EFFECT OF WELD TYPE AND POST WELD HEAT TREATMENT ON THE CORROSION RESISTANCE OF AISI 321 STAINLESS STEEL IN A TAR SAND DIGESTER

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(Received August 2007 and accepted February 2008)

This work has investigated the effect of lap joint and butt joint electric arc welding together with their post weld heat treatments on the corrosion characteristic (resistance) of a stabilized AISI321 stainless steel in a tar sand digester. Water quenching and furnace cooling were the two heat treatment procedures carried out on the welded samples. The corrosion experiment was by the non-electrochemical technique and the analysis of the result was by corrosion rates determination in mils per year (mpy). The tar sand used for investigation was analyzed using energy dispersive x-ray analyzer (EDXA). The result of this work include a comparative analysis of the composite results of the various corrosion rates produced for the welding joint type and the heat treatment procedure. The butt joint welded water-quenched AISI 321 stainless steel came out to be most resistant than the other combinations. The furnace cooled heat-treated lap joint welded stainless steel exhibited the least resistance in the tar sand environment.

1. INTRODUCTION

The different grades of stainless steels usually referred to in the literature are the ferritic, austenitic, martensitic and precipitation hardening stainless steels. All these differ mainly in their compositions, microstructures/crystal structures and stabilities in different aggressive environments. The differences in stabilities are traceable to the differences in their chemical constituent and the differences in their microstructures. In spite of the relative stabilities of these classes of steels in many environments recent investigation has shown that some stainless steels are vulnerable to corrosive attacks in a hot water tar sand digester\[1,2\]. The attacks vary according to the forms of corrosion. The AISI 321 austenitic stainless steel has been found to be relatively more stable than others in the hot water digester medium. Its resistance is however dependent on the stress states imposed on it by fabrication techniques. Sensitization is the phenomenon whereby complex carbides of chromium (Cr23C6) are precipitated along the grain boundaries of most stainless steels when heated in the temperature range 500°C and 800°C. The stabilizing stainless steels, AISI 321 and 347 are known to be less prone to this phenomenon when treated in this temperature range because of the presence of Ti and Nb in their system. Literature has it that beyond 930°C the Ti and Nb carbides are dissolved in stainless steels and that subsequent treatment in the 500-700°C range could therefore make it susceptible to sensitization and subsequently weld decay in a suitable environment\[3\]. Heat treatment is a tool that is often used to maneuver the microstructures of metals with the aim of imparting certain desirable properties on metals and alloys. Welding is a form of fabrication technique that is associated with excessive heating and micro structural changes around the heat affected zone (HAZ). Depending on the type of weld joint, the rate of cooling of the weldment, the chemical composition and the type of segregation around the HAZ, stainless steels are subject to corrosion attacks in many environments. In order to evaluate further the resistance of AISI 321 SS after welding, this study is investigating the effect of two types of weld joints and subsequent post welding heat treatment on the stability of the steel in a hot water tar sand digester.
2. EXPERIMENTAL TECHNIQUE

The stainless steel AISI 321 used in this study was obtained from a metal scrap market at Owode Onirin in Ikorodu, Lagos. The chemical composition of this stainless steel as determined by EDXA is in Table 1.

The lumps of Nigeria rich tar sand used for this work were obtained from a town called Agbabu in Ondo state around where Nigeria has a large deposit of tar sand. The energy dispersive X-ray analysis of the Nigerian rich tar sand used for investigation is as contained in Table 2 in atom per cent. The other materials used apart from the principal ones mentioned above and which were used either to simulate the tar sand digester condition or to assist in the sample preparation were all locally made available.

Table 1. Energy Dispersive X-ray Analysis of stainless steel samples Atomic concentrations (atom%)

<table>
<thead>
<tr>
<th>Stainless Steel AISI 321</th>
<th>Cr</th>
<th>Ni</th>
<th>Ti</th>
<th>Mn</th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18.78</td>
<td>10.37</td>
<td>0.60</td>
<td>0.06</td>
<td>-</td>
<td>1.15</td>
<td>69.04</td>
<td>0.089</td>
</tr>
</tbody>
</table>

Table 2. Energy Dispersive X-ray Analysis of the Nigerian rich tar sand investigated atomic concentrations (atom%)

<table>
<thead>
<tr>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ca</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.89</td>
<td>0.78</td>
<td>14.18</td>
<td>71.15</td>
<td>0.89</td>
<td>7.71</td>
<td>2.70</td>
<td>0.69</td>
</tr>
</tbody>
</table>

3. SAMPLE PREPARATION

Corrosion coupons were made from all the materials experimented in this work. Cutting and grinding of all samples were carefully handled. The electrically driven power saw was used for cutting the AISI 321 austenitic stainless steels because of their strengths. Holes were drilled on each of the sample with a 3 mm drill bit to facilitate suspension in the corrosive media. Each of the coupons, depending on the initial roughness of their surfaces was ground to 600 grits starting with different emery grades of 240, 320 or 400 grits. The 600 grits is the surface finish used for corrosion exposure of coupons according to Fontana and Greene[3]. The grinding operation involved back and forth rubbing of specimens on the emery papers in directions roughly perpendicular to the scratches left by the preceding grinding paper.

