EFFECT OF THERMAL AGING ON FRACTURE TOUGHNESS OF AUSTENITIC STAINLESS STEEL WELDS

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ABSTRACT

In this study, fracture toughness test was conducted in order to evaluate the effect of thermal aging on the fracture behavior of shielded metal arc (SMA) weld and gas tungsten arc (GTA) weld of Type 316L stainless steel. The ferrite content of the SMA weld and the ferrite content of GTA weld were around 9% and 15%, respectively. As a result, it was found that the fracture toughness of aged welds were lower than that of unaged welds and the dendritic structure affected the pre-crack and ductile crack growth shape and direction. The effect tended to be strong in the SMA welds, therefore, the fatigue pre-cracks and the ductile cracks in the SMA welds deflected to the dendritic growth direction. For the specimens whose pre-crack and ductile crack growth direction was along to dendritic growth direction, although the ferrite content of the GTA welds were larger than the SMA welds, the fracture toughness of aged GTA welds tended to be higher than that of SMA welds.

INTRODUCTION

Thermal aging embrittlement of cast austenitic stainless steels (CASSs) such as ASTM CF-3, CF-3M, CF-8 and CF-8M have been studied by many researchers (Chung (1992), Trautwein and Gysel (1982), Chopra (1993), Chopra and Sather (1990), and Miura and Yamamoto (2015)). They revealed that the microstructural evolution in ferrite phase resulted in the embrittlement of CASS and the susceptibility to thermal aging embrittlement was affected by ferrite content and chemical composition of materials. They also reported that molybdenum-bearing CASSs such as CF-3M and CF-8M tended to be more susceptible to thermal aging embrittlement than CF-3 and CF-8 because molybdenum enhanced the thermal aging embrittlement. As a result, thermal aging prediction models such as ANL model by Chopra (2016), H3T model by Kawaguchi et al. (2005) and French model by Faidy (2012) were established and used in plant life management.

Austenitic stainless steels are widely used in light water reactor (LWR) systems because of their good ductility, high fracture toughness, and corrosion resistance. Although the stainless steels are austenitic in the wrought condition, their welds have a duplex structure consisting of austenite phase and ferrite phase, which is similar to CASSs metal structure. While the ferrite phase contributes to the improvement of susceptibility to stress corrosion cracking, it could enhance the susceptibility to thermal aging embrittlement at reactor operating temperature like the thermal aging embrittlement of CASS. Although there are studies on thermal aging of stainless steel welds and the decrease of Charpy impact energy and fracture toughness have been reported (Alexander et al. (2000) and Gavenda et al. (1995)), the data of Type 316L, which is widely used in Japanese boiling water reactor (BWR) plants with relatively high ferrite content, is limited. In this study, tensile test and fracture toughness test were conducted in order to evaluate the effect of thermal aging on the fracture behavior of shielded metal arc (SMA) weld and gas tungsten arc (GTA) weld of 316L stainless steel with relatively high ferrite content.

TEST MATERIAL AND EXPERIMENTAL PROCEDURE
Type 316L Stainless Steel Weld Joint

The investigated materials are the SMA welds and the GTA welds. Table 1 lists the chemical composition of main weld materials which are classified as ES316L-16 and YS316L in the specifications of Japan Industrial Standards (JIS) Z3221 and JIS Z3321, respectively. The base metal for all of the welds was 50 mm thick Type 316L stainless steel plate and a 60° V-groove geometry was used. The SMA welds were approximately 250 mm or 500 mm long and the GTA welds were approximately 500 mm long. The width of each weld was 300 mm. An example of the SMA and GTA welds are shown in Figure 1. Hardness test and measurement of ferrite content were carried out on the cross-section in order to obtain the distribution of hardness and ferrite of two type of welds. The cross-sectional view of the two type of welds are shown in Figure 2 and the hardness (HV1) distributions and ferrite content distribution measured by a ferrite scope are shown in Figure 3 and 4, respectively. For the SMA weld the hardness and ferrite content were around 214(HV1) and 9 %, respectively. For the GTA weld, the hardness and ferrite content were around 219(HV1) and 15 %, respectively.

Table 1: Chemical composition of the two types of 316L stainless steel weld materials

<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>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES316L-16 (SMA)</td>
<td>0.014</td>
<td>0.42</td>
<td>1.63</td>
<td>0.015</td>
<td>0.003</td>
<td>11.76</td>
<td>19.50</td>
<td>2.25</td>
<td>0.066</td>
<td>Bal.</td>
</tr>
<tr>
<td>YS316L (GTA)</td>
<td>0.016</td>
<td>0.44</td>
<td>1.46</td>
<td>0.010</td>
<td>0.015</td>
<td>11.83</td>
<td>19.96</td>
<td>2.80</td>
<td>0.048</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

(a) SMA weld                  (b) GTA weld

Figure 1. Fabricated welded joints

(a) SMA weld                  (b) GTA weld

Figure 2. Cross-sectional view of the two type of welds
The aging condition of 400 °C, 8000 h is assumed to be a fit for 5000 °C due to sample length. 

