Research Article

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Mechanical and micro-structural studies of pulsed and constant current TIG weldments of super duplex stainless steels and Austenitic stainless steels

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Abstract: In the present research work, the influence of heat input rates on microstructures, hot tensile properties, and weld surface hardness number of Super Duplex Stainless Steel 2507 super duplex steels and austenitic steels 316L plates were investigated. Pulsed current and constant current modes were used in Tungsten Inert Gas (TIG) welding to join the dissimilar metals using ER2205 as filler. Microstructural studies were revealed at different zones of pulsed and constant current TIG weldments using optical microscopy. The tensile test was conducted at two different temperature conditions (i.e., 27 and 350°C) to investigate the strength of dissimilar weldments. Hardness measurements were made on the weld surface along the transverse direction using Vicker’s hardness tester. The microstructures revealed the formation of inter-granular austenite at the fusion zone with grain boundaries with austenite structures. Due to the constant heat input, a significant microstructural development with high austenite fractions was observed in constant current (CC)-TIG weldment. In comparison to CC-TIG weldments (UTS at 27°C = 600 MPa UTS at 350°C = 456 MPa), higher tensile characteristics were noted in Pulsed Current (PC)-TIG weldments (UTS at 27°C = 695 MPa UTS at 350°C = 475 MPa). The UTS of PC-TIG weldment is improved by 15.8% when compared to CC-TIG weldment due to the controlled heat input rates. PC-TIG weldments exhibited improved hardness numbers in various zones with smaller HAZ widths than CC-TIG weldments.

Keywords: super duplex steels, austenitic steels, PC-TIG, CC-TIG, microstructural studies, hot tensile properties, micro-hardness

1 Introduction

Duplex stainless steels (DSS) are often used in the chemical, petrochemical, nuclear, and marine industries because they have good mechanical and corrosion resistance characteristics when compared to conventional austenitic stainless steels [1–3]. This is mainly due to their two-phase microstructures; i.e., a combination of ferrite (α) and austenite (γ) [4–6]. However, the conventional DSS possess a higher amount of nickel (~6%), and molybdenum (~3%) limits their use in commercial applications from the perspective of cost and import constraints [6–9]. Lean duplex stainless steel with very low alloying content stands to be a better alternative, as compared to conventional DSS [9–12]. This variety of DSS is popularly used in the oil and gas industry, desalination plants, paper and pulp industry, and chemical transport pressure vessels where mechanical and corrosion properties are of primary importance [13–15]. Fusion welding processes can be used for joining almost all
varieties of duplex steels. However, the core shall be exercised to have the requisite balance between the two phases (austenite and ferrite) in the weld zone; otherwise, mechanical and corrosion properties of the weld metal will be affected as compared to base metal (BM) [16–18]. The phase balance in the weld zone depends on the welding parameters and heat input employed during DSS welding. There are other steel varieties that outperform DSS in a single area, but DSS frequently exhibits exceptional combinations of the aforementioned qualities [18–20].

Among the different grades of Super Duplex Stainless Steel (SDSS), S32750 is widely popular in the manufacturing of high-pressure vessels. The SDSS S32750, with alloying content of 25% chromium, 7% Ni, 3–5% molybdenum, 1.2% manganese, and 0.24% nitrogen [11]. The alloy elements of the SDSS 2507 promote the formation of austenite both in the weld zone and in heat affected zone [12]. It possesses an excellent blend of mechanical strength, toughness, and weldability, making it appropriate for a wide range of uses, especially in media containing chloride [13]. This SDSS grade has low Ni content which can reduce the cost and stabilize the austenite fraction in microstructure. Ni content is balanced with the addition of 0.24% nitrogen and 1.2% manganese to maintain a good microstructure with the balanced phase ratio of ferrite and austenite [14].

In the manufacturing industry, welding is an essential process, which joins the BMs that ensures the functional requirements of the weld joint are as close as possible to that of the base material by maintaining the good mechanical strength and the corrosion resistance of the welded joint at the same level as the parent material [15–18]. Various methods have been employed to fuse disparate materials together, with welding procedures being appropriate for super duplex stainless steels. Because of its high quality and stability, gas tungsten arc welding is the most popular technique among these. Applying heat sources, which are characterized as energy inputs in tungsten inert gas (TIG) welding, and researching them is crucial to understanding the welding process [19,20]. Prakash et al. [21] investigated on change of microstructural and mechanical properties with variation in laser welding parameters of Thyssen Niro-Ostā 4462 duplex stainless steel. They reported a steep reduction in mechanical properties of laser welds with increasing welding speeds, which was correlated to a change in ferrite to austenite ratio caused by weld cooling rate variations. Faster cooling rates result in a higher amount of ferrite and slower cooling rates promote austenite formation in the weld zone. Similarly, lower heat input may increase ferrite percentage in the weld zone, due to the precipitation of chromium nitride phases (CrN and Cr2N) [22,23]. The welding strength, less heat-affected zones with proper weld head formation, microstructural homogeneity, and micro-segregation effects can be seen when the PC-TIG welding technique is employed [24,25]. Also, the grain formation with equi-axis cellular structures can be seen in pulse arc mode as compared to constant arc mode which results in improved surface hardness and impact strength [26]. For better performance of a certain duplex stainless steel, a particular ratio of ferrite versus austenite is recommended, which is significantly affected by the welding heat input range. Therefore, the choice of a suitable welding process controls the welding heat input, and the resulting cooling rates are always important [27,28].

