EFFECT OF OXIDE FLUXES ON ACTIVATED TIG WELDING OF P91 STEEL

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Abstract - The current work investigates effect of different oxide fluxes (TiO₂, Cr₂O₃, CuO, and MoO₃) on single pass autogenous tungsten inert gas welding of P91 steel. Weld bead geometries obtained with and without use of fluxes were studied. All the oxide fluxes resulted in improvement in depth of penetration and reduction in bead width. The role of oxygen content was analyzed and it was found that 30-80 ppm oxygen content is favorable for improving depth of penetration. Additionally, metallurgical studies were done with the help of scanning electron microscopy.

Keywords - P91 steel, A-TIG welding, Oxide fluxes, Dissolved oxygen, Microstructure

I. INTRODUCTION

P91 steel (9Cr-1Mo) is a precipitation hardened creep resistant ferritic-martensitic steel which is mainly alloyed with chromium and molybdenum. It is widely used as a structural material in the nuclear power plants in the service temperature range of 500-600°C [1]. Tungsten Inert Gas (TIG) welding is the most commonly used fabrication process for welding of P91 steels. However, lack of penetration in single pass and tedious joint preparation reduce the productivity of TIG welding process. Conventionally, the depth of penetration in single pass during TIG welding was improved by techniques such as addition of helium/oxygen in the shielding gas, by increasing the welding current or by slight addition of surfactants (sulfur/oxygen) [2]. However, Activated TIG (A-TIG) welding which was developed in the 1960s by Paton Electric Welding Institute, Ukraine improves the process productivity to the larger extent [3]. In A-TIG welding of steel, a layer of oxide flux is applied on the surface of the base metal. Due to the heat of the arc, this flux melts or vaporizes which in turn induces oxygen into the weld metal. The addition of surface active element such as oxygen changes the flow direction of molten pool which yields higher depth of penetration. The literature shows that the plates up to 12 mm thickness can be welded in a single pass [4].

Several research works have been carried out to study the influence of activated fluxes on the weld bead geometries of different steels [5]. However, much of the research work is confined to austenitic stainless steel grades, and a miniature amount of literature is available on effect of single component fluxes on the weld bead geometry of P91 steel. Therefore, systematic study is required to understand the way these oxide fluxes behave during A-TIG welding of P91 steel.

In this work an effort has been made has been made to- a) investigate the differential behavior oxide fluxes on the weld bead geometry of P91 steel, b) identify the range of amount of oxygen content which causes increase in depth of penetration. Further, metallurgical properties of the weld joint were studied.

II. EXPERIMENTAL DETAILS

2.1. Materials and methods

The base metal composition of the P91 steel analyzed with optical emission spectrometer is given in Table 1. P91 steel plates of 110*30*8 mm dimensions were used for bead on plate studies in this work. Prior to welding, the specimen surfaces were polished with an abrasive paper up to 320 grit, followed by cleaning with acetone. Four types of fluxes (TiO₂, Cr₂O₃, CuO, and MoO₃) were used in this study. The fluxes were mixed with acetone and then applied uniformly over the base material surface with the help of a paint brush. Autogenous bead on plate welding was carried out with process parameters which are tabularized in Table 2.

2.2. Characterization of weldments

After welding specimens were cut with an abrasive cutter, polished with emery papers (up to 2000 grit) and then cloth polished with alumina powder. This was followed by etching with Villela’s agent (1g picric acid+5ml hydrochloric acid+95 ml ethanol). The weld bead geometries were analysed under the stereo microscope. The dissolved oxygen content in the weld pool was measured with LECO oxygen analyzer. The microstructures of weldment made with MoO₃ flux was analysed under field emission scanning electron microscope (FE-SEM). Table 1: Chemical composition of base metal

<table>
<thead>
<tr>
<th>Table 1: Chemical composition of base metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
</tr>
<tr>
<td>Weight %</td>
</tr>
</tbody>
</table>
**Table 2: Welding process parameters**

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding current</td>
<td>230 A</td>
</tr>
<tr>
<td>Welding speed</td>
<td>80 mm/min</td>
</tr>
<tr>
<td>Arc length</td>
<td>3 mm</td>
</tr>
<tr>
<td>Shielding gas (flow rate)</td>
<td>Pure argon (10 lpm)</td>
</tr>
<tr>
<td>Power Source</td>
<td>DCEN</td>
</tr>
<tr>
<td>Electrode</td>
<td>Tungsten (2% Th)</td>
</tr>
<tr>
<td>Electrode diameter</td>
<td>2.9 mm</td>
</tr>
</tbody>
</table>

