RELIABILITY OF DISSIMILAR METAL WELDS SUBJECTED TO SULFIDE STRESS CRACKING

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ABSTRACT

Serious concerns have been raised in recent years in the Oil & Gas Industry about the reliability of Dissimilar Metal Welds (DMWs) in sour service. The primary reason for these concerns is because DMW joints exhibit small-localized hard zones that are susceptible to Sulfide Stress Cracking (SSC). In the open literature some methods such as preheating have been suggested to overcome the problem of hard zone formation.

The objective of this study is to assess the effect of Sulfide Stress Cracking (SSC) on the reliability (mechanical integrity) of DMWs specimens fabricated with different preheat temperatures and electrodes exposed to sour service environment. The National Association of Corrosion Engineers (NACE) Standard Tensile Test TM 01-77-96 Method A was used to determine the influence of SSC on DMWs in a systematic manner. Test results show considerable improvement in the Time-To-Failure as a result of the preheating methods used. However, it does not appear that the hard zones can be reliably eliminated for manual welding methods, even with the nickel-base electrode, and the optimum preheat temperature. Metallographic Examination and Scanning Electron Microscope Characterization were also used to assess the susceptibility and the failure modes.

Keywords: *Dissimilar Metal Welds, Sulfide Stress Cracking, Hard Zones, Preheat, Time-to-Failure.*

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1. INTRODUCTION AND BACKGROUND

1.1 Introduction & Background

Dissimilar metal welds (DMWs), such as joining of ferritic steels to either austenitic stainless steels or nickel-base alloys, are frequently required in the petroleum and petrochemical industries. Depending on the application, these welds are usually welded using either the austenitic stainless steel filler metals (electrods) or the nickel-base filler metals.

Serious concerns have been raised in recent years about the reliability of DMWs. The primary reason for these concerns is because DMW joints exhibit small-localized zones along the fusion line that have very high hardness values exceeding VHN (400) [Doody, 1992]. These zones might be susceptible to Sulfide Stress Cracking (SSC) in wet sour service as per NACE MR 01-75 standard [NACE, 1995] because of their high hardness.

The microstructure developed after a welding process is an important factor in cracking. It may influence both crack initiation and crack propagation. The microstructure of DMWs can develop a crack-susceptible matrix in which an additional factor, like hydrogen, can operate with destructive results.

Alloying elements, the metallurgical conditions, play a major role in SSC of DMWs. This is why the selection of a suitable filler metal is an important consideration in the fusion welding of DMW. For example, Nickel-alloy filler metals are often recommended for DMWs, because the nickel provides a more favorable match between the thermal coefficients of the austenitic and ferritic materials. It also significantly reduces carbon transfer from the ferritic steel [Schaefer, 1979].

Another important factor that could play a major role in the mitigation of SSC in DMWs is the use of preheating process, that involves welding on plates that have been heated to an elevated temperature. This results in a reduction in the cooling rates thereby lowering the temperature gradient. Using the optimum preheat temperature is expected to reduce the extent of hard zone formation, lower hardness level and hence reduce the susceptibility to SSC.

1.2 Study Objective

This applied research study aims at assessing the susceptibility to sulfide stress cracking of dissimilar metal weld specimens fabricated with different preheat temperatures and different welding electrodes (filler metals) and exposed to a sour service environment.

2. LITERATURE SURVEY & EXPERIMENTAL PROCEDURE

2.1 Literature Survey

The problem inherent with dissimilar metal weld joints have long been recognized and worked on. However, few studies have been devoted to investigate sulfide stress cracking of these joints. The following general conclusion may be drawn from the literature.

1. Formation of the hard zones in DMWs, regardless of the type of the base metal and/or the electrode, is difficult to avoid.

