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Effect of strain-induced martensitic transformation on fatigue behavior of type 304 stainless steel

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Abstract

The present paper describes the effect of prestrain on fatigue behavior in type 304 stainless steel. Rotating bending fatigue tests have been conducted in laboratory air and in 3\%NaCl solution using specimens subjected to the tensile-prestrains of 15\%, 30\% and 60\%. A particular attention was paid to the strain-induced martensitic transformation during stress cycling. The fatigue strength of the prestrained specimens increased with increasing prestrain in laboratory air, but decreased significantly in 3\%NaCl solution compared with in laboratory air. The strain-induced martensitic transformation occurred in the prestrained specimens, and martensite phase increased with increasing prestrain and with stress cycling at the fatigue limit stress in the 30\% and 60\% prestrained specimens. The coaxing effect took place remarkably in the unprestrained specimen, but decreased with increasing prestrain. The increase in fatigue strength of the prestrained specimens in laboratory air and the coaxing effect were attributed to both work hardening and the strain-induced martensitic transformation, where the contributions of the former and the latter decreased and increased with increasing prestrain, respectively. Since corrosion pits were observed at the crack initiation site in the large prestrained specimens, the decrease in fatigue strength in 3\%NaCl solution was due to larger environmental susceptibility of martensite phase.

Key words: Fatigue; Corrosion Fatigue; Strain-induced Martensitic Transformation; Type 304 Stainless Steel; Coaxing Effect; Prestrain

1. Introduction

18Cr-8Ni austenitic stainless steels are widely used as structural components in machines and structures owing to good toughness, ductility and resistance to corrosion. However, austenitic phase in 18Cr-8Ni austenitic stainless steels obtained by solution treatment is metastable due to less Cr-Ni content, as seen in constitution diagram [1]. Therefore they are known to develop the strain-induced martensitic transformation caused by lower stability of austenitic phase, when they are subjected to plastic deformation [2]. In addition, various machine/structures are usually subjected to some plastic deformation during fabrication process. When such machine/structures are used in service, the strength of machine/structures may be influenced by the extent of plastic deformation.
Type 304 steel is the typical one of 18Cr-8Ni austenitic stainless steels and is known to exhibit remarkable work-hardening [3], thus prestrained type 304 steel would be expected to behave in different manner from unprestrained one and other materials under cyclic loading. Not only work hardening but also martensitic transformation due to prestrain is seen in type 304 steel. However the effect of prestrain on fatigue behavior in type 304 steel, which may undergo work-hardening and martensitic transformation, is unclear. Therefore, the purpose of the present study is to clarify the effect of prestraining on fatigue behaviour of type 304 steel. Several tensile prestrain levels up to the strain corresponding to tensile strength were evaluated.

2. Experimental Procedures

2.1. Material and Specimen

The material used was a type 304 austenitic stainless steel. The chemical composition of the material (wt %) is listed in Table 1. The material was solution-treated at 1353K for 60min. The mechanical properties after solution treatment are given in Table 2. After solution treatment, several tensile prestrains from 15% to 60% were applied to the material. Hourglass-shape fatigue specimens with a reduced section of 5mm diameter were machined as shown in Fig.1. The specimen surface was mechanically polished by emery paper and then buff-finished before experiment. Hereafter, the materials subjected to prestrain are designated as the prestrained specimens, e.g. the 30% prestrained specimen for 30% prestrain, and the material not subjected to prestrain is referred to as the unprestrained specimen. The microstructures of the unprestrained and prestrained specimens are shown in Fig.2 (a)-(d). Slip bands are extensively recognized in the grains of the prestrained specimens, which increase significantly with increasing prestrain.

<p>| Table 1. Chemical composition (wt.%) |</p>
<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.26</td>
<td>1.73</td>
<td>0.034</td>
<td>0.025</td>
<td>8.01</td>
<td>18.64</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

| Table 2. Mechanical properties |
|---|---|---|---|
| Proof stress | Tensile strength | Elongation | Reduction of area |
| $\sigma_{0.2}$ (MPa) | $\sigma_{B}$ (MPa) | $\delta$ (%) | $\phi$ (%) |
| 225 | 552 | 66 | 79 |

Fig. 1. Specimen configuration

Fig. 2. Microstructures of unprestrained and pre-strained materials: (a) unprestrain; (b) 15% prestrain; (c) 30% prestrain; (d) 60% prestrain

2.2. Procedure

Two types of fatigue tests, conventional constant amplitude test and stress-incremental test, were performed using cantilever-type rotating bending fatigue testing machine operating at a frequency of 53Hz in laboratory air. Conventional fatigue tests were also conducted in 3%NaCl solution whose temperature was 30°C. Under stress-incremental tests [4], experiments were started at a stress level of 20MPa below the fatigue limit, $\sigma_{w}$. When
specimens did not fail until $10^7$ cycles, then stress level was increased by 20MPa. This procedure was repeated until fatigue failure took place. Crack initiation was monitored by replicating technique just before stress level was increased. After experiment, fracture surfaces were examined in detail using a scanning electron microscope (SEM). Martensitic transformation was detected by X-ray diffraction method with the target of Cr-Kα. Measured diffraction planes of austenitic phase ($\gamma$) and martensitic phase ($\alpha$) were $\gamma$ (220) and $\alpha$ (211), respectively.

