Original Article

Microstructures and mechanical properties of stainless steel clad plate joint with diverse filler metals

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Abstract

Thick stainless steel clad plate is used widely in the petroleum and petrochemical industries because of its low cost and good corrosion resistance. It is generally welded by the multilayer and multipass welding process with stainless steel filler metal matched with the clad layer. In this research, the base metal of stainless steel clad plates was filled with carbon steel filler metal, and the microstructures and mechanical properties of joints with diverse filler metals were analysed and compared. The results indicate that a local hardening zone (LHZ) forms in the weld filled with the filler metals of stainless steel and carbon steel because of the formation of martensite phase in the first layer of weld with filler metal of carbon steel. The microhardness value in LHZ reaches up to 425 HV\textsubscript{1}, which is significantly higher than that of the base metal. However, the tensile strength value of joints filled with carbon steel filler metal is equivalent to that of the joints with stainless steel filler metal. The results of the side bending test indicate that the LHZ protrudes from the weld, and the crack occurs near the LHZ if the area of the LHZ on the cross section of joint is larger than 17 % of that of the whole cross section of the joint. The studied results show that it is feasible to use carbon steel filler metal to fill the base metal of carbon steel in welding of stainless steel clad plate.

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1. Introduction

Stainless steel clad plate is made of a thin stainless steel plate and thick carbon steel plate and is generally manufactured by roll bonding [1,2], explosion welding [3], weld overlay cladding [4], and other welding processes [5,6]. It combines the advantages of both stainless steel and carbon steel, such as excellent corrosion resistance, high mechanical strength, processing performance, and low cost, and has been used widely in industries such as petroleum, petrochemical, shipbuilding and pressure vessel industries. For stainless steel clad plates, the cladding of stainless steel satisfies with the requirement of corrosion resistance, and the thickness of cladding metal constitutes only 10–20 % of that of the stainless steel clad plate. Compared with stainless steel plates, stainless steel clad plates can reduce alloy elements like chromium (Cr) and nickel
(Ni) by 70–80 %, and reduce costs by 30–50 % because of the low cost of carbon steel.

Welding is an important method in the manufacturing of the products with stainless steel clad plate. By using the proper welding procedure and filler metal, it is important to obtain a joint that satisfies the requirements of different engineering applications.

Currently, various welding methods, such as shielded metal arc welding (SMAW) [7–9], submerged arc welding (SAW) [8,10], tungsten inert gas welding (TIG) [10], CO₂ arc welding [11], and laser welding [12], are used in the welding of stainless steel clad plates, and all the processes are available to satisfy the requirements of mechanical properties and corrosion resistance. Simultaneously, the selection of filler material is crucial to ensure welding quality and satisfy the requirements of the mechanical properties, such as strength, stiffness, and toughness. According to the welding procedure [13], which was issued by the Ministry of Industry and Information Technology of the People’s Republic of China, the properties of the weld can satisfy the requirements if the stainless steel clad plate is welded with stainless steel filler metal matched with the clad layer of stainless steel. To reduce the cost of welding, some researchers used carbon steel instead of stainless steel to weld stainless steel clad plates, and investigated the microstructures and mechanical properties of the joints.

Liao et al. [9] studied the microstructure of the joint of a clad steel plate consisted of Q235 (Chinese code) carbon steel base metal and AISI 310S stainless steel clad metal. In this research, the base metal, transition layer, and cladding of stainless steel were welded sequentially by SMAW. E4303 structural steel electrode was used to weld the base metal to match the strength of carbon steel, while the stainless steel electrodes of A102 and A402 were selected to weld the transition layer and cladding of stainless steel, respectively, to match the component of stainless steel. Ferrite and pearlite were the primary microstructures of both the base metal weld and transition layer, and the weld of cladding was composed of single-phase austenite and a small amount of ferrite. Qiu et al. [8] obtained the joint of Q235 carbon steel to ASTM TP304 stainless steel clad steel plate by SAW and SMAW. Ferrite and pearlite were found to be the primary microstructures of the base metal weld, and a little sorbite formed in the weld near the cladding of stainless steel. The microstructure of the weld of the cladding was columnar austenite, and skeleton or wormlike δ-ferrite was distributed on it. Tian et al. [7] studied the microstructure and mechanical properties of the joint of 16MnR steel to 2205 duplex stainless steel clad steel plate welded by TIG and SMAW. The results demonstrated that the microstructure in the parent metal of 2205 cladding stainless steel was austenite and ferrite, and the amount of ferrite in heat affected zone (HAZ) was 50.5–58.6 %. Ferrite and pearlite were observed in the parent metal of 16MnR base metal, and ferrite accounted for 42–54 % of the HAZ.

