RESEARCH ARTICLE

Effects of shielding gas pureness on quality of orbital TIG welded austenitic stainless steel joints

Jacek Górka, Bernard Wyględacz*, Marcin Żuk
Department of Welding Engineering, Silesian University of Technology, Gliwice, Poland

Abstract: The aim of this research was the determination of the effects of shielding and backing gas pureness on quality of welded joints produced from austenitic stainless steel grade X5CrNi18-10 (1.4301) pipes Ø 50.8 × 1.5 mm by orbital TIG welding without the use of additional material. In the case of stainless steel, it is of importance not only to prepare shielding of the molten metal pool but also as well the protection of welded joint root from oxygen, which causes the formation of colorful oxide layers. The presence of oxidized layer primarily decreases corrosion resistance of stainless steel. Performed examination included as follows: Chemical composition of welded joint material, delta ferrite testing, non-destructive joint testing, visual testing with discoloration assessment from face and root side (acc. to Danish Force Technology Institute report 93.34 and American ASME BPE-2012 norm), radiographic testing, and destructive welded joint testing. Metallurgical shielding of the welded joint face was produced with Argon 5.0 pure, with a flow rate of 8 dm$^3$/min. Root of welded joint was at first protected with Argon 5.0 pure, then argon-atmospheric air mixtures were used. Backing gas flow rate was set to achieve a relative pressure of 300 Pa. Quantity of residual oxygen in gas mixture was selected based on Danish Force Technology Institute report 93.34.

Keywords: X5CrNi8-10 stainless steel; Orbital TIG welding; Temper colors; Backing gas

1. Introduction

In the age of quickly developing global industry, there are many production technologies. Stricter requirements are placed on products. Considering the current need for high tempo of work and constantly rising quality levels to be met, manual labor is often replaced by mechanized and automated processes$^{[1-6]}$. This arises a need for new or upgraded methods of material joining by welding technologies. Fulfilling this need is connected to the development of new process in scope of material groups weldability, process schematics, as well as the development of safety equipment and procedures. An important aspect of stainless steel pipe welding is assurance of adequate gas shielding. In such a way, so detrimental effects of air, especially oxygen, causing among others formation of colorful oxide layers are minimized. Occurrence of colorful oxide residues on the surface of joined elements in considered welding defect and as such must be removed, so pipeline of which said that welded joint is a part conforms to exploitation needs. In case of stainless steel welding aside from molten metal pool shielding, equally important is protection from root side oxygenation. If it is not proper, colorful oxide layer appearance can result in reduced corrosion resistance. It is vital to assure that welding of stainless steel is carried in an atmosphere of shielding gases of high purity and protection from root side oxygenation is provided$^{[7-13]}$. Due to the roles of shielding function, shielding gas of the arc and gases to cover and form the root of the weld are distinguished. The shielding arc gases escape through the burner nozzle, protecting the tungsten electrode, the electric arc, and the pool of liquid metal against air. The gases covering and forming the root of the weld protect the liquid metal from oxidation with the effect of smoothing and evening produced ridge. Ridge protection is particularly important when welding with
full penetration and in the welding of metals (e.g., Ti, Zr, Ta, Mg, stainless steels, and Ni alloys) sensitive to gases at high temperatures, thus avoiding the oxidation\cite{14-19} Classification of temper colors was performed based on division contained in Danish Force Technology Institute report 93.34 (Figure 1) and American ASME BPE-2012 norm (Figure 2).

Division contained in Danish Force Technology Institute report 93.34 classifies following levels of temper colors in mechanically polished stainless steel pipes:

A. Temper colors invisible,
B. Gray scale,
C. Light yellow,
D. Bright yellow,
E. Light blue,
F. Dark blue through violet,
G. Brown and blue areas; dark gray weld metal,
H. Brown and blue areas, visibly thicker oxide layer.

**Figure 1.** Temper colors obtained by welding austenitic stainless steel in argon shielding, acc. to Danish Force Technology Institute report 93.34.

