B = 618$ MPa, $\varepsilon_f = 2.11$ (reduction of area $\varphi = 0.879$) and Young’s modulus $E = 192$ GPa, as obtained from the inspection certificate for type SUS304 stainless steel. The S-N curve in Fig. 11(a) shows the relationship between the strain range and the equivalent number of cycles to failure. It reveals that, as long as the usage factor for cyclic pre-strain is not greater than 0.2 ($UF_{pre} \leq 0.2$), the reduction in the fatigue life is very small. Figure 11(b) shows the relationship between $UF_{pre}$ and $UF_{total}$ ($= UF_{pre} + UF_{post}$), where $UF_{post}$ is the usage factor for the fatigue test. These usage factors were calculated on the basis of the best-fit S-N curve for fatigue test. The error in $UF_{total}$ ranged from 0.7 to 1.4, almost equal to that for virgin material.

Fatigue cracks for all specimens were initiated from the material surface. Though the fatigue tests were carried out in the same strain range, the stress range for the cyclic pre-strained materials was much larger than that for the virgin material. The total fatigue lives, however, were nearly equal, suggesting that the fatigue life in the low cycle range is governed by the strain range.
The fatigue test results for cyclic pre-strained ferrite steel are shown in Fig. 12. These results also are equal to those predicted using the modified Manson's equation (1) with tensile strength $\sigma_B = 475$ MPa, $\varepsilon_f = 1.03$ (reduction of area $\varphi = 0.642$) and Young's modulus $E = 202$ GPa, as obtained from the inspection certificate for STPT410 steel. The S-N curve in Fig. 12(a) shows the relationship between the strain range and the equivalent number of cycles to failure. There was very little reduction in the fatigue life of the cyclic pre-strained material for $\text{UF}_{pre} \leq 0.2$. Figure 12(b) shows the relationship between $\text{UF}_{pre}$ and $\text{UF}_{total}$. The $\text{UF}_{total}$ for pre-strained ferrite steel calculated on the basis of the best fit S-N curve for virgin material was almost equal to 1, and the error in $\text{UF}_{total}$, ranged from 0.7 to 1.4. This range is almost equal to that for non pre-strained ferrite steels.

All fatigue cracks were initiated from the material surface. During the fatigue tests, unlike the austenitic stainless steels, the same hysteresis loops of stress and strain were drawn whether or not there was pre-strain.

The S-N curve results demonstrated that the estimation of fatigue life by using the usage factor is valid not only for virgin materials but also for the plastic pre-strained austenitic stainless steel and ferrite steel for $\text{UF}_{pre} \leq 0.2$. In addition, fatigue test results revealed that materials pre-strained by a seismic load still have sufficient margins to meet the fatigue life.

In the previous section, the hardness was found to be increase when plastic strain was greater than 2-4%. The low cycle fatigue life, however, was not affected by a cyclic plastic pre-strain less than 8%. The plastic strain on the basis of hardness, therefore, is sufficiently accurate for use in assessing the remaining fatigue life of components.
SUMMARY

Hardness tests using austenitic stainless steel and ferrite steel were carried out to identify the most appropriate method for estimating plastic pre-strain in nuclear power plant components that have been subjected to an excessive seismic load. A method using a portable Vickers hardness tester was determined to be the most appropriate on the basis of the hardness test results and the working conditions in actual nuclear power plants.

Tensile and low cycle fatigue tests were performed to evaluate the effect of cyclic pre-strain on the mechanical properties and fatigue life of pre-strained materials. An increase in the pre-strain was found to increase tensile strength and reduce true fracture ductility. The differences in these mechanical properties, however, were not significant in terms of structural strength.

Estimation of the fatigue strength by using usage factor was found to be useful for the pre-strained materials for $UF_{pre} \leq 0.2$. The fatigue test results suggested that the pre-strained materials with $UF_{pre} \leq 0.2$ have sufficient margin for fatigue life.

The hardness was found to be increase when plastic strain was greater than 2-4%. However, the low cycle fatigue life was found not to be affected by a cyclic plastic pre-strain less than 8% for both ferrite steel and austenitic stainless steel. The plastic strain on the basis of hardness therefore is sufficiently accurate for use in assessing the remaining fatigue life of components.

The strain introduced into the main components of Kashiwazaki-Kariwa Nuclear Power Station by the Chuetsu-Oki Earthquake has been estimated to be quite small so far. The results of this study indicate that the main components still have sufficient mechanical and fatigue strength for them to continue to be used.

ACKNOWLEDGEMENT

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REFERENCES