Study of the Martensite Structure at the Weld Interface and the Fracture Toughness of Dissimilar Metal Joints

Deterioration of toughness in the HAZ is more a result of coarse-grained bainite than of martensite

BY ZHIHUI WANG, BIYU XU, AND CIQI YE

ABSTRACT. In austenitic-ferritic dissimilar metal welded joints, the content of alloying elements in the transition zone varies continuously from the heat-affected zone (HAZ) to the weld metal. Due to the low level of Ni content, a martensite layer is formed in this zone during the welding process. The Charpy impact test performed previously by other researchers indicated that the martensite layer was the weakest zone in toughness in the joints. In this study, color metallography and transmission electron microscope (TEM) analysis were used to show the martensite structures at the weld interface. The results show that the structures of the martensite layer at the weld interface are lath martensite. The martensite starting points vary with the distance from the fusion line and are controlled by composition gradient. The boundary of the transition zone could be divided into two types: the “blurred” type and the “sharp” type, which are controlled by diffusion of elements.

A simulation test, in which specimens were prepared by casting steels in accordance with the compositions of the martensite layer, was conducted to evaluate the fracture toughness of the martensite layer. The experiments were also made to investigate the distribution of toughness in the different regions of the joints. The results show that the weakest region in toughness in the dissimilar metal joints is not the martensite layer but the overheated zone in HAZ.

The fracture in the overheated zone is caused by the coarse-grained bainite, and it appears as a quasi-cleavage fracture; however, in the martensite layer, it appears as a tear fracture.

Introduction

Since the 1940s Cr-Mo heat-resistant steels and austenitic stainless steels have been widely used in power plant construction and the chemical industry. Simultaneously, a great number of austenitic electrodes were used in welding low-allow, high-strength steels such as Cr-Mo and armor steels. With the progress of steel construction, austenitic/ferritic (A/F) dissimilar metal joints have become more popular and important.

Dissimilar metal joints have special features as follows:
1) Due to differences in the chemical composition of base metal and filler metal, their alloying elements will diffuse intensely during welding. The structures near the fusion line are very complex. A hard martensite layer will be formed at the weld interface, which could cause the heterogeneity of mechanical properties in the joints.
2) The mismatch of physical properties, such as the heat transfer coefficient and the thermal expansion coefficient, could induce thermal stress at the weld interface.
3) When the joints are used at elevated temperature, carburized and decarburized zones will occur, which could affect the high-temperature properties.

The microstructures of dissimilar metal joints have been studied since the 1930s, and although many investigations on the martensite layer at the weld interface have been conducted, the metallographic observations on the layer were not clear enough because of the different resistance to etchants of the two materials. The martensite layer in the joints as welded appeared to be a “light-etching region” (Refs. 1–5) after etching by common etchant (2–4% nital, picral-nital, and so on). By using the two-step etching method (electro polishing + 2–4% nital), the structures of both materials could be shown, but the structures at the weld interface were still not clearly visible. The existence of the martensite layer had to be distinguished by Vickers hardness or postweld heat treatment (Refs. 1–7). Finding a proper etchant is the key for further studies.

Researchers are concerned about the existence of the martensite layer at the weld interface, which was regarded as the root of crackings. However, if the structure of the martensite layer is a lath martensite, its toughness should be

KEY WORDS

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improved. On the contrary, the coarse structures in the HAZ adjacent to the martensite layer are very brittle, so the effect of the martensite layer on the toughness of the joints has to be evaluated properly.

In this project, the authors investigated the microstructures and fracture toughness at the weld interface of dissimilar metal joints by color metallography, transmission electron microscope (TEM) analysis and crack opening displacement (COD) test.

Experimental Procedure

Materials and Welding

Chemical compositions of base metals and filler metals are given in Table 1. The gas metal arc welding (GMAW) process was employed with 4-mm diameter electrodes and V-groove geometry with root face, prepared on 16-mm thick base metal. The heat input was 12-14 kl/cm.

Metallurgical Examination

Transverse sections used for the optical metallographic observation and TEM were taken from the joints (as-welded) of low-alloy steels welded with austenitic electrodes. Tint echants were used to show the microstructures at the weld interface.

Martensite Layer Simulation

Because the width of the martensite layer at the weld interface of A/F dissimilar metal joints is very narrow (about 30-150 μm), it is difficult to make the fracture toughness test on the narrow layer in the dissimilar metal joints. For this experiment, the fracture toughness test on the martensite layer was made by a simulation method.

First, the chemical compositions in the martensite layer of a Cr25Ni13/13CrMo44 joint was examined by electron microprobe. The Z.A.F. procedure was used to correct the x-ray counts. The compositions at three points at different distances from the fusion line are shown in Table 2. The carbon content was estimated by the linear interpolation method according to the carbon contents of base metal and filler metal.

