EFFECT OF ORBITAL AUTOMATIC WELDING ON THE WELD METAL MECHANICAL PROPERTIES IN API 5L X65 NATURAL GAS TRANSMISSION PIPE

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ABSTRACT

API 5L X65 steel pipes with a 17.5mm wall thickness and 762mm in outer diameter were welded using an orbital automatic welding process. Flux Cored Arc Welding (FCAW) and Gas Tungsten Arc Welding (GTAW) consumables were utilized to evaluate automatic the welding process. Manual welds were deposited using GTAW with ER70S-G filler metal for the root pass and Shielded Metal Arc Welding (SMAW) with low hydrogen E9016-G electrode for the remaining passes. Charpy impact test, CTOD (Crack Tip Opening Test) test and micro-hardness test on the weld metal were carried out and the effects of weld metal composition and microstructure on the weld metal toughness were investigated. The filler metals that have superior fracture toughness were E80T1-K2 and E71T-1 of FCAW process and ER80S-G of GTAW process. The filler metals that have proper hardness were E80T1-K2 and E71T-1 of FCAW process.

INTRODUCTION

Trunk lines consisting of API 5L X65 with a total length of approximately 1,482 km were constructed by Korea Gas Corporation (KOGAS) using manual welding process. Most of the pipes for natural gas transmission in Korea have been constructed by means of manual gas-tungsten-arc-welding (GTAW) for root pass and shielded-metal-arc-welding (SMAW) with low hydrogen electrodes for remaining passes. The use of low hydrogen covered electrodes helps reduce heat-affected zone cracking hydrogen induced cracking but it has poor productivity because it is used for uphill welding (Beeson, 1999).

Major natural gas company or pipeline owners have been aware of the potential advantage of an automatic process for girth welding in the field (Nelson, et al., 1961). An automatic welding system has been widely used in North America and Europe for onshore and offshore pipeline construction since 1970s (Wagner and Patchett, 1991). An automatic welding process has been used for construction of long-distance pipelines to overcome the shortage of skilled welders and to improve the quality of weld joint (Johnsen, 1999). The quality of welds deposited using an automatic welding process less depends on the welder’s ability. It is well known that an automatic welding process was superior to a manual welding process such as conventional stick electrode welding due to high deposition rate, fast welding speed and its easy handling. When large and heavy wall pipes are welded, construction cost can be reduced through adoption of an automatic welding process. The automatic welding processes are largely divided into GTAW and gas-metal-arc-welding (GMAW) processes. The GTAW process uses an inert gas such as argon to shield weld metal from atmosphere during welding and a solid wire of a size of 0.9–1.6 mm. Filler metals used in the GMAW process are classified into solid wire and flux cored wire.

The use of natural gas as a clean energy source is expected to further expand in Korea. To cope with this trend, KOGAS plans to transport large volumes of natural gas from the production site such as Irkutsk, Sakha and Yakutsk to the consuming site. The trunk line of a distance of 4,100 km from Irkutsk to Korea will be installed by the pipes with 56 inch (1,422 mm) in outer diameter (Tussing, 1998). An automatic welding process should be introduced to complete such a long-distance project within confined construction duration. It is necessary to compare the mechanical properties of the automatically and manually welded pipelines prior to implementing the automatic welding process for trunk line construction.
The GTAW and FCAW process were adopted to evaluate the mechanical properties of the weld metal of the API 5L X65 pipe by using the automatic welding process in this work.

EXPERIMENTAL PROCEDURES

The material used in this work was an API 5L X65 pipe for natural gas transmission. The API 5L X65 plates were made by thermo-mechanical control process (TMCP), which combines controlled rolling with on-line accelerated cooling. After hot rolling, the plates were immediately cooled by water rapidly through a temperature range from 780 to 580 °C with a cooling rate of 5–8 °C/sec., followed by air cooling to room temperature.

