Underwater Wet Welding Made Simple

Benefits of Hammerhead® wet-spot welding process

By

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Abstract

A new method of wet welding was investigated to evaluate potential improvements in weld quality, ease of use, increased welding speed and the elimination of welding skill. The new welding process, which has been called Hammerhead ‘wet-spot’ welding, removes the need for skilled welder-divers and eliminates traditional cleaning and preparation techniques, normally associated with conventional (MMA) wet welding. In addition, the process also allows welding to be conducted in nil visibility, yet remains a Manual Metal Arc (MMA) process, using a specially designed Cr-Ni-Mo electrode.

The process utilises a control device, which needs to be pre-set before the diver enters the water and through this device weld parameters are controlled and quality is maintained. The role of the diver is simplified and is to make contact with the material, strike the arc and maintain pressure to the electrode while welding.

A series of spot welds were produced both wet and dry, on 8.0mm carbon steel plates. The welds were evaluated with regards to ease of use, setting up of the device, speed and final weld quality. Initially, the performance of the process was assessed and usage diagrams produced. Work regarding an automated version of the system has also been proposed.
1: Introduction

Underwater wet welding has been employed for many years now, but has commercially been restricted to conventional Manual Metal Arc Welding (MMA) techniques. [1-5] The typical problems associated with MMA welding underwater fall into two categories; those associated with mechanical/metallurgical quality and those associated with skill and ability. It is with both these issues in mind, a new methodology of MMA welding was devised.

Underwater wet welding, although accepted as a low cost, practical alternative to dry or hyperbaric welding, can suffer from quality issues, mainly due to the rapid cooling. [1,4,7-12] It is also well appreciated that the skills and abilities necessary to execute high quality, conventional MMA wet welds are extremely high, therefore labour and training costs are significant factors. [1-5,10,16] This new welding methodology, which has been developed by the reporter, provides a solution to both of these issues. The process is called Hammerhead wet-spot welding.

The process provides an alternative approach to welding, one in which the role of the operator is minimised and therefore, no longer required to use hand-eye co-ordination skills. Rather, this is a method in which two materials are joined together by a spot or plug weld by means of a programmable control device. In this way, the operator simply becomes a means of making contact with the material and providing momentum to ‘push’ the electrode into the material once the arc is struck. The Process also eliminates the need for traditional cleaning, joint preparations, and chipping/cleaning of weld slag. The process utilises one electrode to produce each weld and this weld being localized within the through thickness dimensions of the material. The author has shown that the final mechanical weld qualities have been significantly improved, as has the overall speed of joining when compared to any conventional wet fillet MMA welding techniques. Unlike conventional MMA welding, the process provides a method of controlling the welding current necessary to produce a weld, without requiring the operator to have any welding skills or knowledge, because the current is automatically regulated and controlled by the device on each weld cycle. Thus, the roll of the diver is reduced to that simply of an operator.
2: Literature Review

According to Keats [1] the skills necessary to produce welds underwater are considerable, with training of diver-welders taking a considerable time to perfect. It is also understood that in poor visibility conditions, many of these hard learnt skills can be wasted when hand eye co-ordination cannot occur for the production of quality MMA fillet welds. [1] However, the actual deposition skills necessary to deposit a good weld is not the end of the problem. Equally important must be the joint preparation, gap tolerance and overall cleanliness of the joint to be welded. Given the typical conditions which exist in harbours and ports around the UK, it is not surprising that the quality of wet welding falls below that of above water welding. [1] Wet welding can have defects such as solidification and hydrogen cracking, porosity, slag inclusions and lack of fusion (side wall and inter-run) defects being quite common. [1]

Safety issues concerning underwater wet welding were also considered during the development of this process and reference was made to the Association of Offshore Diving Contractors (now IMCA) code of practice 035 – Safe Use of Electricity Underwater. [2] This code recommends that all underwater wet welding be conducted using DC negative polarity (-Ve) power sources only. In this way, the diver holds the cathode whilst the earth/return becomes the anode. This current flow direction minimises the affects of electrolysis to the diver. [2] These affects exist due to the flow of electrons/ions between the anode and cathode and could result in discomfort or even electric shock for the diver, should a leakage field exist that encapsulates the diver’s body. It is agreed by industry that the maximum safe body DC current, should not exceed 40mA and this lead was adhered to in the development of this system. [1-2]

The first examples of commercial underwater welding were to salvage vessels after the First World War, although it was not until 1983 that the first welding specification was published, by The American Welding Society (AWS D3.6). [3] Although, Sir Humphrey Davey first demonstrated an arc could be maintained underwater in 1802, it was not until the early 1930’s that any notable experiments took place. One such experiment conducted at Lehigh University in America, quickly established that a DC current was required to strike and maintain an arc underwater. [4] All of these early experiments
were conducted in a small glass tank, with the operator standing in air, with only his hands submerged.

The American Welding Society describes the wet-welding process as one in which the diver and the welding arc are exposed to water, with no physical barrier between them. This particular standard was prepared in response to the needs for a specification that would allow users conveniently to specify and produce welds to a predictable performance level. However, this specification covers only MMA welding using conventional welding techniques. A more recent welding specification is BSEN ISO 15618-1, first published in 2002 and also covers underwater wet welding. [5] Once more, this is restricted to conventional wet welding methodology for fillet and butt welds and covers procedures and qualification testing requirements. Neither of these specifications has been able to provide clarification to the possible quality or suitability for a wet-spot welding methodology. In addition, neither AWS nor BSEN ISO specifications take water type into consideration, both stating this to be a ‘non-essential’ variable. However, Kralj et al [6] demonstrated the influence of water type on wet welding parameters showing that they do have a significant influence. In particular, seawater contains up to 40ppt of primarily sodium and magnesium chloride and thus has a higher electrical conductivity than freshwater. Current discharge (dissipation) will therefore occur at various leakage points, (the arc, electrode/holder connection, earth clamp, etc) with the result being that welding in freshwater may require an increase in current by a much as 15%. Due to arc constriction in wet welding the current density can reach a value of 11,200-14,280 amps per square meter (A/m²), which is some 5-10 times higher than in air. In spite of these specific conditions the physical processes taking place in the arc, according to Yushchenko et al, are in a high degree similar to ones in air and data has shown arc voltage increases on average by 1.5 – 2.0 volts with every 10M water depth. [7]

According to Kralj, Gooch and Masubuchi the gas bubble produced while welding is composed of ~62-92% hydrogen, ~11-24% carbon monoxide, ~4-6% carbon dioxide, oxygen, nitrogen and traces of gaseous metals. [6,10-11] It was also reported that hydrogen content reduces by some 5-15% with an increase in water salinity. Other considerations which must be included for wet welds include cooling rates, (which are increased to an average of 2-3 times higher than in air and are in the order of 200-300°C/s). Problems
resulting from incomplete insulation of the welding circuit can also include reduced weld penetration and an increased occurrence of defects. Disassociation of water in the arc atmosphere elevates the risk of hydrogen cracking when using ferritic electrodes, particularly ones having a basic or cellulosic coating.\[6,7,11\]