2. The constituents at the weld interface are difficult to identify, and the precise role of the hard zones is unclear.

3. However, the extent of the hard zones formation can be drastically reduced by the optimum preheat.

4. The hard zones adjacent to the fusion boundary may suffer hydrogen embrittlement in H_2S saturated solution. The extent of martensite formation plays a major factor in the susceptibility of DMWs to hydrogen embrittlement.

5. The higher the hardness of DMW, the higher its susceptibility to SSC.

2.2 Sample Preparation

Test samples were prepared from AISI 316L Stainless Steel (SS) welded to API 5L X60 Carbon Steel (CS) using two filler metals namely, E 309 and Inco 182, and three different preheat temperatures, 350ºF, 400ºF, and 450ºF in addition to the no preheat condition.

2.3 Mechanical Properties Determination

The actual yield strength of DMW specimens was first determined. These values were used for the SSC susceptibility test.

2.4 SSC NACE Test

Sulfide stress cracking susceptibility tests were conducted as per NACE TM 01-77-96 method A, the tests were conducted at different applied loads 60%, 80%, and 110% of the Yield Strength values of the welded samples.

2.5 Metallographic And SEM Characterization

Optical metallography examination of the samples obtained from each welded DMW plate was carried out to examine the microstructure of the critical areas of DMWs before and after the exposure to the SSC NACE test. SEM fractography of the fractured specimen was undertaken to determine the modes of failure.

2.6 EDS And Microhadness Surveys

Energy Dispersive X-Ray Spectrometry (EDS) and Microhardness surveys were also performed to confirm the finding of previous analysis.

3. RESULTS AND DISCUSION

3.1 Metallographic Examination, EDS, and Microhardness Surveys Prior To NACE Testing

Metallographic examination conducted on samples sectioned from all welded plates (3 samples X 8 plates) showed different degrees of hard zone formation. This can be observed in Figures 1 to 4.
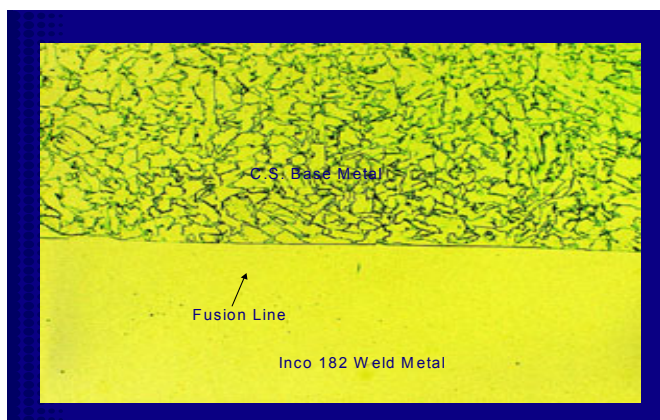

Figure 1. Clear fusion line between the Carbon Steel base metal (top), and Inco 182 filler electrode. Sample welded @ 400°F preheat temperature, 400X.
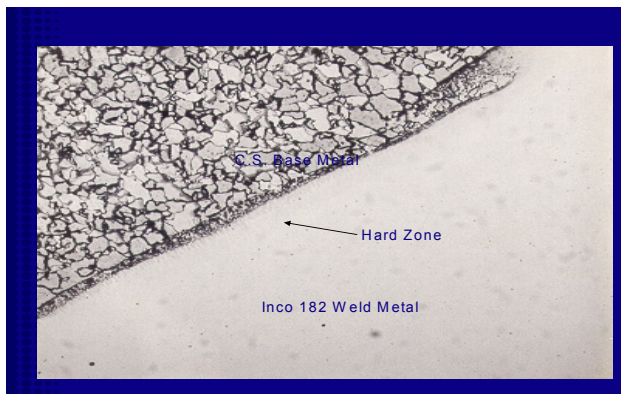
Figure 2. Hard zone formed at the fusion line between the Carbon Steel (Top Left) and the Inco 182 filler. Sample welded @ 450°F preheat temperature, 200X.
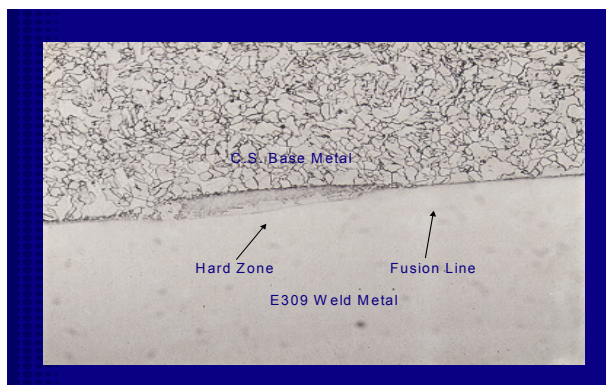

