2011

Development of a DC-LSND welding process for GMAW on DH-36 Steel

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Publication Details


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Keywords
steel, welding, 36, lsnd, dc, development, dh, gmaw, process

Disciplines
Engineering | Science and Technology Studies

Publication Details

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This conference paper is available at Research Online: http://ro.uow.edu.au/eispapers/580
DEVELOPMENT OF A DC-LSND WELDING PROCESS FOR GMAW ON DH-36 STEEL

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ABSTRACT

Weld induced distortion correction is a major cost within the shipbuilding industry. This paper investigates the use of an active cooling process known as Dynamically Controlled – Low Stress No Distortion (DC-LSND) Welding on DH-36 steel. Thermal profiles are obtained and distortion measurements are also achieved. Results show that the application of a localised cryogenic cooling source trailing the welding arc can significantly reduce weld induced distortion using the GMAW process. The effect of forced cooling on the weld microstructure is also observed.

KEYWORDS

DC-LSND, LSND, Weld Cooling, Active Cooling, Cryogenic, Distortion, Residual Stress, Welding

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INTRODUCTION

The development of higher strength steel has led a trend in shipbuilding of thinner plate being used in ship structure [1]. Thinner plate is used to minimise ship weight, reducing fabrication and fuel costs while improving performance [2, 3]. The ratio of steel less than 10mm in thickness used at Northrop Grumman Ship Systems rose to over 90% per vessel in the year 2000, and the trend continues [4]. More recently, plate thicknesses as low as 4mm of DH-36 and X80 grades have been used in warships around the world, including Australia and New Zealand [5]. However, the thinner the material used, the more subjective it is to weld induced distortion.

Distortion is a problem as it can reduce the quality of the end product, either mechanically or aesthetically, and increase assembly costs [1]. It is estimated that 30% of the cost of building a ship is directly related to labour required to repair these effects of weld distortion [6].

Current distortion control methods are looking to move away from the conventional post weld correction methods such as line heating, to ‘active’ in process methods [7]. It is well known that by altering the thermal history of a weld, residual stress and distortion can be altered [8]. One such method, Dynamically Controlled Low Stress No Distortion (DC-LSND) [9] has been researched for the aerospace industry [10, 11]. The DC-LSND welding process utilises a cooling source following the welding arc to locally cool the weld, reducing stress and distortion. More recent work in this area [2] sees the use of a cryogen, CO₂ snow, as the cooling source, achieving distortion free plates of 1.5-2.5mm stainless steel. Much of the research work in this area has been aimed at numerical modelling, or developing equipment only to a proof of concept stage. No fully implemented DC-LSND system using cryogenics has been found to be in use in industry to date. Similar work on 6mm AH-36 steel using a Transient Thermal Tensioning (TTT) LSND process, where heating is used alongside the weld arc, showed a reduction in deformation [8].

In these experiments DH-36 is welded using the DC-LSND method in a gas metal arc welding (GMAW) process comparable to that found in industry. The inclusion of a weld bead in trials has not been widely seen in literature, it will be addressed here.

EXPERIMENTAL PROCEDURE

The purpose of these experiments was to evaluate and develop the distortion control capability of a DC-LSND process when applied to DH-36, common shipbuilding grade steel. The work involved laying weld beads with and without the distortion control process applied and observing the resulting plate deformation.

A GMAW process was used to lay 700mm long weld beads centrally on the samples of DH-36 grade steel cut to dimensions of 900mm x 65mm x 4.5mm. A Fronius ‘TwinTime’ T-GMAW system
was used throughout in single arc mode utilising the leading wire in pulsed transfer mode. The filler wire was 1.2mm ER70S-6. Travel and wire feed speed were varied to according to Table 1 that yielded a constant calculated heat input of approximately 0.4 kJ/mm. Weld travel was provided using an ABB IRB-4400 articulated industrial robot. Samples were clamped down at each end to prevent movement in the vertical direction during welding.

Cooling was achieved by delivering stored compressed liquid CO₂ through CO₂ snow generating nozzles manufactured by Linde. The rapid depressurisation of the liquid CO₂ causes a drop in pressure and hence temperature of the CO₂ resulting in a fluidised solid/gas CO₂ mixture. The solid portion of the mixture is sublimated upon contacting the weld sample, removing heat from the local area. A proprietary nozzle is used to obtain a stable CO₂ flow and corresponding constant heat transfer capability between tests. Two different nozzles in the Linde LINSPRAY® CO₂ cooling range were trialled, TSF 20, delivering 215g/min, and TSF 30, delivering 440g/min according to manufacturer’s specifications [X-add reference]. Nozzles are used in pairs and mounted to the side of the welding torch, as seen in Figure 2b. This allows a nozzle angle of 60° with respect to the sample, angled away from the welding arc to help minimise arc disruption caused by the turbulent CO₂ flow.