Bailey \[8\] demonstrated nickel-based electrodes having a rutile or oxidizing coating offered the best results in wet welding. Nevertheless, minor cracking (~0.5mm) was observed at the fusion boundary when welding carbon steel (of grade 50D to BS4360). Nickel based electrodes were also susceptible to solidification cracking, where dilution was high, especially in the root runs. Hydrogen cracking was best avoided by using austenitic stainless steel electrodes, provided dilution was minimised (Sadowski and Gooch).\[9-10\] Nevertheless, it was observed that bead placement was absolutely critical to prevent martensite formation and cold cracking, in both the weld-metal and fusion boundary for both ferritic and stainless electrodes. The tensile data for fillet weld lap joints resulted, although they failed through the weld throat at relatively low stresses, with slag inclusions and lack of fusion being visible on the fracture face, with some solidification cracking evident also. From these works shear strength values averaged at 214N/mm\(^2\), for austenitic electrodes. In respect to hydrogen cracking and parent material composition, hardenability, expressed in carbon equivalent terms, was considered crucial. It was shown, however, that CEV levels appropriate to structural steels were less important in underwater welding than in air. The average hardness values recorded wet were 258 HV\(_{2.5}\) for filling weld passes and 390 HV\(_{2.5}\) for the diluted HAZ, with severe hydrogen cracking observed in some high dilution austenitic welds. \[10-11\] Increasing water depth also increases hydrostatic pressure, which increases the gas solubility and thus, underwater wet welds may be expected to contain more hydrogen and oxygen with increasing water depth of welding and generally result in harder, more brittle, less ductile welds. \[1,6,8-12\]

The Hammerhead wet spot welding process utilises a Cr-Ni-Mo electrode, which has increased tolerances for hydrogen and carbon over ferritic electrodes, when welding ferritic steels. \[8-10\] Underwater wet welds not only pick up large quantities of hydrogen produced by the decomposition of water, but also, the rapid quenching of the weld ensures higher hardness levels, in comparison to surface welding, for the same material
type. The use of this type of austenitic electrode provides for very high solubility of hydrogen, due to the lower mobility of hydrogen and the FCC lattice, whose larger interstitial spaces, accommodate large amounts of hydrogen and carbon. An austenitic structure can hold up to 2% carbon in solution (1150°C), due to large interstitial space in the closely packed atomic structure. This electrode should also provide for increased toughness and yet isn’t embrittled at low temperatures, when compared to ferritic BCC structures. [1,8-12]

Abson and Cooper [12] showed that attempts to produce conventional wet fillet welds using austenitic stainless steel electrodes produced such extensive cracking that the welds were unable to be used for any useful mechanical testing. The handleability of this austenitic electrode was also recorded by the divers to be difficult and weld appearance was poor. It was further found that the acceptable optimum current setting was +/-5 amps, with the susceptibility to solidification cracking closely linked to travel speed. Even welds produced with a number of ferritic electrodes showed fine-scale cracking in the as-deposited and re-heated regions, and the HAZ; these all being identified as hydrogen cracks. For butt welds deposited using austenitic electrodes the microstructure differed from one bead to another, reflecting differences in dilution. For the passes in early contact with the parent (ferritic) steel, the microstructure was commonly non-uniform with up to 100% martensite. Present however, elsewhere in the early beads, visual estimates of the proportions of the various microstructural constituents were ~80% martensite, ~5-10% ferrite and ~10-15% austenite. These structures not only reflected high dilution for the early passes but welding conditions, including rapid solidification, allowed incomplete mixing to occur. In the second layer, the proportion of ferrite increased to ~10-25% and 60% in the capping runs. The proportion of martensite changed abruptly in bands within the first bead on each side. The microstructure in the bands composed either an estimated 5% ferrite and 95% martensite or ~10-15% ferrite with the remainder austenite. The microstructure for later passes was generally more uniform, with proportion of martensite being ~80% in the second pass, falling to ~50-60% in the last pass. The weld metal hardness ranged from 246 HV₁₀ in the weld cap, to 238 HV₁₀ in the center, to 370 HV₁₀ in the root.

West et al [13] also identified that austenitic electrodes produced both root pass and hot-
pass cracks, and hard martensitic deposits with hydrogen cracking, or fully austenitic deposits with solidification cracks.

Van der Brink and Boltje [14] demonstrated increasing moisture content of the flux increased the occurrence of hydrogen cracking just as it does in surface welding. Szelagowski [15] demonstrated that the type of waterproof coating used to seal the electrode could have a significant affect on the chemical composition of the weld deposit and the coating was more prone to moisture pick-up the deeper the welding depth. The Hammerhead electrode was protected from moisture pick-up while underwater by coating the electrode in a specially formulated vinyl lacquer. Nevertheless, according to Grubbs [16] successful welds have been produced in accordance with AWS D3.6 class ‘B’ welds, using ferritic electrodes, down to depths of 60M.

Corus [17] demonstrated that the Hammerhead process was a valid MMA welding methodology for welding above water also. The welding method was evaluated by them to produce satisfactory welds in a range of material thickness, from 1.6-15.0mm, using 2.0 - 3.25mm diameter electrodes. Electrodes used by them were not limited solely to Hammerhead, but a number of similar grades of electrodes from other manufactures were also used. Their results showed the device to be user friendly, portable and capable of producing welds in air with good fusion and visual appeal, without cracking and without requiring any particular welding skills. Peel tests were performed on the thinner sheet steel sections, the results showed high mechanical integrity with weld nuggets being pulled out from the parent metal and significant plastic deformation occurred. That study suggested that a useful enhancement would be to make the process ‘closed’ arc. This would involve using a safety feature to prevent operation without the covering shroud being in place. Further work was also recommended to make the system a fully automatic welding process. This approach is currently being pursued by joint work between the author and Corus.

According to Rowe and Liu [18] the development of alternative wet welding processes, suitable for use with automated equipment, is necessary if underwater wet welding is to be used in more hostile environments at greater and greater depths.
3: Experimentation and Results:

3.1. Design of Apparatus

The Hammerhead MMA wet-spot welding method utilises an electronic control device which provides the facility to control a number of key welding functions, in order to produce a spot weld underwater.

The functions and features are listed below.

Main on/off switch
1st Peak (high) current control
2nd Background (low) current control
Timer (up to 20 seconds)
High, low and auto current selector
Amp and volt meter
400 amp duel pole isolation switch
110v power supply and remote control function cables.