70 mm long (welding direction), 300 mm wide and 50 thick blocks, which were cut from the welded joints, were thermally aged in air at 350°C for 8000 h, 400°C for 5000 h and 400°C for 8000 h to obtain mechanical properties of aged materials. The aging condition of 400°C for 8000 h is assumed to be saturation of thermal aging.

### Mechanical Property Test

In order to evaluate the fracture toughness of each aging condition, elastic-plastic fracture toughness tests using 0.5T-C(T) specimens were conducted according to the ASTM E1820-15 (2015) at room temperature (RT) and 288°C simulating operating temperature of BWR. For unaged and 400°C for 5000 h aged welds, specimens with two orientations, which were T-S and S-T directions, were machined in order to evaluate the relationship between fracture toughness and the crack growth direction. For other aging condition, only T-S orientation specimens were machined. Schematics of specimen location and orientation are shown in Figure 4. Two C(T) specimens were used for per test condition. For the specimens aged at 400°C for 5000 h, the thickness of the C(T) specimens were 12 mm due to sample volume limitation. Elastic unloading compliance method was used to predict the crack growth lengths.

To establish power-law fit J-R curve and obtain fracture toughness $J_Q$, 0.2% proof stress $S_y$ and ultimate tensile strength $S_u$ of each aging condition materials were obtained from tensile testing at RT and
288°C. The specimens whose diameter were 6 mm and the gage length were 30 mm, were machined from upper part of the welds along the width (T) direction. Three specimens were used for per test condition. The flow stress $S_y$ was calculated from the average values of $S_t$ and $S_u$. In this study, J integral with a stable crack extension $\Delta a$ of 1.5 mm obtained from power-law fit J-R curve is defined as $J_{1.5}$, for the evaluation of short-crack-growth resistance of each specimen aged at various condition. After the fracture toughness test, all specimens were broken using fatigue process and then, the initial and final crack shapes were observed by optical microscope.

![Figure 4. Location and orientation of 0.5T-C(T) specimen on the weldment](image)

**Observation of Crack Growth Behavior**

One more unaged T-S and S-T orientation specimens were tested to observe the relationship between the crack growth direction and the dendritic growth direction. After the tests, the specimens were divided using electrical discharge machining along the centreline of the thickness, and then the cross-sections of the specimens were polished to mirror finish. The cross-sections of the four specimens were observed by optical microscope and scanning electron microscope (SEM) with electron backscatter diffraction (EBSD) in order to evaluate the relationship between the crack growth direction including pre-crack part and the metal structure of weld.

**RESULTS**

**Effect of Thermal Aging on Mechanical Properties**

J-R curves obtained from all specimens and examples of the fracture surfaces tested at RT are shown in Figure 5 and Figure 6, respectively. There were the data whose J integral value decreased or unchanged at the final phases of the tests. In that specimens, ununiformed crack growth were observed on the fracture surfaces such as the SMA S-T orientation specimens shown in Figure 6. For the SMA S-T orientation specimens, the crack length of center region of the thickness were longer than that of around edge regions at both test temperature. For this type of ununiformed crack-growth specimens, the difference of the two J-R curves obtained in this study were relatively large.

The crack growth resistance of GTA welds tended to be higher than that of SMA welds although the ferrite content of the GTA welds were larger than the SMA welds. The slope of J-R curves at 288°C were smaller than that at RT in all aging condition in this study. For a specimen aged at 400°C for 8000 h, pop-in was observed at the stable crack extension of around 2.0 mm during test at RT and the brittle fracture of the ferrite phase was observed on the fracture surface partially. The partial brittle fracture of ferrite were also observed on the fracture surface of aged specimens tested at RT, while there were no brittle fracture on the fracture surfaces of the specimens tested at 288°C.
$S_y$ and $S_u$ values of specimens tested at RT and 288°C are shown in Figure 7. This figure shows that the tensile properties of the GTA weld were higher than that of the SMA weld. The $S_y$ values slightly increased with thermal aging, while the increase in the $S_u$ values were larger than that of the $S_y$. The amount of increase in $S_y$ and $S_u$ from unaged value of GTA welds were slightly larger than that of SMA weld. This result might be due to the difference of welding process and/or the ferrite content. Although the difference in tensile properties between aging conditions were relatively low in this study, $S_y$ and $S_u$ values of 400°C-8000 h aged materials tended to be the most highest in three aging condition except for the GTA weld at RT.