Figure 3. Hard zone at the center of the fusion line beween the Carbon Steel base metal (top), and E 309 filler. Sample welded @ 400°F preheat temperature, 200X.
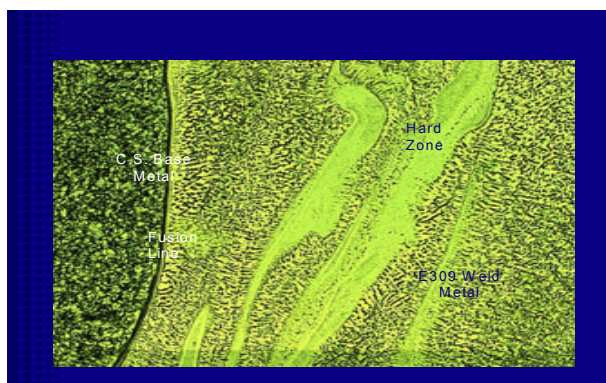

Figure 4. Hard zone formed within the bulk weld metal (center of the photograph, white section), E 309.
Sample welded @ 350°F preheat temperature, 100X.

As can be noticed from the previous set of photo-micrographs, the problem area of DMWs is the fusion line region on the carbon steel side of the joint. This is because of the existence of the hard zones along the fusion line. The hard zones (or intermediate mixed zones) are very thin, noncontinuous layers, typically 0.025 mm (0.001 in) wide, with a hard microstructure. They are of intermediate composition between the carbon steel base metal and the bulk weld metal composition.

Energy Dispersive X-Ray Spectrometry (EDS) conducted on several different DMWs showed that the hard zones have low alloy compositions, typically 3-5% chromium and 2-3% nickel. Findings of these surveys are summarized in Table 1. Details of the EDS analysis are shown in Figure 5.

Table 1. EDS and microhardness surveys results.

Position	Inco 182 Welded Samples		E 309 Welded Samples	
	Micro-Hardness [VHN]	Chemical Comp. [wt%]	Micro-Hardness [VHN]	Chemical Comp. [wt%]
Weld Metal	183	7.09 Cr;	211	8.97 Cr;
Before H.Z.	97.3	3.06 Mn;	191	1.46 Mn;
@ H. Z.	323		405	
		59.98 Fe;		83.15 Fe;
After H.Z.	182		203	
		29.56 Ni		5.58 Ni
Base Metal	186		191	

1) Two explanations for the formation of hard zones are proposed in the literature:
   Based on the EDS and microstructural analysis, it was found that the microstructures of these zones consist of chromium carbides in a martensite matrix. This suggests that diffusion of strong carbide formers (e.g. Cr, W) from the filler metal and carbon from the base metal create a region along the fusion line rich in chromium and tungsten carbides with a martensitic structure [Craig et al, 1991]. Even though the time at elevated temperatures during the welding cycles is short, some slight carbon depletion of carbon steel Heat Affected Zone (HAZ) has occasionally been observed [Doody, 1992]. This indicates that there is some carbon diffusion into the weld metal and the hard zones.