3.2 Control Functions

The control device, which is housed within a utility case, consists of an on/off switch to power the unit, high/low/auto current control potentiometers, a timer and amp and volt meters. (see figures 1-2) To ensure a suitable safe current is available the device is fitted with a transformer to transform 110 volt supply down to a more suitable, safe 9 volts, which is then rectified to DC. A reed switch is fitted to trigger a relay, which starts a timer when the arc is first struck. Two current control potentiometers (pots), independently control high and low current settings. Once these have been set the device can be switched into ‘auto’ mode. These potentiometers are adjusted to deliver the appropriate current, in order to penetrate and fill the materials and thus, produce the spot weld. Once the timer has been triggered, (following arc initiation), the high current potentiometer delivers the preset current for the set time period. Expiration of this control then triggers the low current potentiometer to act, thereby, initiating the required
low level current automatically. This low current function continues until the arc is broken, after which the device automatically resets ready to make the next spot weld, although a five second delay prevents the system resetting, should the diver accidentally break the arc. LED’s light up against each function so the operator can monitor the process at any given moment. All welding parameters are set prior to the diver entering the water and involve the device being connected to the welding machine, via remote control and 110 volt power supply cables. Once connected, complete manipulation of the welding machine is provided and current is controlled from the device. Amp and volt meters are fitted to provide a visual display of the welding current/voltage, as is a 400 amp safety switch to isolate the current to the diver (as required under HSE regulations). This control system is fitted into a utility case, for ease of transportation, together with the remote control and 110v leads. The actual Hammerhead control features can be seen in more detail in Figure 3. The set-up of the welding process is quite straightforward. Prior to entering the water the diver selects a suitable ‘high’ current (selected by eye) to allow for adequate penetration of the two materials to be joined, on the surface. This high current time is recorded in seconds and penetration is again measured by eye. This is ascertained by examining the back of the material for a heat mark, or blister. Providing this is visible on the outside surface of the back-face, penetration is adequate and the timer control and high current function are programmed in and set. The operator now programmes the ‘low’ current control. The low current function does not require the use of the timer and is set simply to provide a suitable current to consume the electrode and complete the weld. After this operation, the device is set into automatic mode. At this point the device is now fully programmed to produce welds automatically. The diver may now enter the water and request for any small adjustments as might be necessary, for the given water type and working depth. After which, the device may be relied upon to give consistent and reproducible welding parameters, as programmed, for each and every weld. Figure 4 shows the operator ready to commence welding. The device may also be set to ‘manual’ mode. In this way, the diver can request either ‘high’ or ‘low’ only current values to be selected, thus, allowing suitable parameters to invoke a repair weld.

Underwater it is essential that the operator does not over penetrate the base materials. Should this occur, weld properties would be compromised by the affects of water back-
pressure, extinguishing the arc and causing slag entrapment, lack of fusion and/or cracks. As the only opportunity for burst-through is while the ‘high’ current cycle is in operation, the timer controls this critical high current time. Excessive penetration is a combined function of both high current and arc time. By accurately controlling both functions, penetration control is accurately achieved. It is not possible for the diver to burst through the material while the ‘low’ current cycle is functioning, as the current is too low. This device thus reduces the role of the diver to that of simply ‘pushing’ the electrode into the materials and to ensuring that contact is maintained. In operation, this requires no more than 5-10kgf and provided the operator consistently maintains this force, nil visibility conditions will in no way affect the outcome or the quality of the weld produced. The applied force was estimated, based on experimentation and became a basis for calculating the necessary pressure to be applied, using a 3.2mm electrode.

\[
\text{Pressure } \text{N/mm}^2 \text{ or (MPa)} = \frac{\text{Force (Kg)}}{\text{Area (mm}^2)}
\]

\[
1 \text{Kg} = 9.80665 \text{ Newtons}
\]

Although the core wire of the electrode measured 3.2mm, the outer flux coating also needs also to be taken into account, thus, increasing the diameter to approximately 6.0mm. Therefore, an applied force of 5-10Kg by the operator will ensure a pressure at the tip of the electrode of some 1.73 – 3.49 N/mm² (MPa).

For much of the welding operation the electrode tip is deep within the wall thickness of the material, so no arc is visible. By removing the welding skills from the individual operator, greater control for the parameters essential to achieve quality has been achieved, the operator’s role simplified, thereby, minimizing the divers influence on weld quality. This simplified operation means that it is no longer essential to have good visibility underwater, or the use of skilled labour, to achieve high quality repeatable welds. This was a specific design feature of the process.

3.3 Weld Samples

All welding was performed on plate having the following dimensions; 150 x 150 x 8.0mm. Materials were restricted to low carbon steel having the composition as shown in Table 1,
with CEV (IIW) shown in Table 2.

CEV formula calculated as $C + Mn + (Cr + Mo + V) + (Ni + Cu)$

$$\frac{6}{5} \frac{15}{1}$$

The following weld ID’s were assigned for each test plate;

<table>
<thead>
<tr>
<th>DRY SPOT WELDS</th>
<th>WET SPOT WELDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>W-1</td>
</tr>
<tr>
<td>D-2</td>
<td>W-2</td>
</tr>
<tr>
<td>D-3</td>
<td>W-3</td>
</tr>
<tr>
<td>D-4</td>
<td>W-4</td>
</tr>
</tbody>
</table>

All spot welds were conducted on simple lap joints, with one plate overlapping the other by ~50%, as shown in Figure 5.

3.4 Equipment, Facilities and Environment

All welding was conducted on-site, in open air conditions, utilizing the following equipment and facilities.

A 400 amp Gen-Set diesel welding generator
Piranha welding monitor/safety switch, fitted with the Hammerhead control system.
Underwater welding stinger
Welding leads (50mm$^2$ copper) double insulated
Brass parallel closing earth clamp

Welding was conducted at Northern Divers facilities in Hull. All diving equipment used was standard commercial surface demand i.e. the diver being fed with an air supply through an umbilical, rather than a SCUBA bottle, as used in sports diving. Full radio communications were also in place throughout, enabling welding data to be supplied and recorded. All personnel engaged were HSE approved commercial divers and all welding was carried out using best working practice. [1-2] Welding was restricted to a freshwater dive tank, at 3M depth. AWS D3.6M-99 and BSEN ISO 15618-1 takes no
account of water type, and the qualification of a welding procedure or operator is given
a +10M extent of approval, thereby, allowing for a maximum welding depth of 13M
and still remaining within specification. (Figure 6 shows dive tank). The environmental
conditions recorded during welding were as follows;

Air; -3°C (+/-1 °)
Water; 0°C (+/- 1 °)

The applied force the diver used in order to ensure the correct pressure was achieved
and maintained, whilst welding, was clearly onerous, and was ‘a best estimate’ made by
each individual, during the experiments but was based on the calculation described
earlier.

3.5 Electrodes

The electrodes used for the experiments were 3.2mm having the chemical composition
shown in Table 3. The electrode used for wet spot welding was specifically designed to
allow for high dilutions, while being capable of maintaining an arc under short-arc
conditions underwater. These electrodes have the potential to allow for dilutions up to a
maximum of 38% without the risk of martensite formation. In order to evaluate fully this
potential, the Shaeffler diagram was used (as shown in Figure 7) to plot a dilution line
based on the mean values as shown below. The Hammerhead electrode provides for the
following Cr and Ni equivalents, based on the following formula.

\[
Cr_{Eq} = \%Cr + Mo + (1.5 \times Si) + (0.5 \times Nb) \\
Ni_{Eq} = \%Ni + (30 \times C) + (0.5 \times Mn)
\]

\[
Cr_{Eq} = 22.5 \%Cr + (3.6) + (1.5 \times 1.1) + (0.5 \times Nb) = 27.75 \\
Ni_{Eq} = 12.7 \%Ni + (30 \times 0.045) + (0.5 \times 0.8) = 14.45
\]

As the Shaeffler diagram shows, the use of this electrode provides for a maximum
dilution of 38.4%, without risking the formation of martensite. It is excepted when using
MMA welding a dilution of around 25% can be expected. Underwater this is normally
slightly reduced, due to ambient temperature and rapid cooling, to approximately 20%.

[1,10-12]

3.6 Welders and Operators

Four individuals were engaged to carry out welding and were identified as follows;

Welder ‘A’ – skilled welder - conducted welds D1 and W1  
Welder ‘B’ - non-welder - conducted welds D2 and W2  
Welder ‘C’ – Skilled welder – conducted welds D3 and W3  
Welder ‘D’ – non-welder – conducted welds D4 and W4

Each diver was asked to produce one weld dry and one weld wet each.