**Figure 2.** Temper colors obtained by welding austenitic stainless steel in argon shielding, acc. to ASME BPE-2012
According to the previously mentioned report, acceptable temper colors for typical austenitic stainless steel, resulting in no noticeable corrosion resistance decrease. They are contained on levels B-C, which corresponds to residual oxygen content in argon of about 20–30 ppm. According to American ASME BPE-2012 norm in case of welding mechanically polished austenitic stainless steel pipes, weld metal must not be discolored. An acceptable temper color of HAZ cannot exceed one presented in sample 3 (Figure 2). Choosing a method as well as optimal parameters and process conditions in concordance with material needs impacts final form of welded joint. Considering food and pharmaceutical industries, as well as many other, needs where to provide transport of varied media and products construction of stainless steel pipelines with joints conforming to highest quality standards is necessary. Due to chosen material and highest quality needs suitable method of joint production is a modification of classic TIG welding – it is an automated orbital TIG welding. Application of automated orbital TIG welding provides ability to control and correct parameters continuously during join formation, which is impossible to achieve during manual TIG welding. High method precision and ability to program and control process result in joints with high esthetic and very good mechanical properties[20-23]. The orbital TIG orbital welding method is designed both for connecting thin-walled and thick-walled pipes. For welding thin-walled tubes, it is usually enough to prepare the edges of the elements on “I,” and the weld is usually single layered with full penetration. However, before welding of thick-walled pipes, appropriate beveling of the edges is required, and the resulting weld consists of several layers[18-20]. During TIG orbital welding, the axes of the welded tubes are usually oriented vertically or horizontally. When the pipes are laid vertically, the welding takes place in a wall position (PC). In the case of a horizontally oriented joint, there are four welding positions: Low (PA), vertical upright (PF), upright down (PG), and ceiling (PE). Changing welding positions, in the second case, affect the variable welding conditions of the pipe joint around its entire circumference. Therefore, it is necessary to divide the joint into individual sectors, the amount of which will depend on the features of the materials to be joined, for example, the type of material, the dimensions of the pipes. The calculation of the number of sectors and specific process parameters for them is possible thanks to the use of TIG orbital welding machines for pipes equipped with control and programming systems[24-30].

2. Methods and Experimental

The aim of this article was the determination of shielding and backing gas cleanness impact on quality of welded austenitic steel. It was used X5CrNi18-10 (1.4301) steel pipe, with dimensions Ø 50.8 × 1.5 mm welded by orbital TIG technique with no additional filler material. Chemical composition and mechanical properties are presented in Tables 1 and 2. The material microstructure is presented in Figure 3.

Welded material was prepared for “I” joint and cleaned with acetone. Test joints were prepared according to the welding procedure instruction based on preliminary tests. Orbital TIG welding was performed on automated welding station ORBIMAT 165 CA (power source with integrated orbital controller) with enclosed orbital weld head ORBIWELD 76S both produced by Orbitalum, Figure 4. Oxygen content in backing gas was measured by residual oxygen meter ORBmax also produced by Orbitalum. Welding head was fixed in such way so horizontal pipe placement during welding was achieved, Figure 5. As a shielding gas Ar 5.0 pure was used, which flow rate was set to 8 l/min. The inner side of pipes was protected by Ar 5.0 pure at first; then, it was substituted with Ar-atmospheric air mixes. Backing gas was supplied by line terminated with diffuser. To provide shielding atmosphere inside the pipes, one of the sides was blocked with sealed baffle and another side was sealed with welding tape in which small holes were pierced to provide means of gas evacuation. The pressure inside welded pipes was measured form tape sealed side. Gauge pressure was measured and backing gas flow was adjusted in such a way so relative pressure would achieve 300 Pa.

Air content regulation in Ar-air mixes was performed with a set of precise pneumatic valves; oxygen content in mixes was controlled with the use of residual oxygen meter ORBmax. Oxygen content in gas mixes for samples was based on Danish Force Technology Institute report 94.34, Table 3.