2) As the mechanical hydrodynamic mixing of the molten boundary into the weld metal does not occur, it is believed that these hard zones are unmixed chunks of carbon steel that were not diluted in the bulk weld metal. This is why its actual composition intermediate between the base metal and the diluted bulk weld metal.

From the two above explanations on the formation of the hard zones, and based on the results and findings obtained from the metallographical examination, and the EDS survey, it is apparent that filler metals with any appreciable chromium content will produce a similar hard zone in the fusion line as presented.

These findings explain why E 309 (Austenitic with 24 wt% Cr) was producing welds with very high amount of hard zone, and hence high susceptibility to SSC (as will be discussed later) compare to Inco 182 (Ni-base with 15 wt %Cr).

Moreover, this study has indicated that the hard zones are still present even with the nickel-based electrodes, but that the size and frequency might be reduced, in comparison to the austenitic stainless steel electrodes. However, it does not appear that the hard zones can be reliably eliminated for manual welding methods, even with the nickel-base electrode, and the optimum preheat temperature.
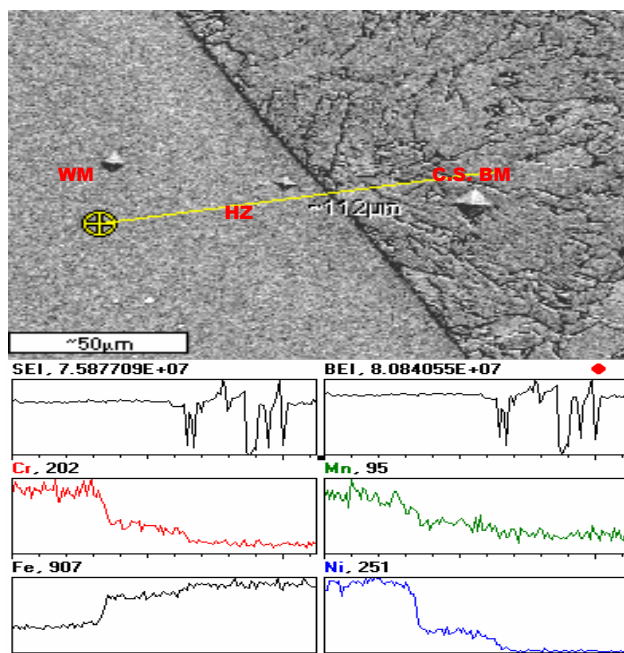

Figure 5. Microhardness indentation (at three different positions) and EDS survey in the fusion line region for a sample welded with Inco 182 filler @ 400° F preheat temperature.

3.2 NACE Standard Tensile Test

With reference to NACE standard TM 01-77-96 method A, and based on the results of Time-To-Failure (TTF) obtained, it can be said that both Inco 182 and E 309 electrodes produce welds with very high susceptibility to sulfide stress cracking. Nonetheless, there has been considerable improvement in the TTF for the Inco 182 welded samples at 400ºF (205ºC) as can be noticed in Figures 6 and 7 where the relation between TTF and the preheat temperatures are presented.

These results support the results reported by Omar [Omar, 1991; 1997], that 400ºF (205ºC) is the optimum preheat temperature for the Inco 182 electrode in welding DMWs. It is the 400ºF (205ºC) preheat temperature, that results in an optimum cooling rate, that helps in avoiding the formation of the martensitic zones during the solidification process of the weld and base metals.

On the other hand as indicated in Figure 7, no consistent relation could be found between the preheating temperatures and the average time to failure for the E 309 welded samples. It can be noticed, from Figures 6 and 7, that the TTF improves as the %Y.S. loading decreases. This is true for both types of welded samples regardless the preheating temperature.

Based on the results obtained from the SSC test and considering TTF as the measuring factor, ranking of the preheat tempertures in terms of their postive effect on the TTF can be done by utilizing Figures 8.

In the case of Inco 182 welded samples, the following observations may be made:

- The 400ºF preheat temperture resulted in longest TTF at all levels of applied stress.