The microstructure in different zones of the joint, regardless of welding method (SMAW, SAW, or TIG), is determined by the type and compositions of the filler metal. If stainless steel is used as the filler metal, the microstructures of the weld metal generally include austenite and ferrite. However, if carbon steel is selected as the filler metal, the weld metal typically consists of pearlite and ferrite. Moreover, martensite may be generated in the weld metal of the transition layer from stainless steel weld to that of carbon steel owing to the high content of carbon and alloying elements [14].

Zhang et al. [11] found that the properties of the joint of Q345 (Chinese code) carbon steel and AISI 312 stainless steel (321SS) clad steel plate, which was welded by SMAW or carbon dioxide arc welding, could satisfy the design requirements. Wang et al. [10] found that the tensile strength of the joint, in which the cladding and transition layer were welded by TIG and the base metal was joined by SAW, was obviously lower than that of the joint entirely welded by TIG, but still higher than the strength of the base metal. According to the bend test requirement of clad steel plate, the tension face of joint must not crack in the 180° bending test under ambient temperature. If the welding parameters are appropriate, the joint welded by SMAW or carbon dioxide arc welding will not crack during the bending test. Nevertheless, the tension face of the joint will display tiny cracks because of the martensite formed in the weld, when the welding process is unreasonable.

The microhardness of weld is determined by the microstructure; the weld consisting of austenite and ferrite or pearlite and ferrite exhibits a lower hardness. Zhang et al. [11] welded the Q345 carbon steel and AISI 312 stainless steel clad steel plate by carbon dioxide arc welding, and the measured microhardness value was not higher than 350 HV. Qi et al. [15] and Wang et al. [16] studied the stainless steel clad plate joint welded by flux cored wire welding, and obtained the values of microhardness below 20 HRC and 225 HB, respectively. When martensite appeared in the transition layer, the microhardness in the local region of the weld is generally higher than that of the cladding weld and base metal weld, which exceeded 420 HV. Zina et al. [17] studied the effect of welding sequence on joint performance, and three types of joints welded in different sequences were compared.

According to the literature, it is reasonable to first join the base metal with carbon steel filler metal, and subsequently weld the transition layer and cladding of the stainless steel with stainless steel filler metal in welding stainless steel clad plates. This welding sequence is suitable for welding large parts such as chemical tanks and pressure vessels with large diameter, which can be welded from both sides. However, owing to the structural limitations of pipes with small diameter used widely in petrochemical industries, the pipe inner wall of the stainless steel cladding has to be first welded, and then the base metal of carbon steel is welded with the same filler metal with the stainless steel cladding. Moreover, the studies on the replacement of filler metal in the specific welding sequence are little reported.

In order to investigate the feasibility of welding the base metal of carbon steel with carbon steel filler metal in the welding of stainless steel clad plates and pipes, the stainless steel clad plates were welded in the sequence from the stainless steel cladding metal to the carbon steel base metal. The cladding of stainless steel and the transition layer were welded with stainless steel filler metal, and the base metal of carbon steel was filled with stainless steel and carbon steel, respectively. The microstructures and mechanical properties of the joints with diverse filler metals were analysed and compared.
The studies here can provide the technical references for the engineering application of welding stainless steel clad plates and pipes.

2. **Experimental procedures**

2.1. **Stainless steel clad plate and its welding process**

The stainless steel clad plates used in the experiments were manufactured by explosive welding. The Q345R carbon steel plate of 16 mm in thickness and the AISI 321 austenitic stainless steel plate of 3 mm in thickness were considered as base metal and clad metal, respectively. Fig. 1 shows the geometrical details of the stainless steel clad plate. The nominal chemical compositions and mechanical properties of the plate are shown in Table 1.