It is evident from the aforementioned literature survey, the type of welding process employed, prevailing welding conditions, and cooling rates play a vital role which considerably affects the weld microstructures, mechanical properties, and corrosion resistance. The pulse frequency plays a significant role in improving the welding quality characteristics, especially welding strength, segregation effect, and homogeneity in the weld structures [29,30]. In this research, the pulsed and constant arc modes are used in the TIG welding method to join the dissimilar metals of super duplex stainless steel (SDSS 2507) and austenitic steels 316L using ER2205 filler wire. An experimental investigation has been made to study the microstructural changes, tensile properties at high temperature and room temperature, and micro-hardness of PC-TIG and CC-TIG weldments. The tensile properties of both TIG weldments are evaluated at room temperature (27°C) and elevated temperature (350°C) using a Universal Testing Machine. Weld surface hardness number along the transverse direction is measured using Vicker’s hardness tester.

2 Materials and experimentation

The base materials, SDSS 2507 and Stainless Steel 316L, of dimensions $120 \times 60 \times 6$ mm, are used in the present research. The BMs were prepared as mentioned dimensions using a wire cut EDM process. The edge preparation was made in each BM with an included angle of 30°. ER2205 filler wire was used to join the dissimilar BMs using a TIG welding machine. The chemical composition of BM and electrode filler wire is represented in Table 1. The mechanical properties of BMs are listed in Table 2. The welding setup along with arc modes are shown in Figure 1. Prior to welding, a groove angle of 60° with a 2 mm root face was considered [31]. TIG welding (LINCOLN375) with direct current Straight polarity is used by maintaining pulse and constant arc modes during the joining process. Shielding
gas (argon) was kept flowing at a rate of 10 LPM during welding operations to shield the area around the weld area from damage [32]. The welding process parameters used in both pulse and constant arc modes are listed in Table 3. Root pass (first) followed by cap pass (second) was used to join the dissimilar metals in both welding arc modes. A
constant frequency of 4 Hz [33,34] was chosen for joining dissimilar welded joints in PC-TIG welding. During welding, the BMs were fixed using a fixture. The welded structures developed under pulse and continuous arc mode are shown in Figure 2.

### 2.1 Characterization

After welding, the welded samples were subjected to an X-radiography test to reveal the internal defects in both weldments. The welded samples were sliced into various welding coupons using Wire-EDM in order to reveal the macro/microstructures and mechanical properties as shown in Figure 3. For microstructural analysis, sample preparation was done according to ASTM E3-95 [35]. Samples were polished with the emery papers (180, 400, 600, 800, 1,200, 1,500) grit silicon carbide followed by alumina suspension. Lastly, diamond polishing was carried out to get a clean and shiny surface. Polished samples were etched with Kallings reagent for 20–30 s to get metallographic images under optical microscopy. For obtaining optical images, the BX51M-LED Olympus stream is basic with image analysis software and surface morphology of the sample. The metallographic analyses were made at the middle zone (3 mm from the weld root) for the interface and HAZ of both BMs. The weld zone micrographs were captured at the root pass and bead pass. The tensile test was performed as per ASTM E/8 standards [36] at different temperature conditions. Surface hardness was measured along the transverse directions using Vicker’s hardness tester. The hardness measurement was made at the middle zone (3 mm from the root) of weldment with a 200 gf load. The impression is made on the weld surface using diamond shape indentation at an interval of 0.5 mm.

### Table 3: Parameters used during welding

<table>
<thead>
<tr>
<th>Sample Id</th>
<th>Peak current [I_p] (A)</th>
<th>Background current [I_b] (A)</th>
<th>Frequency (Hz)</th>
<th>Voltage (V)</th>
<th>Argon gas rate (lpm)</th>
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<td>80</td>
<td>24–26</td>
<td>15</td>
</tr>
<tr>
<td>CC-TIG</td>
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<td>—</td>
<td>—</td>
<td>25–28</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2nd pass</td>
<td>140</td>
<td>—</td>
<td>25–28</td>
<td>15</td>
</tr>
</tbody>
</table>

![Figure 2: Dissimilar weldments of SS316L and SSDS2207 developed by (a) CC-TIG welding and (b) PC-TIG welding.](image-url)
3 Results and discussions

3.1 X-Ray radiography

The XRT test results were examined, and Figure 4 displays the welded X-ray films. The X-ray films plainly demonstrated that the dissimilar metals welded with both methods were free from weld cracks, flaws, voids, and porosity. The weldments developed by CC-TIG and PC-TIG welding techniques, the uniform distribution of filler wire toward base plate surfaces, and the complete bead structure were observed.

