Microstructure, Recrystallization, and Mechanical Property Evolutions in the Heat-Affected and Fusion Zones of the Dissimilar Stainless Steels

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The purpose of this study was to discuss the microstructure, recrystallization, and mechanical property evolutions in the heat-affected zones and fusion zones during dissimilar stainless steels welding. The morphology, quantity and chemical composition of the δ-ferrite were analyzed by using optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive spectrometer (EDS) and electron probe micro-analyzer (EPMA), respectively. The recrystallization phenomenon was evident with the second pass heat-affected zone (HAZ-2) and indicated equiaxed grains after second pass welding. The contents of δ-ferrite exhibited the highest value of all situations in the first pass fusion zone (FZ-1) during the first pass welding. Furthermore, the solidification mode of fusion zones transformed from massive as well as acicular δ-ferrite into lathy and skeletal structures as increased the welding pass number from 1 to 3. [doi:10.2320/matertrans.MRA2007162]

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1. Introduction

Dissimilar metal welds between austenitic and ferritic stainless steels with low carbon content are extensively utilized in many high temperature applications such as energy conversion systems. For instance, in central power stations, sections of the boilers subjected to lower temperature are made from ferritic stainless steel for economic reasons. The other operating at higher temperatures, are constructed with austenitic stainless steel. Therefore, the transition welds are needed between the two stainless steels.1,2)

In stainless steel welds, the microstructures were related to solidification types3) i.e., solidification and subsequent transformation behavior. The composition balance between ferrite stabilizing elements and the austenite stabilizing elements (i.e., Cr<sub>eq</sub>/Ni<sub>eq</sub> ratio4)) is used to predict the solidification microstructures such as residual δ-ferrite contents5,6) and the solidification types7–9).

The solidification mode of the stainless steel weld metal is normally classified into four types such as austenite (A), austenite-ferrite (AF), ferrite-austenite (FA), and ferrite (F).10–16) The A and AF solidification modes are associated with primary austenite solidification, whereby austenite is the first phase to form upon solidification. Types FA and F solidification have δ-ferrite as the primary phase. Solidification microstructures in the stainless steels as function of Cr/Ni equivalent are classified into several morphologies, which including lathy, skeletal, acicular, and vermicular etc.17–21)

It was widely known that dissimilar stainless steels joints are intrinsically an uncertainty because two steels with different mechanical, metallurgical, and physical properties are welded together. This paper focused on the microstructure, recrystallization, and mechanical property developments in the heat-affected and fusion zones of the dissimilar stainless steels during the gas tungsten arc welding (GTAW). To contribute to the practice of engineering concerns especially the welding joints between austenitic and ferritic stainless steels.

2. Experimental Procedures

Two types of stainless steels namely 304 and 430 were used, which are representatives of fully austenitic containing a few ferrite phase and fully ferritic microstructures respectively. And their chemical compositions were listed in Table 1. The dimension of the raw materials was 70 mm × 25 mm × 3 mm.

The welding joints were made by an automatic gas tungsten arc welding (GTAW). The appearance of weld metal of dissimilar stainless steels was shown in Fig. 1. The multi-passes welding was performed without filler at a welding current of 100 A and an arc voltage of 11 V with a travel speed of 120 mm/min. Different welding regions were defined as a series of symbols (HAZ-1, HAZ-2, HAZ-3, FZ-1, FZ-2, and FZ-3). However, the former part means the welding region and then the latter part means the welding pass number. The detail experimental parameters were listed in Table 2. After multi-passes welding, the samples were cooled to room temperature in air and mounted by molding epoxy, then ground using SiC paper and polished with Al<sub>2</sub>O<sub>3</sub> powder paste.

Table 1 Chemical composition of the raw samples. Values are given in mass%.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Alloy element</th>
<th>Cr</th>
<th>Ni</th>
<th>Si</th>
<th>Mn</th>
<th>C</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td></td>
<td>19.0</td>
<td>10.9</td>
<td>1.0</td>
<td>2.0</td>
<td>0.08</td>
<td>1.22</td>
<td>Bal.</td>
</tr>
<tr>
<td>430</td>
<td></td>
<td>18.0</td>
<td></td>
<td>0.75</td>
<td>1.0</td>
<td>0.12</td>
<td>1.18</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

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The mounted samples were etched using Nital (100 mL Ethanol + 5 mL Potassium nitrate) for 180 s in order to observe the morphologies of δ-ferrite in the heat-affected and fusion zones. The morphologies observations of δ-ferrite carried out in the stainless steels samples using an optical microscope (ZEISS Axioskop 2 MAT, OM), and their chemical compositions were identified by energy dispersive spectrometer (EDS).