The welding was carried out on the API 5L X65 steel pipes with a 17.5 mm wall thickness and 762 mm in outer diameter. All weld joints were welded with a 25°C preheat, 60-degree single V-groove, 2–4 mm root gap and 0.8–2.4 mm root face preparation. The root and hot pass of weld joints used in this work were welded by manual GTAW process with 2.4 mm ER70S-G wire. The M-220 welding machine of CRC-EVANS Co. was employed for FCAW process with filler metal of E81T1-Ni, E80T1-K2 and E71T-1 of 1.2 mm diameter. Shielding gas was Argon with 25% CO₂. Manganese increased the proportion of acicular ferrite at the expense of grain boundary ferrite and thereby reduced the toughness of the weld metal. Previous investigators observed that optimum carbon content of commercial electrode is 0.03–0.095% to guard toughness of the weld metal (Evans, 1983). It seems that carbon level of a range of 0.055–0.076% in this work was not detrimental to Charpy toughness. Manganese content was measured as 1.35% in the base metal and 1.12–1.70% in the weld metals. Carbon that plays an important role in strength increment of steel is confined within a range of 0.05–0.1% to prevent brittle fracture and hydrogen-induced cracking in the weld metal. Previous investigators observed that optimum carbon content of commercial electrode is 0.03–0.095% to guard toughness of the weld metal (Evans, 1983). It seems that carbon level of a range of 0.055–0.076% in this work was not detrimental to Charpy toughness. Manganese content was measured as 1.35% in the base metal and 1.12–1.70% in the weld metals. Manganese level of FCAW process was higher than that of GTAW process. It is well known that strength of the base metal and weld metal is increased by addition of manganese acting as solid solution strengthening element (Pickering, 1977). Manganese increased the proportion of acicular ferrite at the expense of grain boundary ferrite in as-deposited region and decreased the grain size in fine-grained reheated region so that Charpy toughness of weld metal increased (Evans, 1980).

Silicon content was analyzed as 0.31% in the base metal. Silicon level was the highest as 0.98% in process A of FCAW and the lowest as 0.16% in process D of GTAW. Silicon has an influence on strength increment of the base metal by means of solid solution strengthening effect and plays a role of deoxidizer in the weld pool. When silicon content is over 0.5%, however, the toughness of the weld metal becomes poor. In general, optimum silicon content of commercial electrode is limited to 0.30–0.5% to guard toughness of the weld metal (Teledyne, 1972).

Sulphur and phosphorous in process A and E were higher than those in the other processes. These elements are detrimental to the welding crack and toughness by the diffusion and segregation into grain boundary during the solidification of weld pool.

The carbon equivalent on the base metal was found from calculation to be 0.325 according to the IIW equation, Ceq=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15 (Dearden and O’Neil, 1940). The carbon equivalent on the base metal of API 5L X65 is controlled under 0.43 in the KOGAS as a specification. The carbon equivalent of the weld metal was calculated to 0.270–0.492.

Silicon content in the weld metal was differently produced with variation of welding process and filler metals according to above chemical compositions results.

RESULTS AND DISCUSSION

Chemical Composition

The chemical compositions of the base metal and weld metals in weight percent were given in Table 2. As presented in the Table 2, carbon content was 0.084% in the base metal and 0.055–0.076% in the weld metals. Carbon levels of FCAW process showed lower than that of GTAW process. Carbon that plays an important role in strength increment of steel is confined within a range of 0.05–0.1% to prevent brittle fracture and hydrogen-induced cracking in the weld metal. Previous investigators observed that optimum carbon content of commercial electrode is 0.03–0.095% to guard toughness of the weld metal (Evans, 1983). It seems that carbon level of a range of 0.055–0.076% in this work was not detrimental to Charpy toughness. Manganese content was measured as 1.35% in the base metal and 1.12–1.70% in the weld metals. Manganese level of FCAW process was higher than that of GTAW process. It is well known that strength of the base metal and weld metal is increased by addition of manganese acting as solid solution strengthening element (Pickering, 1977). Manganese increased the proportion of acicular ferrite at the expense of grain boundary ferrite in as-deposited region and decreased the grain size in fine-grained reheated region so that Charpy toughness of weld metal increased (Evans, 1980).

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Microstructure Observation

The microstructures of the weld metal on the process A and C of FCAW, process E of GTAW and manual process F were shown in Fig. 1. Weld metal such defects as incomplete fusion, slag inclusions, inadequate penetration and cracks were not observed. There were no significant changes in the penetration depth and width of HAZ in the weld metals as variation of welding process. A width of HAZ was about 1~3mm.

