Effects of Welding Parameters on Hard Zone Formation at Dissimilar Metal Welds

Controlled optimum preheat/cooling rate resulted in drastic reduction and often complete elimination of hard zone formation at dissimilar metal welds fabricated with ENiCrFe-3 electrodes

BY A. A. OMAR

ABSTRACT. An experimental study was conducted to determine effects of welding parameters and to optimize those parameters that have the most influence on eliminating or reducing the extent of hard zone formation at dissimilar metal welds (DMWs). Preheat, base metal thickness, and welding electrode composition were found to have the most influence. Maintaining an optimum preheat for a given base metal thickness and controlling the maximum interpass temperature throughout welding resulted in drastic reduction and often complete elimination of hard zones at DMWs fabricated with ENiCrFe-3 electrodes, but not those fabricated with E309 stainless steel electrodes. This finding indicates that depending on the cooling rate and composition of the welding electrode, hard zones in DMWs can be eliminated. The cooling rate must be slow enough to allow formation of hard allotropes (i.e., martensite) and fast enough to avoid precipitation of hard intermetallic phases. The optimum welding electrode composition is one that will retard formation of allotropes and austenite/harden the formation of hard intermetallic phases during welding while the preheat temperature is maintained. Unfortunately, DMWs have several fabrication and metallurgical drawbacks that can often lead to in-service failures. The most pronounced fabrication faults are hot cracks and the inadvertent use of incorrect welding electrodes, primarily carbon steel electrodes. Use of carbon steel welding electrodes results in the formation of a very hard, crack-susceptible bulk structure on the stainless steel side of the DMW joint. Examples of these faults can be found in the open literature (Refs. 1, 2). However, the most troublesome drawback of DMWs is the inherent formation of discontinuous brittle and hard zones primarily along the fusion line of the ferritic side of the joint (Fig. 1). Hardness of these zones ranges between 300–425 VHN (HRC 30–43). Such hard and brittle zones may render DMWs susceptible to localized pitting corrosion attack, hydrogen embrittlement, sulfide stress cracking (SSC) and stress rupture, which often occurs in the weakened structure of the ferritic material heat-affected zone (HAZ) of the DMW joint. Indeed, several in-service failures of DMWs in wet corrosive environments and many failures in high temperature service have been reported in the open literature (Refs. 3–5, 7, 9, and 10).

Background

In the oil and gas industry, DMWs are sometimes used in lieu of flanged connections and for weld cladding of equipment in wet and high temperature corrosive environments containing hydrogen sulfide and in high pressure, high temperature hydrogen services. For wet sour service, the equipment is designed to the requirements of NACE standard MR-0175 (Ref. 8). While NACE limits the maximum hardness of carbon and stainless steel base metals and weld deposits to HRC 22 (VHN 250), it does not address hardness of DMWs and that of the resulting hard zones. Accordingly, DMWs are outside the scope of the subject NACE standard and the aforementioned NACE limits on hardness are not intended to be used as an acceptance-rejection criterion for DMWs in wet sour service. Nevertheless, and because the higher the hardness, the more susceptible the material becomes to environmental stress cracking, concerns about reliability and long term performance of DMWs are paramount. This concern, coupled with the reported in-service failures of DMWs in wet sour service, prompted some oil and gas companies including Saudi Aramco to restrict the use of DMWs in hydrogen and hydrogen sulfide services. Accordingly, flanged
connections are the option for equipment where dissimilar metals must be joined together. However, use of flanged connections in facilities that handle hydrocarbons or lethal products also raises some safety concerns.