Chemical composition examinations of X5CrNi18-10 steel were performed by BRUKER S1 TITAN X-ray spectrometer. Delta ferrite content determination was performed with FISCHER FMP30 Ferritometer. Examinations were performed on joint circumference for each joint from face side and in parent material, Figure 6. To classify welding...
imperfections and perform quality assessment, visual testing acc. to PN-EN ISO 6520-1, ASME BPE-2012 standards, as well as Danish Force Technology Institute report 94.34 was carried. Welded joints were sectioned along a plane along pipe axis, to enable root side observation. For the detection of potential inner defects in welded joints, radiographic examinations with ICM SITEX CP200D lamp were performed. Sample exposures were performed with the use of elliptical exposure which is used for X-ray imaging of circumferential joints and create double wall radiograph. For each joint, two exposures were made, with 90° of rotation between them. Welded joints were also subjected to static tensile testing and

**Table 1.** Chemical composition of examined steel acc. PN-EN 10088-1 standard.

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Chemical composition, wg. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Number</td>
</tr>
<tr>
<td>X5CrNi18-10</td>
<td>1.4301</td>
</tr>
</tbody>
</table>

**Table 2.** Mechanical properties of 1.4301 steel acc. PN-EN 10217-7 standard.

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Number</td>
</tr>
<tr>
<td>X5CrNi18-10</td>
<td>1.4301</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
bend testing. Tests were performed on universal testing machine R20 with 4 kN load. Tensile testing was performed acc. to PN-EN ISO 6892–1:2010 norm performed in temperature of 22 ± 3°C and with elongation rate of 0.0067 s\(^{-1}\). Bend tests, consisting of root side (RBB) and face side (FBB) bends, were carried in accordance to PN-EN ISO 5173:2010 standard. The former diameter of 10 mm was used (two samples were made for each joint) and test temperature was 22 ± 3°C. Hardness tests were performed in accordance to PN-EN ISO 9015-1 norm on one measurement line through joint cross-section. Hardness tests by Vickers method HV1 were made on Wolpert Wilson Micro-Vickers 401MVD. Macroscopic cross-section examination was performed on stereoscopic microscope Olympus SZX9, examined joints were etched with Adler reagent. Microscopic examinations were performed on Nikon Eclipse light microscope. Joints microstructure was revealed using aqua regia.

3. Results and Discussion

Approximate additives weight content in X5CrNi18-10 steel parent material was as follows: 17.5% chromium, 8.4% nickel, 1.5% manganese, 0.2% cobalt, 0.5% copper, and 0.03% titanium. Results of delta ferrite tests are presented in Tables 4 and 5. Root side views of welded joints are presented in Table 6. Sample radiographs can be shown in Figures 7 and 8.

Results of mechanical examinations are shown in Figures 9 and 10. The bend test allowed to reach the 180° angle without tears and scratches. Results of hardness measurements are shown in Figure 11. Macroscopic cross-sections are visible in Table 7. Microstructures of welded join are visible in Figure 12.
Delta ferrite examinations show that parent material is characterized by ferrite number of circa 0.73; however, after orbital TIG welding, delta ferrite content in joints was between 6.87 FN and 7.47 FN. Achieved results are, however, contained in acceptable range of 3–15 FN (acc. to PN-EN 1011-3). This delta ferrite content is enough to reduce hot cracking susceptibility and not too high, to reduce: Hardness, plasticity, and corrosion resistance. Visual tests have shown high linearity of welded joints. Moreover, joints were characterized by regular, uniformly scaled 5 mm wide face. On

<table>
<thead>
<tr>
<th>Joint number</th>
<th>Shielding gas</th>
<th>Backing gas</th>
<th>Quantity of residual oxygen in backing gas (ppm)</th>
<th>Gas pressure inside pipes (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Measured during welding</td>
<td>acc. to Force Technology Institute report 93.34</td>
</tr>
<tr>
<td>1</td>
<td>argon 5.0</td>
<td>argon 5.0</td>
<td>4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>2</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>4</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>7</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>900</td>
<td>1000</td>
</tr>
<tr>
<td>8</td>
<td>argon 5.0</td>
<td>argon 5.0 and air</td>
<td>9000</td>
<td>9000</td>
</tr>
</tbody>
</table>

Table 3. Shielding and backing gas used for welding experimental joints

Table 4. Results of delta ferrite determination in parent material (steel X5CrNi18-10)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Measurement point</th>
<th>Mean FN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.73</td>
</tr>
<tr>
<td>2</td>
<td>0.66</td>
<td>0.79</td>
</tr>
<tr>
<td>3</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>4</td>
<td>0.58</td>
<td>0.65</td>
</tr>
<tr>
<td>5</td>
<td>0.64</td>
<td>0.73</td>
</tr>
<tr>
<td>6</td>
<td>0.69</td>
<td>0.79</td>
</tr>
<tr>
<td>7</td>
<td>0.72</td>
<td>0.73</td>
</tr>
<tr>
<td>8</td>
<td>0.66</td>
<td>0.71</td>
</tr>
</tbody>
</table>

