Effect of Welding on Gigacycle Fatigue Strength of Austenitic Stainless Steels

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Abstract : A mercury target vessel, composed of SUS316L stainless steel, is used for the pulsed spallation neutron source and is assembled via gas tungsten arc welding. While in operation, the target vessel suffers approximately 108 loading cycles with a high strain rate of approximately 50 s\(^{-1}\) because of the proton-beam-induced pressure waves in mercury. The gigacycle fatigue strength for solution annealed SUS316L stainless steels and its welded specimens were investigated through ultrasonic fatigue tests. The experimental results showed that an obvious fatigue limit was not observed at fewer than 109 cycles for the base metal. In the case of no weld defects observed via penetration tests, the fatigue strength of the removed-weld-bead specimen, in which the weld lines were arranged at the center of the specimen, appeared to be slightly higher than that of the base metal. By contrast, as-welded specimens with the weld bead intact showed apparent degradation of the fatigue strength owing to the stress concentration around the weld toe.

Keywords: Gigacycle fatigue, Welding, Ultrasonic fatigue test, Stainless steels

1. Introduction

A pulsed spallation neutron source, which generates neutrons via injecting high-intensity 3 GeV proton beams into liquid mercury, is installed in the Japan Proton Accelerator Research Complex (J-PARC). A mercury target vessel, which contains liquid mercury and is composed of SUS316L stainless steels, suffers cyclic impact stress at a strain rate of approximately 50 s\(^{-1}\) caused by proton-beam-induced pressure waves in addition to exposure to proton and neutron irradiation [1]. The target vessel suffers approximately 108 stress cycles, a so-called gigacycle, at 25 Hz while in design life, which is decided on the basis of ductility under irradiation. In addition, the target vessel is assembled via gas tungsten arc welding (GTAW), and the vessel has a multiwalled structure, which makes complete removal of the penetration bead difficult [2].

In the gigacycle region, fatigue failure often occurs below the fatigue limit decided on the basis of conventional fatigue tests up to 107 cycles. Internal fracture originating from inclusions, so-called fish-eye fracture, occurs in the austenitic stainless steels used in nuclear reactor components, gigacycle fatigue data is insufficient. Fatigue failure originating from the surface has been reported to be dominant in the solution-annealed SUS316L stainless steels [4,5].

In the case of welded austenite stainless steels, obvious fatigue strength degradation has been reported. Iwata, et al. investigated the effect of the groove shape of SUS316L butt welding joints on the fatigue limit and found that the fatigue limit was reduced by approximately half as a result of a lack of weld penetration regardless of groove shape. Yuri, et al. investigated fatigue strengths of welded SUS316L cut from butt-welded plate, and concluded that the fatigue crack originated from inclusions at the final solidification part of the weld metal. However, in the case of gigacycle fatigue, the fatigue strength of welded stainless steels and the effect of their weld bead have not been reported thus far.

In this study, to investigate the effect of welding on the gigacycle fatigue strength of SUS316L stainless steels, ultrasonic fatigue tests were conducted using the weld specimens. Furthermore, the effect of the weld bead on the fatigue strength was investigated via comparing the specimens with and without weld beads.

2. Experiment

2.1 Materials and specimens

A commercial SUS316L, which is the structural material of the mercury target vessel used for the pulsed spallation neutron source, was selected as the base metal. The base metal was annealed at 1080°C for 6 min and then water quenched. Two types of weld plates were prepared for the fatigue tests. One was 260L × 90W × 15t mm\(^3\) for hourglass and plate specimens. The other was 370L × 75W × 3t mm\(^3\) for plate specimens to investigate the effect of the weld bead on fatigue. Table 1 shows the chemical compositions of the 15t and 3t plates and the welding rod. GTAW with a V-groove angle of 50° without a root face, which was the same groove shape used to fabricate the target vessel, was selected as the base metal.

<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>Mo</th>
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</thead>
<tbody>
<tr>
<td>15t</td>
<td>0.011</td>
<td>0.43</td>
<td>0.027</td>
<td>0.001</td>
<td>12.09</td>
<td>17.55</td>
<td>2.1</td>
</tr>
<tr>
<td>3t</td>
<td>0.021</td>
<td>0.72</td>
<td>0.031</td>
<td>0.000</td>
<td>12.25</td>
<td>17.20</td>
<td>2.09</td>
</tr>
<tr>
<td>WR*</td>
<td>0.08</td>
<td>0.39</td>
<td>1.52</td>
<td>0.023</td>
<td>0.001</td>
<td>18.50</td>
<td>2.13</td>
</tr>
</tbody>
</table>