Literature Survey

A literature survey revealed more than 170 entries that address DMW features, hard zones, laboratory and field tests as well as case histories of in-service failures. Hard zones are described by Lundin (Ref. 9) as carbon enriched zones that may contain many constituents such as martensite, but carbides predominate. A significant number of the articles refer to the hard zones as unmixed zones (UMZs), transition zones, or intermediate mixed zones (IMZs) and intermetallics that develop during arc welding/solidification at the weld interface of the ferritic material (Refs. 11-17). UMZs have also been reported to form along the weld interface of high alloy stainless steels like 904L and 254 SMO welds fabricated with non-matching/enriched filler metals such as ENiCrMo-3. These zones were found to be susceptible to selective pitting corrosion attack in oxidizing environments (Refs. 15-17). It should be noted that the term "UMZs" appears to be incorrectly used by some authors. As can be seen in Fig. 1B, a truly UMZ is comprised of a small piece of the base metal that has not mixed into the bulk weld metal and it may or may not be located at the weld interface. For these UMZs, hard structure is often located along their boundary interface with the weld metal. This feature can also be seen in Fig. 1B. Accordingly, the "transition," the "unmixed," and the "intermediate mixed" zones will be referred to herein as "hard zones."

The intermetallics, on the other hand, are the products of solid state transformation, which also include carbides and nitrides. While intermetallic formation is normally associated with extended thermal cycles between 800-1650°F (425-900°C) during either postweld heat treatment (PWHT) or high temperature service, recent studies have shown that significant precipitation of intermetallics (i.e., Sigma, Chi, etc.) can occur during welding (Refs. 16, 21). Depending on the chemical composition of the filler metal used, the same intermetallic phases form at different thermal experiences (Refs. 20-22).

Equally important, but of a much lesser concern than those situations of butt and groove DMWs, is hard zones formation and cracking along the interface of the austenitic stainless steel weld cladding. Austenitic stainless steel and nickel-based weld cladding are widely used in the fabrication of pressure vessels and reactors of carbon and low alloy steels in wet sour and in high pressure, high temperature hydrogen service. Hydrogen disbonding/interface cracking of weld cladding has been studied by many researchers. A summary of their findings follows:

- Cracking at the weld overlay interface is affected by many parameters. The most pronounced parameter is carbon content of both the base and weld metals.
- Disbonding of the weld cladding occurs primarily due to two types of cracks. One type occurs along the martensitic/carburized zone structure and the other occurs along the bound-
Welding parameters and their effects on electrode are used, cracking of DMWs structure that forms when carbon steel hard zones formation at DMWs; 2) with lighted: 1) none of the surveyed articles curs in the weakened partially molten zones (Ref. 10). This observation suggests that our efforts should be focused on means of preventing or drastically reducing the formation of hard zones and the associated weakened interface structure of DMWs. Based on this observation, the two-phase in-house study was initiated.

Objectives of the Study

The primary objectives of the two-phase study were to determine: 
- **Effects of welding parameters including type of welding electrode, welding process, base metal thickness, carbon content, joint design, preheat, postweld heat treatment (PWHT), and buttering/temper bead on the extent of hard zone formation.**
- **The optimum welding parameters that may either eliminate or drastically reduce hard zones formation.**
- **Effects of welding parameters on hard zone formation were studied in 1990 and the findings were presented at the Fifth Middle East Corrosion Conference (MECC) of NACE International in Bahrain, October 1991** (Ref. 1). Accordingly, detailed discussion of the first phase of the study will not be presented in this paper, but a brief summary of its findings will be included for continuity and cohesiveness of findings of both phases of the study. The second phase of the study was conducted in July 1995 and was repeated in March 1996 for verification of the findings. It focused on optimizing those parameters that were determined during the first phase of the study to be most effective in reducing hard zone formation. These parameters included preheat temperature, base metal thickness and chemical composition of the welding electrode.

