EXPERIMENTAL INVESTIGATIONS ON PLASMA ARC WELDING OF LEAN SUPERMARTENSITIC STAINLESS STEEL

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Abstract

Nowadays the lean super martensitic stainless steel (LSMSS) becomes an economical alternative to the traditional carbon and/or austenitic-ferritic (duplex) stainless steel for the construction of pipelines in transport of gas and corrosive oils. Lean super martensitic stainless steel exhibits higher toughness, corrosion resistance and weldability properties when compared to conventional martensitic stainless steel. The main purpose of this study is to investigate the mechanical and metallurgical properties of welds made by the keyhole mode of plasma arc butt welded joints. The macrostructure and microstructure were evaluated through optical microscope. The mechanical properties such as tensile and impact tests were carried out at room temperature and their fractured surfaces were also analysed through scanning electron microscope (SEM). The corrosion resistance of the weld is determined by electro chemical analysis using Tafel plot and the same is correlated with their microstructures.

Keywords: Lean super martensitic stainless steel, Mechanical and Metallurgical characterization, Corrosion resistance.

1 Introduction

The super martensitic stainless steels (SMSS) are also known as weldable 12%Cr steels, weldable 13%Cr steels, low carbon martensitic stainless steels and soft martensitic stainless steels. These steels have carbon contents of the order of 0.01% and Nickel addition in the range 1-6% to stabilize the martensitic microstructures and chromium is typically between 10-13%. Due to different alloying and processing requirements, compared with 22%Cr duplex stainless steels, these super martensitic steels are substantially cheaper than the competing duplex grades for pipeline and flow line applications (Goldschmitz et al., 2004, Lauro et al., 2003, Gooch et al., 1999, Carrouge 2002, Lippold et al., 2005, van-der-Winden et al., 2002). Two classes of SMSS may be identified: 'high' and 'lean' grades. Lean super martensitic stainless steel (LSMSS) typically contain approximately 12%Cr, <4%Ni, no molybdenum and about 0.01%C. The microstructure of such steels is predominantly tempered martensite with some austenite but delta ferrite and untempered martensite may form in weld HAZs (Woollin et al., 2002, Marshall et al., 2001, Gooch et al., 1999, Folkhard 1984).

This alloy was developed as a practical and economical alternative to carbon steel and corrosion inhibitors, replacing some of the duplex stainless steels used in offshore pipelines (Woollin et al., 2006). Crack free welds with good HAZ toughness can be processed without pre and post weld heat treatment (Dufrane et al., 1999, Enerhaug et al., 1999). In supermartensitic alloys, the Cr and Ni ratio equivalents promote the formation of a martensite and retained austenite microstructure. The retained austenite phase may represent a volume of only a few percent (characteristic of low alloy) up to 40% (characteristic of high alloy), but it is nevertheless very difficult to identify because it is dispersed in the martensitic structure (Toussaint et al., 2002). Super martensitic stainless steels combine good mechanical properties, weldability, toughness and corrosion resistance to CO₂ and H₂S. Corrosion in supermartensitic welds is clearly dependent on the metallurgical phases present, like retained austenite and δ ferrite. It was demonstrated that pitting...
potential becomes nobler with the retained austenite content. Moreover, δ-ferrite increases corrosion susceptibility because it promotes the precipitation of chromium nitrides or carbides and the formation of chromium depleted zones (Bilmes et al., 2006, Aquino et al., 2008). Also, micro segregation, welding thermal cycles and inclusions are important factors in the resulting microstructure of a weld and its corresponding corrosion susceptibility.

The plasma arc welding (PAW) closely resembles the tungsten-inert gas (TIG) welding process in that it also uses a non-consumable tungsten electrode and a shielding gas such as Argon. The keyhole welding is generally obtained by using a stiff and constricted arc. With increased plasma gas flow rate and electrode setback, a hole known as the “keyhole” is pierced through the entire metal thickness at the leading edge of the weld pool, where the forces of plasma column displaces the molten metal(Wu et al., 2011, Wu et al., 2013).