FN: Ferrite number

Table 5. Results of delta ferrite determination in steel X5CrNi18-10 joints; measurements were performed from joint face side

<table>
<thead>
<tr>
<th>Joint</th>
<th>Residual O₂ content in backing gas</th>
<th>Measurement point</th>
<th>Mean FN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 ppm</td>
<td>7.5</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>25 ppm</td>
<td>7</td>
<td>7.8</td>
</tr>
<tr>
<td>3</td>
<td>55 ppm</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>4</td>
<td>90 ppm</td>
<td>7.4</td>
<td>6.9</td>
</tr>
<tr>
<td>5</td>
<td>180 ppm</td>
<td>7.5</td>
<td>7.4</td>
</tr>
<tr>
<td>6</td>
<td>500 ppm</td>
<td>7.7</td>
<td>6.6</td>
</tr>
<tr>
<td>7</td>
<td>900 ppm</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>8</td>
<td>9000 ppm</td>
<td>7.9</td>
<td>6.8</td>
</tr>
</tbody>
</table>

FN: Ferrite number

Delta ferrite examinations show that parent material is characterized by ferrite number of circa 0.73; however, after orbital TIG welding, delta ferrite content in joints was between 6.87 FN and 7.47 FN. Achieved results are, however, contained in acceptable range of 3–15 FN (acc. to PN-EN 1011-3). This delta ferrite content is enough to reduce hot cracking susceptibility and not too high, to reduce: Hardness, plasticity, and corrosion resistance. Visual tests have shown high linearity of welded joints. Moreover, joints were characterized by regular, uniformly scaled 5 mm wide face. On
the surface of HAZ from joint face side temper colors were visible (imperfection 610 acc. PN-EN ISO 6520-1 standard). Temper colors caused by chromium oxidation and resulting in reduced chromium content in material areas under oxide potentially reducing corrosion resistance. It is vital to acknowledge that liquid metal pool was shielded by Ar 5.0 pure, which measured 4 ppm of residual oxygen. No other surface imperfections on the face side of the joints were found. Welded joint root side observation has also shown colorful oxide layer presence on the inner joint surface. Color of oxide layer was varying depending on residual oxygen content in backing gas. Temper colors evolved from light yellow on the

**Figure 7.** Radiograph of joint 1 (4 ppm residual O$_2$ content in backing gas mix) and joint 2 (25 ppm residual O$_2$ content in backing gas mix); first exposure

**Figure 8.** Radiograph of joint 1 (4 ppm residual O$_2$ content in backing gas mix) and joint 2 (25 ppm residual O$_2$ content in backing gas mix); second exposure (rotated 90°)

**Figure 9.** Ultimate tensile strength of X5CrNi18-10 steel joints; O$_2$ content in backing gas: 1–4 ppm, 2–25 ppm, 3–55 ppm, 4–90 ppm, 5–180 ppm, 6–500 ppm, 7–900 ppm, 8–9000 ppm
root side of HAZ in joints 1 and 2, to blue-gray on both weld medal and HAZ in joints 6–9. Different colors of oxide layers indicate varying thickness of oxide layer, which was characterized by non-uniform chemical composition, as well as the presence of mechanical stress and defects in these layers. It can result in lowered corrosion resistance of welded joint. Depending on the area of welded construction, application imperfection 610 is acceptable or must be repaired by the removal of oxide layer (e.g., installations in food, chemical and pharmaceutical industries). However, joints, where oxide layers are unacceptable, must be fully removed and remade. Considering said criteria only joints 1 and 2 were acceptable

Figure 10. Elongation of X5CrNi18-10 steel joints; O₂ content in backing gas: 1–4 ppm, 2–25 ppm, 3–55 ppm, 4–90 ppm, 5–180 ppm, 6–500 ppm, 7–900 ppm, 8–9000 ppm