*WR: YS316L Welding rod (contains 0.19% of Cu)
Fe: balance for each material

Table 2 Typical welding conditions for GTAW

<table>
<thead>
<tr>
<th>Layer</th>
<th>Path</th>
<th>Current</th>
<th>Voltage</th>
<th>Weld speed</th>
<th>Max. Heat input [kJ/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15t</td>
<td>7</td>
<td>11</td>
<td>110-150</td>
<td>47-60</td>
<td>21.1</td>
</tr>
<tr>
<td>3t</td>
<td>2</td>
<td>70-90</td>
<td>10</td>
<td>25-30</td>
<td>21.6</td>
</tr>
</tbody>
</table>
selected for the both plates. Typical welding conditions are shown in Table 2. Penetration testing (PT) was performed to detect welding surface defects. A solvent-removable-dye-penetrant testing method, the so-called VC-S method, was applied to the first and last layers for all welded plates; the results confirmed that the no visible welding surface defects existed.

Figure 1 shows the schematics of the arrangement of weld lines and fatigue specimens. Hourglass-shaped specimens were machined from the base metal (hereinafter referred to as hourglass base metal (HBM)) and from the welded plate of 15 mm thickness (hourglass weld (HW)). Plate specimens were cut from 15 mm welded plate (plate weld (PW)), and 3 mm base metal (plate base metal (PBM)), and welded plates (plate with weld bead (PWB)) using wire electric discharge machining. Obvious deformation of specimens owing to the weld residual stress were not recognized. Part of the PWB specimen was ground to remove the weld bead (plate removed-weld-bead (PRB)). The cut surface was finished using #800 SiC paper.

3.1 Mechanical properties

The universal hardness, Hs, was estimated from the load and depth curve as follows:

\[ H_s = \frac{L_{\text{max}}}{26.43 D_{\text{max}}} \]  

wherein \( L_{\text{max}} \) and \( D_{\text{max}} \) are the maximum load and depth, respectively [5]. The maximum load and loading rate were 29.4 mN and 1.47 mN/s, respectively.

2.3 Ultrasonic fatigue tests

Gigacycle fatigue tests were conducted using an ultrasonic fatigue testing machine (Shimadzu, USF-2000). Figure 2 shows a photograph of the experimental setup. Stress was applied to a specimen at a rated frequency of 20 kHz through an ultrasonic horn that was fixed to one end of the specimen. The stress amplitude was controlled by adjusting the displacement amplitude of the free end of the specimen. The ratio of stress \( R = \sigma_{\text{min}} / \sigma_{\text{max}} = -1 \), that is tension-compression. The stress applied to an hourglass-shaped specimen, \( \sigma_{\text{a}} \), can be estimated on the basis of Webster equation, which as follows [8]:

\[ \sigma_{\text{a}} = aE\beta \cos \left( \frac{\omega l}{c} \right) \cosh \left( \frac{bL}{2} \right) \left( \frac{1}{2} \sinh \beta \right) \]  

\[ b = \frac{2}{L} \cosh^{-1} \left( \frac{D_1}{D_2} \right) \]  

\[ \beta = \sqrt{b^2 - \left( \frac{\omega}{c} \right)^2} \]  

\[ l = \frac{c}{\omega} \tan^{-1} \left[ \frac{c}{\omega} \left( \beta \coth \left( \frac{\beta L}{2} \right) - b \tanh \left( \frac{bL}{2} \right) \right) \right] \]

wherein \( a \) is the displacement amplitude of the specimen, \( E \) is the Young’s modulus, \( \omega \) is the angular velocity, \( c \) is the sound speed, \( l \) and \( L \) are the lengths of the shoulder and the circular parts, and \( D_1 \) and \( D_2 \) are the diameters of the shoulder and center parts, respectively. The shoulder length \( l \) of specimens was decided the resonance frequency to be 20 kHz based on following equation [8]:

In the case of the plate specimens, because of the lack of suitable equations, the shoulder length was decided through the eigenvalue analysis; in addition, the stress amplitude was
defects existed. The results confirmed that the no visible welding surface was applied to the first and last layers for all welded plates; dye-penetrant testing method, the so-called VC-S method, to detect welding surface defects. A solvent-removable acid. The universal hardness, microhardness was measured using a microindenter and the crosshead displacement, respectively. 