The keyhole is a positive indication of full penetration, and it allows higher welding speeds to be used in PAW. LSMSS have high strengths, around 480 MPa proof strength and above consequently, high strength filler metals are required to provide matching weld metal strength. Matching 12/13% Cr consumables have been developed in solid wire and metal cored wire forms but have not been successfully used for industrial applications. Therefore, keyhole mode of PAW is the great alternative to weld LSMSS without using the filler material. The preferred welding processes to date for LSMSS have been automatic pulsed gas metal arc (PGMA) and gas tungsten arc welding (GTAW) welding. There is no metallurgical reason why other conventional arc welding processes such as manual metal arc (MMA) and flux cored arc welding (FCAW) may not be used for girth welds. At present, there is little information regarding welding of LSMSS using high energy density welding processes such as plasma arc welding (PAW), laser beam welding (LBM), ion beam welding (IBM).

In the present work, 410S lean super martensitic stainless steel plates were welded using keyhole mode of PAW process and the welded joints were evaluated by mechanical and metallurgical and corrosion tests.

2 Methodology

The flow chart of methodology is presented below:

### Table 1 Chemical composition of base material

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>In %</td>
<td>0.028</td>
<td>11.9</td>
<td>0.21</td>
<td>0.40</td>
<td>0.41</td>
<td>0.03</td>
<td>0.005</td>
</tr>
</tbody>
</table>

2.1 Material

AISI 410S plates of 6 mm thickness, hot rolled shot blasted plate in solution annealed & pickled condition were used as the base material. The base material has the yield strength of 348 MPa and ultimate strength of 480 MPa. The specimens were prepared in dimension of 100 x 150 x 6 mm³. The chemical composition of the base material is presented in Table 1.

2.2 Welding Trials

Through preliminary trials welding parameters were identified. Initially bead on plate experiments were carried out and suitable parameters and their range were obtained. The identified parameters such as welding current (I), welding speed (S), plasma gas flow rate (FR), nozzle standoff distance (D) were used to conduct the keyhole mode of plasma arc welding (PAW) on the material in flat position. Using bead on plate tests, the full penetration was achieved as shown in the Table 2.

The plasma arc welding (Fronius Magic Wave 440) set up was used for welding is shown in Fig.2.
2.3 Mechanical Testing

In order to evaluate the variation in the mechanical properties of the material tensile test at room temperature (RT), Charpy impact at RT and -196°C and hardness tests were carried out. Standard specimens for all the mechanical testing were prepared as per the guidelines of ASTM A370 standard. The fractured surfaces of tensile and impact tested specimens were examined through the scanning electron microscope (SEM).

2.4 Metallurgical Study

An optical microscope was used to identify the microstructural changes in the base material, HAZ and weld region. The specimens were prepared, mechanically polished and etched with Villella’s reagent (5 ml HCl + 1 gm Picric acid + 100 ml Ethanol) until the phases were identified.

2.5 Corrosion test details

The electrochemical measurements were performed using a conventional three electrode cell. It contained a platinum grid, a saturated calomel reference electrode (SCE) and a plate of the lean supermartensitic stainless steel, of 1 cm² cross-sectional area, used as working electrode. The corrosive medium was prepared from distilled water by adding 3.5% NaCl. Polarisation curves were plotted under potentiodynamic regulation using a core running 1287 electrochemical interface (ACM-Grill). The cathodic and anodic branches were plotted in corrosion potential (Ecorr) verses corrosion current (Icorr). The SEM images of base and welded corroded surface were studied to analyze the corrosion properties.

3 Results and Discussion

3.1 Macrostructure Examination

The weld bead was cross-sectioned in correspondence of its normal symmetrical plane, as shown in the Figure 4, in order to investigate the bead characteristics. Cross-section was polished for observation with optical microscope and the bead geometry was studied by measuring the following parameters, bead width, bead height and depth of penetration using image J software.