![J-R curves of tested specimens](image-url)
Figure 6. Fracture surfaces of the specimens tested at RT

Average of fracture toughness $J_Q$ and $J_{1.5}$ of two specimens are shown in Figure 8 and Figure 9. In this study, almost all data were invalid as fracture toughness $J_c$ mainly because of the ununiformed crack growth shown in Figure 6. For the results of SMA S-T orientation, 400°C -5000 h aged values were higher than the values of unaged materials. This might be because of the characteristic crack shapes including fatigue pre-crack of the SMA S-T orientation specimens, which is discussed later. As for SMA T-S, GTA T-S and GTA S-T orientation specimens, $J_Q$ and $J_{1.5}$ values tended to decrease with thermal
aging and the $J_0$ values decreased to around 40-60% of unaged values, while the fracture toughness $J_{1.5}$ values decreased to around 60-70% of unaged specimen except for $J_0$ values of SMA T-S orientation specimens at 288°C. For the specimens aged at 400°C, $J_0$ and $J_{1.5}$ values decreased as aging time increased. As shown in Figure 8 and Figure 9, fracture toughness of GTA weld specimens tended to be higher than that of SMA weld specimens although the ferrite content of the GTA weld were larger than that of the SMA weld; therefore, welding process is an important parameter of fracture toughness of type 316L SS weld. The effect of welding process on fracture toughness has been reported by Chopra (2015). The difference of initial fracture toughness between welding processes might result from the difference of the amount of inclusion in weld metal.

For the GTA welds whose cracks grew relatively straight and uniform, fracture toughness of S-T orientation specimens were higher than that of T-S orientation specimens. This result suggests that using T-S orientation fracture toughness is applicable for conservative evaluation of thermal aging embrittlement of SS welds.

![Figure 8. Fracture toughness $J_0$](image)

![Figure 9. Fracture toughness $J_{1.5}$](image)
As shown above in Figure 5, although the slope of J-R curves of unaged SMA T-S orientation specimens were relatively steeper than that of 350°C-8000 h aged specimens at 288°C, $J_Q$ value of unaged specimen was lower than that of 350°C-8000 h aged specimen. SS welds are relatively difficult to extend ductile crack in early stage of the test because of its specific metal structure; therefore, $J_Q$ value tends to vary widely like the crack growth behavior of CASS. On the other hand, J-integral value with certain stable crack extension tended to be reliable to some extent. Therefore, for the evaluation of thermal aging effect on fracture toughness of SS weld, other fracture parameter, for example $J_{2.5}$, which is used to differentiate between nonsignificant and potentially significant reductions in fracture toughness of CASSs in NRC GALL (2010), could be a candidate.

**Relationship between Crack Growth Direction and Metal Structure**

Figure 10 shows cross-sectional crack shapes of each unaged specimen observed by the optical microscope. This figure also shows the pre-crack part and ductile crack part which propagated during fracture toughness test. The pre-crack length on side face before machining of side groove were set to around 1.4 mm, however, the length in this cross-section were significantly varied. As for the SMA S-T orientation specimen, significant deflection of pre-crack was observed, while pre-cracks of the other specimens were straight. The crack shape of T-S orientation specimens are relatively straighter than that of S-T orientation specimens in terms of ductile crack growth behavior. Inverse Pole Figure (IPF) maps of pre-crack part of S-T orientation specimens are shown in Figure 11. This figure clearly shows the difference of metal structure between welding processes. The SMA weld has relatively coarse and long dendritic structure, whereas the GTA weld has fine metal structure. For the SMA S-T orientation specimen, pre-crack growth direction were strongly affected by the coarse dendritic structure and its growth direction. For the GTA S-T orientation specimen, although the metal structure also grows along T-S direction, the effect of metal structure on pre-crack direction seems to be small because of the grain size is relatively small.

![Pre-crack (fatigue) Ductile crack](image)

**Figure 10. Cross-sectional crack shapes of the unaged specimens at the centerline of the thickness**
Figure 11. IPF maps of pre-crack part superimposed on the S-T direction specimens

Figure 12 show IPF maps of ductile crack part of each orientation specimen. Although the dendritic growth directions are different between the S-T and T-S orientation specimens, same fracture process were observed; that is, the ductile cracks penetrate the dendritic structure for the S-T orientation specimens and the cracks of T-S orientation specimens also penetrate the dendritic structure more linearly along the structure. However, as mentioned above, the ductile cracks of S-T orientation specimens tended to deflect. The difference of fracture toughness might result from anisotropy of weld structure and the deflected fatigue and ductile crack growth such as the SMA S-T orientation. Of course, this result contains only one cross-sectional information of each unaged specimen, therefore more data including aged material is needed for evaluation of the effect of weld metal structure on fracture behaviour of SS weld.

Figure 12. IPF maps of ductile crack part superimposed on the optical photographs

SUMMARY

In this study, the effect of thermal aging on the fracture behavior of type 316L SMA and GTA welds aged at 350°C and 400°C for up to 8000 h, were evaluated using fracture toughness test and tensile test and SEM-EBSD observation. As a result of the tests, it was found that the fracture toughness of aged
welds tended to be lower than that of unaged welds except for the SMA S-T orientation specimens whose fatigue pre-crack was significantly deflected and the ductile crack growth was ununiformed. The effect of welding process was strong and the fracture toughness of SMA T-S orientation were lowest at both temperature in each aging condition. The SEM-EBSD observation revealed the difference of weld metal structure between the SMA and the GTA weld. The observation also clarified the crack growth behavior; that is, the ductile cracks of S-T orientation specimens tended to deflect and the fatigue pre-cracks and ductile cracks of T-S orientation specimens tended to grow straight along the dendritic growth direction.

REFERENCES