A review of current literature highlights that a shielding device is required between the cooling source and welding arc to maintain arc stability [2, 12, 13]. Initial experiments conducted as part of this research confirmed the shielding problem and as such, a shielding device was developed to protect the arc and molten weld pool from the turbulent cooling source. The application of the cryogen on the weld bead trailed the welding arc by 80mm as not to upset the molten weld pool and to allow sufficient room for the shielding device. A Contact Tip to Work Distance (CTWD) of 30mm was also used to facilitate the installation of the shielding device.

Figure 1 shows the geometry of the welded samples. The 700mm weld bead was placed in the centre of the 900mm long sample. A section 80mm long at the end of each weld was not cooled during the distortion control tests due to the displacement between the cooling nozzle and the weld arc.

![Figure 1: Plan view of sample showing dimensions and cooling locations.](image-url)
For the measurement of deformation, each sample was scanned using a Micro-Epsilon displacement sensor driven by an industrial robot in the longitudinal direction. The entire process was automated to ensure repeatability with a total of 10 samples being welded and scanned.

<table>
<thead>
<tr>
<th>Weld Sample</th>
<th>Weld Speed (mm/min)</th>
<th>Wire Feed (m/min)</th>
<th>CO2 Cooling (g/min)</th>
<th>Welding Voltage (V)</th>
<th>Welding Current (amps)</th>
<th>Heat Input (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>3</td>
<td>0</td>
<td>20.1</td>
<td>72</td>
<td>0.41</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>6</td>
<td>0</td>
<td>24.8</td>
<td>131</td>
<td>0.42</td>
</tr>
<tr>
<td>3</td>
<td>900</td>
<td>9</td>
<td>0</td>
<td>25.8</td>
<td>210</td>
<td>0.41</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>3</td>
<td>430</td>
<td>20.4</td>
<td>72</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>450</td>
<td>4.5</td>
<td>430</td>
<td>22.2</td>
<td>101</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>6</td>
<td>430</td>
<td>24.9</td>
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<tr>
<td>7</td>
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<td>9</td>
<td>880</td>
<td>25.7</td>
<td>211</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Note: Average welding voltage, current, and heat input is shown. Heat input is calculated using the instantaneous current and voltage readings of the pulsed waveform and differ from a calculation using the average voltage and current.

**TEMPERATURE PROFILES**

To understand the effect of cooling, temperature profiles were generated using type-k thermocouples spot welded to the underside of 4mm thick DH-36 plate. Data from the thermocouples was read using LabVIEW. Distance of the thermocouples from the weld centreline can be noted in Figure 3(a-b). The differences in peak temperatures can be attributed to slight misalignment of the thermocouples to the weld centreline. The weld/cooling source travel speed...
was 600mm/min for each of the temperature profiles and the smaller TSF 20 cooling nozzles were used.

The effect of the cooling source can be easily seen in the temperature profiles. After climbing to peak temperature the weld cools naturally before being subjected to a secondary forced cooling period 8 seconds after the initial welding arc. This forced cooling effect is clearly depicted in Figure 3(c-d) by a sharp increase in the cooling rate at about 15 seconds. Others [2, 10, 14] have discussed that the key feature of the DC-LSND process is the existence of a temperature valley just behind the welding heat source. This is characterised by a drop in the temperature at the weld centreline to values below the temperature of the parent metal either side, subjecting the weld to heating-cooling-heating-cooling cycle. The aforementioned reheating cycle is not apparent in the thermal profile obtained (Figure 3(b)), possibly due to the thermocouple measurements being taken on the underside of the 4mm sample.

![Temperature plots for 4mm DH-36 welded at 600mm/min. (a) Conventional GMAW, measurements taken from weld centreline. (b) DC-LSND welded sample. (c) Comparison of temperatures at weld centreline. (d) Comparison of heating rates.](image-url)
DISTORTION RESULTS

Figure 4: Photo of difference in weld deformation. Samples welded at 600mm/min, conventional welded sample on left with DC-LSND welded sample on right, cooled using TSF 20 nozzles.

The effect of the DC-LSND process on the weld deformation observed is shown in Figure 4. In all tested cases, the CO$_2$ cooled plates resulted in less deformation than the plates subjected to the conventional GMAW process only. As there was limited adjustment in the welding/cooling device, travel speed was varied for an equivalent heat input. This has the effect of modifying the resultant heat sink per unit length, and the time between application of heating and cooling sources. The measured resultant longitudinal plate deformation can be seen in Figure 5(a-c).

Figure 5: Measured longitudinal plate deformation for (a) conventional welds, (b) welds cooled with 430g/min of CO$_2$, (c) welds cooled with 880g/min CO$_2$. 
Using the measured deformation, the plate angle in degrees was calculated along with the distortion in degrees/metre. The angle and distortion calculations were made over a 100mm distance (±50mm from sample point) to minimise the effect of noise amplification due to differentiation. Figure 6 shows a comparison of samples welded at 600mm/min. Note the increase in distortion at the ends of the weld. This was attributed to cooling not being applied to the last 80mm of each weld (Figure 8(b)). As the ends of the welds were uncooled, increasing distortion at that point, the central 300mm of plate was analysed for the distortion results shown in Figure 7.

