Joining of Duplex Stainless Steel by Plasma Arc, TIG, and Plasma Arc+TIG Welding Processes

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Joining of Duplex Stainless Steel by Plasma Arc, TIG, and Plasma Arc + TIG Welding Processes

EMEL TABAN

Department of Mechanical Engineering, Engineering Faculty, Kocaeli University, Kocaeli, Turkey

1.4462 duplex stainless steel (DSS) with a thickness of 6.8 mm was joined by plasma arc, Tungsten Inert Gas (TIG), and plasma arc + TIG welding processes. Impact toughness testing was carried out and fractographs were examined by Scanning Electron Microscopy (SEM). Microstructural analysis, ferrite content, and hardness survey of the weld zones were done while the variation in chemical composition was investigated with energy dispersive X-ray spectroscopy (EDX). Results were compared due to the heat inputs of the joints and the relation between microstructure, and toughness was explained. Promising results showed that plasma arc welding (PAW) and/or plasma + TIG welding, which are considered immature processes for DSS, can successfully be employed for increased productivity.

Keywords Duplex stainless steel; EN 1.4462; Ferrite content; Fracture; Hybrid welding; Microstructure; Microstructure-property relation; Plasma arc welding; Stainless steel; TIG welding; Toughness; UNS S31803; Welding; X2CrNiMo22.5.3.

INTRODUCTION

Duplex stainless steels (DSSs), with almost 50% ferrite and 50% austenite at their room temperature microstructure, have evolved rapidly since the 1980s due to the significant improvements both in material design and weldability. DSSs range from the cost efficient lean grades to the high alloyed superduplex grades for more demanding applications and are often selected to substitute austenitic alloys where stress corrosion cracking and pitting corrosion are of concern. They are used in many applications such as in the oil and gas, paper and pulp, petrochemical industries, and in power generation because of their superior corrosion resistance, strength, and/or a combination of both properties due to their strict composition control and microstructural balance [1–6]. The weldability of duplex stainless grades mainly with conventional arc welding processes has been studied by various researchers [7–12]. Studies on flash butt welding [13] and friction stir welding [14] have also been focused. Recently, high energy welding methods, especially electron beam welding, have been used for the joining of austenitic and ferritic types of stainless steels due to some advantages over conventional fusion processes such as low heat input and high welding speed [15]. High energy beam welding of 1.4462 was studied by Muthupandi et al., Karlsson, and Ku et al. [6, 11, 15]. However, published work on laser welding of duplex stainless steels concluded that significant amounts of filler metal addition is difficult, and due to the high cooling rate, austenite content at the laser weld metal is less than 30%, which is undesirable [12, 16]. Plasma arc welding (PAW) of DSS finds increasing demand due to the lower cooling rates compared to laser or electron beam welding and with the advantages of high welding speed providing higher productivity. Determined research work concentrated on plasma welding of these steels is found to be relatively scarce [17–21]. Since conventional fusion welding required for construction assembly has a significant influence on duplex microstructure of weld zone [18], and due to the increased demand of DSSs in many fields, both plasma and tungsten arc welding properties of 1.4462 steel were studied here. The properties of PAW were compared with TIG weld as a conventional fusion welding process and with hybrid (plasma + TIG) welded joint due to the heat input range. Characterization and analysis of relationships between toughness, microstructure, ferrite content, chemical composition, and hardness properties of the joints were considered. The possibility of plasma and/or hybrid processes which are relatively new for DSSs in industrial applications still obtaining an acceptable ferrite-austenite ratio was also investigated.