A V-groove with the angle of 60° was prepared before welding. The welding sequence is shown in Fig. 2, and the filler metal of each pass and its corresponding welding parameters are listed in Table 2. As shown in Fig. 2, the manual TIG with the filler wire of stainless steel that matched with the stainless steel clad was used to weld the stainless steel clad metal as a backing welding. To reduce the fusion ratio, the transition layer of weld from the stainless steel clad metal to the carbon steel base metal was welded with the same manual TIG welding process as that of the backing welding. The base metal of the carbon steel was welded using SMAW, and the stainless steel and carbon steel electrodes were used for the filler metals, respectively.

As illustrated in Table 2, the filler metals in the backing welding and filling welding of the transition layer are the ER347 and ER309 stainless steel welding wires, respectively. For the filling welding of the carbon steel base metal, the E309-16 stainless steel electrodes and E4315 carbon steel electrodes were used to form two types of joints. The chemical compositions of the filler metals are listed in Table 3. After welding, the microstructures and mechanical properties of two types of joints were analysed and compared to investigate the feasibility of filling carbon steel base metal layer with carbon steel filler metal instead of stainless steel filler metal.

2.2. **Microstructures analyses**

The samples were cut from joints with diverse filler metals for the base metal of carbon steel and used to analyse the microstructures of the joints. A wire cutting electric discharge machine was used to prepare the samples, and all samples were ground and polished mechanically using 80, 120, 240, 400, 600, 800, and 1000 grits of SiC paper, followed by the final polishing with 3.5, 1.5, and 0.5 μm diamond powders. Because of the different corrosion resistances of stainless steel and carbon steel, different etchants were used in this study. The base metal was etched with 4% nitric acid alcohol solution for 30 s at room temperature, while nitro-hydrochloric acid diluted with equal volume of water was chosen to corrode the clad and transition layers for 150 s at room temperature. The microstructural characteristics were analysed using an optical microscope (GX71, Olympus Corporation, Japan) and a scanning electron microscope (SEM, JSM-5800, Japan Electron Optics Laboratory Co. Ltd., Japan). Owing to the complexity of the microstructure inside and near the transition layer, the microstructure analyses focused on the second (transition layer), third, and fourth welds.

2.3. **Testing mechanical properties**

The Vickers microhardness of each layer of weld in the joints was tested under a load of 1 kg using a microhardness tester (DHV-1000, Shanghai Shangcai Tester Machine Co. Ltd., China). Taking into consideration the complexity of the microstructure of the two joints, the microhardness in different regions of the two joints may be varied. Therefore, seven microhardness curves were obtained for each specimen. The curves were measured crossing different areas as shown in Fig. 2. In the direction parallel to the plate, the microhardness of each layer near the fusion line was measured with a minimum separation of 0.25 mm, and one microhardness profile in the centre of the joint crossing all passes was obtained in the normal direction.

To characterize the tensile properties of the joints welded with diverse filler metals, tensile test samples were prepared according to ISO 16528 for two joints, and the tensile properties were tested at room temperature using a universal mechanical test machine of 500 kN capacity (SANS, MTS Industrial System Co. Ltd., China). Experiments were conducted at the drawing rate of 2 mm/min. Three specimens were tested for each filler metal and the average values were used to study the tensile properties.

In addition, bending tests, which were divided into three categories according to the different pressure directions, were implemented to two joints filled with different metals. A side bending test revealed that pressure was applied on the cross section of the weld. A root bending test was defined to press on the 321SS clad metal, and the bending test with pressure loaded on the carbon steel base metal was named as the face bending test. It is noteworthy that specimens for the face bending test were pre-processed to remove excess weld metal. Three samples were prepared for each test and all samples were bent to 180°. The sampling locations and sample dimensions of tensile tests and bending tests are presented in Fig. 3.

3. **Results and discussion**

3.1. **Microstructures**

3.1.1. **Stainless steel filled joints**

To avoid the repeated results due to similar optical micrographs in different weld beads, the typical views of the
Table 1 – Nominal chemical compositions and mechanical properties of stainless steel clad plate.