3.2 Macro/microstructural behavior

The macro/microstructures of dissimilar welded structures developed by pulse arc mode at 4 Hz pulse frequency of SDS2207 and AISI316L are shown in Figure 5. Uniform

Figure 3: (a) 3D welded model of test specimens, (b) tensile test specimen, and (c) microstructure/micro-hardness specimen.

Figure 4: X-Ray radiography films of dissimilar weldments: (a) CC-TIG and (b) PC-TIG welding.
filler distribution towards the BMs was observed as shown in Figure 5(a). It is also witnessed from the same figure that the weld penetration along the root gap and clear bead formation would be attributed to improving the welding strength. Figure 5(b) depicts the Interface of SSDS2207 BM and weld zone. The HAZ of SSDS2207 exhibits tiny grain structures with equi-axes grain development because of the lower 4 Hz pulse frequency employed during welding. A similar observation can be seen in other researcher’s work where the dissimilar BMs were joined using pulse arc mode [37,38]. The fusion zone of 1st- and 2nd-pass microstructures is shown in Figure 5(c) and (d), respectively. The austenitic phases with long dendritic structures can be observed in the bead pass, which would enhance the surface hardness number. Also, grain growth can be seen in the bead pass microstructure. Figure 5(e) depicts the Interface of AISI316L BM and weld zone. The austenitic phases and filler alloying elements can be seen at the interface with proper bonding. At the AISI 316L side’s HAZ, twin grains are visible, which would strengthen the welding. At the interface of both BMs, there is little to no micro-segregation of the alloying components of filler wire ER2207. The uniform weld bead formation with good penetration, clear grain structures with uniform distribution of filler alloying elements, and less segregation of alloying elements can be seen in dissimilar welded structures due to the proper heat input rates and pulse frequency at 4 Hz.

The macro/microstructures of dissimilar welded structures developed by continuous heat input (CC-TIG) of SSDS2207 and AISI316L are shown in Figure 6. In the root pass, the penetration depth and width were high due to the continuous heat input, which can be seen in Figure 6(a).
However, the uniform filler distribution toward the BMs can be in bead pass welding. Figure 6(b) depicts the Interface of SSDS2207 BM and weld zone. The longer dendritic structures with increased grain size can be observed at the HAZ of SSDS2207. The fusion zone of 1st-pass and 2nd-pass microstructures is shown in Figure 6(c) and (d), respectively. The observation of austenitic phases in the bead pass, characterized by lengthy dendritic structures and increased grain size filler alloying components, can aid in the creation of proper bead formation. Figure 6(e) depicts the Interface of AISI316L BM and weld zone. Super duplex filler is distributed more widely toward AISI316L than it is toward other BMs, increasing the HAZ width. The segregation of alloying elements from alloying elements are shown in Figure 6(d), which would affect the quality of the welded structure. Similar results can be seen in other researcher’s work where the dissimilar BMs were joined using pulse arc mode [39,40]. Due to the continuous heat input rates that prevent the fused metal from cooling quickly, dissimilar welded structures can be observed with uniform weld bead formation with larger penetration toward the BMs, coarse grain structures with improper filler alloying element distribution, and segregation of alloying elements towards the BM AISI 316L side [41–51].

Figure 6: Macro/microstructures of dissimilar weldments of SSDS 2207 and SS316L developed by CC-TIG welding.
3.3 Tensile properties at room and elevated temperatures

The tensile properties were evaluated at two different temperature conditions for pulsed and constant current dissimilar welded structures as per ASTM E/8 Standards. The tensile specimens before and fractured samples under hot temperature and room temperature conditions along with their tensile stress–strain graphs are shown in Figure 7. It is observed that the fracture under uniaxial loading at the HAZ of the AISI 316L side in all the welded structures. The YS and UTS values of welded structures are tabulated in Table 4. The UTS values of constant and pulsed current TIG weldments were observed as 456 and 475 MPa, respectively, at 350°C whereas UTS values of constant and pulsed current TIG weldments were observed as 600 and 695 MPa, respectively, at room temperature. The higher UTS values were observed in PC-TIG weldments at room temperature and elevated temperature than the CC-TIG weldments due to the controlled heat input rate and lower pulse frequency. Similar observations were observed when the dissimilar metals joined using the PC-TIG welding technique [10]. The UTS of PC-TIG weldments at 4 Hz pulse frequency is improved by 15.8 and 4.1% at room temperature (27°C) and elevated temperature (350°C) as compared to CC-TIG weldments. Also, higher YS values were observed in PC-TIG welded joints. The ratio of YS to UTS is observed to be 0.53 which is higher in PC-TIG welded samples at room temperature and elevated temperature than the CC-TIG welded samples at room temperature due to the proper fine grain structure formation and austenitic structures.