3. Results and Discussions

3.1 Mechanical properties

3.1.1 Tensile strength

Figure 3 shows the load and crosshead displacement curves for the fatigue specimens before the fatigue tests, as obtained via the quasi-static tensile tests. Because the specimens have no parallel length, engineering strain and yield stress were difficult to estimate from the load and elongation curves. The estimated ultimate tensile strengths (UTSs) for each specimen were HBM 613 MPa, HW 632 MPa, PBM 613 MPa, PW 642 MPa, PWB 721 MPa. Notably, we estimated the stress for PWB while ignoring bead shape. The UTS for welded specimens was slightly higher than that of the corresponding base metal. Furthermore, total elongations for welded specimens were obviously less than those of the base metals. Figure 4 shows the photographs of plate specimens after tensile tests. The necking for PWB occurred at a weld toe by stress concentration. Although the cross-sectional image will be shown later, the substrate at the weld toe is base metal, so that total elongation of PWB was nearly equivalent to PBM.

3.1.2 Hardness distribution

Figure 5 shows the cross-sectional hardness distribution along with the etched optical microscope image for the HW specimen before the fatigue test. Notably, the universal hardness in each location is the average value of five data points, and the hardness distribution is assumed to be symmetric about the origin. The solid line in the figure denotes the smoothed curve obtained by applying a Sine function [11]. The hardness at approximately 4 mm from specimen center (heat-affected zone) is slightly higher than that of weld metal and the substrate of base metal. The weld metal is harder than that of base metal, although the data exhibit a large scatter. The higher UTS than that of the base metal obtained from quasi-static tensile test seems to be attributed to the hardened weld metal and the heat-affected zone.

Figure 5 Change in the cross-sectional hardness as a function of the distance from the specimen center for the HW specimen.
3.2 Fatigue strengths
Figure 6 shows the relationship between the applied stress amplitude and the number of cycles to failure (S–N curve) obtained through the ultrasonic fatigue test for hourglass-shaped specimens. Fatigue failure occurred after a number of cycles greater than \(10^6\) cycles; this value was treated as a cycle limit to decide the non-failure stress amplitude in conventional fatigue tests, regardless of the welding. Furthermore, the fatigue limit was obviously not reached for the HBM up to \(10^6\) cycles. The fatigue strength of the HW is approximately the same as that of the HBM. By contrast, in the gigacycle region, the fatigue strength of the HW appears to be greater than that of the HBM. This trend is correlated with the results of tensile tests (Fig. 3). The fatigue limit is known to be correlated with the hardness and the ultimate tensile strength [12]. In order to compare with the conventional fatigue test, literature data of SUS304 hourglass base metal (HBM*) and hourglass weld via GTAW (HW*) [13] tested at less than 12 Hz under a stress ratio of -1 are shown in Fig. 6. Although the obvious difference in fatigue limit was not observed in literature, it can be seen that the present data shows the same trend with the literature data.

Figure 7 shows the S–N curves for the plate specimens. Notably, we estimated the stress amplitudes of the PWB while ignoring the bead thickness. The results show that the fatigue strength of the PW is greater than that of the PBM irrespective of the number of cycles. Furthermore, fatigue strength of the PRB is slightly higher than that of the PBM, although the failure data in the gigacycle region are insufficient. The difference in fatigue strength between the PW and the PRB might be caused by the weld residual stress and the difference of the size of the heat-affected zone resulting from the differences in welding conditions.

On the basis of the results of fatigue tests of both hourglass and plate specimens, in the cases where the specimen had no weld defects and a smooth surface, we concluded that the fatigue strength of the weld specimen was higher than that of the base metal. By contrast, in the case of PWB, in which the specimen surface retained the weld bead, an apparent fatigue strength degradation was observed. Literature data of conventional fatigue tests for SUS316L base metal (BM*) and metal active gas (MAG) weld with weld bead (WB*) [6] tested at less than 20 Hz under a stress ratio of 0.1 are shown in Fig. 7. Fatigue strength of BM* is obviously higher than that of HBM*, because the UTS of BM* (642 MPa [6]) was higher than that of HBM* (613 MPa). By contrast, fatigue strength degradation due to weld bead in reference shows the similar trend with the present study.

The reason for this degradation will be discussed further in detail.

3.3 Crack and fracture surface
To investigate the crack origin locations, we observed surfaces and cross-sections of fatigue-failed specimens using an optical microscope. Both of the specimen surface and the cross-section were polished and electrochemically etched to enhance the weld metal. Figure 8 shows the typical examples of surface and cross-sectional images of weld specimens.