3. Experimental Results

3.1. Hardness Measurement

Vickers hardness of the prestrained specimens was measured. The results obtained are shown in Fig.3 as a function of prestrain. It can be seen that the hardness increases with increasing prestrain. The hardness values of the unprestrained and prestrained specimens are HV166 (unprestrain), HV236 (15% prestrain), HV286 (30% prestrain) and HV347 (60% prestrain), where the increases in hardness to the unprestrained specimen are 42%, 72% and 109% in the 15%, 30% and 60% prestrained specimens, respectively.

3.2. Fatigue Strength

The S-N diagram obtained in laboratory air and in 3%NaCl solution is shown in Fig.4. As can be seen in the figure, fatigue strengths in laboratory air increase with increasing prestrain. The fatigue limits of the unprestrained, 15%, 30% and 60% prestrained specimens are 250MPa, 320MPa, 420MPa and 480MPa, respectively. The increases in fatigue limit to the unprestrained specimen are 28%, 68% and 92% in the 15%, 30% and 60% prestrained specimens, respectively. In addition, non-propagating cracks are not recognized in run-out specimens at $10^7$ cycles [5]. On the other hand, fatigue strengths in 3%NaCl solution also increase with increasing prestrain, but are significantly reduced compared with those in laboratory air. The fatigue strengths at $10^7$ cycles in the 15%, 30% and 60% prestrained specimens are 280MPa, 320MPa and 320MPa, respectively. The reductions in fatigue strength increase with increasing prestrain, where they are 13%, 24% and 33% relative to the unprestrained specimen in the 15%, 30% and 60% prestrained specimens, respectively.

The fatigue strength at $10^7$ cycles of the unprestrained specimen is slightly higher in 3%NaCl solution than in laboratory air. Since the internal friction and the heat conductivity in austenitic stainless steels are larger and less compared with other alloys, respectively, temperature rise of specimen takes place under cyclic loading. Therefore, the increase in fatigue strength in 3%NaCl solution seems to be due to the cooling effect of the solution [6]. On the other hand, the decrease in fatigue strength of the prestrained specimens may be due to the effect of corrosion.

Fig. 3. Vickers hardness as a function of prestrain

Fig. 4. S-N curves in laboratory air and in 3%NaCl solution
3.3. Fractography

SEM micrographs of the crack initiation site in laboratory air and in 3%NaCl solution are shown in Figs. 5 and 6, respectively. Although Fig. 5 (a) and (b) reveal the crack initiation sites of the 15% and 30% prestrained specimens, respectively, the cracks in laboratory air were generated due to cyclic slip deformation in all specimens. Fracture surfaces near the crack initiation site are flat and ductile feature. In 3%NaCl solution, on the other hand, a ductile facet is seen at the crack initiation site in the unpretrained and 15% prestrained specimens, while cracks were generated from corrosion pit in the 30% and 60% prestrained specimens as shown in Fig. 6 (a) and (b). This suggests that the crack initiation was affected significantly by environmental sensitivity of martensite phase.

3.4. Change in Volume Fraction of Martensite with Cyclic Loading

When metastable austenitic stainless steels are subjected to plastic deformation, the strain-induced martensitic transformation may occur. The amount of transformed martensite phase with cyclic loading was measured by X-ray diffraction method. The measurements were performed at the stress level of fatigue limit. Figure 7 shows the change in volume fraction of martensite phase as a function of number of cycles. The initial volume fractions of the unprestrained, 15%, 30% and 60% prestrained specimens are 3.5%, 4%, 5.5% and 8.4%, respectively, i.e., they increase with increasing prestrain. As seen in the figure, the martensite volume fractions of the unprestrained and 15% prestrained specimens hardly change during stress cycling, while the 30% and 60% prestrained specimens show a remarkable increase of martensite volume fraction in the region of \( N > 10^6 \) cycles. The martensite volume fractions of the unprestrained, 15%, 30% and 60% prestrained specimens after \( 10^7 \) cycles are 3.1%, 5.9%, 13% and 15.3%, respectively. It is considered that the martensite phase detected in the unprestrained specimen may be caused by the machining and surface polishing.

