Experimental Investigation on Effects of Carrier Solvent and Oxide Fluxes in Activated TIG Welding of Reduced Activation Ferritic/Martensitic Steel

Jay J. Vora\(^1\), and Vishvesh J. Badheka\(^2\)

**Abstract**—This work attempts to investigate the effect of oxide fluxes on 6mm thick Reduced Activation ferritic/martensitic steels (RAFM) during Activated TIG (A-TIG) welding. Six different fluxes \(\text{Al}_2\text{O}_3\), \(\text{Co}_3\text{O}_4\), \(\text{CuO}\), \(\text{HgO}\), \(\text{MoO}_3\), and \(\text{NiO}\) were mixed with methanol for conversion into paste and bead-on-plate experiments were then carried out. This study, systematically investigates the influence of oxide-based flux powder and carrier solvent composition on the weld bead shape, geometric shape of weld bead and dominant depth enhancing mechanism in tungsten inert gas (TIG) welding of reduced activation ferritic/martensitic (RAFM) steel. It was inferred from the study that flux \(\text{Co}_3\text{O}_4\) and \(\text{MoO}_3\) imparted full and secure (more than 6mm) penetration with methanol owing to dual mechanism of reversed Marangoni and arc constriction. The use of methanol imparted good spreadability and coverability and ultimately higher peak temperatures were observed with its use owing to stronger depth enhancing mechanisms than use of acetone with same oxide fluxes and welding conditions.

**Keywords**—A-TIG, flux, oxides, penetration, RAFM, temperature, welding

I. INTRODUCTION

Welding is by far the most widely used fabrication process for manufacturing of pressure vessels, components for aerospace and defense industry, automobile components etc. Based on the needs and final application there are several number of welding processes developed and studied by the researchers. Out of all these processes, Tungsten inert gas (TIG) welding is the most widely used conventional welding process where high quality welds are required. However, an inherent disadvantage of the process is its limited penetration capability in singles pass autogenous welds [1]. Maximum penetration of around 3 mm is achieved in single pass and hence in order to weld plates of 6mm thick double sided welds or addition of filler metal needs to be carried out. Both of these techniques make the process, time consuming and costly. To encounter this problem, a variant of TIG welding was developed at Paton institute of electric welding in 1960 and was termed as Activated TIG (A-TIG) welding. In this process an activating flux layer comprised of metal oxides, prominently halides, oxides or sulphides is applied on the surface before welding by mixing the powder with alcohol based carrier solvent such as methanol, ethanol or Acetone [2, 3]. During autogenous welding, this fine layer of flux is melted and vaporized at arc temperatures and penetration capability is reported to be increased up to 300% while using A-TIG compared to conventional TIG process [4]. Owing to this advantage several researchers have used this technique on different steels with varied chemical composition.

In one the studies Ramkumar et al. [5] successfully applied the A-TIG welding on similar and dissimilar weldments of super-duplex and austenitic stainless steel welds. Additionally, in one of the separate studies by Ramkumar et al. [6] used the A-TIG welding technique for Inconel 718 joints. Manu such research on stainless steels [7-10] has been successfully carried out by various researchers which dictates the capability of this new emerging process. Apart from this, several researchers have tried implementing the technique on conventional and advanced alloy steels. Authors Vasudevan et al. [4, 11, 12] studied the A-TIG process for P22 steel and P91 steels. In all cases the penetration capability of the TIG welding was enhanced. However, the A-TIG welding is greatly influenced by the chemical composition and hence the technique needs to be developed for new steels with different chemical composition. The use of flux was also claimed to reduce the susceptibility to changes in penetration caused by cast-to-cast variability in material composition and reported to produce consistent penetration regardless of heat-to-heat variations in base metal compositions.