3.7 Welding Procedures

To ensure accurate data collection of welding parameters, all welding operations were recorded throughout.

Applied arc energy was calculated by use of the standard formula;

\[
\text{Arc Energy} = I \times V \times \frac{\text{ROLL}}{\text{time in seconds}}
\]

\[I = \text{current}\]
\[V = \text{volts}\]
\[\text{ROL} = \text{run out length of the electrode}\]

At present, no specification exists for wet-spot welding using any MMA welding process. Any attempt therefore, to evaluate and determine how many welds may be required to bare a given load was based on use of the following formula. To do this, the size of any given weld and therefore the number of welds required, is based on the required shear stress exerted on the component. Thus, each single spot weld can offer the following theoretical strength properties.
Max load = \( \pi d^2 \times \) shear strength. (Neglecting any bending moment).

In calculating the shear strength for plain carbon steel it is common industrial practice to assume this to be \( \frac{4}{5} \), or \( \sim 80\% \) of the ultimate tensile strength. The Hammerhead electrode offers a tensile strength of 650MPa (all-weld ‘dry’ test) and thus, based on this assumption, shear strength becomes 520MPa.

Thus, load carrying area (mm\(^2\)) is \( \pi d^2 \) where \( d \) is the spot diameter (mm).

Thus, for a 10.0mm spot weld, the area is \( \pi \times 100 = 78.54 \text{mm}^2 \).

Max design shear stress for a 10.0mm spot weld is therefore 40840.8 MPa or 40.84kN. Number of 10mm dia welds required \( N \) is total shear load \( (\text{kN}) \)

40.84

Alternatively, the shear stress can be calculated per mm\(^2\) of weld. This would produce the total spot weld area required and thus, lead to a selection of spot welds.

Shear Stress ‘X’ kN mm\(^2\) = \( \frac{40.84 \text{ (kN)}}{78.54 \text{ (mm}^2\))

Thus, shear stress = 0.52 kN/mm\(^2\) (520 N/mm\(^2\)).

Therefore, the total spot weld area required for a load of 45kN is 86.54mm\(^2\). In order to show desired joint strength against a specific number and/or size of individual spot weld, the results shown in Figure 8, based on the above calculations, and detailed in appendix 1A and 1B, may be utilized. The actual results obtained for all wet and dry spot welds are shown in Figure 9.

3.8 Spot Welds

The welding parameters and techniques for all welds were preset and recorded as follows;
<table>
<thead>
<tr>
<th><strong>Amps:</strong></th>
<th>Primary (1st) value 250-260</th>
<th>Secondary (2nd) value 150-160</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Timer:</strong></td>
<td>5-6 seconds for peak (1st) current value</td>
<td></td>
</tr>
<tr>
<td><strong>Volts:</strong></td>
<td>25-35</td>
<td></td>
</tr>
<tr>
<td><strong>Polarity:</strong></td>
<td>DC-Ve electrode</td>
<td></td>
</tr>
<tr>
<td><strong>Electrode Angle:</strong></td>
<td>$90^\circ \pm 10^\circ$</td>
<td></td>
</tr>
<tr>
<td><strong>Pressure Applied:</strong></td>
<td>Constant 5-10kgf</td>
<td></td>
</tr>
<tr>
<td><strong>Material thicknesses:</strong></td>
<td>2 x 8.0mm plates</td>
<td></td>
</tr>
<tr>
<td><strong>Electrode:</strong></td>
<td>3.2mm Hammerhead</td>
<td></td>
</tr>
<tr>
<td><strong>Position:</strong></td>
<td>Flat</td>
<td></td>
</tr>
<tr>
<td><strong>Weld Time:</strong></td>
<td>25-27 seconds</td>
<td></td>
</tr>
</tbody>
</table>

The welding operation itself is somewhat unusual, as little sight of the arc is visible after arc initiation. This is a deliberate design feature of the process, removing from the welder any necessity to interpret the arc condition and thus, removing the skill requirement to produce a weld. Prior to welding, plates were simply clamped together to prevent relative movement between them. No cleaning or other joint preparations were used for any of the welds. Welding was conducted on plates in the as delivered condition, although the material was rust free for welder ‘A’ plates. Welder ‘A’ produced both wet and dry spot welds, at the time of welding underwater, visibility was moderate at approximately 30-45cm (see Figures 10 & 11).

Welder ‘B’ produced both wet and dry spot welds. He was permitted a short practice period, to allow for a period of familiarisation. Welder ‘B’s underwater plates had not been cleaned, and were covered with a light surface rust. The welding parameters & techniques for welder ‘B’ were exactly the same as for welder ‘A’. At the time of underwater welding, visibility was very poor <25cm (see Figures 12 & 13).

Welder ‘C’ also produced both wet and dry spot welds and was asked to produce his welds after a brief introduction of the technique. Welder ‘C’s underwater plates had once again not been cleaned, and were covered with a light surface rust. At the time of underwater welding, visibility was very poor <25cm (see Figures 14 & 15).
Welder ‘D’ also produced both wet and dry welds but was asked to produce his welds completely unaided, without any opportunity to practice, in a bid to demonstrate the feasibility of a no-skill process. Welder ‘D’s underwater plates had not been cleaned, and were covered with a light surface rust. At the time of welding underwater visibility was completely nil and all welding was carried out by touch (see Figures 16 & 17).

4: Results

4.1 Visual Appearance

The overall quality of welds produced for both wet and dry spot welds was surprisingly similar, especially when one considers the visibility under which wet welds were made. Equally, there appears to be no substantial difference between welds made by the skilled welders over non welders (see Figures 10-17). All welds showed adequate fusion between base materials and weld metal. Although not completely defect free, some wet spot welds did show evidence of minor gas voids/slag inclusions in the weld body. However, none of the recorded defects appeared to make a significant impact on the overall average strengths of welds made wet, as compared to welds made dry. No appreciable defects were observed, by the naked eye, for any dry spot welds.

Welds generally had an overall convex circular appearance, but a clear difference existed between wet and dry. Wet spot welds had a somewhat untidy appearance and didn’t blend in well with the top plate surface, unlike dry welds. This appearance was due to the existence of a more restricted weld puddle. Also, as the operator was discouraged from manipulating the electrode, having only to apply pressure, this reduced any effect of electrode manipulation and weld puddle control which had an influence on the final weld appearance. For dry spot welding it was possible to manipulate the electrode during the final stages of welding, which assisted in working/wetting out the weld puddle. This manipulation produced a smoother, more blended appearance and as a result, dry welds did not show excess ‘flash’ material, (which was evident in all wet spot welds). This flash was due to excess material being ejected from within the molten nugget. It appeared that excess flash metal resulted from additional weld metal from the electrode, causing some still, molten-metal, to be ejected as a result of continued pressure applied to the
electrode. Although untidy in appearance, this flash material was easily removed later by a simple hammer blow.

One common feature for both wet and dry spot welds was the heat mark, or blister, formed on the back face of the base material. This provided a very useful indicator as to the success of penetration. Although not accurate in terms of measurement or depth, it did provide an excellent method of visually establishing whether penetration had occurred. Where no heat mark/blister was present then the depth of penetration into the back material was limited.