<table>
<thead>
<tr>
<th>Chemical compositions/wt%</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elements</strong></td>
<td><strong>C</strong></td>
</tr>
<tr>
<td>Q345R</td>
<td>≤0.20</td>
</tr>
<tr>
<td>321SS</td>
<td>≤0.08</td>
</tr>
</tbody>
</table>

Fig. 2 – The welding sequence and microhardness measured lines of two joints: (a) joint filled with stainless steel; (b) joint filled with carbon steel.

Table 2 – Welding parameters for two joints.

<table>
<thead>
<tr>
<th>Filler metal</th>
<th>Number of passes</th>
<th>Welding methods</th>
<th>Filler metal diameter</th>
<th>Welding current</th>
<th>Arc voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER347</td>
<td>1</td>
<td>GTAW</td>
<td>2.4 mm</td>
<td>70–100 A</td>
<td>8–14 V</td>
</tr>
<tr>
<td>ER309</td>
<td>2</td>
<td>GTAW</td>
<td>2.4 mm</td>
<td>70–100 A</td>
<td>8–14 V</td>
</tr>
<tr>
<td>E309-16</td>
<td>3–6</td>
<td>SMAW</td>
<td>3.2 mm</td>
<td>80–120 A</td>
<td>22–26 V</td>
</tr>
<tr>
<td>E4315</td>
<td>3–6</td>
<td>SMAW</td>
<td>3.2 mm</td>
<td>90–120 A</td>
<td>22–26 V</td>
</tr>
</tbody>
</table>

Table 3 – Nominal chemical composition of filler metal (wt %).

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Mo</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER347</td>
<td>≤0.08</td>
<td>0.30–0.65</td>
<td>0.65–1.00</td>
<td>≤0.03</td>
<td>≤0.03</td>
<td>9–11</td>
<td>≤0.75</td>
<td>19–21.5</td>
<td>Bal.</td>
</tr>
<tr>
<td>ER309</td>
<td>≤0.12</td>
<td>≤0.60</td>
<td>1.00–2.50</td>
<td>≤0.02</td>
<td>≤0.03</td>
<td>12–14</td>
<td>–</td>
<td>23–25</td>
<td>Bal.</td>
</tr>
<tr>
<td>E309-16</td>
<td>≤0.15</td>
<td>≤0.90</td>
<td>0.5–2.50</td>
<td>≤0.03</td>
<td>≤0.04</td>
<td>12–14</td>
<td>≤0.75</td>
<td>22–25</td>
<td>Bal.</td>
</tr>
<tr>
<td>E4315</td>
<td>≤0.12</td>
<td>≤0.90</td>
<td>≤1.25</td>
<td>≤0.035</td>
<td>≤0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
microstructure in the weld joints were presented in the section. Fig. 4 shows the microstructures of the weld filled with stainless steel. As clearly observed in Fig. 4(a), austenite grains are obtained at the centre of the weld. This can be due to the decisive effect of the stainless steel filler metal and little influence of the carbon steel base metal. The micrographic examination also indicates that the austenite grains in the first two welds are finer than those of the subsequent welds because of the better cooling conditions at the beginning of welding. It is evident in Fig. 4(b) that columnar austenite grains are formed in a direction vertical to the fusion line at the edge of every weld. The phenomenon is likely to occur because the welding heat is more easily liberated to the fusion zone and the nucleation energy required at the fusion line is lower.

Fig. 4 also indicates the microstructure in the carbon steel HAZ. It is revealed in Fig. 4(c) that ferrite (bright grains) and pearlite (dark grains) are the dominant microstructures of the carbon steel HAZ. Owing to element diffusion, a decarburized layer is formed in the carbon steel side between the stainless steel weld metal and Q345R base metal interface, as shown in Figs. 4(c) and (d). The precipitated carbon is clearly aggregated along the fusion line in Figs. 4(c) and (d). Similar phenomena occurred in other research about the welding of dissimilar materials [4,14,18]. Wang et al. [19] investigated the microstructure and pitting behaviour of a dissimilar metal weld of 309 L and low alloy steel including the diffusion layer. Jiang et al. [20] indicated that the diffusion of carbon generates stress concentration, and reduces the high-temperature strength and plastic ductility. Microstructural examinations of different layers also reflected that, owing to the diversity of the heat input, the differences in grain size between different layers are notable. The grains are coarser in the high heat input areas and a small amount of martensite is found in the carbon steel HAZ, as clearly observed in Fig. 4(d). These may be due to the alloying elements diffused from the stainless steel welds. Different microstructures distributed in the joint may result in changes in the microhardness.

