Low Cycle Fatigue Life Estimation of Stainless Steel

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Abstract: The purpose of this study is to propose an effective procedure to predict the low cycle fatigue life of stainless steel products. By using the cantilever type rotational bending fatigue tester, the low cycle fatigue behavior of stainless steel was evaluated. In order to confirm the obtained low cycle fatigue behavior is correct, the fatigue life prediction of drilled flat bar specimen under cyclic four points bending load was conducted. Test results showed that the low cycle fatigue characteristics could be evaluated by developed fatigue tester. Moreover, the fatigue life of flat bar specimen was well predicted by the Miner’s Cumulative Damage Rule. Test results showed that the low cycle fatigue characteristics could be evaluated by developed fatigue tester. Moreover, the fatigue life of flat bar specimen was well predicted by the proposed procedure.

Keywords: Fatigue life, Strain amplitude, Plastic deformation, Fatigue test, Stainless steel, Low cycle fatigue

1. Introduction

From the earliest times, material testing has been conducted for selecting a material for an appropriate application based on its mechanical strength. Mechanical strength of materials could be classified by its type of load applying during test, such as quasi-static load, dynamic load, and cyclic load, so on. Mechanical engineers and designers should be considered the material behavior under not only the quasi-static loading, but also under cyclic loading has to be considered. Under cyclic loading, the progressive and localized structural damage have occurred and strength of materials has degraded compared with that under quasi-static load. This strength degradation behavior with respect to number of cyclic load applied to specimen is known as the fatigue behavior of materials.

Generally, fatigue behavior of materials could be classified into two part, high cycle fatigue and low cycle fatigue. At high cycle fatigue, the specimen is subjected to primarily elastic cyclic deformation and its fatigue life is exceeding more than $10^8$ cycles. In high-cycle fatigue, the fatigue behavior of materials is commonly characterized by the magnitude of cyclic applied stress $(S)$ against the logarithmic scale of cycles to failure $(N)$, called as $S$-$N$ curve [1]. When applying the stress exceeds elastic limit of materials, the cyclic plastic deformation is occurred during test, and type of fatigue changes high cycle fatigue to low cycle fatigue. In order to evaluate the low cycle fatigue behavior of materials, the local strain approach was developed in the 1950s [2]. L. F. Coffin [3] and S. S. Manson [4] revealed that the plastic strain amplitude was governing the low cycle fatigue region, and proposed an effective equation known as Coffin-Manson law. For ensuring the safety and reliability of structure, the evaluation of low cycle fatigue characteristics and prediction of fatigue life is important. Therefore, a lot of previous studies were conducted to reveal the low cycle fatigue behaviors. For example, at stainless steel products, the effect of test temperature [5], cold work effect [6] or creep [7] on its low cycle fatigue behaviors were studied. However, most of studies characterized the fatigue behavior under the cyclic tensile-compression load. For easy and faster evaluation of low cycle fatigue characteristics, the cantilever type rotational bending fatigue tester is newly developed.

The purpose of this study is to reveal the effectiveness of developed tester by obtaining the low cycle fatigue behavior of stainless steel. By using developed tester, the constant deflection was applied to the tip of specimen while it’s rotating at constant rotational speed. The number of revolutions till failure was defined as the fatigue life of specimen. In order to confirm the obtained low cycle fatigue characteristics, the fatigue life prediction of drilled flat bar specimen with small drilled holes under cyclic four points bending load was conducted.

2. Material and Methods

2.1 Material

In this study, the martensitic stainless steel (JIS-SUS431) was used as raw material. The chemical compositions of raw materials are described in Table1. In order to obtain the controlled micro structure, a raw material of 16 mm round bar was quenched and tempered by using furnace. The conditions for quenching and tempering were shown in Table 2. After heat treatment, the round bar was cut into specified length and machined to specimen.

| Table 1 Chemical compositions of material (wt%) |
|-------------------|---|---|---|---|---|---|---|---|---|---|
| C     | Si   | Mn   | P   | S    | Ni   | Cr   | Mo  | Cu  |
| 0.140 | 0.296| 0.643| 0.0245| 0.0038| 1.280| 15.208| 0.070| 0.105|

| Table 2 Condition for heat treatment |
|-------------------|---|---|---|---|
| Quenching  | 1020°C | 60min | Gas quench |
| Tempering   | 580°C  | 210min | Oil Cooling |
| Stress relief| 550°C  | 180min | Air Cooling |