Experimental Procedure

The following conditions were used to shop fabricate test welds for optimizing the above mentioned welding parameters of the second phase of the study.
- **Joint design:** Full penetration single groove butt joint with 60 degrees included angle, 1/16-in. (1.6-mm) root face and 1/16-1/8-in. (1.6-3.2 mm) root opening
- **Welding process:** Shielded metal arc welding (SMAW)
- **Welding electrode:** 1/8 in. (3.2 mm) diameter, E309 and ENiCrFe-3
- **Preheat temperatures:** 300, 350, 400, 450 and 500°F (150, 177, 205, 232 and 260°C) maintained throughout welding
- **Welding current range:** 70-110 amperes
- **Arc voltage range:** 22-27 volts
- **Welding speed range:** 6-8 in./min (152-203 mm/min)/root pass and 3.5-6 in/min (89-152 mm/min)/fill and cap passes

The test plates were fixed at a 45 degree angle and the welds were fabricated in the uphill welding direction by a welder qualified to ASME Section IX welding code. All welds were fabricated from one side only, using the inner bead for the root pass and weaving the fill and cap passes. Backgouging and backwelding were not permitted. The specified preheat temperatures were applied and maintained throughout welding using hand held heat sources, representative of field welding. The Interpass temperature was also controlled to a maximum of 25°F (14°C) above the preheat temperature. This practice is done to avoid an overlap in preheat temperatures of 50 deg increments and help maintain control over the cooling rate for the specific set of welding conditions. Preheat and Interpass temperatures were monitored using Tempil-sticks and a laser gun. The welded plates were held in the fixture until their temperature reached ambient. Heat input was controlled by controlling the range of the above listed welding parameters.

Test Procedure

All fabricated joints were first radiographed to document weld quality and identify location of weld discontinuities. Multiple transverse metallographic cross sections were prepared for microstructural examination and hardness testing to determine effects of the above welding parameters on the extent of hard zone formation, microstructure and hardness levels. The metallographic cross sections were removed from identical locations at 2 in. (51 mm) from ends and from the center of each weld joint. Hardness measurements were made on the most pronounced hard zones of cross sections from the three locations of all test welds. A combination of the Vickers and Knoop microhardness testing methods were used as mandated by the width of the specific hard zone. Extent of hard zone formation was documented by visual measurements through the binocular tube and by measuring the overall length of all hard zones along the weld interface of each metallographic cross section using the measuring grid of the microscope. Microprobe analyses were used to determine chemical composition of typical hard zones of selected specimens. The resulting compositions of typical hard zones are listed in Table 1. The nominal composition of welding electrodes and base metals are shown in Table 2.

Findings

**Summary of First Phase Findings**

Findings of the first phase of this study revealed that all welding parameters can either increase or decrease the extent of hard zone formation and optimization is essential. For examples variations in preheat, wall thickness and temper bead resulted in varying hardness. Significant reduction in the extent of hard zone formation in welds deposited with ENiCrFe-3 was observed, but not in welds fabricated with E309 electrodes. PWHT resulted in several detrimental effects as follows:
- Carbon depletion, grain growth and softening of the heat-affected zone (HAZ) structure along the weld interface of the ferritic material (Fig. 2).
- Formation of very pronounced carbide rich localized bands along the weld interface of the ferritic material due to carbon diffusion (Fig. 2).


**Table 1 — Microprobe Analyses of Hard Zones at DMWs of Welding Electrodes Used**

<table>
<thead>
<tr>
<th>Welding Electrode</th>
<th>Element, wt-%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cr</td>
</tr>
<tr>
<td>E309</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>ENiCrFe-3</td>
<td>5.5-15</td>
</tr>
</tbody>
</table>

**Table 2 — Nominal Chemical Composition of Welding Electrodes and Base Metals Used**

<table>
<thead>
<tr>
<th>Electrode/Base Metal</th>
<th>C</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Nb (wt-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E309</td>
<td>0.07</td>
<td>1.90</td>
<td>60</td>
<td>13</td>
<td>23</td>
<td>0.50</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>ENiCrFe-3</td>
<td>0.03</td>
<td>1.0</td>
<td>8</td>
<td>60</td>
<td>15</td>
<td>—</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>ASTM A36</td>
<td>0.25</td>
<td>0.9</td>
<td>97</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>API 5L X60</td>
<td>0.05</td>
<td>0.95</td>
<td>Ba</td>
<td>0.08</td>
<td>0.02</td>
<td>0.10</td>
<td>0.18</td>
<td>0.036</td>
</tr>
<tr>
<td>AISI 316 SS</td>
<td>0.08</td>
<td>2.0</td>
<td>66</td>
<td>12</td>
<td>17</td>
<td>2.5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>AISI 316 L</td>
<td>0.03</td>
<td>2.0</td>
<td>65</td>
<td>13</td>
<td>17</td>
<td>2.5</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

- Sensitization of the stainless steel base metal structure.