3.1 Degreasing and Weighing

In order to remove the organic substances on the surfaces of the polished samples, the specimens were washed with non-bleaching scouring powder, swabbed with water and then with acetone. This process removed all the grease, or dirt, present on the samples’ surface, which would have been a potential source of errors and inaccuracy in the measurements of corrosion rates. The degreased surfaces were then air-dried with warm air from a laboratory drier. The samples were weighed using a sensitive chemical balance and recorded to the nearest 0.1 mg. The metallographic samples/coupons on the other hand, were not weighed but were etched subsequent to the microscopic study under the inverted metallurgical microscope.

3.2 Preparation of corrosion environment

In order to be able to have a good assessment of the corrosion of the stainless steels in the tar sand environment, the stainless steel was tested for its resistance in the environment. The effect of welding procedure and post weld heat treatment on the corrosion resistance of AISI 321 stainless steel have been investigated in the tar sand digester medium. Rectangular test pieces were cut from the stainless steel for the purpose of the investigation. After welding, all the samples were drilled with a 3 mm drill bit at a distance about 4 mm towards the edge of each specimen to allow for suspension in the tar sand environment.

All the welded samples, butt and lap welded were divided into three groups, for the purpose of different investigations. The first group comprised of the as-welded samples without heat treatment, the second group comprised of welded samples subjected to rapid cooling in water (quenching) after heating and soaking at the temperature of about 950°C for 30 minutes. The third group of the remaining welded samples were given the same post-weld heating and solutionizing treatment as the second group at 950°C for 30 minutes respectively but were cooled very slowly in the furnace (annealing) to the ambient temperature. In order to be able to prevent metallurgical changes due to oxidation and decarburization during the heat treatments, the sodium chloride salt bath solutionizing approach was used for the austenitizing treatment.

After the heat treatment phase the samples were then taken through the necessary metallographic techniques to prepare them for exposure in the tar sand environment. They were finally weighed and immersed in the corrosion medium to test for their corrosion resistance in the tar sand digester.
4. RESULTS AND DISCUSSIONS

From the results of the EDXA analysis of a Nigerian rich tar sand due to this study it is clear that the tar sand environment contains in traces the following elements calcium, iron, potassium, magnesium, sodium, nickel and vanadium. All these elements apart from nickel and vanadium are more bases (i.e. more active) than iron/steel because of their positions in the electrochemical series or the galvanic series. From the vanadium to nickel ratios quoted in the table it can be deduced that these two elements are available in fairly equal amount.

In a corrosion environment like that of tar sand bitumen it is expected that where galvanic cells are set up between iron of steel and the vanadium and nickel metals, the iron will be anodic while these trace metals (V and Ni) will be cathodic. The corrosion reactions between the three elements in the tar sand environment can be written as

Anodic reaction: Fe = Fe^{2+} + 2e^{-}

Cathodic reactions: V^{+} + e^{-} = V

Ni^{2+} + 2e^{-} = Ni \quad \text{metal atom depositions}

The other trace elements because of their electrode potentials with respect to that of iron in steel are expected to put up sacrificial cathodic protection of the steel structure according to the reactions:

\[
\text{Ca}^{2+} + 2e^{-}; \quad \text{K}^{+} + e^{-}; \quad \text{Mg}^{2+} + 2e^{-} \quad \text{and Na}^{+} + e^{-}
\]

at the anode and \( \frac{1}{2} \text{O}_{2} + \text{H}_{2} \text{O} + 2e^{-} = 2\text{OH}^{-} \) (due to the presence of dissolved \( \text{O}_{2} \)) and \( 2\text{H}^{+} + e^{-} = \text{H}_{2}\text{O} \) (due to the presence of \( \text{H}^{+} \) produced by the dissociation of the organic acids in the medium) at the cathodes.

Figure 1 is a combination of results of the effect of welding type on the corrosion resistance of AISI 321 stainless steel. From this figure the unwelded as-received specimen exhibited the best resistance in the environment followed by the butt-welded sample. The lap welded stainless steel samples exhibited the least resistance. The microstructural variations caused by welding are generally believed to be responsible for the alterations in the chemical and mechanical properties of steel. The structures of the weld metal, the heat affected zone (HAZ) and the base metal of the weldment are different. It has even been reported\(^5\) that there are distinct microstructural variations even within the HAZ. The microstructure in the HAZ adjacent to the fusion boundary consists of a bainitic structure with a prior austenite grain size of around 100μm. Adjacent to this coarse grain region in the HAZ towards the base metal, a fine grain bainite region (prior austenite grain size of 15μm) is said to consist of uniformly distributed carbides in a ferritic phase surrounded by austenite. The heterogeneity of these features coupled with the possible sensitization of the welded region could be said to have caused the drop in the corrosion resistance of the as-received AISI 321 SS after welding. The butt welded stainless steel is probably able to exhibit better corrosion resistance in the medium than the lap welded samples because the area subjected to these microstructural variations and possible sensitization is much smaller than those of the lap welded AISI 321 SS.