3.1.2. Stainless steel and carbon steel filled joints
Fig. 5 exhibits different microstructures in different areas of the joint welded with stainless steel and carbon steel. A typical view of the first two stainless steel welds is displayed in Fig. 5(a). Austenite is the primary microstructure that is similar to the welds filled only with stainless steel. Compared with the microstructures shown in Fig. 4(a), the austenite in the first two stainless steel welds is almost not affected by the subsequent welding of the carbon steel weld.

Fig. 5(b) explicitly reveals the microstructure of the first carbon steel filled layer that is adjacent to the stainless steel weld, which is the third layer of the joint. It is clear that pearlite and ferrite are still dominating, but a large amount of martensite are generated. The martensite in the third layer weld in SEM photo is shown in Fig. 6. Pearlite and ferrite are typical in carbon steel weld while martensite can be generated as a result of the high content of alloying elements or high cooling rate. In the welding of the first carbon steel filled layer, some of the stainless steel weld and base metal melt owing to weld heat, which may cause an increase in content of alloying elements, such as C, Cr, and Ni, in the third layer. The formation of martensite in the third layer could be attributed to the complex composition resulting from the contribution of both stainless steel and carbon steel.

As shown in Fig. 5(c), the basic microstructure of other carbon steel welds is proeutectoid ferrite and pearlite. The proeutectoid ferrite occurs along the original austenite grain boundaries and appears as strips or a network. This may be due to the higher average C content in the weld compared with the base metal, and the rapid cooling conditions of the welding process. The micrograph of the fusion line in the carbon steel weld is observed in Fig. 5(d); the weld metal consists of more pearlite and less ferrite compared with the base metal. In the comparison of compositions between the filler metal and base metal, the C content in the carbon steel filler metal is found higher than that in the base metal shown in Tables 1 and 3, which may result in the discrepancy of the microstructure content between the weld metal and base metal.

As mentioned above, the third layer of the weld is composed of martensite, which likely exhibits a complex composition. Therefore, a line scanning across the base metal, HAZ, second layer and third layer was performed with SEM. The scanning results are shown in Fig. 7.

It is apparent in Figs. 7(c) and (d) that the second layer contains an extremely high level of Cr and Ni elements in contrast with either the base metal or third layer because of the stainless steel filler metal. However, the alloying element (Cr, Ni) content of the third layer is higher than that of the base metal and HAZ. This phenomenon may be due to the partial melting of the stainless steel weld during the welding of the third layer and diffusion of alloying elements at high temperatures.

Based on the analysis above, the partial melting of the second layer, which is filled with stainless steel, results in the increase in the content of alloying elements (mainly Cr, Ni) in the third layer. This is the immediate cause of martensite formation in the third layer and the formed martensite will cause an increase in hardness. Martensite usually appears in the welding of dissimilar steels [4,14,21–23]. As reported by Anwar et al. [14], the presence of martensite was similar to a metallur-
4.2. Microstructures of joints filled with stainless steel: (a) centre of stainless steel weld; (b) edge of stainless steel weld; (c) HAZ of carbon steel; (d) HAZ with high heat input.

Fig. 4 – Microstructures of joints filled with stainless steel: (a) centre of stainless steel weld; (b) edge of stainless steel weld; (c) HAZ of carbon steel; (d) HAZ with high heat input.

Fig. 4 – Microstructures of joints filled with stainless steel: (a) centre of stainless steel weld; (b) edge of stainless steel weld; (c) HAZ of carbon steel; (d) HAZ with high heat input.

Fig. 4 – Microstructures of joints filled with stainless steel: (a) centre of stainless steel weld; (b) edge of stainless steel weld; (c) HAZ of carbon steel; (d) HAZ with high heat input.