The microstructures of the base metal and weld metals were presented in Fig. 2. The microstructure on the base metal of API 5L X65 consisted of fine grained ferrite and pearlite of a size of 10~15 μm. Banded structures by the rolling during the TMCP were not nearly examined in the base metal. The microstructures of the top bead of the process C were mainly comprised of fine acicular ferrite. It is well acknowledged that a microstructure possessing a high level fine acicular ferrite is beneficial to mechanical properties for low carbon and low alloy weld metal due to its very small grain size. The microstructures of the top bead in the process E largely consisted of fine acicular ferrite and martensite. The microstructure such as martensite is detrimental to toughness because this structure provided preferential easy crack propagation paths. The microstructures of the top bead in the process F exhibit a typical columnar solidification structure, which consisted of fine acicular ferrite and proeutectoid ferrite at the prior austenite grain boundary. The ferrite side plates which a feather-like appearance were partly formed at the prior austenite grain boundary.

Micro-hardness Test

The microstructure of the weld metal was varied as variation of the welding process and filler metal. The hardness measured on the specimens used in the microstructure examination and its result was indicated in Fig. 3.

The hardness was measured at the top bead of each weld metals. The hardness of process A showed a range of 300-377 Hv at the weld metal. High hardness of the process A was account for the formation of the martensite in the microstructure. One of the formation reasons of the martensite in the microstructure was related with silicon content in the weld metal. Silicon content of process A was analyzed to be 0.98% as shown in Table 2. It is generally known that high silicon content assists the formation of the martensite in the weld metal (Evans, 1986). It is usually recognized that silicon and manganese are known as solid solution strengthening element. Excessive content of silicon and manganese in the weld metal expedites the increment of hardness by the formation of martensite in the microstructure and can be anticipated the declination of the fracture toughness. Hardness in the process B presented an extent of 210~270 Hv. It indicated that the hardness of process B had a lower than that of process A. Low hardness value in process B is explained as the formation of the fine acicular ferrite in the microstructure, silicon content of 0.59% and manganese content of 1.27%. The hardness of process C with 190~220 Hv had a lower than that of process A and B because the filler metal used in the process C is E71T-1 with tensile strength of 70,000 psi (482 MPa).

The hardness distribution in the process D is a range of 240~290 Hv at the weld metal, 190~220 Hv at the HAZ and 190~210 Hv at the base metal. The hardness of the process E is a range of 240~280 Hv at the weld metal. The hardness of process F welded by means of manual SMAW with low hydrogen E9016-G electrode showed a range of 210~220 Hv at the weld metal.

The maximum hardness in the weld metal does not exceed 275 Hv in the BSI 4515. The Japan Shipbuilding Research Committee (SR193) reports that the maximum permissible hardness is confined to 248 Hv under condition of H2S environment. The Foothills Pipe Lines Ltd, which is one of the largest transporters of natural gas in Canada, specifies less than 350 Hv in the weld metal (Bryhan and Troyer, 1980).

The hardness in process B and C of FCAW and process F of SMAW was below the allowed maximum values according to above standard and specification.

Charpy V-notch Impact Test

The requirement of the impact toughness on the material is classified by used temperature. Charpy impact energy on the weld metal is specified to be 34 J as an average of three specimens with no specimen lower than 27 J in the BSI 4515. Charpy impact energy of the API 5L X65 pipe for natural gas transmission in the API 5L specifies average 68 J and minimum 27 J on the three specimens at 0 °C.

Charpy transition curves on the weld metal were presented in Fig. 4. The values of Charpy impact energy in the process A, B and C presented more than 34 J down to -40 °C. The impact energy of the process A showed the lowest value among the FCAW process. The impact behavior of process B is similar to that of process C but the impact energy of process B was higher than that of process C below -40 °C. The high impact energy in the process B and C is attributed to fine acicular ferrite in the microstructure. It is usually recognized that a high level fine acicular ferrite in the microstructure is beneficial to impact property due to its very small grain size. The values of Charpy impact energy in the process D and E presented above 34 J at 0 °C. The process D showed more than 34 J even at -60 °C whilst the process E showed low Charpy impact energy below 34 J at -20 °C. High Charpy toughness of the process D was due to fine acicular ferrite in the microstructure and low silicon content as 0.16% in the weld metal. The microstructures in the process E largely consisted of fine acicular ferrite and partly were composed of martensite. According to chemical compositions of Table 2, silicon content in the process E was analyzed to be 0.68%. As mentioned previously, high amounts of silicon above 0.5% in the weld metal are detrimental to Charpy toughness and act as...
martensite former in the microstructure. Charpy impact energy of process E showed a rather low value compared with the other processes by the combined effect above. The value of Charpy impact energy in the process F welded with low hydrogen E9016-G electrode presented as high as about 121 J at 0 °C and 66 J at -20 °C.