The magnetic δ-ferrite contents in the dissimilar stainless steels welds were evaluated by a ferritscope (Fisher MP30, FS). Thirty different test points were measured to obtain the maximum, minimum and average values for weld metals respectively after multi-pass GTAW process. An electron probe micro-analyzer (JXA-8900R JEOL, EPMA) was used to observe the stabilization level of elements in the heat-affected and fusion zones.

Hardness of the materials was measured by a Vickers hardness tester with a 0.98 N load for 10 s at a quarter plane from the specimen surface. Twenty test points were measured to gain the maximum, minimum and average values in the fusion zones after multi-pass welding.

3. Results and Discussion

3.1 Macrostructure observation in the fusion and heat-affected zones

Figure 2 showed the macrostructure of the fusion and heat-affected zones during multi-pass welding. The larger grains were found in the 430 stainless steel side and its morphology indicated bulky structures. In 304 stainless steel side, the finer grains and dendrite morphologies were observed. Furthermore, it had a larger grain size in the FZ-1 than in FZ-2 and FZ-3 when welding pass number increased from 1 to 3. It might exhibit various recrystallization behaviors in the common boundary of fusion zones through multi-pass welding. For this reason, HAZ part was discussed on the recrystallization behavior in the following latter section during the multi-passes welding.

3.2 The recrystallization of the heat-affected zones

Figures 3(A)–(C) showed the recrystallization of the heat-affected zones (HAZ-1, HAZ-2, and HAZ-3) during multi-pass welding. During the first pass welding, it indicated coarser equiaxed and columnar mixed grains with HAZ-1 at outer the two fusion zones (FZ-1 and FZ-2) attributed to the presence of large grains in the FZ-1 and 430 stainless steel sides. However, the recrystallization was evident and then finer equiaxed grains were found in the HAZ-2 at outer the two fusion zones (FZ-2 and FZ-3) after second pass welding. Consequently, single equiaxed grains and the recrystallization behavior were unobvious in the HAZ-3 near the 304...
stainless steel side after third pass welding. From result in Section 3.1, the 430 stainless steel side exhibited massive grains and then the 304 stainless steel side showed smaller columnar grains. We believe that the presence of equiaxed and columnar grains was derived from elemental diffusion of the 304 stainless steel side.

3.3 The morphologies and contents of δ-ferrite in the fusion zones

Figures 4(A)–(C) showed the variation of δ-ferrite morphology in the fusion zones during multi-pass welding. The δ-ferrite indicated massive and acicular morphologies in the fusion zone after the first pass welding. Katayama et al.\textsuperscript{22} have reported the acicular δ-ferrite was a primary ferrite precipitation because it presented great amounts of δ-ferrite contents in the weld metal. The morphology showed the lathy structures in the fusion zone through second pass welding. In the stainless steels, this morphology was belongs to the solidification mode of FA (primary ferrite plus austenite). In Fig. 4(C), the δ-ferrite transformed from lathy to skeletal shape when welding pass number was increased from 2 to 3. The skeletal δ-ferrite was also the FA solidification mode after third pass welding.

Figure 5 indicated the δ-ferrite contents in the fusion zones (FZ-1, FZ-2, and FZ-3) after multi-pass welding. However, the δ-ferrite indicated the highest content (59.3%) of the all regions with the FZ-1. This was because the primary ferritic solidification occurred in the fusion zone via the first pass welding and exhibited great amounts of δ-ferrite contents at the same time.

When the welding pass number increased from 1 to 2, the δ-ferrite content was decreased rapidly from 59.3% to 19%. This was due to austenitization phase transformation\textsuperscript{23,24} takes place and decreased δ-ferrite contents at the same time. Moreover, the δ-ferrite content decreased from 19% to 7% after third pass welding and then the austenitization transformation happened obviously in this condition.

We drew a schematic diagram to explain the morphologies and contents of δ-ferrite through multi-pass welding during GTAW process, as shown in Fig. 6.\textsuperscript{25} When welding pass number was 1, the δ-ferrite indicated a higher content and its morphology was acicular structure. Increasing the welding pass, the solidification mode changed from F mode to FA mode, so that δ-ferrite contents decreased. Finally, the δ-ferrite exhibited a minimum value attributed to the skeletal δ-ferrite had a lower Cr\textsubscript{eq}/Ni\textsubscript{eq}.