The overall diameter of the welds produced in air, (measured across the top outside diameter of the weld), was somewhat larger than welds produced wet, with the average diameter for a dry weld being 21.48mm against an average diameter for the wet weld of 14.39mm. Wet welds on average were thus nearly 50% smaller in diameter (49.27%) compared to dry welds made under similar current/voltage conditions. However, this increase in diameter appeared mainly due to operator manipulation of the electrode, (despite being requested not to) just prior to completing the weld. This can be seen from studying the weld shapes more closely in the macrophotographs, shown in Figures 18-21.

4.2 Transverse Tension Shear Tests

In order to establish the load required to failure, both wet and dry spot welds were subjected to transverse shear tensile tests. Tables 4 and 5 show individual test results for each wet and dry spot weld. The average failure load of each weld type was;

Dry spot welds – 45.63kN
Wet spot welds – 39.95kN

A difference of 5.68kN between wet and dry was found. Thus, the average dry spot weld offered a 14.2% strength improvement over underwater welds produced. The average CSA of the weld nugget size for all welds was;

Dry spot welds – 86.24mm$^2$
Wet spot welds – 97.17mm²

Wet welds showed an increased measured area of 10.93mm², thus increasing the CSA of deposited weld metal, by 12.67% (12.7). By factoring in this percentage change in the CSA of wet welds, in order to match the CSA of dry welds a new load to failure of 34.88kN (34.9) may be calculated. This difference of 10.75kN further reduces the wet strength results, as compared to the dry, by 23.55% (23.6). (See appendix 1A and 1C).

Clearly, the affects of rapid cooling on welds made underwater, should have effected a change in the mechanical strength of the weld, due to the faster cooling rates experienced. To understand these results better, hardness surveys and weld macros/micros were also examined to identify the total affect brought about by welding underwater. Unfortunately however, these particular tests were carried out after shear testing and thus, may have obscured any minor defects that may have been present. It was also noted that the dry spot welds had larger weld reinforcement, (which accounted for the initial observation that the CSA of dry spot welds were actually larger), although this is unlikely to have offered any real advantages in terms of failure strength. The major influence in effective joining was adequate penetration of the nugget into the base materials, rather than the size of weld reinforcement. The reinforcement was not a product of the excess ‘flash’ material, but that of the still molten weld-metal, having completely filled the nugget to plate surface. It should also be noted that the visibility conditions for making the wet spot welds, especially for welders ‘B’ and ‘C’ was poor, with conditions for ‘D’ completely nil.

4.3 Hardness Survey

A number of hardness surveys were carried out in accordance with BSEN 1043-1: 1996 with two traverse lines being used and six indentations for parent metal, six for HAZ and three for weld-metal, per traverse line (see Figures 22 & 23 for welds D2 and W3). Table 6 shows the average results for all dry spot welds, whilst Table 7 shows the average results for all wet spot welds. When considering the combined average hardness’s it was
seen that the wet results were similar to the dry welds. Somewhat surprisingly, however, was the actual wet welds produced lower hardness’s than the dry welds. This is contrary to what might be expected, with conventional underwater welds cooling more rapidly, thus resulting in harder weld and HAZ metals. In the case of dry spot welds this appeared due to two anomalously high reading in traverse ‘2’, on welds ‘D2’ and ‘D4’ and was assumed to be the result of increased dilution, whilst operating on the ‘high’ current setting. This situation produced a hotter, more fluid puddle, thereby, diluting more carbon from the plate into the weld pool. This combined with the switch over from ‘high’ to ‘low’ current, effectively limited any further alloying, which together with the affects of plate cooling caused the formation of martensite. As far as HAZ results were concerned, although wet welds were harder than dry ones, their values were still acceptable under BSEN ISO 15614-1 and AWS D3.6 and showed some improvements over conventional wet MMA fillet welds.

4.4 Macro/Microscopic Survey

To understand better what has actually happened to weld ‘D2’ (highest hardness dry weld) and also wet weld ‘W3’, a series of microphotographs were taken to study the microstructures present. Weld ‘D2’ was also subjected to a Cameca SX50 EPMA electron microscope to map the weld area (see Figures 24-26). The results for weld ‘D2’ showed reduced Cr, Ni and Mo levels present in the root area of the weld, located just at the point where the switch-over from high current to low current took place. This demonstrates that higher dilution occurred in the root area, resulting in higher carbon levels. This factor may account for the observed elevated hardness readings, despite a slower cooling rate having been experienced than weld ‘W3’. Microphotographs for weld ‘D2’, apparently confirmed this effect and shows that higher carbon martensite existed, as did also numerous spherical carbide particles (see Figures 27c-p). Martensite and carbides were evident to some degree throughout the whole weld body, as was the occasional isolated globular oxide (see Figure 27c-m). Both welds, wet and dry, showed a microstructural similarity, with the existence of delta ferrite in an austenitic matrix, together with isolated globular oxides being present. The underwater weld ‘W3’ showed evidence of a small crack in the root area, which may have been the result of the shear testing, as no other significant metallurgical factors were observed in the weld that may
have brought about such a crack. This may be explained by the pronounced loss of material that occurred from the weld nugget, which appeared to show a ductile break (see Figure 28a). In addition, it was also clear that the material for weld ‘D2’ and weld ‘W3’ were not the same, despite the material specification, as shown in table 1. Weld ‘D2’ clearly had a higher carbon content, as shown by the ferrite and pearlite content, which may in fact, be as high as 0.25% (see Figure 27b). Whereas, weld ‘W3’ showed a considerably lower percentage of pearlite (smaller and less carbide platelet formation). This may more accurately reflect a material composition closer to 0.15% carbon (see Figure 28b).

5: Discussion

In considering the weld strength vs. weld size and therefore, the number of welds required for any given load carrying capacity, the following principle to calculate overall stress can be employed:

\[
\text{Force (load)} = \frac{\text{Stress}}{(\text{UTS})} \times \text{Area}
\]

The dry results as shown in Table 4 and Figure 9 show the average CSA for dry spot welds was 86.24mm², with the average load to failure being calculated at 45.63kN, whilst the average UTS was 548.5N/mm². Whereas the wet tensile results shown in Table 5 and Figure 9, show the average CSA for wet spot welds was 97.17mm², with the average load to failure being calculated at 39.95kN, whilst the average UTS was 474.50N/mm². Thus, the average dry spot weld CSA was, by comparison, some 10.93mm² smaller than the average wet spot weld, but offered an increase in shear strength of some 5.68kN.

By comparing the wet shear test results to the theoretical based value (10.0mm diameter nugget) which produced a load to failure of 40.8kN, with UTS of 408N/mm² (as shown in Figure 9). The actual weld deposited offered a slight reduction of 0.85kN or 2.1%. However, by calculating the reduction in CSA (which equated to 2.83mm²) the strength reduction becomes 2.9%. The design principle that predicts a given number of spot
welds for a given load would appear therefore, to over value actual wet weld strengths by approximately 3%. Nevertheless, this approach demonstrates the principle that simple calculation would provide a reliable base method for determining the number of spot welds necessary to carry a given load. (See appendix 1A and 1B).

The overall appearance of the wet welds was somewhat more untidy when compared to dry welds, with the more restricted weld puddle in evidence. Although, the weld profile (cap) did not appear to significantly affect the results of mechanical testing.