**III. RESULTS AND DISCUSSION**

3.1. Effect of fluxes on weld bead geometries

The weld beads produced during of A-TIG welded P91 steel with and without oxide fluxes are shown in Fig.1. The geometry of the weld beads is presented in terms of depth of penetration (D), width (W) and depth to width ratio (D/W). These parameters are tabulated in Table 3. Autogenous welding without flux resulted in wide and shallow weld with 2.66 mm depth of penetration and bead width of 11.92 mm. The use of oxide fluxes led to an increase in depth and to width ratio, and a decrease in bead width of the weldments as shown in Fig.2. Welding with Cr₂O₃ led to a decent improvement in depth of penetration (D=5.19 mm) and reduction in bead width (W=8.23 mm). The weld showed cup-shape appearance with depth to width ratio value of 0.63. TiO₂ yielded a weld with conical geometry. The depth of penetration and bead width observed with TiO₂ flux were 6.72 and 7.01 mm. The resultant depth to width ratio (0.95) was highest amongst all fluxes used in this study. Welding MoO₃ produced through thickness depth of penetration i.e. 8 mm and bead width of 9.16 mm. MoO₃ weld bead had conical appearance with depth to width ratio of 0.72. The use CuO flux however, resulted in shallow bead with penetration and width of 2.78 mm and 11.32 mm respectively. Therefore, the higher depth of penetration and narrower welds in A-TIG welding could be directly attributed to the presence of the flux.

Various mechanisms have been proposed to correlate the change in weld bead geometry due to application of active flux in TIG welding. The reversal of Marangoni convection is the most commonly accepted mechanism for higher depth of penetration during A-TIG welding which is elaborated in Fig.3.[5,6]. The presence of surface active elements such as oxygen, sulfur, selenium in certain amount reverses the direction of the flow of the liquid metal which in turn promotes flow of molten metal from the edge to the center of the weld pool. The resulting centripetal convection movement is known as a reversal of Marangoni convection. The reversal of Marangoni convection in the weld pool increases the heat being transferred at the centre from the top of the weld surface to the bottom of the weld, thereby increasing the depth of penetration [7].

The oxygen addition over a certain range in the molten weld pool plays an important role in improving depth of penetration by changing the gradient of surface tension with respect to temperature from negative to positive. Out of this range, the gradient of surface tension is negative, which causes centrifugal motion of molten metal and reduces the depth of penetration [8].

![Without flux](image1)
![Cr₂O₃](image2)
![TiO₂](image3)
![MoO₃](image4)
![CuO](image5)

**Fig.1. (a-e) Macrographs showing weld beads obtained with and without use of oxide fluxes**

**Table 3: Weld bead depth, width and depth to width ratio with and without fluxes**

<table>
<thead>
<tr>
<th>Flux</th>
<th>Depth (D)</th>
<th>Width (W)</th>
<th>Depth to width ratio (D/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Flux</td>
<td>2.66</td>
<td>11.92</td>
<td>0.22</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>5.19</td>
<td>8.23</td>
<td>0.63</td>
</tr>
<tr>
<td>TiO₂</td>
<td>6.72</td>
<td>7.01</td>
<td>0.95</td>
</tr>
<tr>
<td>MoO₃</td>
<td>8</td>
<td>11.05</td>
<td>0.72</td>
</tr>
<tr>
<td>CuO</td>
<td>2.78</td>
<td>11.32</td>
<td>0.25</td>
</tr>
</tbody>
</table>

![Effect of different fluxes on D, W and D/W ratio](image6)

**Fig.2. Effect of different fluxes on D, W and D/W ratio**

![Schematic showing flow patterns due to Marangoni convection](image7)

**Fig.3. Schematic showing flow patterns due to Marangoni convection**

A correlation between depth of penetration and dissolved oxygen content in the weld pool can be made as shown in Fig.4. Weldment fabricated without the use of flux had very low oxygen content.
(20 ppm), which is not enough to change surface tension gradient from negative to positive, which in turn resulted in low depth of penetration. The use of Cr$_2$O$_3$, TiO$_2$ and MoO$_3$ resulted in oxygen levels of 42, 50 and 70 ppm respectively. This increase is oxygen content facilitates positive surface tension gradient and increased depth of penetration continuously. However, very high dissolved oxygen levels as obtained with CuO (150 ppm) makes gradient of surface tension negative, which creates centrifugal flow pattern within the weld pool. Therefore the bead obtained with CuO was shallow and wide. Therefore a dissolved oxygen content between 30 to 80 ppm is needed to improve penetration in P91 steel. Too low or too high oxygen levels were found to have detrimental effect on depth of penetration.

**CONCLUSIONS**

Effect of activated fluxes namely TiO$_2$, Cr$_2$O$_3$, CuO, and MoO$_3$ on activated TIG welding of P91 steel was studied. Following major conclusions can be made from this work:

1. The use of activated fluxes improves depth of penetration in single pass as compared to welding without flux.

2. Oxygen content plays an important role in reversing the direction of Marangoni convection from negative to positive. Oxygen content between 30-80 ppm was observed to improve the depth of penetration. Out of this range, the weld bead obtained was shallow and wide.

3. The weld zone exhibited untempered martensitic structure along with delta ferrite and oxide inclusions.

**ACKNOWLEDGMENTS**

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