Compared with SMAW, the GTAW process did not contribute to any reduction in the extent of hard zone formation. Regardless of type of welding electrode or process used, narrow groove weld joints (45 deg and narrower) and stringer beads contributed considerably to the formation of hard zones when compared with those joints of wider groove utilizing weave beads for the fill and cap passes (Ref. 1). DMWs utilizing the relatively high carbon content ASTM A-36 steel resulted in the formation of a more distinct carbide rich band along the weld interface than those utilizing the low carbon API 5L X60 steel pipe. However, extent of hard zone formation did not increase proportionately with the increase in carbon content. Finally, DMWs with thickness less than 3/16 in. (4.8 mm) exhibited the least amount of hard zone when compared with DMWs of thicker joints using the same welding parameters.

**Second Phase Findings**

Findings of the second phase revealed that formation of hard zones at DMWs can either be prevented or drastically reduced when a combination of the correct cooling rate and welding electrode composition are used. This statement is based on results of microscopic examination and hardness testing of many metallographic cross sections of all welds fabricated for this study. A summary of these findings follow:

- A reduction of about 70-85% in the extent of hard zone formation in DMWs fabricated with ENiCrFe-3 electrode was achieved when the optimum preheat temperature was used. The percent reduction in hard zone formation in welds fabricated with E309 electrode was about 30-50%. (The percent reduction is calculated based on extent of hard zones formed in welds fabricated with the controlled optimum preheat temperature vs. those hard zones found in welds fabricated with the same welding electrode and other welding conditions but with different preheat temperatures). Unfortunately, the optimum preheat temperature for DMWs fabricated with ENiCrFe-3 electrode had a very narrow range of plus and minus 25°F (-3.8°C). This result is shown in Fig. 3.
- Electrode composition had a marked effect on the extent of hard zone formation at DMWs. This observation is also shown in Fig. 3.
- High hardness levels can be eliminated only by the elimination of hard zones. This condition was accomplished in DMWs fabricated with ENiCrFe-3 electrode under controlled optimum preheat and interpass temperatures.
- For DMWs fabricated with ENiCrFe-3 electrode under optimum preheat, but with uncontrolled interpass temperatures, a reduction of 50-70 VHN points in hardness level was experienced, compared with hardness levels of welds fabricated under other preheat temperatures. However, hardness levels of hard zones remained well above the NACE limit of HRC22 (VHN250) for all welds. This situation is shown in Fig. 4.
- Level and degree of control of both preheat and interpass temperatures had significant and very important effects on the resulting carbon steel-to-metal interface microstructure as follows:
  - DMWs fabricated with ENiCrFe-3 electrode under controlled optimum preheat and interpass temperatures resulted in a hard zone-free carbon steel-to-weld metal interface with a very uniform and homogeneous microstructure. This result is shown in Fig. 5.
  - DMWs fabricated with ENiCrFe-3 electrode without preheat and with uncontrolled interpass temperature developed localized hard zones with a variety of mixed microstructure. The hard zones consisted of a relatively wide carbide band located at the interface between the ferritic structure of the carbon steel base metal and a zone of largely untempered martensite. This observation is shown in Fig. 6.
  - DMWs fabricated with ENiCrFe-3 electrode under controlled optimum preheat but with uncontrolled interpass temperature developed hard zones with mixed microstructure. The microstructure consisted of a very narrow band of...
carbides located at the interface between the ferritic structure of the carbon steel base metal and a zone of duplex structure consisting of tempered martensite and austenite. This situation is shown in Fig. 7.