The average hardness values for wet and dry spot welds were acceptable showing no particular hardness concerns. (see Table 6/7) In fact, considering the average values between wet and dry (excluding D2 and D4) the differences was so minimal as to be irrelevant. It should be appreciated differences in material carbon content for welds ‘D2’ and ‘W3’ could be sufficient to show a difference in the hardness readings obtained.

Hardness testing was conducted using national standards, although it is accepted that in order to fully evaluate this type of weld and better understand the affects of cooling, further additional hardness testing may need to be conducted.

The weld macros showed deposit weld quality was similar between wet and dry, although not defect free, no greater incidence of defects were produced wet, as compared to dry. It should also be noted that all welds, both wet and dry, had been mechanically tested prior to macro/micro examination and hardness surveys. This may therefore, have had some affect on the results obtained. Nevertheless, the quality of wet spot welds produced showed that this method of welding can be relied upon to produce underwater welds, at the very least, every bit as affective as has been shown for the conventional wet fillet welds described in the referenced literature, [8-13] although it is accepted that Martensite is likely exist in the root area of any welds produced, thus limiting this process to low carbon steels only.

No weld cleaning or joint preparation was necessary to execute any weld, unlike that of conventional wet fillet welding and therefore welding efficiency was significantly increased, with a completed weld being produced within 27 seconds. The control device,
specifically designed for this method, provided a suitable means to control the essential welding parameters and demonstrated the means to reduce the role of the diver, even under nil visibility conditions. It must be accepted however, that the role of the diver is still essential in the production of a satisfactory weld, due to the need to apply adequate pressure. Nevertheless, this welding method has demonstrated a successful means of joining carbon steels together that eliminates the need for skilled welders, as well as all conventional cleaning/preparation methods. Furthermore, successful wet welds were produced, even under conditions of nil visibility, an approach which offers significant cost savings over conventional wet MMA fillet welding methods.

6: Conclusions & Further Work

The experiments conducted demonstrated that the wet spot welding method tested was capable of making an affective mechanical fixing for structural steels underwater. At the same time, the technique provided commercial benefits in the way of speed, quality and repeatability over conventional wet MMA fillet welding, without using skilled welders and working in poor/nil visibility conditions.

To demonstrate the commercial advantages of this process, the experiments concentrated on the following conditions;

1: Producing spot welds in nil visibility, while still providing for an effective weld
2: Elimination of preparation/cleaning of materials and increased welding speeds
3: Elimination of welding skills
4: Repeatability and consistent weld quality

To facilitate this, spot welds were produced under different conditions for evaluation. These consisted of both dry and wet spot welds. Dry welds were produced as a baseline comparison against which to compare weld quality and thus, highlight any differences in mechanical and metallurgical qualities. This work was limited to welding low carbon structural steel plate (8.0mm) in freshwater, at a depth of 3M, using the processes specially designed control device. The experiment had not taken into account the affects welding in seawater may bring, nor did it consider other welding positions. [1,3-6,8] Welding was restricted to the use of a single type of Cr-Ni-Mo stainless electrode, of
3.2mm diameter, with all welding being conducted in the flat position. Further work would be required to evaluate this welding methodology more fully. Other materials, electrode sizes, positions and changes in water type/depth, together with different grades of structural steels need also to be tested. All underwater welding was conducted in poor and/or absolute nil visibility conditions with both skilled and non-skilled welder-divers being employed. Although only a few welds in total were produced, insufficient to provide for a comprehensive outcome, the evidence showed that divers with little or no welding skills/knowledge were able to produce acceptable spot-welds as easily as skilled welders. It was also shown that visibility had no affect on performance, or weld quality. Neither did the lack of weld preparation or cleaning appear to substantially affect final weld quality. Although not a fully automatic welding method, the control device proved suitable to control the welding parameters essential to produce welds repeatedly. It was axiomatic that each individual diver must ensure a suitable pressure be applied to the electrode to ensure an acceptable weld was produced. The wet spot welds provided suitable weld quality in terms of strength, with properties closely matching those of dry spot welds. **Although it is accepted, due to the metallurgy, the process is likely to be limited, underwater, to welding non-load bearing joints, eg anodes.** It became evident that the spot welding method provided for a considerably faster joining method than conventional wet MMA fillet welding, as the process did not require any time spent on joint preparation or cleaning of the material/weld and spot welds (wet and dry) were produced in a matter of seconds.

The Hammerhead welding process clearly remains a manual operation, despite the control device, whereas Sadowski’s [9] work involved automatic fixed welding heads, working in hand deep test tanks only. In contrast, the hammerhead process was used by a diver, being fully submerged underwater in a 3M dive tank. The welding process was designed as a one-shot, one-spot process, i.e. one electrode produced one spot weld and eliminated the need to make a second weld over the first, thus eliminating inter-run cleaning and the difficulties encountered in attempting accurate weld placement. [12] The Hammerhead welding method appears to lend itself to automation and this may well prove of great interest, as presently there remains a level of control required by the diver, during welding, to apply pressure to the electrode.
It was reported by Gooch, [10] Masubuchi, [11] and West et al, [13] that the use of austenitic electrodes to produce conventional fillet and butt welds underwater often produced cracking in the weld root and hot pass zone. Abson and Cooper [12] also found extensive cracking when using this type of electrode, thus, preventing any useful mechanical testing. As can be seen from the microphotographs throughout Figures 28 for the wet spot weld (W3), with the exception of a small micro-crack (≤ 0.3mm) in zone ‘E’ as shown in Figure 28k, no other cracking was observed in the weld or the HAZ. Although this crack may be metallurgical in nature, it may have just as easily come about as a result of the shear testing, as evidence exists that the weld underwent significant stress, with large sections of weld material missing from the fracture face. The microstructures reported by Abson and Cooper [12] also stated that martensite was severe, particularly in the root area, where contact with the parent material meant high dilutions had taken place. Nevertheless, martensite was observed throughout the whole weld body in these samples. The reported hardness values also show significant increase over those produced by the Hammerhead process. The evidence, as shown in Figures 28g-l, clearly shows martensite present, although apparently less significant than those reported by Abson and Cooper.[12] The hardness values, as shown in Figure 23, are also considerably lower and clearly suggest evidence of an improved welding process, when compared to conventional wet welding techniques. The average shear strength values as reported by Gooch [10] suggest that the Hammerhead process provides equally effective mechanical strength properties.

Van der Brink and Boltje [14] demonstrated that the moisture content of the electrode flux covering was critical, just as in surface welding, to avoid hydrogen cracking. The experiments detailed herein were conducted on a specially developed electrode, manufactured in such a way as to minimise moisture pick-up. Furthermore, the number of electrodes taken into the water at any one time was limited to no more than six to minimise moisture pick-up and thus, help prevent hydrogen cracking. Szelaowski [15] reported that the type of waterproof coating could also have a significant affect on chemical composition of the weld deposit, although no evidence was observed on the welds produced in this work, although further work in this regard may be beneficial. The waterproof coating used for the Hammerhead electrode was a specially formulated vinyl lacquer.
According to Grubbs,\textsuperscript{[16]} conventional wet fillet welds, using ferritic electrodes, can be successfully made in accordance with AWS D3.6 class 'B', at depths down to 60M. The opportunity to test the Hammerhead process at these depths was not available during these experiments, although it is accepted that deep welding trials would be necessary to fully evaluate this process/electrode and investigate any differences in weld quality from the shallow water tests undertaken. However, from the results obtained for the Hammerhead process, evidence exists that further additional alloying of the electrode may be necessary to help reduce martensite in the weld body, \textbf{although it is accepted that is cannot be achieved in the root area.} Since commencing this work, a number of further advancements have been made. The control device now has a specifically designed PCB board and the reed switch control feature, which triggered the timer, has been replaced completely. This feature is now controlled through the shunt, which offers an all together more reliable method of initiating the timer, after the arc is struck.