CTOD Test
Fracture toughness was evaluated through Crack Tip Opening Test (CTOD) at -20 °C. CTOD value and tensile properties were presented in Table 3. CTOD value of process D had the highest among the weld metals. CTOD value of process A had relatively poorer than that of other processes. Such a poor CTOD value in the process A was related with mechanical properties of weld metal. The weld metal of process A had much higher yield strength and hardness value compared with the other processes. CTOD value has reciprocal proportion relation with yield strength according to BSI 7448. CTOD values of all the processes except process A had revealed over 0.005 inch (0.127mm), which was minimum CTOD value required in API 1104 appendix A. As a whole, process B, C and D had high CTOD values like behavior of Charpy impact energy. High fracture toughness in process B, C and D is account for microstructure and chemical composition in the weld metal. In the weld metal of these processes, the microstructures mostly consisted of fine acicular ferrite and silicon content which is detrimental to fracture toughness was suitable to the range of 0.16–0.59%. On the other hand, process A and E possessed high silicon level to the range of 0.68–0.98%. It is necessary that silicon level should be controlled below 0.6% not to drop fracture toughness of weld metal.

CONCLUSIONS
Mechanical testing was performed on the API 5L X65 weld metal by GTAW and FCAW using automatic welding process and the manual process. The test results can be summarized as follows.

1. The microstructures of top bead in process A and E largely consisted of fine acicular ferrite and partly were composed of martensite, while the microstructures of the other processes consisted of fine acicular ferrite.
2. Charpy impact energy and CTOD revealed low values in process A and E while proper values in the other processes. The filler metals that have superior fracture toughness were E80T1-K2 and E71T-1 of FCAW process and ER80S-G of GTAW process. The filler metals that have proper hardness were E80T1-K2 and E71T-1 of FCAW process.
3. It was considered that the ranges of the alloying elements to improve Charpy impact energy and CTOD value in the weld metal were 0.05–0.09% in carbon, 1.1–1.3% in manganese and below 0.6% in silicon.

REFERENCES
Teledyne Incorporated, UK Patent No. 1 297 865, 1972
Table 1. Welding conditions used in this work.

<table>
<thead>
<tr>
<th>Condition Process</th>
<th>AWS</th>
<th>Diameter (mm)</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Welding speed (cm/min)</th>
<th>Heat input (kJ/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCAW Process A</td>
<td>E81T1-Ni1</td>
<td>1.2</td>
<td>24-26</td>
<td>150-230</td>
<td>20</td>
<td>10.8-17.9</td>
</tr>
<tr>
<td>Process B</td>
<td>E80T1-K2</td>
<td>1.2</td>
<td>24-26</td>
<td>140-220</td>
<td>20</td>
<td>10.1-17.2</td>
</tr>
<tr>
<td>Process C</td>
<td>E71T-1</td>
<td>1.2</td>
<td>24-26</td>
<td>200-260</td>
<td>20</td>
<td>14.4-20.3</td>
</tr>
<tr>
<td>GTAW Process D</td>
<td>ER80S-G</td>
<td>1.2</td>
<td>11-19</td>
<td>160-270</td>
<td>7.2</td>
<td>14.7-42.7</td>
</tr>
<tr>
<td>Process E</td>
<td>ER80S-Ni1</td>
<td>1.2</td>
<td>11-19</td>
<td>190-270</td>
<td>7.2</td>
<td>17.4-42.8</td>
</tr>
<tr>
<td>Manual Process F</td>
<td>ER70S-G</td>
<td>2.4</td>
<td>3.2-4.0</td>
<td>80-130</td>
<td>6-20</td>
<td>3.0-30.0</td>
</tr>
</tbody>
</table>