- At stress levels between 35 and 55 ksi, 350ºF and 450ºF preheats result in the same time to failure.

- The 450ºF preheat temperture was the second best in term of its positive effect on TTF at all applied stress levels.

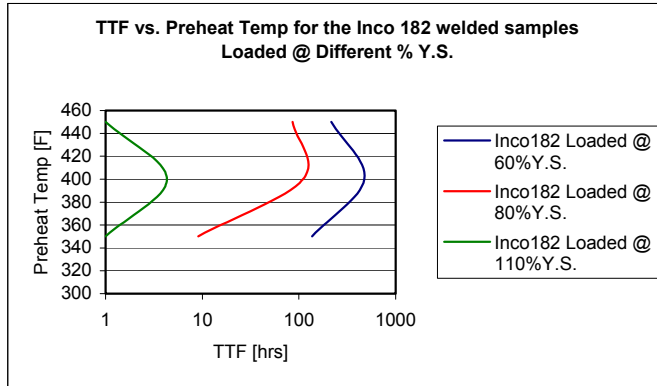- And finally, the 350ºF preheat temperature was the worst in term of TTF.

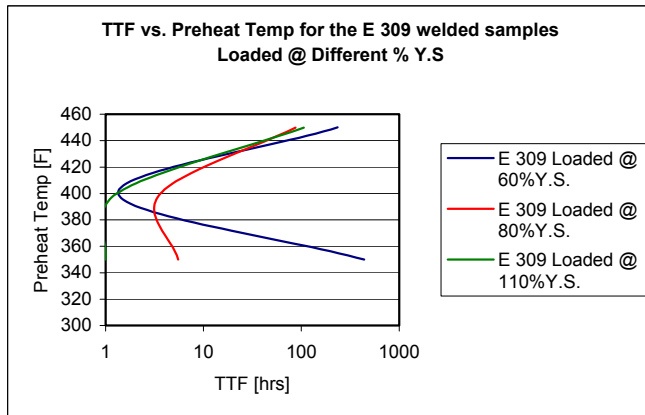Figure 6. Improvement in the TTF @ 400ºF preheat temperature for the Inco 182 welded samples.

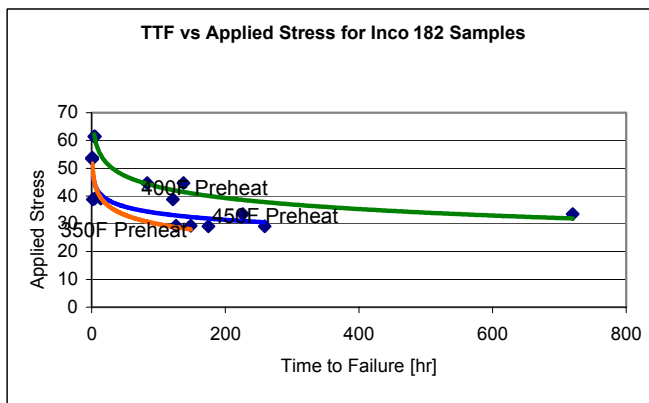Figure 7. TTF trend for E 309 welded samples.

Figure 8. Ranking of preheat temperature based on TTF.

3.3 Metallographic and Scanning Electron Examination After SSC Test

Figures 9-a and b are photo-micrographs for typical samples that passed the NACE SSC Proof Ring test and those that failed the test. In figure 9-b, it is clear that the fracture is along the weld fusion interface with the carbon steel base metal. Visually, most of the failures were brittle failures along the weld fusion interface with the carbon steel base metal.

Figure 10 is a cross section through the gauge length of a failed sample (carbon steel side at the top, and the stainless steel side with the weld metal at the bottom).

Cracks initiate at the hard zones and go along the fusion line between the carbon steel and the weld metal. The crack may propagate into the carbon steel HAZ. This can be noticed as follows:

- Figure 11, the carbon steel side of a failed sample showing traces of a white band (hard zone) attached to the carbon steel base metal.