![Figure 7: Tensile test specimens along their stress–strain graphs at (a) room temperature and (b) hot temperature.](image-url)
3.4 Micro-hardness

The micro-hardness measurement was made on the weld surfaces developed by PC-TIG and CC-TIG welding techniques and their measurements were plotted shown in Figures 8 and 9. The average hardness number along with the width of PC-TIG and CC-TIG weldments is calculated at various zones and presented in Table 5. The hardness measurement was made at a distance of 3 mm from the root of the weld. The Vicker’s micro-hardness and width of PC-TIG weldment 271 HV and 3.24 mm at the HAZ of SSDS 2207, 235 HV and 7.05 mm at weld bead and 171 HV and 4.02 mm at the HAZ of SS316L was observed. The higher hardness is observed at the weld zone than the HAZ and BM of SS316L due to the higher dense alloying elements in the filler wire. The higher HAZ width is observed at the SS316L side than at the SSDS 2207 side due to the lower thermal conductivity rate [33]. The accumulation of heat energy at the SS316L side is more than the super duplex steel side which could be attributed to increased hardness number and lower HAZ. The Vicker’s micro-hardness and width of CC-TIG weldment 270 HV and 4.83 mm at the HAZ of SSDS 2207, 230 HV, and 7.28 mm at weld bead and 160 HV and 5.15 mm at the HAZ of SS316L were observed. The higher hardness number with lower HAZ width was observed on SSDS 2207 side than on the SS316L side similar to PC-TIG weldment. As compared to CC-TIG weldments, the improved hardness number at various zones with reduced HAZ width was observed in PC-TIG weldments which could be reasoned fine grain structures and lower micro-segregation effect at the interface of base the metals [32].

4 Conclusions

In this research article, the dissimilar metals of super duplex steels and austenitic steels were joined successfully using PC-TIG and CC-TIG welding methods employing ER2207 filler wire. The microstructural changes under pulse arc mode and continuous arc mode were studied at various zones of dissimilar welded structures. The welding strength at room temperature and elevated temperature is evaluated by a conducted tension test. Micro-hardness number is measured across the weldments along the transfer direction and reported the effect of pulse and continuous current welding techniques. The following conclusions were drawn from the above investigations:

- The welded structures developed with PC-TIG and CC-TIG welding techniques were free from internal defects such as voids, cracks, and under-cuts.
The uniform weld bead formation with larger penetration towards the BMs, coarse grain structures, and segregation of alloying elements towards the BM steel 316L side can be seen in CC-TIG weldments due to the continuous heat input rates. The austenitic phases with long dendritic structures could be observed at the weld zone due to the pulse frequency of 4 Hz employed in PC-TIG weldments. Also, the fine grain structures with equi-axes grain growth can be seen at the HAZ of the SS316L side.

The UTS of CC-TIG weldments is observed as 600 and 456 MPa at room temperature and elevated temperature, respectively, whereas the UTS of PC-TIG weldments is

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**Figure 8:** Micro-hardness and HAZ width of dissimilar weldments of SSDS 2207 and SS316L developed by PC-TIG welding.

**Figure 9:** Micro-hardness and HAZ width of dissimilar weldments of SSDS 2207 and SS316L developed by CC-TIG welding.

**Table 5:** Average micro-hardness of PC-TIG and CC-TIG weldments

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>SSDS 2207 HAZ</th>
<th>SS316L HAZ</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Hardness (HV)</td>
<td>Width (mm)</td>
</tr>
<tr>
<td>PC-TIG</td>
<td>271</td>
<td>3.24</td>
</tr>
<tr>
<td>CC-TIG</td>
<td>271</td>
<td>4.83</td>
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</table>
observed as 695 and 475 MPa at room temperature and elevated temperature, respectively. The UTS of PC-TIG weldments is improved by 15.8 and 4.1% at room temperature and elevated temperature as compared to CC-TIG weldments.

• PC-TIG weldments showed better hardness numbers in different zones with lesser HAZ widths than CC-TIG weldments due to the fine grain structures with uniform distribution of alloying elements.

For improved mechanical properties and homogeneity structures throughout the weld area, pulse arc mode in TIG welding is proposed for joining super duplex steels and low and medium carbon steels.

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Ethical approval: The conducted research is not related to either human or animal use.

References