Fig. 4 – Microstructures of joints filled with stainless steel: (a) centre of stainless steel weld; (b) edge of stainless steel weld; (c) HAZ of carbon steel; (d) HAZ with high heat input.

3.2. Mechanical properties

3.2.1. Microhardness

Fig. 8(a) shows the microhardness values of the stainless steel filled joints. The microhardness values of different passes vary little and are similar to the HAZ and 321SS base metal. The reason is that the microstructure of the weld is austenite as well as the stainless steel base metal. However, the microhardness values of the carbon steel base metal are lower than those of the austenite stainless steel.

It is evident from Fig. 8(b) that the microhardness values of the first carbon steel filled weld are significantly higher than those of other welds. The high level of microhardness can be ascribed to the martensite observed in Figs. 5(b) and 7. In contrast, the microhardness values of other carbon steel metal filled welds are obviously lower, but still higher than those of the carbon steel base metal, owing to the high speed of cooling and grain refinement of the weld metal.

The microhardness profiles of different joints crossing all passes in the normal direction are shown in Fig. 9. It is also obvious that the microhardness values of the stainless steel filled weld are stable, but the profile of another joint increased significantly in the first carbon steel filled layer and the max-
imum value is 425 HV1. Fig. 9 clearly shows the difference in microhardness of different layers between two joints. The local hardening zone (LHZ) in the stainless steel and carbon steel filled joints may adversely affect the mechanical properties of the joints owing to inhomogeneity.

### 3.2.2. Tensile properties

The tensile strength was obtained by testing the standard flat tensile samples processed from welded plates. Fig. 10 shows the representative samples after testing. The typical tensile curves are displayed in Fig. 11. The results of the tensile tests indicate that all specimens are fractured at the base metal. The tensile strength of all samples is within the range of 462–472 MPa. The results indicate that when either carbon steel or stainless steel is used as the filler metal, sound welded joints owing higher tensile strengths than the base metal can be obtained. This finding also indicates that the LHZ in the stainless steel and carbon steel filled welds has no significant effect on the tensile strength of the joints.

### 3.2.3. Bending properties

Fig. 12 shows the typical macrostructure of the samples after the bending test. The results indicate that all stainless steel filled joints display no cracks and fractures. However, different bend tests for joints filled with stainless steel and carbon steel present different consequences. No defects, tearing, or fractures occur in the samples after the root bending test and face bending test for joints filled with stainless steel and carbon steel. However, bulging appears in the weld after the face bending test, which is caused by the LHZ with low plasticity, as
is protruded because of its low plasticity and high hardness, which results in the compatible plastic deformation between the first carbon steel filled layer with high hardness and low plasticity, and its surrounding metal with low hardness. The fractures will occur when the deformation of the metal surrounding LHZ is larger than its plastic limit.

3.3. Discussions

Stainless steel clad plate is used widely because of its excellent corrosion resistance, strength, and low cost. Welding is an important method in the manufacturing the products with stainless steel clad plate. In this research, a novel welding procedure for welding stainless steel clad plate under a specific welding sequence has been proposed. In addition to the mechanical properties, the cost-effectiveness of the proposed welding procedure need to be analysed. It should be noted that two types of stainless steel welding wires (ER347 and ER309) and one type of stainless steel welding electrode (E309-16) were applied in the original welding procedure, as shown in Table 3. The replacement of stainless steel welding electrode with carbon steel welding electrode (E4315) did not change the application of the first two types of stainless steel welding wires, nor did it increase the complexity of welding procedure and indirect additional costs such as labour costs. According to market research, the unit price ratio of stainless steel welding wire, stainless steel welding electrode and carbon steel welding electrode of the same brand is 4.5:4:1, and the price

shown in Fig. 12(a). In the side bending test, not only bulging, which is revealed in Fig. 12(c) and (d), but also cracks with a length of 3–5 mm appear in the weld shown in Fig. 12(b).

The results of the bending tests reveal that the LHZ formed in the first carbon steel filled layer affects the bending property considerably, especially in the side bending test. The plasticity and toughness of the LHZ are worse than those of the low hardness metal surrounding LHZ. Moreover, the outer surface of the specimens for the side bending test is subjected to tension stress state. The LHZ undergoing tension stress state

Fig. 6 – Martensite in the third layer weld.