Figure 11. HV1 hardness measurements on X5CrNi18-10 steel joint cross-section

Figure 12. Microstructure of joint 4 (90 ppm O₂ in backing gas), etching: Aqua regia
because residual oxygen during welding in backing gas Ar was correspondingly 4 ppm for joint 1 and 25 ppm for joint 2 which is not enough to cause considerable oxidation. In all other joints, residual oxygen content in argon was exceeding 30 ppm. However, ASME BPE-2012 standard does not provide residual oxygen content in shielding gas during welding sample joints. It is possible to classify only joints 1 and 2 as acceptable considering this norm, as only in these two joints, both from face and root sides, only slight discolorations are visible in HAZ with no temper colors on weld metal. Based

**Table 6.** View of root side of steel X5CrNi18-10 joints

<table>
<thead>
<tr>
<th>Joint</th>
<th>Joint 1</th>
<th>Joint 2</th>
<th>Joint 3</th>
<th>Joint 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backing gas</td>
<td>Ar</td>
<td>Ar + air</td>
<td>Ar + air</td>
<td>Ar + air</td>
</tr>
<tr>
<td>Residual O₂</td>
<td>4 ppm</td>
<td>25 ppm</td>
<td>55 ppm</td>
<td>90 ppm</td>
</tr>
<tr>
<td>Joint</td>
<td>Joint 5</td>
<td>Joint 6</td>
<td>Joint 7</td>
<td>Joint 8</td>
</tr>
<tr>
<td>Backing gas</td>
<td>Ar + air</td>
<td>Ar + air</td>
<td>Ar + air</td>
<td>Ar + air</td>
</tr>
<tr>
<td>Residual O₂</td>
<td>180 ppm</td>
<td>500 ppm</td>
<td>900 ppm</td>
<td>9000 ppm</td>
</tr>
</tbody>
</table>

**Table 7.** Macrostructure of welded joints, etching: Adler

<table>
<thead>
<tr>
<th>Joint 1</th>
<th>Joint 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint 3</th>
<th>Joint 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint 5</th>
<th>Joint 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint 7</th>
<th>Joint 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
on the results of radiographic testing, welding imperfection 515 – root concavity in joint 4 and 7 was observed. Tensile testing resulted in UTS of joints being in the range of 500–700 MPa acc. to PN-EN 10217-7 norm (fracture in weld metal) and elongation A5 in the range of 25–36%. Increase of the residual oxygen content in backing gas did not have a significant impact on ultimate tensile strength of X5CrNi18-10 steel joints. Increase of the residual oxygen content in backing gas over 55 ppm resulted in noticeable decrease of the elongation of X5CrNi18-10 steel joints; however, the elongation of joints was still on an acceptable level. Bending testing was carried from face and root side revealed no cracks or other damages to joint after achieving bending angle of 180°. It shows high joint plasticity and lack of inner defect or structural components that can result in exploitation cracking. Macroscopic examinations revealed mean joint width, measured in the middle of joint thickness, in the range from 3 to 3.45 mm. With the increase of residual oxygen content in backing gas root width was increased. Microscopic examinations revealed the existence of twinned grains in parent material and HAZ, which is the result of plastic working pipes were subjected to during manufacturing. Weld metal was characterized by vermicular delta ferrite morphology. In the root area of weld metal, local increase in delta ferrite content was observed. Vickers hardness tests with load of 1 kgf have shown that joint part with the highest hardness was parent material (about 200 HV). Mean hardness of HAZ was around 186 HV and weld metal had mean hardness of about 189 HV. The hardness measurement values exhibit slight variation with change of the residual oxygen content in backing gas during welding. No trend is visible in the hardness values and the value is contained within an acceptable limit.

4. Conclusions

Conducted examinations of orbital TIG welding without additional material of X5CrNi18-10 steel pipes butt joints revealed that increase of residual oxygen content in backing gas results in a change of temper colors in HAZ area and can cause formation of oxide layer on weld metal in root area; however, no surface and inner defects of other sorts were observed. Delta ferrite content in test joints is contained in the range of 3–15 FN acc. to PN-EN 1011-3, which resulted in lack of hot cracks, as well as limited hardness and ductility decrease in joints. Welded joints fulfill requirements considering tensile strength of PN-EN 10217-7. Considering requirements of Danish Force Technology Institute report 93.34 and American ASME BPE-2012 applying to temper colors only joint 1 (residual O₂ content in backing gas – 4 ppm) and joint 2 (residual O₂ content in backing gas – 25 ppm) can be accepted for use after cleaning and passivation procedures.

References