Figure 6: Comparison of samples welded at 600mm/min showing (a) absolute deformation, (b) plate angle, and (c) plate distortion.

Average distortion was compared for all experiments (Figure 7). The central 300mm of plate shows a significant difference between the conventional GMAW process to the LSND process. 7.84º/m of distortion was measured in the plate without DC-LSND applied, compared to 1.46º/m and 2.39º/m in the plates with the LSND process applied. An 81% and 70% reduction in distortion respectively.
Due to the limited sample size it is difficult to draw trends, however for this nozzle geometry and heat input, a weld speed of 600mm/min appears to be optimal. Increasing travel speed has the effect of reducing cooling input per unit length, whilst decreasing travel speed allows the weld time to cool sufficiently such that the DC-LSND process is less effective.

![Figure 7: Distortion comparison of all experiments.](image)

**WELD APPEARANCE**

The main issue observed during these experiments was arc instability when the cooling nozzles were active. The final CO₂ cooled welds in all cases contained a small amount of porosity as shown in Figure 8a. This can be attributed to the suboptimal shielding device performance. The shielding device has since been upgraded and porosity free welds are now achievable. Cooled welds showed minimal difference in bead geometry and fusion to conventional welds. It is evident the high velocity of the CO₂ snow delivered to the weld samples has a cleaning effect, visible in Figure 8(b).
**EFFECT OF THE DC-LSND PROCESS ON MICROSTRUCTURE**

The microstructure of the parent material is shown in *Figure 9*. It consisted of proeutectoid ferrite and lamellar pearlite with average hardness of 180 HV0.2.

The microstructure resulting from the DC-LSND process was similar to that of the conventional GMAW process for a travel speed of 600mm/min (Figure 11). They both consist of a grain boundary ferrite formed at prior austenite grain boundaries, plates of Widmanstätten ferrite and acicular ferrite. Weldments from the cooled sample also showed smaller prior austenite grains and the formation of coarse grain boundary ferrite was slightly reduced in favour of finer acicular ferrite.

The Coarse-grain area experienced substantial grain growth with the mixed mode microstructure consisting of various forms of ferrite (grain boundary ferrite, Widmanstätten ferrite, polygonal ferrite, and long ferritic laths) and bainite. The weldment subjected to the DC-LSND process also contained some martensite. Microstructure of the coarse-grain region of the weldment generated from conventional welding contained substantial volume fraction of acicular ferrite. Fine-grain region of both samples consisted mainly of polygonal and Widmanstätten ferrite and bainite. Microstructure of the weldment that experienced higher cooling rate contained less polygonal ferrite and higher volume fraction of Widmanstätten ferrite and bainite. Microstructure of the inter-critical region of the two weldments showed marginal differences consisting mainly of polygonal ferrite and bainite.

Although only subtle differences in microstructure were observed, a large difference in harness across the sample was measured between the conventional and LSND processes. This increases the risk of Hydrogen Assisted Cold Cracking (HACC) occurring, however it is expected that the LSND process will result in lower residual stresses minimising HACC risk.
Figure 9: Parent material microstructure. Micronbar is 20μm.

Figure 10: Hardness profile of conventional and DC-LSND welded samples.
Figure 11: Microstructure of welded samples. Conventional GMAW showing (a) weld metal, (b) course grain region, (c) fine grain region, (d) inter critical region. DC-LSND process showing (e) weld metal, (f) course grain region, (g) fine grain region, (h) inter critical region. DC-LSND process. Scale is 20 μm.
CONCLUSION
The DC-LSND process has been applied to DH-36 grade steel. The following conclusions have been drawn from these experiments:

1. The DC-LSND process has an effect on longitudinal weld distortion and can reduce it by as much as 81%.
2. The most optimal travel speed is 600mm/min for the tested cooling geometry and heat input using the smaller TFS 20 cooling nozzles.
3. Propriety CO$_2$ snow generating nozzles are successful in providing stable flow of CO$_2$ snow, resulting in consistent heat sink application between tests.
4. Microstructure shows minimal change between the conventional and DC-LSND process, however HAZ hardness is significantly affected potentially increasing the risk of HACC in weldments.

ACKNOWLEDGEMENTS
The authors acknowledge the support of the Defence Materials Technology Centre, which was established and is supported by the Australian Government’s Defence Future Capability Technology Centre (DFCTC) initiative. In addition thanks are due to DMTC partner Forgacs Engineering for the supply of plate and consumables used in this work and BOC for the supply of Linde LINDSPRAY® CO$_2$ cooling nozzles.

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