The fatigue cracks are located inside the weld metal except in the case of PWB, because the weld line is arranged at the center of circular and tapered specimens. On the contrary, in the case of PWB, a fatigue crack is recognized at the weld toe. To compare the difference in cracks between the high-cycle and gigacycle regions, cross-sectional images for PWB that failed at 5.61 \(\times\) \(10^6\) and 7.03 \(\times\) \(10^6\) are shown in Fig. 9. Notably, the images show the cross-section around the center of specimen. In both cases, fatigue cracks propagated from around the weld toe toward the bottom side. Furthermore, around the specimen surface, the fatigue crack propagated...
inside the weld metal in the case of the gigacycle specimen, whereas the crack propagated between the base metal and the weld metal in the high-cycle region. Crack shape for high-cycle specimen seems to be coarser than that of gigacycle.

Furthermore, fracture surfaces corresponding to the high-cycle and gigacycle regions were compared. Because the specimen did not completely fail in this experiment, the remaining half of the specimen used for cross-sectional observation was fractured forcibly, and the fracture surface was observed. Figure 10 shows SEM images for specimens that failed in the high-cycle and gigacycle regions. The fatigue fracture surfaces are observed at least approximately 1 mm from the specimen surfaces which are recognized in Fig. 9 as the cracks. Notably, the roughness of the fracture surface in the high-cycle specimen is coarser than that of the gigacycle specimen in the low-magnification images. In the high-magnification image, a ratchet mark attributable to the overlap of multiple fatigue cracks is observed; in addition, the crack origins appear to be located on the surface in high-cycle specimen. By contrast, in the case of the gigacycle specimen, the fatigue crack originated from near the corner of the specimen, and the location appears to be the weld metal (Fig. 9). The direction of crack propagation in the gigacycle specimens differs from that in the high-cycle specimens.

3.4 Effect of weld bead

An obvious fatigue strength degradation due to the stress concentration at the weld toe was observed in the PWB. To characterize the stress concentration around weld beads, we calculated the stress distribution of PBM and PWB using the LS-DYNA FEM program. Although details are not shown here, a symmetrical model about the longitudinal direction with an elastoplastic material model was applied for the calculation. The shapes of weld beads for the PWB specimens were measured. Both ends of specimen were oscillated at 20 kHz under constraining center of the model. Figure 11 shows the calculated stress distribution at a displacement amplitude of 11.8 µm when the stress amplitude was within the elastic region. Stress concentrated around the weld toe at the discrete shape portion. The crack locations shown in Figs. 8 and 9 are correlated with the location of stress concentration. The maximum stress for PWB was approximately 1.5 times greater than that for PBM.

The relation between the stress amplitude and the displacement amplitude at the end of the PWB specimen was determined to be $\sigma_a = 16.59a$ by simulation, although the shape of the weld bead is strictly not the same for every specimen. Figure 12 shows the $S$–$N$ curves of plate specimens for the corrected stress amplitudes of PWB. The
fatigue strength of PWB is higher than that of PBM when the number of cycles is less than $10^6$. By contrast, when the number of cycles is greater than $10^6$, the fatigue strength of PWB appears to be the same or smaller than that of PBM. Additional fatigue data for PBM are needed to elucidate the effect of the weld bead on gigacycle fatigue.

4. Conclusions

The gigacycle fatigue behavior of SUS316L, which is the structural material used for the mercury target vessel for the spallation neutron source, was investigated through the ultrasonic fatigue tests at room temperature using welded specimens whose weld lines were arranged at the center of the specimen. Prior to the fatigue tests, the mechanical properties of the specimens were measured. The results showed that the ultimate tensile strength and the universal hardness of the weld metal were approximately 3%–5% and 15% higher than those of the base metal, respectively.

With respect to the hourglass-shaped specimens, the fatigue strength of the HW in the gigacycle region appeared to be higher than that of the base metal HBM, whereas no remarkable difference was observed in the high-cycle region.

In the case of the plate specimens, the fatigue strength of the weld specimen cut PW was slightly greater than that of the PRB. In both cases, the high-cycle fatigue strength was greater than that of the base metal PBM. By contrast, the fatigue strength for the weld bead specimen PWB, wherein we estimated the stress amplitude while ignoring the weld bead, was obviously degraded because of the stress concentration at the weld toe in comparison with the PBM and the removed-weld-bead PRB specimens.

In future work, to better clarify the effect of welding in gigacycle fatigue, we will conduct additional fatigue tests focused on samples subjected to more than $10^7$ cycles. Furthermore, the effect of the heat-affected zone on fatigue will be investigated by displacing the arrangement of the weld lines on specimens.

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References