Reduced activation ferritic/martensitic (RAFM) steels are specially developed steels for fusion reactor components as they simplify the waste disposal procedures. RAFM steels are developed by replacing Molybdenum (Mo) by Tungsten (W), Nickel (Ni) by Tantalum (Ta) and reducing the content of Vanadium (V) to decrease its activation tendency. This allows the shallow land burial of reactor components after their service life times are exhausted. The fabrication of this steel for fusion reactor is primarily by welding [13, 14], and hence A-TIG welding of RAFM steel can be considered as an emerging field for study. However limited literatures are available on A-TIG welding of RAFM steels. The most relevant study was carried out by the authors [2, 15] where the effect of the oxide fluxes mixed with acetone was reported on 6mm thick RAFM steel. It was reported that, fluxes \(\text{Co}_3\text{O}_4\) and \(\text{CuO}\) gave full and secure penetration in 6mm thick RAFM steel. This was attributed to the simultaneous presence of two different deep penetration mechanisms due to these fluxes. In addition this, a study by reports the use of different carrier

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solder with same flux and welding conditions. The carrier solvent decides the consistency of the flux layer which in turn dictates the effectiveness of A-TIG process. In this study [3], the author reported the use of methanol and ethanol as a carrier solvent and its effect on A-TIG process. It was reported that methanol and ethanol provided good spreadability and coverability and in turn exciting results in terms of depth of penetration. The present study deals with studying weld bead dimension such as DOP, BW, HAZ width and D/w ratio for bead-on-plate welds by A-TIG process using 6 different oxide fluxes such as Al₂O₃, CoO₃, CuO, HgO, MoO₃, and NiO by using methanol as a carrier solvent and further comparing the results with acetone.

II. EXPERIMENTAL WORK

A. Base material and fluxes

As received plates of 6mm thick RAFM steel were used in the present study, supplied by M/S Mishra Dhatu Nigam Ltd. Hyderabad, India. The chemical composition of the steel is as shown in table I. Methanol was used as a carrier solvent and the characteristic properties as shown in table II. The oxide fluxes Al₂O₃, CoO₃, CuO, HgO, MoO₃, and NiO used in present study, were in powdered form.

TABLE I: CHEMICAL COMPOSITION (WT. %) OF RAFM STEEL USED IN PRESENT STUDY

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>0.1</td>
<td>0.03</td>
<td>0.54</td>
<td>0.003</td>
<td>0.002</td>
<td>0.0</td>
</tr>
<tr>
<td>Co</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.23</td>
<td>1.42</td>
<td>0.15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>V</td>
<td>O</td>
<td>N</td>
<td>Nb</td>
<td>Mo</td>
<td>Al</td>
<td>B</td>
</tr>
<tr>
<td>O</td>
<td>0.09</td>
<td>0.025</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.008</td>
<td>&lt;0.002</td>
</tr>
</tbody>
</table>

TABLE II: CHARACTERISTIC PROPERTIES OF CARRIER SOLVENT

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Viscosity (20°C, mPa·s)</th>
<th>Vapour pressure (20°C, mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>0.817</td>
<td>96</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.389</td>
<td>184</td>
</tr>
</tbody>
</table>

B. Application of fluxes

In order to evenly apply the flux on the surface, it was converted to paste form by mixing it with methanol. Base material plate of 6mm thick was cut into strips of 75 x 25 (mm) for bead on plate trials and flux paste was applied on 10mm width at the centre of strip throughout the length with a paint brush. Thickness of flux was approx 0.15 mm and for having a uniform amount of flux constituents over entire length of strip, the brush was moved in both forward and reverse direction over the desired area until entire flux paste was consumed. In order to measure the peak welding temperatures, a contact type “K” type thermocouple was fixed at the centre of the plate by drilling a hole of approx. 2mm diameter and 3mm depth during the welding trials.

C. Bead-on-plate trials

Extensive welding trials were conducted in autogenous mode with Panasonic make GTAW power source having capacity of 200A with 25% duty cycle and customized special purpose machine for torch movement. The welding parameters used for the study are shown in table III. In order to compare the effect of oxide fluxes, samples were welded with same operating conditions by applying six oxide fluxes individually. Additionally, the welding conditions were kept the same as used by the authors in their previous study with acetone as a carrier solvent. After welding, the macrostructures of the welded samples were developed by conventional metallographic techniques and different weld bead dimensions such as DOP, BW and HAZ width were measured using a travelling vernier microscope.