- Figure 12, the stainless steel side of the same sample shown in Figure 11 where part of the carbon steel HAZ has detached with the bulk weld metal confirming the propagation of the crack as indicated above.
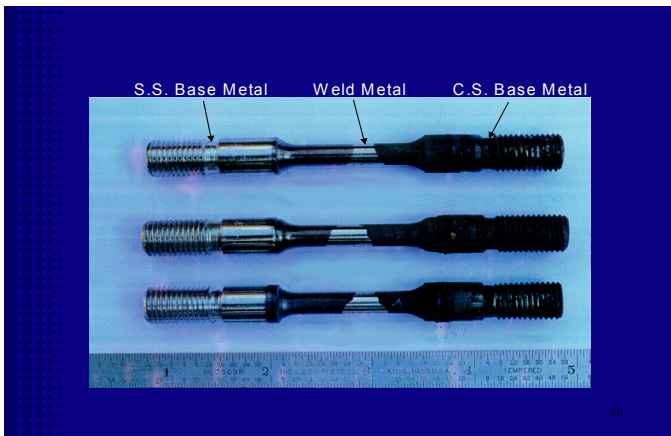
Figures 9-a. Photograph of samples passed the SSC test.
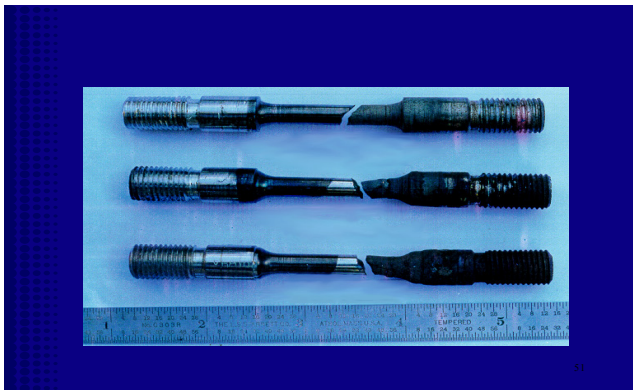
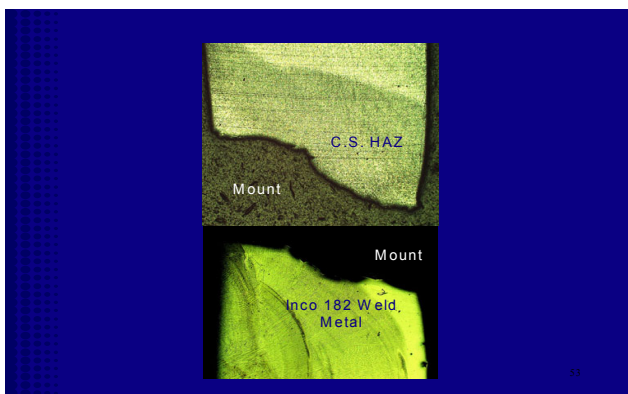Figures 9-b. Photograph of samples failed the SSC test.

Figure 10. Cross section of a failed sample welded by Inco 182 @ 350°F preheat, (C.S side @ top, and S.S. + weld metal @ the bottom), 16X.
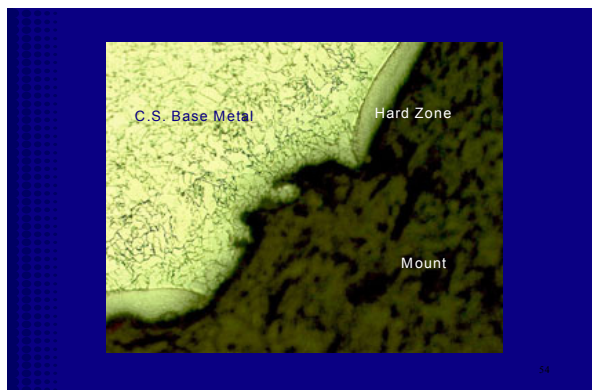