This work has also been further extended by working closely with Corus.\textsuperscript{[17]} The work undertaken by Corus demonstrated the welding methodology to be valid, even for above water applications and was more than capable of joining an even wider range of material thicknesses than had been investigated. The process offered a rapid method of joining plates and sheet steel and was equally capable of joining both very thin and thick materials (1.6-15.0mm) and the control of penetration, by means of the device, was quite satisfactory. Welding was performed in both the flat and vertical orientation and no significant weld defects were reported, although some voids were located and reported on thicker materials. Nevertheless, all joints contained large fused regions providing mechanically strong joints. The welding of thin galvanized steel sheet provided joints with high mechanical integrity, with the weld nugget being pulled out from the parent material, with significant plastic deformation. It was noted that further work was needed to investigate the maximum gaps that might be able to be bridged, as no particular gap was preset during the initial trials. This is recognised to be an area of extreme interest and significance. Following this initial investigation, Corus wished to discuss the possibility of joint work, with the intention of developing a fully automatic version of the system; this has been agreed and work has commenced. Although nothing to do with underwater, Corus immediately recognised the commercial benefits of this welding
methodology, in particular, for welding of heavy plate. This new approach would utilize a track system and electrode cassette to load and un-load electrodes automatically. The joint working agreement permits the originating company to utilize the technology enhancements achieved, thereby, allowing them further to develop and enhance this technology for underwater welding. This would reduce the diver’s role to simply placing a welding head in the location and press a button, as was identified by the work reported by Rowe and Liu [18] in offering significant advantages, especially for deep wet welding. Further work has also been conducted with the German welding equipment manufacture, Mahe, where the Hammerhead system is currently available as a software package that can be programmed into their 420 amp delta digital range of inverters. This has the added commercial advantage of both welding power source and Hammerhead control feature being one unit. This offers significant commercial advantages, allowing the maximization of commercial opportunities without any of the associated manufacturing costs. It should be understood, at least in the UK, most underwater welding is carried out using diesel welding machines, although this is not the case in Holland/Belgium, where a number of diving companies have expressed an interest in this technology, using the Mahe 420 amp inverters.

Since winning the DTI SMART Award in November 2003 and completing the original trials in Nov 2004, a total of six systems have been sold, four systems for use with diesel welding machines, as detailed in this report and two Mahe 420 amp delta digital welding machines. To date, well over 2000 anodes have been welded underwater using the Hammerhead method, with significant cost savings and satisfactory weld quality achieved. As part of the original SMART Award trials, wet spot welding materials up to a combined thickness of 30.0mm in the flat, vertical and overhead positions, with both 3.2 and 4.0mm electrodes had to be investigated. Although not part of this submission, these results have shown similar outcomes as outlined in this work. Although, it became clear welding in the overhead position was unlikely to be successful with the sizes of electrodes used, as liquid weld material simply poured out of the joint. Despite this shortcoming the welding method has already provided a significant contribution to the underwater industry, but more importantly, can perhaps provide an even bigger contribution to the general main stream welding industries and the future looks very promising for the Hammerhead spot welding process. The author has been successful in

7: Tables

<table>
<thead>
<tr>
<th>Element:</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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<td>0.55</td>
<td>1.6</td>
<td>0.035</td>
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Table 1: Composition of steel plates.

<table>
<thead>
<tr>
<th>CEV</th>
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Table 2: Carbon equivalent value of steel.

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<th>Element</th>
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<th>Ni</th>
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<th>Mo</th>
<th>Mn</th>
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<td>5</td>
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Table 3: Composition of Hammerhead electrodes.

<table>
<thead>
<tr>
<th>Welder / weld #</th>
<th>CSA of weld (mm²)</th>
<th>UTS (MPa)</th>
<th>Failure Load (kN)</th>
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<tbody>
<tr>
<td>Welder ‘A’ – D1</td>
<td>66.62</td>
<td>717</td>
<td>47.8</td>
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<tr>
<td>Welder ‘B’ – D2</td>
<td>78.07</td>
<td>587</td>
<td>45.9</td>
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<tr>
<td>Welder ‘C’ – D3</td>
<td>87.92</td>
<td>594</td>
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<tr>
<td>Welder ‘D’ – D4</td>
<td>112.36</td>
<td>326</td>
<td>36.6</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>86.24</strong></td>
<td><strong>548.5</strong></td>
<td><strong>45.63</strong></td>
</tr>
</tbody>
</table>

Table 4: Tensile test results for dry spot welds.
Welder ‘C’ – W3  |  107.16 |  379 |  40.6  
Welder ‘D’ – W4  |  152.7 |  244 |  37.2  
**Average**     |  97.17 |  474.5 |  39.95

Table 5: Tensile test results for wet spot welds.

<table>
<thead>
<tr>
<th>Welder ‘A’ - D1</th>
<th>PARENT</th>
<th>HAZ</th>
<th>WELD</th>
</tr>
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<tbody>
<tr>
<td>TRAVERSE 1 (Top)</td>
<td>117</td>
<td>183</td>
<td>272</td>
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<tr>
<td>TRAVERSE 2 (Btm)</td>
<td>123</td>
<td>182</td>
<td>282</td>
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<tr>
<td>Welder ‘B’ – D2</td>
<td>PARENT</td>
<td>HAZ</td>
<td>WELD</td>
</tr>
<tr>
<td>TRAVERSE 1 (Top)</td>
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<td>168</td>
<td>237</td>
</tr>
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<td>TRAVERSE 2 (Btm)</td>
<td>138</td>
<td>172</td>
<td>458</td>
</tr>
<tr>
<td>Welder ‘C’ – D3</td>
<td>PARENT</td>
<td>HAZ</td>
<td>WELD</td>
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<tr>
<td>TRAVERSE 1 (Top)</td>
<td>154</td>
<td>197</td>
<td>188</td>
</tr>
<tr>
<td>TRAVERSE 2 (Btm)</td>
<td>148</td>
<td>176</td>
<td>189</td>
</tr>
<tr>
<td>Welder ‘D’ - D4</td>
<td>PARENT</td>
<td>HAZ</td>
<td>WELD</td>
</tr>
<tr>
<td>TRAVERSE 1</td>
<td>125</td>
<td>165</td>
<td>215</td>
</tr>
<tr>
<td>TRAVERSE 2</td>
<td>122</td>
<td>173</td>
<td>401</td>
</tr>
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</table>
| **Combined average** | **135** | **177** | **280**

Table 6: Hardness surveys for dry spot welds using Vickers method at HV-10.