Table 2. Chemical compositions on the weld metals and API 5L X65 and their carbon equivalent (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>P</th>
<th>Mn</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cu</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Fe</th>
<th>Ceq</th>
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<tbody>
<tr>
<td>Process A</td>
<td>0.066</td>
<td>0.016</td>
<td>1.70</td>
<td>0.011</td>
<td>0.98</td>
<td>1.38</td>
<td>0.04</td>
<td>0.04</td>
<td>0.180</td>
<td>0.02</td>
<td>Bal.</td>
<td>0.492</td>
</tr>
<tr>
<td>Process B</td>
<td>0.055</td>
<td>0.014</td>
<td>1.27</td>
<td>0.008</td>
<td>0.59</td>
<td>1.16</td>
<td>0.02</td>
<td>0.03</td>
<td>0.003</td>
<td>0.01</td>
<td>Bal.</td>
<td>0.354</td>
</tr>
<tr>
<td>Process C</td>
<td>0.069</td>
<td>0.013</td>
<td>1.34</td>
<td>0.008</td>
<td>0.49</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.004</td>
<td>0.03</td>
<td>Bal.</td>
<td>0.310</td>
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<tr>
<td>Process D</td>
<td>0.075</td>
<td>0.014</td>
<td>1.15</td>
<td>0.008</td>
<td>0.16</td>
<td>0.80</td>
<td>0.15</td>
<td>0.05</td>
<td>0.430</td>
<td>0.01</td>
<td>Bal.</td>
<td>0.428</td>
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<tr>
<td>Process E</td>
<td>0.076</td>
<td>0.016</td>
<td>1.12</td>
<td>0.012</td>
<td>0.68</td>
<td>0.96</td>
<td>0.19</td>
<td>0.02</td>
<td>0.250</td>
<td>0.01</td>
<td>Bal.</td>
<td>0.399</td>
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<tr>
<td>Manual F</td>
<td>0.073</td>
<td>0.021</td>
<td>1.06</td>
<td>0.005</td>
<td>0.53</td>
<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
<td>0.003</td>
<td>0.016</td>
<td>Bal.</td>
<td>0.270</td>
</tr>
<tr>
<td>API 5L X65</td>
<td>0.084</td>
<td>0.020</td>
<td>1.35</td>
<td>0.001</td>
<td>0.31</td>
<td>0.02</td>
<td>0.02</td>
<td>0.002</td>
<td>0.04</td>
<td>Bal.</td>
<td>0.325</td>
<td></td>
</tr>
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</table>

Table 3. CTOD value and tensile properties and at -20°C.

<table>
<thead>
<tr>
<th>Process Properties</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTOD (mm)</td>
<td>0.026</td>
<td>0.12*</td>
<td>0.343</td>
<td>0.575</td>
<td>0.603</td>
<td>0.233</td>
</tr>
<tr>
<td></td>
<td>0.047</td>
<td>0.439</td>
<td>0.610</td>
<td>0.58*</td>
<td>0.523</td>
<td>0.276</td>
</tr>
<tr>
<td></td>
<td>0.278</td>
<td>0.564</td>
<td>1.051</td>
<td>0.73*</td>
<td>0.157</td>
<td>0.162</td>
</tr>
<tr>
<td>YS (MPa)</td>
<td>740.20</td>
<td>614.43</td>
<td>557.12</td>
<td>613.43</td>
<td>577.07</td>
<td>494.38</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>751.39</td>
<td>678.07</td>
<td>638.08</td>
<td>719.48</td>
<td>701.06</td>
<td>662.91</td>
</tr>
</tbody>
</table>

* : Average of three specimens.
Figure 1. Macrostructures of the automatic and manual welding process.
(a) Process A, (b) Process C, (c) Process E and (d) Process F.

Figure 2. Microstructures of the base metal and weld metals.
(a) API 5L X65, (b) Process C, (c) Process E and (d) Process F.
Figure 3. Hardness distribution on the weld metal by means of Vickers hardness tester.
(a) Hardness of process A, B and C and (b) Hardness of process D, E and F.

Figure 4. Distribution of Charpy impact energy on the weld metal.