Figure 11. Carbon steel side of a failed sample welded with Inco 182 @ 350°F preheat temperature indicating crack path, 200X.
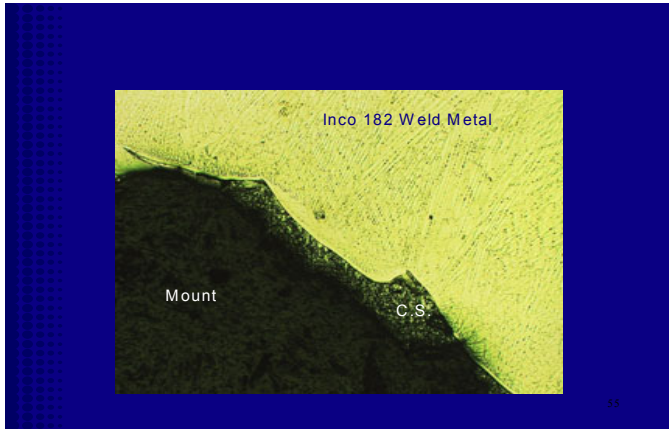
Figure 12. The stainless steel side of the same sample shown in figure 11, 63X.

Figures 13 through 16 show the fractography of selected surfaces (viewed under the SEM) as they appeared after the NACE SSC Proof Ring Test.

Figure 13 is a low magnification SEM of fracture surface of weld interface, weld side, of an Inco 182 welded sample with no preheat. From the surface profile two distinct fracture modes (Brittle and Ductile) can be observed. Figure 14 is a higher magnification of the brittle section from Figure 13, area (A). This is a typical view observed in almost all the fracture surfaces. The weld metal solidification grain boundaries are clearly visible in the photograph. Figure 15 is also a high magnification of another brittle region (area B in Figure 13). It shows similar features as in Figure 14. Figure 16 is a high magnification of the ductile region of Figure 13 (area C) where a typical micro void coalescence fracture mode represents a ductile failure. This type of fracture was also noticed in almost all the fracture surfaces.
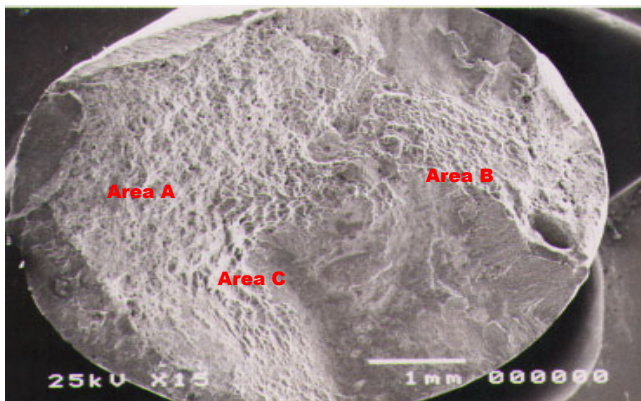

Figure 13. Low magnification SEM photograph of a fracture surface (S.S. Side) welded with Inco 182 @ no preheat, 15X.
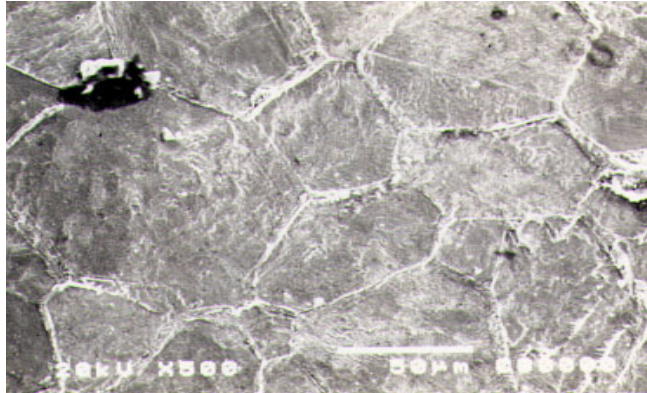
Figure 14. Brittle fracture with the solidification of weld metal grain boundaries clearly shown, 500X.