2.2 Configurations of specimens

In this study, two types of fatigue tests were conducted. For evaluate the low cycle fatigue characteristics, the cantilever type rotational bending fatigue test was conducted. For demonstrating the fatigue life prediction,
four point bending fatigue test was also conducted. Figures 1 and 2 shows the dimensions of specimens for each fatigue tests. For rotational bending fatigue test, the hourglass type specimen was prepared. In this study, to uniform the bending strain along test section, the diameter of test section was tapered along axial direction. For four point bending fatigue test, the coupon type specimen was also prepared. In order to promote the strain concentration and to control the fracture region, the five of small holes along thickness (Φ0.4 THRU) and width (Φ2 THRU) direction were machined at the center portion of specimen. In order to eliminate the effect of surface roughness on the fatigue life, the test section of both specimens were polished by emery paper.

2.3 Rotational bending fatigue test
For avoiding the buckling during fatigue test, the rotational bending fatigue test was newly developed and used to investigate the low cycle fatigue characteristics. Figure 3 shows the schematic illustration of fatigue tester used in this study. The specimen was set to the collet type chuck and rotated by AC motor at specified rotational speed of 100 rpm. By applying the constant deflection to the other end of specimen, the bending strain was applied to the test section. By rotating the specimen, the sinusoidal tensile-compressive strain was repeatedly applied to the test section. The deflection of specimen was measured by laser displacement meter and number of rotations of specimen was also measured by rotary encoder. In this study, the number of rotations until specimen failure was defined as the number of cycles to failure. To investigate the low cycle fatigue characteristics, the applied deflection to the specimen was controlled to be 6, 7, 8, 9 and 12 mm. At least 2 specimens were tested for each condition.

2.4 Four point bending fatigue test
The low cycle fatigue life prediction by using fatigue characteristics obtained by rotational bending fatigue test was demonstrated by four point bending type fatigue test. Figure 4 shows the schematic illustration of fatigue tester used in this study. The specimen was set to the tester by using the outer fixed support block and inner moving support block. The inner moving support block was connected to the ball screw driven by motor. By moving the inner support block, the four point bending deformation was applied to the specimen. The inner support length and outer support length were set to 30 mm and 90 mm, respectively. The deflection of specimen was measured by laser displacement meter to feedback control the motor rotation by computer. To obtain the smooth contact between supports and specimen, the miniature ball bearings which outer diameter is 10mm was used as supports. During test, the surface of specimen around small hall was observed by camera.

2.5 Elasto-plastic analysis of specimen
For investigating the plastic strain change during both of bending tests, elasto-plastic analysis was performed by commercial finite element code. For rotational bending test, the full of specimen was modeled and forced displacement was applied to its tip as deflection. While applying deflection, the forced rotation was also applied to the specimen to calculate the plastic strain variation during test. On the other hand, the calculation model for four point bending test was consisted of 1/4 of specimen contacted with rigid four supports as shown in figure 5. In this analysis, 3-dimensional elasto-plastic behavior was considered for the specimen, while support was modeled to 3-dimensional rigid surface. The symmetric condition was also considered in width and longitudinal direction for the specimen. To obtain the smooth strain distribution
3. Results and Discussions

3.1 Results of rotational bending fatigue test

Figure 7 shows the measured and calculated bending strain amplitude with respect to applied deflection. Test results showed that the strain amplitude was almost linearly increased with increase of applied deflection. By using the obtained relationship between bending strain and applied deflection, the controlled deflection was applied to the specimen. In this study, 0.6, 0.7, 0.8, 0.9, and 1.2% of total bending strain amplitude was applied to the specimen during fatigue test. Figure 8 also shows the calculated result of plastic strain distributions along test section. Here, the start of R16 section of specimen was referred as the origin. Because of changing the diameter of test section as taper, the almost uniform bending strain was confirmed when applied deflection less than 12 mm. In this study, to eliminate the effect of distribution along test section, the average of the calculated plastic strain among test section was used to calculate the plastic strain amplitude during rotation. For fatigue life prediction, the test results were tried to fit to Coffin-Manson law given by following equation.

\[ \frac{\Delta \varepsilon_p}{2} = \varepsilon_{f}'(2N_f)^C \]  

Here, \( \Delta \varepsilon_p \), \( \varepsilon_{f}' \), \( 2N_f \), and \( C \) denote the plastic strain range, fatigue ductility coefficient, number of reversals to failure, and fatigue ductility exponent. The plastic strain range was simply calculated by subtracting the minimum plastic strain from maximum plastic strain during rotation. Figure 9 shows the relationship between calculated plastic strain amplitude with respect to number of cycles to failure. In this figure, fitted Coffin-Manson law was also indicated by dotted line. Calculated results showed that the fatigue life of specimens was well explained by Coffin-Manson law. These results also suggested that the low cycle fatigue characteristics could be evaluated by developed tester.