MATERIAL AND EXPERIMENTAL PROCEDURE

Chemical composition of the DSS base metal conforming to grades 1.4462 and X2CrNiMo22.5.3 in Euronorm and UNS S31803 in ASTM A240 are given in Table 1. Data were obtained from chemical analysis by X-ray spectrometer and from the steel producer [22]. The welding processes that has been applied in industrial conditions within this study are PAW, TIG welding, and hybrid welding (plasma + TIG). PAW in keyhole mode of 6.8 mm thick duplex stainless steel was accomplished without any filler metal and by using direct current electrode negative (DCEN) polarity. Straight plate edges perpendicular to the plate surface have been prepared while the weld pool was protected by a high purity Ar gas. The plasma weld was produced in one pass and with a heat input between 1.82kJ/mm and 1.96kJ/mm and the joint which was named as Weld 1. TIG welding with a solid ER2209 filler metal, see Table 2, as recommended [1, 3], was protected by nitrogen for root and high purity argon for filler passes. Nitrogen as backing gas is recommended depending on the advantages of improved prevention against oxidation,
Table 1.—Chemical composition (in wt%) of the base metal.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>Cr</th>
<th>Cu</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>V</th>
<th>Al</th>
<th>Nb</th>
<th>Fe</th>
<th>Co</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.021</td>
<td>0.46</td>
<td>1.48</td>
<td>0.037</td>
<td>22.55</td>
<td>0.12</td>
<td>5.64</td>
<td>3.13</td>
<td>0.013</td>
<td>0.064</td>
<td>0.06</td>
<td>0.04</td>
<td>66.35</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>[0.020]</td>
<td>[22.5]</td>
<td>[5.8]</td>
<td>[3.1]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Values between square brackets are obtained from the steel producer.

better wetting, and improved weld appearance [3]. The plate preparation consisted of a Y-shape with an opening angle of 60°. Six passes were used to complete the whole weld. No preheat was applied while the heat input varied between 3.52 kJ/mm to 4.14 kJ/mm. This welded joint was named Weld 2. Y groove preparation with an opening angle of 60° was used for plasma + TIG welding, which was presented as Weld 3. High purity Ar and no filler metal was used for PAW, while a 2209 type of electrode, see Table 2, was preferred for TIG welding for the cap run protected by Ar as shielding gas. The total heat input ranged from 3.12 kJ/mm to 3.26 kJ/mm for Weld 3.

Subsized notch impact test samples were extracted transverse to the weld and prepared with notches positioned at the weld metal centre (WM), heat affected zone (HAZ), and base metal (BM). Impact toughness testing of over one hundred samples—three samples for each position for each temperature per weld—was carried out at 0°C and at subzero temperatures such as −20°C, −40°C, and −60°C. Examinations of the fractographs were carried out with a JEOL JSM 5600 SEM equipped with a calibrated EDX system. All joints were cross-sectioned perpendicular to the welding direction for metallographic analyses. Specimens were prepared, polished, and etched electrolytically in NaOH solution. Macro- and microphotographs by light optical microscope (LOM) with 200× magnification at the BM, WM, and HAZs were obtained. Ferrite content measurements in ferrite % were done with a Fischer Ferritscope across BM and HAZ from both sides and WM of the cross-sections. The variation in chemical composition at WM structure components austenite and ferrite (wt%) was investigated with EDX. Microhardness measurements were carried out over the weld cross-sections.

RESULTS AND DISCUSSION

The mean notch impact values of the related welded joints expressed in J are shown in Fig. 1.

Impact toughness of DSS welds is specified at design temperature or another specified temperature. Although the acceptance criteria vary significantly, examples of typical impact toughness requirements are a minimum of 34 J at −40°C, and 35 J average and 27 J minimum at −46°C [11]. Depending on these criteria, it can easily be said that all joints pass the minimum requirements with much higher values such as mean values of 98 J, 74 J, and 92 J for WM and 102 J, 110 J, and 100 J for HAZ, respectively for Weld 1, Weld 2, and Weld 3 even at −60°C. Scatter of the testing data varied between 1.00 and 1.50 which can be regarded as low. Individual WM impact toughness data were generally determined to be less than that of the HAZ data for each temperature for Weld 2 similar to the situation in the literature [11], while very close, WM and HAZ toughness data were obtained for Weld 1 and Weld 3. Due

Table 2.—Chemical composition (in wt%) of the ER2209 duplex type of filler metal [1].

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.03</td>
<td>0.9</td>
<td>0.5–2.0</td>
<td>21.5–23.5</td>
<td>0.010</td>
<td>0.010</td>
<td>7.5–9.5</td>
<td>2.5–3.5</td>
<td>0.08–0.20</td>
</tr>
</tbody>
</table>
to the relatively low toughness results of WM with regard to those of Weld 1 and Weld 3, fractographs from Weld 2 tested at −60°C at the notch positions of WM and HAZ were examined with SEM, see Fig. 2. In accordance with the toughness test results, WM showed mixed ductile and brittle fracture while HAZ reveals more ductile fracture.

The microstructural examination has been carried out on the metallography specimens using LOM with 200× magnification. The investigation of the weld has been performed from BM across HAZ to WM, respectively. The macro- and microstructures of the related BM and weld zones are shown in Figs. 3–5.