TABLE III: WELDING PARAMETERS FOR BEAD ON PLATE TRIALS

<table>
<thead>
<tr>
<th></th>
<th>Welding current</th>
<th>Crater current</th>
<th>Travel speed</th>
<th>Electrode type</th>
<th>Electrode diameter</th>
<th>Electrode Angle</th>
<th>Arc Gap</th>
<th>Shielding Gas</th>
<th>Gas flow rate</th>
<th>Welding position</th>
<th>Electrode extension</th>
<th>Nozzle diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. No-Flux</td>
<td>200 A</td>
<td>200 A</td>
<td>100 mm/min</td>
<td>Tungsten (2 % Thoriated)</td>
<td>2.9 mm</td>
<td>18 - 20° (Blunt ground at tip)</td>
<td>2 - 3 mm</td>
<td>Argon (99.999% purity)</td>
<td>10-12 L/min</td>
<td>1G (Flat)</td>
<td>5-6 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>B. CoO₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. MoO₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

III. RESULTS AND DISCUSSION

The present study investigates the effect of oxide fluxes mixed with methanol on the A-TIG welding of RAFM steel using six different oxide fluxes. Furthermore, the comparison between the effectiveness of acetone and methanol as a carrier solvent has also been done.

A. Effect on Weld macrostructures

The macrostructures developed are as shown in figure 1. It can be seen that, full and secure penetration is obtained with the use of fluxes CoO₃ and MoO₃. From the figure it can also be observed that the weld bead shape for these two fluxes is different than the characteristic TIG welded bead shape. The bead shape is narrow and deep for A-TIG welding whereas with the TIG welding the bead shape is shallower and wider [2]. Thus it can observed that an evident mechanism is present with the use of oxide fluxes in A-TIG welding which is elaborated in coming sections.

(a) No-Flux

(b) CoO₃

(c) MoO₃

Fig. 1 Macrostructures of Bead-on-plate weldments

B. Effect on Weld Bead dimensions

The weld bead dimensions as measured by the travelling vernier microscope are as shown in table IV. It can be seen from the table that fluxes CoO₃ and MoO₃ gave penetration of
more than 6mm. Hence a full and secure penetration is obtained with the use of these oxide fluxes. Furthermore, it can also be observed that the D/w ratios for both these fluxes are found to be near to unity. Near to unity D/w ratio indicates that the DOP is increased at the expense of BW, which is a highly desirable condition. It proves that the most popular activation mechanism of reversed Marangoni flow is present with the use of these fluxes and these fluxes can further be termed as activating fluxes. The reversed Marangoni flow changes the direction of fluid flow (molten metal in present case) during welding to radially inwards and hence a deeper and narrower bead is obtained. It can also be noted from the table IV that flux NiO, CuO and Al₂O₃ gave an increase in DOP compared to DOP of 3.6 mm with autogenous TIG welding without flux. Thus it can be attributed that, there is an evident Marangoni effect present with these fluxes, however it is independently not capable of giving full and secure penetration. Thus, there must be an additional mechanism [2] responsible for deeper penetration with fluxes Co₃O₄ and MoO₃ which is discussed in next section.