3.4 The variation of hardness in the fusion zones

Figure 7 showed the effect of various welding passes on hardness value in the fusion zones (FZ-1, FZ-2, and FZ-3). However, the hardness value indicated the highest tendency (540 Hv) of the all conditions under third pass welding. Hsieh et al.\textsuperscript{26} have pointed out that the massive δ-ferrite had an excellent mechanical property attributed to the massive phase transformation. Furthermore, the hardness value was decreased gradually from 534 Hv to 450 Hv after second pass welding. The hardness value decreased from 450 Hv to 280 Hv at third pass welding. The reason was because lower δ-ferrite content would lead to decrease of hardness values. In stainless steels, it was widely known that the presence of δ-ferrite can maintain better mechanical strength; therefore, it showed a lower hardness value with the FZ-2 and FZ-3 than FZ-1.
3.5 The observation of massive $\delta$-ferrite

The massive $\delta$-ferrite was examined by SEM plus EDS systems in order to further understand the strengthening behavior of massive $\delta$-ferrite. In Fig. 8, the massive precipitates were dispersed homogeneously at the matrix in the FZ-1. Various analyzed points (1~7) were examined by EDS and focused on the Cr, Ni, and Si elements, as illustrated in Table 3. The points of #1~#4 were identified as massive $\delta$-ferrite due to higher Cr content. Furthermore, it indicated a higher Ni content with the points of #5~#7 and then examined as $\gamma$-phase. It was found that the stabilized level with Si in $\delta$-ferrite was more efficient than in $\gamma$-phase in the fusion zone after the first pass welding. Therefore, the Si element can promote and stabilize the massive $\delta$-ferrite precipitation with the FZ-1 during dissimilar stainless steels welding. Lin et al.\textsuperscript{27,28} have pointed out that the Si elements played a significant role to enhance the formation of $\delta$-ferrite in stainless steels.

3.6 The stabilized level of Cr and Si in the fusion and heat-affected zones

The elemental concentration profiles were performed by EPMA in order to observe the stabilization of Cr and Si in the FZ-1, as shown in Figs. 9(A)–(C). It was found that Cr had a higher and lower enriched level in the FZ-1 and near the HAZ of 430 stainless steel side, respectively. It meant that high Cr enriching increased the formation of $\delta$-ferrite. Nevertheless, it was observed that the Si elements also indicated a higher and lower concentration profile in the FZ-1 and closed to HAZ of the 430 side, respectively. According to this result, it can be proved that the Cr and Si elements had a stable effect for the $\delta$-ferrite in the fusion zone and agreement with results in Section 3.5.

4. Conclusions

The microstructure, recrystallization, and mechanical property evolutions of the heat-affected zones (HAZ-1, HAZ-2, and HAZ-3) and fusion zones (FZ-1, FZ-2, and FZ-3) was investigated during dissimilar stainless steels welding. The important results can be summarized as follows:

(1) The recrystallization was obvious and then showed finer equiaxed grains in the HAZ-2 after second pass welding.

(2) Increasing the welding pass number, the solidification mode transferred from A mode to AF mode, and then the morphology of $\delta$-ferrite changed from acicular to lathy as well as skeletal structures.

(3) The $\delta$-ferrite content indicated the highest tendency of the all conditions through the first pass welding attributed to primary ferritic solidification.

Table 3  WDS analysis of massive precipitates in the FZ-1. Values are given in mass%.

<table>
<thead>
<tr>
<th>Area</th>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (δ)</td>
<td>23.2</td>
<td>5.32</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>#2 (δ)</td>
<td>22.4</td>
<td>6.12</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>#3 (δ)</td>
<td>23.5</td>
<td>5.43</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td>#4 (δ)</td>
<td>23.3</td>
<td>5.20</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>#5 (γ)</td>
<td>18.6</td>
<td>9.12</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>#6 (γ)</td>
<td>18.6</td>
<td>8.14</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>#7 (γ)</td>
<td>19.6</td>
<td>9.23</td>
<td>0.73</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7 Variation of hardness value of the fusion zone during multi-pass welding.

Fig. 8 The SEM observation of the massive $\delta$-ferrite in the FZ-1 after the first pass welding.

Fig. 9 The concentration profile of the heat-affected and fusion zones by EPMA (A) SEI image; (B) Cr Mapping; (C) Si Mapping.
The formation of massive δ-ferrite was because the Cr and Si elements enriching in the FZ-1 during the first pass welding.

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