DMWs fabricated with ENiCrFe-3 electrode with controlled preheat and interpass temperatures that are higher than the optimum preheat temperature, developed a narrow and almost continuous carbide band along the interface of the carbon steel base metal and the austenitic weld metal. This result is shown in Fig. 8.

Discussion

While no attempts were made to measure the cooling rate for the different welding conditions used in both phases of this study, cooling rate is known to be affected by preheat, heat input and joint thickness. Similarly, hard zone formation at DMWs is also known to be affected by composition of both the base metal and welding electrode as well as the resulting composition of the diluted weld metal structure and the cooling rate. As was demonstrated by this study, welding of dissimilar metals requires the application and maintenance of the correct cooling rate. This condition can be accomplished by determining and maintaining throughout welding the optimum preheat temperature for the given material thickness and chemical composition of both the base metal and welding electrode with relatively constant heat input. While most DMWs of carbon-to-austenitic stainless steels are fabricated in thicknesses that do not require preheating of either base metal, and with the exception of joints under 3/16 in. (4.8 mm) thick, joining these steels together would require the application and maintenance of high preheat temperatures. This requirement is because of the resulting low alloy steel composition of the localized hard zones that form along the weld interface of the ferritic material. As shown in Table 1, chemical composition of hard zones at DMWs fabricated with either E309 or ENiCrFe-3 may vary from 1.5-7 wt-% Cr. Welding steels with these compositions requires, by the piping codes, a minimum preheat temperature of 300-500°F (150-260°C). The preheat must be applied and maintained throughout welding and the joints must be slowly cooled after weld completion. Accordingly, the relatively high preheat temperatures used in the second phase of this study were based on composition of hard zones fabricated under the first phase.

As can be observed from Figs. 3 and 4, extent of hard zone formation is affected by both preheat temperature and welding electrode composition. For DMWs fabricated with ENiCrFe-3 electrode, hard zones were often eliminated when the optimum preheat temperature was controlled throughout welding at 400°F (205°C) for the 3/8 in. (10 mm) thick joint and at 450°F (232°C) for the 1/2 in. (12.7 mm) thick joint. This result is shown in Fig. 5, where elimination of hard zones resulted in a very uniform and homogeneous interface microstructure along the fusion line of the carbon steel side of the joint. This practice should considerably enhance the performance of such welds in both wet and high temperature corrosive environments. Similarly, a significant, but much less, reduction in hard zone formation at DMWs fabricated with E309 stainless steel electrode was also experienced at temperatures of 350°F and 400°F (177°C and 205°C) for the tested thicknesses, respectively.

As can also be observed from Figs. 3 and 4, the optimum preheat temperature has a narrow tolerance range of plus or minus 25°F, above or below which hard zone formation increases. This observation highlights the importance of controlling the optimum preheat and the
maximum interpass temperature to within that narrow range throughout welding. This practice will assure controlling the cooling rate needed to prevent the formation of both allotrophic structures and intermetallic phases. Accordingly, it is to be expected that increasing the preheat beyond that of the optimum temperature will result in an increase in the hard zone formation due to the formation and precipitation of intermetallic phases. Similarly, a decrease in the optimum preheat temperature below the indicated range will also result in an increase in hardness due to the formation of the hard martensitic structure. A graphical illustration of this principle is shown in Fig. 9 (presented strictly for illustration purposes and not based on measured or calculated cooling rates for a specific welding electrode composition). This inference also explains why high hardness levels of DMWs could be drastically reduced only by the disappearance of hard zones. Otherwise, and regardless of the type of weld deposit and preheat temperature, the average hardness of hard zones would remain much higher than HRC22 (VHN 250) required by NACE standard MR0175 for carbon and stainless steel base metals and weld deposits.
Conclusions and Recommendations

Based on findings of this study, the following conclusions and recommendations are made:

1) Hard zones at DMWs can be eliminated if a combination of the correct welding electrode composition and optimum preheat/cooling rate is utilized. Optimum preheat and interpass temperatures must be maintained throughout welding to ensure that the required cooling rate is controlled within the bounds of the very narrow corridor between the time-temperature-transformation (TTT) curves of the intermetallic phases and those phases of the allotropes.