From Figure 4, it is observed that the weld has achieved full penetration without any defects with

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**Table 2 Parameters used for PAW process**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>d (mm)</th>
<th>I (amp)</th>
<th>S (mm/min)</th>
<th>FR (l/min)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>140</td>
<td>375</td>
<td>1.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>160</td>
<td>375</td>
<td>1.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>160</td>
<td>250</td>
<td>2.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>170</td>
<td>125</td>
<td>2.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>160</td>
<td>375</td>
<td>1.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>160</td>
<td>250</td>
<td>1.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>160</td>
<td>125</td>
<td>2.5</td>
<td>Partial penetration</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>170</td>
<td>125</td>
<td>2.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>170</td>
<td>125</td>
<td>2.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>170</td>
<td>375</td>
<td>1.5</td>
<td>Not welded</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>160</td>
<td>375</td>
<td>2.5</td>
<td>Partial penetration</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>160</td>
<td>250</td>
<td>1.5</td>
<td>Welded but porosity</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>160</td>
<td>375</td>
<td>1.5</td>
<td>Partial penetration</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>160</td>
<td>250</td>
<td>2.5</td>
<td>Full penetration but undercut</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>160</td>
<td>125</td>
<td>2.5</td>
<td>Full penetration without defect</td>
</tr>
</tbody>
</table>

The cut blanks were machined with perpendicular to each other than surface grounded to make air tight gap between two joining plates. Just prior to welding, plates were cleaned with fresh stainless steel wire brush followed by acetone swabbing. The welding process was performed under Argon as shielding gas and plasma gas. The photographic views of the weld samples are presented in Figure 3. After welding, the weld surfaces were cleaned with steel wire brush followed by acetone swabbing. The weld was then subjected to liquid penetrant test and radiographic tests. It is confirmed that there is no micro cracks and discontinuities.
wine cup shaped bead profile. The full penetration in the weld zone due to the effect of keyhole mode of PAW. The bead width and height are 12.71, 1.67 mm respectively.

3.2 Microstructure Characterization

The microstructure of the base material, 410S LSMSS is shown in Figure 5. The steels typically contain several percent of stable revert austenite together with tempered martensite containing a population of carbides. Published literature indicates that it is possible to attain 20-30% stable austenite in 13%Cr steel with 2-4%Ni, if tempering is performed at about 100°C above Ac₁.[9-10] Martensite, is a metallic magnetic or a supersaturated solid solution of carbon trapped in a body-centred tetragonal structure. It appears microscopically as a white needle like or acicular structure sometimes described as a pile of straw. From Figure 5, it is observed that the dark phase martensite is present in the matrix of bright phase ferrite.

![Figure 5 Microstructure of base metal](image)

The HAZ microstructures of the LSMSS are presented in Figure 6 with different magnification. The banded structures of ferrite and dark phase are martensites along with precipitated globular particles of Cr₂C₃ were observed. Less amount of martensite than base metal microstructure is observed. Some martensite converted into ferrite phase.

![Figure 6 Microstructure of HAZ](image)

The weld metal microstructures are presented in Figure 7. It is clearly seen that the two different distinguished structures like dark phase and light phase. Dark phase is called as martensite with leaf structures and light phase is called as a ferrite phase. More amount of leaf martensite was observed as compared to HAZ but less as compared to the base material. Some martensite got converted into ferrite phase during welding process.

![Figure 7 Microstructure of weld zone](image)

3.3 Mechanical Evaluation

The welded specimens were tested for their tensile strength. The obtained values for the percentage of elongation, yield and tensile strength of the welded joints are presented in Table 3.