Fig. 7 – Line scanning map of joint filled with stainless steel and carbon steel: (a) position of the scan path on the joint; (b) different areas on the scan path; (c) content profile of Cr; (d) content profile of Ni.
of stainless steel welding materials is much higher than that of carbon steel welding materials. The deposition efficiency of GTAW and SMAW adopted in this study is about 90%, and 65%, respectively. In addition, the areas of different weld layers filled with diverse filler metal are calculated. The weld filled with E309-16 or E4315 by SMAW account for approximately 84.3% of the entire weld. After calculation, approximately 66.4% welding costs will be saved by adopting the novel welding procedure compared with the original welding procedure, which is a significant cost savings.

Fig. 8 – Microhardness profiles of different joints in the direction parallel to the clad plate: (a) stainless steel filled joint; (b) stainless steel and carbon steel filled joint.

Fig. 9 – Microhardness profiles of different joints in the weld penetration direction.

The stainless steel clad layer in the stainless steel clad plate achieves the performance requirements for corrosion resistance. The welding of dissimilar metals is inevitable in the bonding of stainless steel clad plates. However, the welding of dissimilar materials, such as stainless steel and carbon steel, is extremely difficult because the composition and mechanical properties of the two metals vary considerably. It is well known that the welding joints of dissimilar metals are usually weak regions. The diffusion of carbon between stainless steel and carbon steel generates stress concentration, and reduces the high-temperature strength and plastic ductility. The brittle martensite can induce an undesirable effect similar to the metallurgical notch, which causes the occurrence of cracking. Chen et al. [24] found that notches would bring more damages to the welded samples, and there was no Luders band propagation in the welds during the yielding stage. In addition, elemental diffusion layer and martensite are more susceptible to corrosion in corrosive environments where stainless steel clad plates are often used.

However, the welded joints of stainless steel clad plates are different from ordinary joints of dissimilar metals. The joint filled with stainless steel and carbon steel in service is schematically shown in Fig. 13. During the service of welded joints of stainless steel clad plates, only the inner stainless steel layer including the first stainless steel weld is exposed to corrosion environments. The dissimilar metal welds cannot be exposed to a corrosive medium when the quality of the first two layers of stainless steel is eligible. Therefore, the weld-
ing of the first two welds is crucial, and the influence of the third layer on the front layers should be minimised. Moreover, martensite is formed in the third layer, which is the centre of the entire weld. The LHZ containing martensite in the weld is protected well by the high plastic homogenous welds on both sides. Therefore, the joint filled with stainless steel and carbon steel exhibits equal tensile properties as joint filled with stainless steel, and no defects appear in root bending test and face bending test. However, stress concentration may be caused by the inhomogeneity around the LHZ. The stress corrosion resistance will be studied in a future research.

Certainly, the possibility of cracking caused by the LHZ is present in the side bending test. Some scholars discovered similar findings. Zina et al. [17] studied the effects of different welding sequences on the performance of stainless steel clad plate joints. They found that the formation of martensite in weld configuration 1, which was the same as the welding sequence in this research, caused cracks in the joints during bending tests. However, they did not specifically analyse the microstructure and microhardness of each layer of weld, but considered that the LHZ appeared in the 309 L stainless steel weld metal instead of the carbon steel weld metal.