### Table IV: Effect on Weld Bead Dimensions and Peak Welding Temperature

<table>
<thead>
<tr>
<th>Flux</th>
<th>BW (mm)</th>
<th>DOP (mm)</th>
<th>HAZ Width (mm)</th>
<th>D/w</th>
<th>Peak Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>8.9</td>
<td>5.0</td>
<td>4.1</td>
<td>0.56</td>
<td>606</td>
</tr>
<tr>
<td>Co₃O₄</td>
<td>7.1</td>
<td>7.1</td>
<td>4.1</td>
<td>1.00</td>
<td>830</td>
</tr>
<tr>
<td>CuO</td>
<td>10.1</td>
<td>4.5</td>
<td>2.9</td>
<td>0.45</td>
<td>690</td>
</tr>
<tr>
<td>HgO</td>
<td>9.0</td>
<td>3.1</td>
<td>3.5</td>
<td>0.34</td>
<td>640</td>
</tr>
<tr>
<td>MoO₃</td>
<td>7.1</td>
<td>7.5</td>
<td>4.1</td>
<td>1.06</td>
<td>802</td>
</tr>
<tr>
<td>NiO</td>
<td>6.1</td>
<td>5.1</td>
<td>2.9</td>
<td>0.84</td>
<td>616</td>
</tr>
</tbody>
</table>

#### C. Effect on Peak Welding Temperatures

From table IV it can be observed that the peak temperatures achieved with the use of fluxes Co₃O₄ and MoO₃ are on higher side compared to other fluxes. Thus it can be recommended that another mechanism of arc constriction was present. Arc constriction mechanism tends to focus the arc energy towards the centre by altering the arc shape. Researchers have observed the arc images with A-TIG welding and a clear demarcation in the physical shape have been observed under this mechanism. As a consequence of the same, the total arc energy which was same in all cases (all fluxes) was concentrated at the centre and the peak temperatures were increased even though the welding conditions and parameters were same. This directed nature of arc assisted in melting the metal efficiently and increasing the DOP. These can be compared with the phenomenon which occurs in laser beam welding. Contrary to the same, the peak temperatures reported with the use of other fluxes were on lower side and hence no flux was able to impart full and secure penetration. Thus this study supports the authors’ theory of dual mechanism in A-TIG welding [2].

#### D. Comparison of Acetone and methanol as a carrier solvent

The experimental data obtained from present study was compared with the already published[2] data by the authors and a meaningful comparison was observed from both these studies. Figure 2 gives the comparison on DOP obtained with the use of same oxide fluxes on A-TIG welding of RAFM steels. It can be observed that flux Co₃O₄ was capable of giving full penetration in 6mm thick RAFM plate with use of both methanol and acetone. However, flux CuO and MoO₃ imparted full penetration only with acetone and methanol respectively. Similarly from figure 3 it can be noted that BW values obtained with the use of acetone is higher than that obtained with methanol.
Another argument to the same can be given by observing figure 4 and figure 5 which compares the HAZ width values and peak welding temperatures respectively. As discussed as the flux components available with acetone are less compared to methanol, arc energy available for welding is slightly less and hence HAZ width and peak welding temperature are less compared to methanol.

IV. CONCLUSIONS

The effect methanol as a carrier solvent in addition to six different oxide fluxes on A-TIG welding of RAFM steels were analyzed and comparison between the effect of carrier solvent was presented. From the study, following conclusions can be made:

1) Fluxes CoO₂ and MoO₃ are capable of giving full and secure penetration of 7.1 mm and 7.5 mm respectively with methanol in 6mm thick RAFM steel plates. Apart from reversed Marangoni, additional mechanism of arc constriction was present. Under the synchronized effect of these two depth enhancing mechanisms, enhanced penetration was achieved.

2) Fluxes NiO, CuO and Al₂O₃ enhanced the penetration capability of TIG welding processes, however full penetration was not achieved because of the absence of arc constriction mechanism. This was evident by lower values of peak temperatures at same welding conditions.

3) CoO₂ was able to impart full penetration in 6mm thick RAFM steel plate with acetone as well as methanol as the carrier solvent. However, flux CuO and MoO₃ imparted full penetration only with acetone and methanol respectively.

4) Methanol imparts good spreadability as well as coverability to the flux paste. Also methanol tends to evaporate less likely compared to acetone and hence effective flux ingredients available for A-TIG welding is more with the use of methanol and hence comparatively stronger mechanisms are present with the methanol.

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