<table>
<thead>
<tr>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>% of Elongation</th>
<th>Point of Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>378</td>
<td>512</td>
<td>14.20</td>
<td>Parent Metal</td>
</tr>
</tbody>
</table>

The weld specimen exhibited higher yield strength and tensile strength than the base material. The fractured tensile test sample is presented in Figure 8, fractured at base material.

![Figure 8 Tested tensile specimen](image)

The base material got mean impact energy of 190 J at room temperature (RT). For measurement of toughness, the dominant parameter is the ferrite grain structure and orientation. The results of Charpy impact tests are given in Table 4. The results shows that weld specimen exhibited more impact strength than base material at room temperature and the impact energy is reducing drastically as the temperature reduced to cryogenic temperature (-196°C). Impact fractured surfaces is shown in Figure 9.

![Figure 9 Impact fractured surfaces](image)
is observed that there is a significant difference (p<0.05 is considered to be statistically significant) between the coarse martensite and marginally higher ferrite levels. In the HAZ region, a relatively higher hardness value than weld zone was noticed (279 HV0.5) in regions of a much finer martensitic structure than that was observed in the weld metal region. However from the statistical analysis (p<0.05 is considered to be statistically significant) there is a significant difference in hardness was observed between base and weld zones.

The fracture surface of tensile and impact specimens were examined by Scanning Electron Microscopy (SEM) to identify the mode of fracture. The fractographic analysis of the tensile specimen tested in air showed a ductile fracture by micro void coalescence (dimples) as observed in Figure 10. This typical dimple appearance may be also attributed to the existence of internal interfaces due to austenite particles and precipitates, which may act as void nucleation sites. It is observed that impact fracture at RT exhibited ductile fracture and at -196°C, it is cleavage and trans granular fracture. completely brittle behaviour of fracture.

The microhardness values for the welded joint are shown in Figure 11. The parent metal hardness was around 306 HV0.5 due to fine grain of martensite and carbides are distributed in the matrix. The hardness value dropped in the coarse grained weld zone to about 278 HV0.5 due to the higher heat concentration in this region, leading to coarse martensite and marginally higher ferrite levels. In the HAZ region, a relatively higher hardness value than weld zone was noticed (279 HV0.5) in regions of a much finer martensitic structure than that was observed in the weld metal region. However from the statistical analysis (p<0.05 is considered to be statistically significant) there is a significant difference in hardness was observed between base and weld zones.

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<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Testing temperature</th>
<th>Impact value in joule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RT</td>
<td>182</td>
</tr>
<tr>
<td>2</td>
<td>-196°C</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 9 Impact fracture specimens

Table 4 Impact energy values

Figure 10 SEM fractograph

Table 5 Corrosion test results

Based on the experimental results, the following conclusions were drawn.

i. The welds were produced without any defects.

ii. The microstructure consists of leaf martensite and ferrite phase.

3.4 Corrosion test results

Figure 12 shows the typical anodic polarization curves for both welded and base metal specimens and Table 5 lists their Ecorr and Icorr values. From the polarisation curve it reveals that welded specimen is more resistant to pitting corrosion than the base metal as the corrosion current (Icorr) value is less. Tafel curve of welded sample is shifted towards left, so more corrosion resistance as compared to base material. The two phase microstructure of LSMSS consisting of significant amount of δ-ferrite.

Table 5 Corrosion test results

Figure 12 Tafel plots of base & welded specimen

4 Conclusions
iii. The higher tensile properties were obtained than the base metal.
iv. The ductile mode of fractured was observed in tensile fractured surface.
v. The impact energy value for welded joints is more than base metal at room temperature and drastically reduced at cryogenic temperature (-196°C).
vi. The ductile mode of fractured was observed in impact fractured surface at room temperature. Cleavage and brittle mode of fractured was observed in impact fractured surface at cryogenic temperature (-196°C).

vii. The hardness of weldment is higher than the HAZ hardness value.

viii. The corrosion resistance of welded sample is more than the base metal sample.

5 References

Materials Park, OH, USA.