Next, according to the chemical compositions of the martensite layer shown in Table 2, the simulated samples were made in an induction furnace. The chemical compositions of the simulated samples are shown in Table 3.

After that, the Ac1, Ac3 and Ms of the simulated samples were obtained by Formaster-Digital Transformation Measuring Apparatus, and then, heat treatment of the samples was made to get a similar grain size as the martensite layer in the dissimilar metal joint.

Finally, the half-finished samples (10.5 x 10.5 x 55 mm) were prepared to simulate the welding thermal cycling.

Thermal Simulation

The welding thermal simulation was made with a Gleeble 1500 in order to simulate the structures of martensite layer and HAZs. The thermal cycle was based on the thermocouple measurements in the welding process. The parameters in the thermal simulation are shown in Table 4.

The structures of thermal simulated samples of the martensite layer are shown in Fig. 1. Figure 2 shows the structures of a thermal simulated sample of
HAZ (T_{max}=1300°C) and the overheated zone of a Cr18Ni8/13CrMo44 joint. The structure of the martensite layer at the weld interface is shown in Fig. 3.

COD Test

The COD test was made at room temperature. When the R-δa curve was obtained, the experimental data had to be treated by means of the monadic linear regression method. The regions to be tested in the COD test were weld metal, martensite layer (simulated samples), HAZ (thermal simulated samples) and base metal. The size of specimens was 10 × 10 × 55 mm (0.4 × 0.4 × 0.2 in.).

### Results of the Experiments

**Microstructure at the Weld Interface and Distribution of Alloy Elements**

The microstructures of the interface of the Cr25Ni13/13CrMo44 dissimilar joint are shown in Fig. 3. The color of the HAZ is brown, and the weld is white. Between them there is a blue layer which could wedge into the weld metal to form an islet. The Vickers hardness tests indicate that the hardness of the blue structure was 400-500 HV. At high magnification, the blue structure of Cr18Ni8/13CrMo44 becomes distinguishable: it is low-carbon martensite — Fig. 4. The martensite laths have a different orientation at the two sides of the original austenitic grain boundary, and many “cross” type structures are formed.

It is interesting that the Cr25Ni13/12Ni3CrMoV joint has an obvious structure gradient. Figure 5 shows various phases — the martensite layer is at the upside of the photograph and the bainite + martensite (B + M) region (HV=300) connects with the layer. From the overheated zone to the B + M region, the structure changed gradually. However, from the B + M region to the martensite layer, the structure changed abruptly. From other combinations of base metals and filler metals, shown in Figs. 6 and 7, you can find that the structure of the martensite layer is very similar.

It was found that the fusion line could be divided into two types as shown in Fig. 8. The interface at some parts along the whole fusion boundary is sharp (Fig. 8A), but at other parts it is not so distinct. It appears to be a transition zone (Fig. 8B). The former is called “sharp” fusion line and the latter “blurred” fusion line.

### Table 4 — Parameters in Thermal Simulating

<table>
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<th>Regions</th>
<th>Tmax (°C)</th>
<th>t_{0.5} (s)</th>
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<td>Martensite Layer</td>
<td>N10</td>
<td>1320</td>
</tr>
<tr>
<td></td>
<td>N20</td>
<td>1320</td>
</tr>
<tr>
<td></td>
<td>N30</td>
<td>1320</td>
</tr>
<tr>
<td>HAZ (13CrMo44)</td>
<td>Overheated zone</td>
<td>1300</td>
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<tr>
<td></td>
<td>Tempered zone</td>
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<tr>
<td></td>
<td>Fine-grained zone</td>
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Fig. 2 — Microstructures of HAZ, 140X, enlarged 13X.

Fig. 3 — Structures of Cr25Ni13/13CrMo44 joint as-welded, 53X, enlarged 13X.

Fig. 4 — Structures of Cr18Ni8/13CrMo44 joint as-welded, 280X, enlarged 13X.

Fig. 5 — Structures of Cr25Ni13/12Ni3CrMoV joint as-welded, 140X, enlarged 13X.

Fig. 6 — Structures of Cr25Ni13/35CrMoA joint as-welded, enlarged 13X.
Obviously, the formation of two types of fusion lines is related to the diffusion of elements. By the aid of EPMA, the distribution of elements for the two types of fusion line is shown in Fig. 9. The transition zone of alloy elements is very narrow in the “sharp” fusion line, and the diffusion phenomena are not obvious. Conversely, for the “blurred” fusion line, the elements transit gradually and the transition zone is wide.

**TEM on the Original Thin Foil of Weld Interface**

The specimens used for TEM were cut from Cr18Ni8/13CrMo44 joints. Figure 10 shows the microstructures. In the case of low magnification (Fig. 10A) the fusion line between the martensite layer and HAZ could easily be distinguished. Figure 10B shows the high magnification in the martensite layer 10 μm from the fusion line. The electron diffraction patterns indicate that the lath is a bcc structure (Fig. 11). The appearance of the structure (Fig. 10B) is a typical dislocation martensite, and the width of the lath is 0.1 to 0.7 μm. The martensite lath adjacent to the fusion line is parallel to it. At the position about 4 μm, the lath turns to an angle of 30–90 deg with the fusion line, and forms some “cross” structures — Fig. 12.