Can martensite be formed in stainless steel weld in the welding of stainless steel clad plate? Can the formation of martensite be avoided? In order to study the possibility and rationality of formation of martensite in different layers of the joint filled with stainless steel and carbon steel, the phase composition of different areas is quantitatively analysed from the elemental composition. The \(\text{Cr}_{eq}\) (chromium equivalent) and \(\text{Ni}_{eq}\) (nickel equivalent) of Q345R, 321SS and each filler
metal are calculated. Then the Cr$_{eq}$ and Ni$_{eq}$ of each layer of weld are estimated according to the approximate fusion ratio. The positions of different layers of weld on the Schaeffler diagram is shown in Fig. 14. According to the calculation, the first layer and second layer of weld filled with stainless steel and carbon steel is difficult to form martensite, because they are not within the proper elemental content range for the formation of martensite. But the formation of martensite in the third layer weld is almost inevitable from the Schaeffler diagram. An et al. also studied the formation mechanism of martensite during the welding of stainless steel clad plates. In their research, the carbon steel backing welding (CSBW) was first welded, and the stainless steel covering welding (SSCW) was performed at the end. The martensite and bainite were also found in some areas of CSBW where no re-melting occurred. The line scanning results of CSBW indicated that there was no significant difference in Cr and Ni gradients along the thickness direction of the CSBW weld of about 1.7 mm. However, different findings are reported in other researches. For example, the concentration gradients and diffusion coefficients of Cr and Ni between cladding layer and substrate layer could lead to the diffusion distances of 10–13 μm and 3–4 μm, respectively. The thicknesses of the decarburized layer and carburized layer at the interface of the carbon steel base metal and the stainless steel cladding layer were about 60–80 μm and 20–40 μm, respectively. Although the heat input of welding may increase the diffusion distance, such a uniform element distribution is unreasonable. The appearance of martensite should be caused by the melting of partial stainless steel base metal during the CSBW. The method of inhibiting the formation of martensite in the novel welding procedure proposed in this paper may be to reduce the heat input during the welding of the third layer weld, and then to reduce the melting of stainless steel weld while ensuring the joint quality.

The rule associated with the influence of the areas of the LHZ containing martensite on the side bending test is now investigated. Fig. 15 shows the relationship between the areas of the LHZ of different joints and the sample condition after side bending test. According to the statistics, the critical area for cracks is about 54 mm², and the entire weld area is about 320 mm². The critical area for cracks is about 17% of the entire weld area. The statistical analysis of all side bending test results indicates that the cracks in the weld could be avoided efficiently once the area of the LHZ on the cross section is controlled to be less than 17% of the entire weld area.

**Fig. 14 – Positions of different layers of weld in Schaeffler diagram [25].**

**Fig. 15 – Relationship between the areas of LHZ and the sample condition after side bending test.**
As mentioned above, the elemental conditions for the formation of martensite in the third layer of weld filled with stainless steel and carbon steel are sufficient, but whether the martensite can be removed by other welding processes including heat treatment processes after welding requires further research. Additionally, the effect of martensite on the mechanical properties of the stainless steel clad plate joint can be reduced by reducing the area of the LHZ, and how to control the area of the LHZ needs more research in a future work.

4. Conclusions

The microstructures and mechanical properties of different metal filled joints were investigated and compared, and the cost-effectiveness of the replacement of filler metal in the welding of carbon steel base metal was analysed. The conclusions can be summarized as follows:

- In terms of microstructure, austenite grains dominate in the weld filled with stainless steel owing to the decisive effect of stainless steel filler metal. For the weld with stainless steel and carbon steel, different layers exhibit different microstructures. A microstructure associated with martensite is found in the first layer of weld filled with carbon steel owing to the fusion of adjacent stainless steel weld and the complexity of alloy elements.

- A local hardening zone (LHZ) forms in the first layer of weld with carbon steel filler metal because of the formation of martensite phase. The maximum recorded Vickers micro-hardness value of the LHZ reaches up to 425 HV₁, which is significantly higher than those of stainless steel welds and the original metal.

- The tensile test results show that the LHZ has no adverse effects on the tensile strength of the joints. Stainless steel clad plate joints filled with different filler metals exhibit safe and satisfactory tensile strength, and the fractures occur in the base metal in tensile test.

- Bending tests demonstrate that no defects, tearing, or fractures occur in the samples after the root bending test and face bending test for joints filled with different filler metals. Nevertheless, the LHZ protrudes in bending test. The cracks will appear near the LHZ in the side bending tests if the area of LHZ in the cross section is higher than 17 % of the entire weld area.

- The welds filled with carbon steel account for 84.3 % of the entire weld, and about 66.4 % welding costs will be saved by adopting carbon steel filler metal instead of stainless steel filler metal in the welding of carbon steel base metal.

Conflict of interest

The authors declare no conflicts of interest.

REFERENCES