The DSS base metal, see Fig. 3(b), has shown an elongated grain structure, typical of that of a rolled product with almost equal amounts of ferrite and austenite in accordance with the literature [1, 7]. Since the primary solidification phase is ferrite in DSSs, and given the fairly rapid cooling related with a weld thermal cycle, diffusional transformation to austenite can be suppressed on cooling to room temperature providing a predominantly ferritic structure at the fusion zone. The microstructure of a fusion weld of the DSS can significantly differ from its BM compared to the martensitic and austenitic types. The HAZ is heated to temperatures close to the solidus, inducing transformation from the original two phase microstructure to ferrite and this retains again on cooling [23]. Especially for Weld 1 and Weld 3, a significant fusion line was not observed. In the Figs. 3 to 5, a narrow HAZ and some grain growth affecting subsequent epitaxial growth of the columnar ferrite grains inside the fusion pool, mainly for Weld 1 and root part of Weld 3, can be seen similar to the

Figure 2.—Fractographs of TIG weld samples from WM and HAZ tested at −60°C.

Figure 3.—(a) Macrograph; (b) BM; (c) WM; and (d) WM + HAZ micrographs of Weld 1.
Figure 4.—(a) Macrograph; (b) WM face; (c) WM root; and (d) WM + HAZ micrographs of Weld 2.

Figure 5.—(a) Macrograph; (b) TIG WM; (c) PAW WM; and (d) WM + HAZ micrographs of Weld 3.
study by Urena et al. [18], secondary austenite mainly at the WMs in the form of Widmanstatten needles growing into the ferrite grains was observed in accordance with literature [9, 18]. For ensuring the excellent combination of properties of DSS, it is essential to maintain a ferrite/austenite ratio close to 50/50. However, the phase balance is upset during welding on account of the rapid cooling involved in most weld thermal cycles. This can result in WM ferrite contents much in excess of 50% [17]. In order to restore the phase balance, weld filler materials are usually overalloyed with 2/4% more Ni than the BM [6]. More austenitic structure can be observed at the TIG WM due to the duplex type of electrode used, with regard to Weld 1 without filler metal, see Figs. 3(c) and 4(b) and (c). Due to the nitrogen use as backing gas for Weld 2, which was used in order to replace losses of nitrogen during the melting and solidification stages as recommended by Tavares et al. [24], the microstructure at the root of the WM was mainly austenitic, see Fig. 4(e), this situation will be more clarified by ferrite content measurements below. WRC-1992 diagram allows ferrite prediction based on composition up to 100 FN [1]. Taking this into account, Cr<sub>eq</sub> and Ni<sub>eq</sub> values of BM and filler metal were calculated to predict the ferrite content of the WM. Chromium equivalents of approximately 25.7 and 25.8, and nickel equivalents of 6.4 and 12.55 for BM and filler metal, respectively, were calculated using chemical composition data. A FN of approx. 63 is obtained for the TIG WM. Since, a rough conversion from FN to volume percent for the duplex alloys is 70%, approx. 44% ferrite is predicted for the related weld. For Weld 1 and Weld 3, when a similar calculation is done and put into the WRC-1992 diagram, respectively, 92 FN so 64% and 78 FN so 55% ferrite content are found. As a result, 64%, 44%, and 55% ferrite were predicted due to the WRC diagram, respectively, for the weld metals of Weld 1, 2, and 3. Ferrite content data obtained with a Fischer Ferritscope on the macrosections across the BM left, left part of the HAZ, WM, right part of the HAZ, and BM right are given in Table 3. Ferrite % data also include the values obtained from the face, middle, and root parts, e.g., face part starts from the face surface and every part contains approx. a depth of 2 mm for each position.