**Results of COD Test**

The results of the COD test are shown in Fig. 13. The overheated zone of HAZ has the lowest COD value. From the fractograph shown in Fig. 14, it appears as cleavage and quasicleavage fracture. The propagation of the cracks behaves...
as a brittle mechanism. The COD values in the martensite layer are not high, but the fractograph shown in Fig. 15 indicates that it is a tear fracture in this layer. Although the COD values of the martensite layer and the overheated zone are lower, they have a different fracture mechanism, and the cleavage and quasi-cleavage fracture of the overheated zone determined that this region is the weakest zone in toughness. It is caused by the coarse-grained bainite, which severs the primary austenitic grain and reduces the resistance of the structures to the crack propagation.

Martensite Start Points Distribution in the Martensite Layer

The $M_s$ points vary with the distance from the fusion line shown in Fig. 16. They are higher near the fusion line and lower away from it.

Discussions

Model of the Formation of the Martensite Structure

The formation of the martensite structure at weld interface of dissimilar metal joints is not the same as that of homogeneous materials which have a constant $M_s$ point. Because there is a gradient of chemical compositions in dissimilar metal joints, the $M_s$ points vary continuously in the martensite layer (Fig. 16). This corresponds to the region of Ni content below 7% (Fig. 9). This feature makes the martensite structure exhibit its special appearance. In regard to homogeneous materials, an original austenitic grain is divided into lath regions, and in the same lath regions, a bundle of laths has the same orientation (Ref. 12). But in the weld interface of dissimilar joints, the lath regions appear “jumbled” in an original austenitic grain and many “cross” structures are formed. This phenomenon was also confirmed by TEM — Fig. 12. We explain this phenomena as follows:

In the martensite layer, because the $M_s$ points vary with the distance from the fusion line, the martensite transformation cannot perform simultaneously. We name the highest temperature at which the martensite starts to transform in the weld interface as $M_{s\text{max}}$ and the lowest temperature as $M_{s\text{min}}$ — Fig. 16. To make it easy to consider this problem, the assumption is made that there is no temperature gradient in the martensite layer during the cooling period of the welding process. As the temperature drops to the $M_{s\text{max}}$, the region adjacent to the fusion line in the weld begins to transform to martensite. As cooling continues, regions away from the fusion line transform to martensite, and the martensite region develops further. Figure 17 describes the formation of the martensite in the weld schematically; because of the nonuniformity of the chemical composition in the weld, the interface of martensite and austenite must be ragged (zigzag). This can be seen in Fig. 8. As the temperature drops, the interface of the region transformed to the martensite and the region untransformed in the weld (L in Fig. 17) develops toward the weld metal. Consequently, because
of the different orientation of the martensite lath, the newly formed martensite has the chance to form the intersecting structure (cross structures) at the weld interface.

The Effect of Martensite Layer on the Toughness of the Dissimilar Metal Joints

Due to the low level of Ni content, a martensite layer is unavoidably formed in the A/F dissimilar metal joints. This layer is regarded as harmful to the toughness of the joints (Ref. 5) and the Ni content should be increased to prevent the formation of this layer. Our research indicates that the microstructures of this layer are lath martensite, which is tougher than the overheated zone.

Bailey (Ref. 9) performed a cracking test by welding high-strength steel (σs=980 MPa) with Cr9Ni13Mn austenitic electrodes. He found that many cracks appeared in the overheated zone in the HAZ instead of the martensite layer. When the base metals are high-strength steels, it means that the strength in HAZ is similar to the martensite layer. In this case, the toughness of the joint is determined by the region lowest in toughness. From our experimental results, we attribute the better resistance to cracking propagation of the martensite layer as follows: 1) the structure of the martensite layer is lath martensite, which presents better toughness; 2) the weld metal adjacent to the martensite layer could dissolve more hydrogen; and 3) the yield stress of weld metal is lower, which lends itself to reducing the stress level in the martensite layer.

Conclusion

The structure of the martensite layer at the weld interface of dissimilar metal joints is lath martensite. In the martensite layer, the Ms points vary with the distance from the fusion line, which is controlled by the chemical composition gradient. This feature causes the formation of many cross structures.

The fusion line of austenitic ferritic dissimilar metal joints could be divided into two types: “sharp” and “blurred”. The type is determined by diffusion of elements.

The weakest region in toughness in the dissimilar metal joints is not the martensite layer but the overheated zone in the HAZ. The fracture in the overheated zone is caused by the coarse-grained bainite, and it appears as a quasicleavage fracture; however, in the martensite layer, it appears as a tear fracture.

References