Fig. 5. Crack initiation sites in laboratory air: (a) 15% prestrain \((\sigma_{s}=340\text{MPa}, N_f=2.5\times10^5)\); (b) 30% prestrain \((\sigma_{s}=440\text{MPa}, N_f=1.7\times10^5)\)

Fig. 6. Corrosion pits observed at crack initiation site: (a) 30% prestrain \((\sigma_{s}=340\text{MPa}, N_f=1.3\times10^5)\); (b) 60% prestrain \((\sigma_{s}=380\text{MPa}, N_f=1.2\times10^5)\)

Fig. 7. Change in volume fraction of martensite phase with stress cycling at a stress level of fatigue limit
3.5. Stress-incremental Test

Effect of strain-induced martensitic transformation on the coaxing effect was examined. From material reasons (lack of material), the different SUS304 was used in stress-incremental tests. The chemical composition (wt. %) of the material was as follows; C:0.06, Si:0.32, Mn:1.35, P:0.04, S:0.02, Ni:8.38, Cr:18.3, Fe:bal.. Because of this alteration of the material, the fatigue limits of the unprestrained and pretrained specimens were changed, i.e., fatigue limits of the unprestrained, 30% and 60% pretrained specimens were 300MPa, 440MPa and 470MPa, respectively. Figure 8 shows the stress-incremental test results. The failure stresses of all specimens increase compared with the fatigue limits, indicating that the coaxing effect occurs remarkably regardless of prestrain level. The failure stresses of the unprestrained, 30% and 60% pretrained specimens are 540MPa, 620MPa and 670MPa, respectively. The increases in the failure stress to the fatigue limit are 73%, 36% and 38% in the unprestrained, 30% and 60% pretrained specimens, respectively. Crack initiation was monitored when stress level was increased, but cracks were not detected in all specimens.

4. Discussions

4.1. Increase in Fatigue Strength Caused by Prestraining

According to the results, the hardness, the fatigue strengths in laboratory air and the martensite volume fraction increase with increasing prestrain (Fig.3, 4 and 7). In addition, the martensite volume fractions of the pretrained specimens also increase during stress cycling. These results indicate that the increase in fatigue strength by prestraining is attributed to work hardening and strain-induced martensitic transformation. Figure 9 shows the increase in fatigue limit caused by prestraining in SUS304 and SUS316 [7]. It is well known that the strain-induced martensitic transformation is hardly observed in SUS316, because of the higher stability of austenite phase. As can be seen in the figure, the increases in fatigue limit are similar below 20% prestrain between both steels, but above that prestrain level, they are significantly larger in SUS304 than in SUS316. Since the strain-induced martensitic transformation hardly occurred in SUS316, it is suggested that the increase in fatigue limit of the pretrained specimens of SUS304 may be attributed to the martensitic transformation.

It is known that there exists the relationship between the fatigue limit, $\sigma_w$, and Vickers hardness, $HV$, i.e., the following equation has been obtained [8];

$$\sigma_w = 1.6 \times HV$$  \hspace{1cm} (1)

Figure 10 indicates the relationship between $HV$ and $\sigma_w$, where the scatter band is shown by dotted line. The results are on the lower bound of the scatter band, indicating lower fatigue limit than that estimated by hardness.
4.2. Mechanisms of the coaxing effect

When steels are subjected to step-wise stress cycling started from a stress level just below the conventional fatigue limit, they are strengthened, which is known as the coaxing effect [4]. As possible mechanisms for the coaxing effect, work hardening, strain aging and strengthening at the tip of non-propagating cracks have been proposed [4,9,10], but the effect of prestrain on the coaxing effect in austenitic stainless steels is unclear. While strain aging should be considered, SUS304 showed no strain aging ability. In addition, non-propagating cracks were not detected until failure stress was reached. Thus, it is concluded that the coaxing effect of SUS304 is affected by neither strain aging nor strengthening at the tip of non-propagating cracks. On the other hand, work hardening and strain-induced martensitic transformation would be the expected mechanisms of the coaxing effect [11,12].

After stress-incremental tests, Vickers hardness of failed specimens was measured. The obtained results are given in Table 3, in which the hardness values before experiments are slightly different from the results in Fig.3, because of the different SUS304 (see section 3.5). The increases in hardness before and after experiments were 60%, 31% and 7% in the unprestrained, 30% and 60% prestrained specimens, respectively, i.e., they decrease with increasing prestrain. Based on these results, it is considered that work hardening occurred during stress-incremental tests in the unprestrained specimen, while in the prestrained specimens that work hardened by prestraining, the increase in hardness becomes smaller. This implies that the work hardening ability and the influence of work hardening on the coaxing effect decrease with increasing prestrain.