<table>
<thead>
<tr>
<th>Position</th>
<th>Weld 1</th>
<th>Weld 2</th>
<th>Weld 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM left face</td>
<td>52-49-48</td>
<td>55-55-54</td>
<td>53-51-50</td>
</tr>
<tr>
<td>BM left middle</td>
<td>51-50-47</td>
<td>54-53-53</td>
<td>52-50-52</td>
</tr>
<tr>
<td>BM left root</td>
<td>52-49-48</td>
<td>52-56-55</td>
<td>53-52-51</td>
</tr>
<tr>
<td>HAZ left middle</td>
<td>56-56-53</td>
<td>65-62-63</td>
<td>56-55-54</td>
</tr>
<tr>
<td>HAZ left root</td>
<td>54-52-52</td>
<td>54-51-50</td>
<td>54-53-53</td>
</tr>
<tr>
<td>WM face</td>
<td>59-63-61</td>
<td>49-49-47</td>
<td>61-57-59</td>
</tr>
<tr>
<td>WM middle</td>
<td>62-62-60</td>
<td>47-41-40</td>
<td>58-57-56</td>
</tr>
<tr>
<td>WM root</td>
<td>59-57-53</td>
<td>35-33-30</td>
<td>56-55-52</td>
</tr>
<tr>
<td>HAZ right face</td>
<td>57-50-56</td>
<td>57-62-65</td>
<td>57-56-57</td>
</tr>
<tr>
<td>HAZ right middle</td>
<td>51-54-56</td>
<td>62-62-61</td>
<td>53-52-53</td>
</tr>
<tr>
<td>HAZ right root</td>
<td>50-55-54</td>
<td>59-57-59</td>
<td>53-53-52</td>
</tr>
<tr>
<td>BM right face</td>
<td>53-52-56</td>
<td>55-55-54</td>
<td>54-52-53</td>
</tr>
<tr>
<td>BM right middle</td>
<td>53-52-56</td>
<td>53-54-53</td>
<td>54-53-51</td>
</tr>
<tr>
<td>BM right root</td>
<td>52-52-56</td>
<td>52-54-55</td>
<td>54-52-52</td>
</tr>
</tbody>
</table>

Depending on the results obtained from the Ferritscope measurements, average WM ferrite content of approx. 59%, 41%, and 57% were obtained, respectively, for Weld 1, 2, and 3, which are close with the predicted ones by WRC-1992 diagram as mentioned above. In order to maintain the original chemical and physical properties of the as received duplex BM, the phase balance of the WM and the HAZ is critical [17]. WM shall fulfill a Ferrite Number (FN) requirement of FN = 30–70 (approx. 22–70%) in TIG weldments. With other processes and at locations exposed to the corrosive environment and/or possible hydrogen cracking, ferrite content of the WM of approx. 22–60% may be required [3], but usually 30–70% range is acceptable for practical applications [17, 18]. Measured ferrite content of WM values varied between 53 and 62% for Weld 1, between 30 and 47% for Weld 2, and from 52 to 61% for Weld 3 passed the requirements. If the average values of each nine ferrite content measurements for each position are calculated, a graph as illustrated in Fig. 6 can be plotted roughly describing the ferrite/austenite phase distribution of the weld cross-sections across the left side of BM and HAZ, WM, right side of the HAZ, and BM.

It is clearly shown that mainly in plasma welds, ferrite contents of the WMs are higher than the BM (almost 50%).

**Table 3.**—Ferrite content analysis of the welded joints (ferrite %).

**Figure 6.**—Ferrite austenite ratio of (a) Weld 1; (b) Weld 2; and (c) Weld 3.
see Fig. 6. This is because the WM of DSS solidifies primarily as delta ferrite. When it cools down, a partial transformation to austenite initiates at the ferrite grain boundaries and then continues intergranularly. As the weld cools faster, less austenite was formed in the plasma weld metals compared to 1.4462 base metal [17]. Combining the impact testing data at $-60^\circ\text{C}$, $-40^\circ\text{C}$, and $-20^\circ\text{C}$ from Fig. 1 and Table 3, Fig. 7 can be plotted to determine the ferrite content and impact toughness relationship for the related welds.