Figures 2 and 3 show the effects of post weld heat treatment: furnace cooled annealing and water quenching of the differently welded samples. The results obtained according to these figures show that the water quenching heat treatment given to the welded steel is better than the furnace annealed system. It is interesting to note that none of the post weld heat treatments was able to impart a corrosion resistance similar to that of the as-received to the welded pieces of the AISI 321 SS.

The annealed products of both the butt-welded and lap welded 321 SS showed substantial loss in corrosion resistance because of the re-dissolution of the titanium carbide in stainless steel. According to Fontana and Green\(^{2,3}\) when stabilized stainless steels are heated to temperatures above 930°C they have their carbides of titanium, tantalum and niobium dissolve into the matrix of the austenitic stainless steel to form solid solution alloys. When they are cooled slowly as obtained in the furnace annealing of the 321 samples of this study, they do so quasi-statically between sensitizing temperatures of 800 and 500°C. This condition brings about chromium carbide (\( \text{Cr}_{23}\text{C}_{6} \)) segregation at the grain boundaries of the HAZ regions. Once this happens and in the presence of a corrosive environment like that of the hot water tar sand digester medium, intergranular corrosion sets in leading to the dissolution of iron (Fe) in the chromium depleted regions around the grain boundary. Since this region is highly localized compared to the bulk of the stainless steel, which probably serves as the cathode region, the corrosion rate will be high because of the unfavourable low anode to cathode area ratio. The similarity between the corrosion resistance of the as-received, butt-welded and the water quenched butt welded sample of the steel may be an indication that the water quenching treatment is not necessary after all. A plausible explanation for this phenomenon is that cooling in air after the butt or lap welding of the samples is also rapid enough to prevent sensitization around the heat affected zone of the welded region.

Figure 4 gives the composite results of the effect of weld types and the corresponding post weld heat treatment on the corrosion characteristic of the 321 stainless steel. At a glance, this figure (Fig. 4) shows the annealed lap-welded samples of the 321 stainless steels as the most corrosive state. The as received butt-welded sample however remained the most corrosion resistant.

The result of the energy dispersive X-ray analysis of a tar sand investigated in this study (Fig. 5) shows that the Nigerian rich tar sand contains more than 7 per cent by weight of sulphur. The sulphur according
Figure 1. Effect of weld type on the corrosion of AISI 321 stainless steel in tar sand digester

Figure 2. Effect of post weld heat treatment on the corrosion of butt-welded AISI 321 stainless steel in tar sand digester medium

Figure 3. Effect of post weld heat treatment on the corrosion of lap-welded AISI 321 stainless steel in tar sand digester medium
to literature could exist as elemental sulphur, hydrogen sulphide, mercaptans, sulphides, disulphides (e.g. carbon disulphide and carbonyl disulphide), sulphur dioxide, sulphur trioxide, polythionic acid, naphthenic acid and a wide variety of complex heterocyclic and substituted homocyclic aromatic compounds[2]. Most of these compounds in their pure state are not known to be corrosive[6], however, in the presence of water, some like the sulphur dioxide and sulphur trioxide demonstrate mild corrosion, while the hydrogen sulphide show aggressive corrosion. In order words, the activities of these sulphur compounds must have been responsible for the corrosion activities of the AISI 321 in tar sand environment. The other compounds only show their aggressions to corrosion on steaming[7], cracking or on fractional distillation[6] by decomposing to H2S and some gases.

A synthesis of the information above coupled with the pitting corrosion and general corrosion that were visible on all the materials exposed to the tar sand digester, and as evident on the SEM micrographs of some of the stainless steels studied confirms the major role that sulphur corrosion would have had in the environment. H2S has been cited as the most active sulphur compounds towards corrosion activities in refining and petrochemical industries. This position has been corroborated by others[9-10]. According to them H2S is known to adversely affect the general corrosion resistance of steels and in most cases lead to sulphide stress corrosion cracking (SSCC) at low temperature. Slow strain tests have been shown to highlights the sensitivity of even duplex alloys to SCC at around 80°C. However, for low partial pressures he explained that the signs of SCC
disappeared for the high yield strength (around 140 ksi) alloys. In other words most of the cracks observed under the microscopes were the sulphur stress corrosion cracks due to H₂S in the tar sand environment.

6. CONCLUSIONS

On the strength of the results obtained in this work for the corrosion resistances of the AISI 321 stainless steel under different welding conditions, it can be concluded that butt-welding coupled with water quenching as a post-weld heat treatment should be adopted for the construction of tar sand digester. It can also be concluded that the tar sand digester by the hot water technique derives its corrosiveness mainly from the components of the Nigeria rich tar sand rather than from NaOH that served mainly to neutralize the acidic components of the tar sands thereby aiding digestion.

REFERENCES