2) To help achieve a full understanding of the behavior and suitability of DMWs in corrosive service, complete characterization of hard zone microstructure and mode and location of in-service cracking at DMWs must be established. The study should include effects of grain liquation and possible embrittlement of the partially melted and often carbon depleted HAZ structure. It should also include effects of variations in the solidus-liquidus temperatures of the inhomogeneously mixed structures on hard zone formation along the weld interface of DMWs. In addition, the acceptable hardness level for wet sour service should be determined if hardness of hard zones is determined to be the key factor that controls cracking resistance of DMWs in corrosive service.

3) Where possible, all dissimilar metal butt joint welds in corrosive and high pressure service should be shop fabricated under the above prescribed welding conditions using nickel-based electrodes.

4) PWHT resulted in several detrimental effects on DMW structures and, consequently, it is not recommended.

Acknowledgments

The author thanks Saudi Aramco management for its support to conduct and permission to publish this work. He also thanks his colleagues in the Corrosion Control and Materials Engineering Division of the Consulting Services Department for their review of this paper and their valued comments. Special thanks are extended to Mr. B. Busbait for monitoring the fabrication of the test welds of the second phase of the study, preparing the metallurgical specimens and collecting the data. Thanks are also extended to Mr. M. Al-Omairy and his metallurgical laboratory staff for their assistance.

References


Preparation of Manuscripts for Submission to the Welding Journal Research Supplement

All authors should address themselves to the following questions when writing papers for submission to the Welding Research Supplement:

- Why was the work done?
- What was done?
- What was found?
- What is the significance of your results?
- What are your most important conclusions?

With those questions in mind, most authors can logically organize their material along the following lines, using suitable headings and subheadings to divide the paper.

1) Abstract. A concise summary of the major elements of the presentation, not exceeding 200 words, to help the reader decide if the information is for him or her.

2) Introduction. A short statement giving relevant background, purpose and scope to help orient the reader. Do not duplicate the abstract.

3) Experimental Procedure, Materials, Equipment.
4) Results, Discussion. The facts or data obtained and their evaluation.
5) Conclusions. An evaluation and interpretation of your results. Most often, this is what the readers remember.
6) Acknowledgment, References and Appendix.

Keep in mind that proper use of terms, abbreviations and symbols are important considerations in processing a manuscript for publication. For welding terminology, the Welding Journal adheres to ANSI/AWS A3.0-94, Standard Welding Terms and Definitions.

With regard to units of measurement, it is suggested that authors present measurements first in the units by which they were actually made and then convert them into SI units or U.S. customary units, whichever is appropriate.

Where a large number of measurements and their conversions will appear together in a text, omit the conversions and, instead, present a table of conversions for each of the units used. The point here is to avoid impairing the readability of the article.

The fiscal costs of printing today make it necessary to observe an economical use of space. For a Welding Research Supplement paper, an acceptable length for text plus tables plus illustrations is six printed pages (approximately 6000 words or less of text). A well-balanced paper will have one figure for each 500 words.

Papers being submitted for consideration for publication in the Welding Research Supplement are required to undergo Peer Review before acceptance for publication. An original and one copy (double-spaced on 8 1/2 x 11-in. paper) should be submitted, along with figures, tables and figure captions separate from the text. Upon completion of any optional or required revisions mandated by the reviewers, the final manuscript should be submitted as listed above.

Authors are encouraged to submit manuscripts by computer disk. The preferred format is from any Macintosh word processor, 3.5-in. double or high-density disk. Other acceptable formats include IBM ASCII Text, WORD PERFECT or WORD STAR on 3.5-in. double or high-density disks. A hard copy of the complete manuscript, including tables and figure captions, still must accompany the disk. Send papers to Doreen Kubish, Peer Review Coordinator, American Welding Society, 550 NW LeJeune Rd., Miami, FL 33126.