According to Figs. 6 and 7, it could basically be said that when the ferrite/austenite phase balance is protected after welding, such as close to 50:50, toughness data increases. When balance changes such as 35:65, low temperature toughness values of WM and HAZ decrease generally with regard to the BM. The ferrite/austenite ratio depends on the energy input in welding, since it controls the cooling rate and ferrite/austenite transformation. Cooling time has strong effects on the toughness that the ferrite content and microhardness decreases with the increasing of cooling time. On the other hand, such conditions also tend to produce coarse-grained weld deposits and possibly precipitation of brittle intermetallic phases. Then it is desirable to control welding conditions such that cooling is slow enough for adequate austenite formation, but fast enough to prevent deleterious precipitation [4, 6, 12, 25, 26]. Dense austenitic structure at the root part of the WM of Weld 2, due to the nitrogen backing gas since it is a strong austenite forming power, had been observed at the microstructures, see Fig. 4(c). Nitrogen present in the backing gas may show some effect on the root run weld metal nitrogen content [3]. This is now also confirmed with the ferrite content measurements with the values between 30% and 35% ferrite at the root of TIG WM. The face WM part of the same joint contained approx. 48% ferrite, see Table 3. It is believed that this difference between the ferrite and austenite phases content so the change in the phase balance for the related joint has led WM impact toughness values to decrease compared to Weld 1 and Weld 3. Ferrite content depends on the chemical composition of WM and the cooling rates of the weld which are related to the heat input during welding [18]. The heat input varied in the range 3.5–4.1 kJ/mm thereby exceeding the upper limit of 3.45 kJ/mm recommended in Weld 2 by the steel producer [22]. It would be interesting to compare microstructures and properties of the joints. The increase in heat input and the number of weld beads in Weld 2 may have led impact toughness values to decrease with regard to Weld 1 and Weld 3. In accordance with the recommendation by Karlsson and Tolling [12], it could be said that to decrease the number of weld runs, thereby reducing the number of thermal cycles heating the material to a critical temperature range, could have additional benefical effect on impact toughness and reducing the risk of undesired intermetallics [12]. The EDX analysis was carried to in order to determine the concentrations of Cr, Ni, and Mo (wt%) at the positions of WM face, WM root, HAZ face, HAZ root, and BM for Weld 2, see Table 4 and Fig. 8.

There is an increase of Cr concentration with regard to the BM can be observed due to the filler metal. The Mo content remained almost constant for both phases. Hardness measurements carried out at a depth of 1.5 mm from the surface of both face and root parts and with a distance of 0.5 mm between each indentation over the weld cross-sections are illustrated in Fig. 9.

For Weld 1, WM hardness was between 275HV1 and 300HV1. Maximum hardness of 315HV1 was measured at the HAZ while the minimum was 280HV1. For Weld 2, maximum HAZ hardness value was 300HV1. For Weld 3, in addition to face and root, a line hardness

![Figure 7](image-url)

**Figure 7.**—Toughness and ferrite content relation graphs (a) Weld 1; (b) Weld 2; and (c) Weld 3.

<table>
<thead>
<tr>
<th>Weld region</th>
<th>wt% Cr</th>
<th>wt% Ni</th>
<th>wt% Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal face</td>
<td>24.5</td>
<td>7.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Weld metal root</td>
<td>23.2</td>
<td>8.8</td>
<td>3.4</td>
</tr>
<tr>
<td>HAZ face</td>
<td>24.8</td>
<td>5.1</td>
<td>3.6</td>
</tr>
<tr>
<td>HAZ root</td>
<td>24.5</td>
<td>5.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Base metal</td>
<td>22.5</td>
<td>5.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Table 4.**—Results of wt% content of Cr, Ni, and Mo on Weld 2 obtained by EDX analysis.
analysis was done also for the mid-thickness position. HAZ values ranging from 270HV1 to 300HV1 and WM values between 290HV1 to 320HV1 were measured. Some increased root region hardness for almost all welds can be observed (see Fig. 9), usually due to work hardening caused by deformation induced by shrinkage similar to the literature [11].

Conclusions

The following conclusions concerning the plasma arc, TIG, and plasma arc + TIG welding of DSS study have been drawn:

1. Defect-free joining of 6.8 mm thick 1.4462 stainless steel is possible by PAW, TIG, and plasma + TIG welding without filler metal for plasma weld and with filler metal for TIG and for TIG cap pass of plasma + TIG weld.
2. The impact test results showed that all welds have exhibited good toughness properties at low temperatures such as down to $-60^\circ\text{C}$, which is very encouraging.
3. Ferrite content measurements and EDX analysis to determine the compositional variations between phases at WM revealed that the ferrite content varied in an acceptable range depending on the heat input which affects the microstructure and so the toughness properties. If good toughness properties are desired, then the phase balance should be controlled by means of the heat input range carefully.
4. Hardness at the HAZs, for all types of welds studied here, can be limited to 315HV1.
5. As the improved weldability of duplex stainless steels with controlled heat input range and acceptable ferrite/austenite balance has been demonstrated leading to higher welding speeds and productivity in welding, plasma and/or plasma + TIG welding applications for industrial fields, which are considered as immature processes for duplex grades, will be extended largely in the near future.

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