![Fig.5 Analysis model for four point bending test](image1)

![Fig.6 True stress-strain curve of SUS431](image2)

![Table3 Material constant for calculation](image3)

<table>
<thead>
<tr>
<th>Elastic Modulus [GPa]</th>
<th>Poisson's ratio</th>
<th>Elastic limit [MPa]</th>
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<tr>
<td>220</td>
<td>0.27</td>
<td>700</td>
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![Fig.7 Resultant total strain amplitude with respect to applied deflections](image4)

![Fig.8 Calculated plastic strain distributions along axial direction at surface of specimen](image5)
3.2 Results of four point bending fatigue test

Figure 10 shows typical results of applied deflection against reaction force during specific number of cycles at fatigue test. Here, N=538 shows the endurance life in which crack opening was obviously confirmed. Figure 11 also shows the microscopic observations around small hole machined at center portion at corresponding number of cycles with Figure 10. According to the number of cycle increases, the decrement of reaction force and the tiny cracks around small hole were confirmed at N=200. Figure 12 shows the calculated normal strain distribution around small hole at specified deflection that applied in the test. The strain concentration around small holes was confirmed and its distribution was almost coincident with the position where tiny cracks were observed during test. Considering symmetrical condition, the strain concentration was confirmed in the direction of 1, 5, 7, and 11 O’clock. As the increase of number of cycles (N=538), the tiny crack in the direction of 1 and 5 O’clock were selectively propagated while tiny crack in the direction of 7 and 11 O’clock were not propagated. Moreover, because of crack propagation, the crack openings of non-propagated tiny cracks were seemed to be closed and barely visible by camera. The similar crack propagations were observed not only at center hole, but also at other 4 holes. Because of the spacing of small holes (2 mm) is relatively larger than the diameter of small holes (φ0.4 mm), the each cracks from edge of small holes might had been simultaneously propagated.

Figure 13 also showed the SEM observation of fractured surface of specimen. Due to excessive plastic deformation, the shrinkage in thickness direction was confirmed at the surface of specimen. The parallel series of small grooves, known as striation was confirmed at magnified observation. These results suggested that failure
mode of specimen could be classified into low cycle fatigue manor. Almost same results were obtained when applied deflection was controlled to be ±1.4 and 1.6 mm.

3.3 Fatigue life prediction
The cyclic bending deformation was applied to the model to investigate the strain change during four point fatigue test. Figure 14 also shows the calculated time history of normal plastic strain at edge of small holes and applied deflection. Calculated results showed that the plastic strain at edge of small hole was changed trapezoidally, while applied deflection was changed triangularly. By using the calculated normal plastic strain amplitude and fitted Coffin-Manson law given by 3.2, the fatigue life of flat bar specimen was estimated. In this study, by considering the periodical configuration of small holes, the fatigue life estimation was done by only at the center hole. Figure 15 shows the comparison of predicted fatigue lives and experimental results, and it shows the predicted results shows good agreements between experimental results. These results indicated that the low cycle fatigue properties characterized by using rotational bending tester is useful to predict the actual low cycle fatigue life of products.

4. Conclusions
In this study, the low cycle fatigue characteristics of stainless steel was evaluated by cantilever type rotational bending fatigue tester, and fatigue life prediction based on obtained fatigue characteristics was conducted. The following conclusions were given as.

[1] The low cycle fatigue characteristics could be evaluated by cantilever type rotational bending fatigue tester.
[2] The low cycle fatigue was confirmed at flat bar specimen with drilled hole subjected to cyclic four point bending load.
[3] The fatigue life of flat bar specimen was well predicted by the low cycle fatigue properties obtained by developed rotational bending tester.

Nomenclature

\[ \Delta \varepsilon \]  plastic strain range [-]
\[ \varepsilon^f \]  fatigue ductility coefficient [-]
\[ 2N_f \]  number of reversal to failure [-]
\[ C \]  fatigue ductility exponent [-]

References