Figure 15. Another brittle fracture view of the same sample in figure 13, 500X.
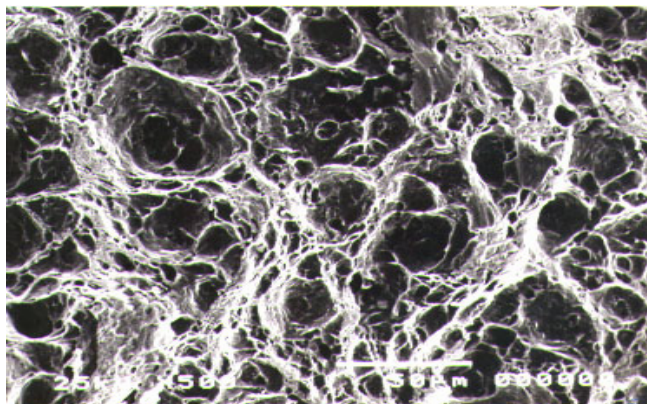

Figure 16. Micro void coalescence ductile fracture of the sample in figure 13, 500X.

4. CONCLUSION

The objective of this study was to assess the effect of sulfide stress cracking on the reliability of dissimilar metal weld specimens fabricated with different preheat temperatures and different welding electrodes (filler metals) exposed to a sour service environment.

With reference to NACE standard TM 01-77-96 (which was used to determine the influence of SSC on DMWs), and based on the results presented on Time-To-Failure, it can be said that both Inco 182 and E 309 electrodes produce welds with very high susceptibility to sulfide stress cracking. Nonetheless, there has been considerable improvement in the TTF for the Inco 182 welded samples at 400ºF (205ºC). On the other hand no consistent relation could be found between the preheating temperatures and the average time to failure for the E 309 welded samples.

An improvement in the TTF has been noticed as the %Y.S. loading decreases for both type of welded samples regardless of the preheating temperature.

Ranking of the preheat temperatures in terms of their postive effect on the TTF for the Inco 182 welded samples is as follows:

- The 400ºF preheat temperature resulted in longest TTF at all levels of applied stress.

- At stress level between 35 and 55 ksi, 350ºF and 450ºF preheat result in the same time to failure.

- The 450ºF preheat temperature was the second best in terms of its positive effect on TTF at all applied stress levels.

- And finally, the 350ºF preheat temeprature was the worst in term of TTF.

Visual examination of the samples after the NACE SSC test indicated that most of the failures were brittle failures along the weld fusion interface with the carbon steel base metal. Metallographic examination showed that cracks initiate at the hard zones and go along the fusion line between the carbon steel and the weld metal. The crack may propagate into the carbon steel HAZ. SEM examination of these samples indicated that two distinct fracture modes (Brittle and Ductile) were on all fractured surfaces.

Based on the results and findings obtained from the metallographical examination, and the EDS survey, it is apparent that filler metals with any appreciable chromium content will produce hard zone in the fusion line as presented. This explains why E 309 (Austenitic with 24 wt% Cr) was producing welds with very high amount of hard zone, and hence high susceptibility to SSC compared to Inco 182 (Ni-base with 15 wt %Cr).

Moreover, this study has indicated that the hard zones are still present even with the nickel-based electrodes, but that the size and frequency might be reduced, in comparison to the austenitic stainless steel electrodes. However, it does not appear that the hard zones can be reliably eliminated for manual welding methods, even with the nickel-base electrode, and the optimum preheat temperature.

In conclusion, Dissimilar Metal Welds fabricated in accordance to the stated welding conditions, and procedure are still susceptible to sulfide stress cracking.

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