The volume fraction of martensite phase was measured by X-ray diffraction method during stress-incremental test. Figure 11 shows the change in martensite volume fraction as a function of stress amplitude during stress-incremental tests. As seen in the figure, the martensite volume fraction of the unprestrained specimen begins to increase at a stress level of 420MPa and then increase remarkably with increasing stress level. On the other hand, the 30% and 60% prestrained specimens show a small amount of martensite phase at an initial stress level of 420MPa and 450MPa, respectively, and indicate an increase in martensite volume fraction with increasing stress level. The initial martensite volume fractions in Fig.11 are slightly different from those in Fig.7, because the different SUS304 was used (see section 3.5). Based on the results, the strain-induced martensitic transformation may occur at stress levels above 420MPa in all specimens. Therefore, it is considered that the strain-induced martensitic transformation significantly affects the coaxing effect.

4.3. Decrease in fatigue strength in 3%NaCl solution

As can be seen in Fig.4, fatigue strengths in laboratory air increased with increasing prestrain, while in 3%NaCl solution fatigue strengths significantly reduced in comparison with those in laboratory air, except for the unprestrained specimens. Figure 12 shows the reduction in fatigue strength at 10^7 cycles relative to fatigue limit in

<table>
<thead>
<tr>
<th>Prestrain (%)</th>
<th>Unprestrain</th>
<th>30</th>
<th>60</th>
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<tbody>
<tr>
<td>Before experiment</td>
<td>192</td>
<td>247</td>
<td>335</td>
</tr>
<tr>
<td>After experiment</td>
<td>307</td>
<td>323</td>
<td>357</td>
</tr>
<tr>
<td>Increased ratio (%)</td>
<td>60</td>
<td>31</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3. Vickers hardness before and after stress-incremental test

Fig. 10. Relationship between fatigue limit and Vickers hardness
laboratory air as a function of prestrain. The reductions in fatigue strength increase with increasing prestrain where they are 13%, 24% and 33% in the 15%, 30% and 60% prestrained specimens, respectively.

From SEM observations of the crack initiation site in 3%NaCl solution, a ductile facet was seen in the unpretreated and 15% prestrained specimens. On the other hand, in the 30% and 60% prestrained specimens, cracks were generated from corrosion pit (see Fig.6). Since martensite phase is inferior to austenite phase in corrosion property [13], it seems that anodic dissolution took place in the 30% and 60% prestrained specimens that contain a significant amount of martensite phase. This suggests that the corrosion fatigue behavior of SUS304 is affected by environmental sensitivity of martensite phase.

5. Conclusions

In the present study, the influence of strain-induced martensitic transformation on the fatigue behaviour of metastable austenitic stainless steel, SUS304, was investigated. Rotating bending fatigue tests were conducted in laboratory air and in 3%NaCl solution using specimens subjected to the tensile-prestrains of 15%, 30% and 60%.

The results obtained are as follows;

1. Fatigue strengths in laboratory air increased with increasing prestrain. The fatigue limits of the unprestrained specimens, the 15%, 30% and 60% prestrained specimens were 250MPa, 320MPa, 420MPa and 480MPa, respectively. Non-propagating cracks were not observed in the run-out specimens at 10^7 cycles.

2. In 3%NaCl solution, fatigue strength also increased with increasing prestrain, but significantly reduced in comparison with those in laboratory air. The fatigue strengths at 10^7 cycles in the 15%, 30% and 60% prestrained specimens were 280MPa, 320MPa and 320MPa, respectively. The fatigue strength at 10^7 cycles in the unprestrained specimen increased in 3%NaCl solution due to the cooling effect of the solution.

3. The amount of transformed martensite phase increased with increasing prestrain. The martensite volume fractions of the unprestrained and 15% prestrained specimens hardly changed during stress cycling, while the 30% and 60% prestrained specimens showed a remarkable increase of martensite volume fraction in the region above 10^7 cycles.

4. The remarkable coaxing effect was seen in the unprestrained specimens compared to the prestrained specimens. The increases in the failure stress to the fatigue limit in the unprestrained, 30% and 60% prestrained specimens were 73%, 36% and 38%, respectively. Work hardening and the strain-induced martensitic transformation were the possible mechanisms of the coaxing effect. The influence of work hardening on the coaxing effect decreased...
with increasing prestrain, while the strain-induced martensitic transformation in stress-incremental tests was seen at the stress levels above 420MPa in all specimens.

(5) From SEM observations of the crack initiation site in 3%NaCl solution, corrosion pits were seen at the crack initiation site in the 30% and 60% prestrained specimens. Since martensite phase was inferior to austenite phase in corrosion property, anodic dissolution took place in the 30% and 60% prestrained specimens that contain significant amount of martensite phase. This suggests that the corrosion fatigue behavior of SUS304 was affected by environmental sensitivity of martensite phase.

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