<table>
<thead>
<tr>
<th>Welder ‘A’ - W1</th>
<th>PARENT</th>
<th>HAZ</th>
<th>WELD</th>
</tr>
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<tr>
<td>TRAVERSE 1 (Top)</td>
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<td>208</td>
<td>134</td>
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<tr>
<td>TRAVERSE 2 (Btm)</td>
<td>122</td>
<td>248</td>
<td>217</td>
</tr>
<tr>
<td>Welder ‘B’ - W2</td>
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<td>HAZ</td>
<td>WELD</td>
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<td>TRAVERSE 1 (Top)</td>
<td>139</td>
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<td>276</td>
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<td>TRAVERSE 2 (Btm)</td>
<td>164</td>
<td>224</td>
<td>284</td>
</tr>
<tr>
<td>Welder ‘C’ - W3</td>
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<td>HAZ</td>
<td>WELD</td>
</tr>
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<td>TRAVERSE 2 (Btm)</td>
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<td>262</td>
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</table>
| **Combined average** | **135** | **226** | **233**

Table 7: Hardness surveys for wet spot welds using Vickers method at HV-10.
8: Figures

Figure 1 shows the control device with the remote and 110v power leads connected.

Figure 2 shows the control panel, with isolation switch, amp/volt meters and the Hammerhead control device (bottom left).
Figure 3 shows detailed sketch of the Hammerhead control device showing the timer (1), high amp control (2), low amp control (3), on/off switch and LED (4) and the high/low/auto selecting switch and LED’s (5).

Figure 4 shows the operator ready to strike the arc.
Figure 5 shows typical lap joint/plate set-up for all spot welds

Figure 6 shows diver entering the dive test tank.
Figure 7 shows maximum dilution possible without risk of martensite forming is 38.4%.
Figure 8 shows the number of welds required against desired weld strength, based on the calculations discussed on page 17.
Figure 9 shows the results of the actual wet and dry spot welds produced and the results identified against the calculations discussed on pages 17.
Figure 10 shows dry spot weld ‘D1’ and heat blister conducted by welder ‘A’.

Figure 11 shows wet spot weld ‘W1’ and heat blister conducted by welder ‘A’.
Figure 12 shows dry spot weld ‘D2’ and heat blister conducted by welder ‘B’.

Figure 13 shows wet spot weld ‘W2’ and heat blister conducted by welder ‘B’.
Figure 14 shows dry spot weld ‘D3’ and heat blister conducted by welder ‘C’.

Figure 15 shows wet spot weld ‘W3’ and heat blister conducted by welder ‘C’.
Figure 16 shows dry spot weld ‘D4’ and heat blister conducted by welder ‘D’.

Figure 17 shows wet spot weld ‘W4’ and heat blister conducted by welder ‘D’.
Figure 18 shows macrophotograph for welds D1 (left) and W1 conducted by welder ‘A’.

Figure 19 shows macrophotograph for welds D2 (left) and W2 conducted by welder ‘B’.
Figure 20 shows macrophotograph for welds D3 (left) and W3 conducted by welder ‘C’.

Figure 21 shows macrophotograph for welds D4 (left) and W4 conducted by welder ‘D’.
Figure 22 shows actual hardness survey for weld 'D2' (dry weld) conducted by welder 'B'.

<table>
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<th>INDENT</th>
<th>LOCATION</th>
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SPACING: PARENT - 2.0mm  
HAZ - 0.5mm  
WELD - 0.01mm
Figure 23 shows actual hardness survey for weld W3 (wet weld) conducted by welder ‘C’.

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<th>INDENT</th>
<th>LOCATION</th>
<th>HARDNESS</th>
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<td>170</td>
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<td>PARENT</td>
<td>161</td>
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</table>

SPACING: PARENT - 2.0mm
HAZ - 0.5mm
WELD - EQUAL
Figure 24 quantitative map plotted for Cr in weld D2.

Figure 25 quantitative map plotted for Ni.
Figure 26 quantitative map plotted for Mo.
Figures 27a shows weld macro of weld ‘D2’ (dry weld), conducted by welder ‘B’

Figure 27b shows parent material comprising predominantly ferrite and pearlite.
Figure 27c structure appears to comprise of delta ferrite in an austenitic matrix. Isolated globular oxides and fine carbides can also be seen - zone (a).

Figure 27d structure at higher magnification appears to contain some martensite. Light islands are delta ferrite and small dots are carbides - zone (a).
Figure 27e structure appears to comprise of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite – zone (b).

Figure 27f structure at higher magnification appears to contain some martensite. Light islands are delta ferrite and small dots are carbides – zone (b).
Figure 27g structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite zone (c).

Figure 27h structure at higher magnification appears to contain some martensite. Light islands are delta ferrite and small dots are carbides – zone (c).
Figure 27i structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite – zone (d).

Figure 27j structure at higher magnification appears to contain some martensite. Light islands are delta ferrite and small dots are carbides – zone (d).
Figure 27k structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite - zone (e).

Figure 27l structure at higher magnification appears to contain some martensite. Light islands are delta ferrite and small dots are carbides – zone (e).
Figure 27m structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite – zone (f).

Figure 27n structure at higher magnification appears to contain some higher carbon martensite. Light islands are delta ferrite and small dots are carbides – zone (f).

Weld D2 Mag: x200 Position f

Weld D2 Position f. Mag: x400
Figure 27o structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen. Darker coloration may suggest martensite – zone (g).

Figure 27p structure at higher magnification appears to contain some higher carbon martensite. Light islands are delta ferrite and small dots are carbides – zone (g).
Figure 28a shows weld macro of weld ‘W3’ (wet weld), conducted by welder ‘C’

Figure 28b parent material comprising of predominantly ferrite with a small amount of pearlite. Carbon content appears to be approximately 0.10–0.15% based on the pearlite present.
Figure 28c structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen – zone (a).

Figure 28d structure at higher magnification comprising of delta ferrite in an austenitic matrix – zone (a).
Figure 28e structure comprises of delta ferrite in an austenitic matrix isolated globular oxides and fine carbides can also be seen – zone (b).

Figure 28f structure at higher magnification comprising of delta ferrite in an austenitic matrix – zone (b).
Figure 28g small amount of ferrous material stirred within the weld. Weld comprises of delta ferrite in a predominantly austenitic matrix. Some martensite may be present. Ferrous material comprises of pearlite with proeutectoid ferrite at grain boundaries – zone (c).

Figure 28h structure at higher magnification. Delta ferrite in austenite, some martensite may be present – zone (c).
Figure 28i structure comprises of delta ferrite, austenite and some martensite. Large globules are oxides – zone (d).

Figure 28j structure at higher magnification comprising of ferrite martensite and austenite – zone (d).
Figure 28k structure comprises of delta ferrite and some martensite with evidence of a small crack – zone (e).

Figure 28l delta ferrite and fines carbides in a matrix of martensite and austenite – zone (e).
9: References


10: Acknowledgements

The author would like to express his gratitude and appreciation to the following individuals and organizations for their assistance;

Northern Divers (Eng) Ltd for use of their diving facilities and personnel
Drew Maslin
John Sparrowe
Ian Macklam

Laspro - for their development of the Hammerhead electrode.

Corus - for use of their electron microscope to map welds as seen in this report and the work presently being undertaken to further enhance this welding process.

Arc Electronics – design and development of PCB board

A special word of thanks to Dr. Bob Fenn for his kind assistance.
APPENDIX 1A

Theoretical value for a spot weld, based on $3.141 \times \frac{d^2}{4} \times 520$

Load (kN)  \textbf{40.84}

Table 1 - Recorded dry-spot weld values (kN)

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<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>(Average)</th>
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<td>45.9</td>
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Reductions in wet-spot weld strengths, as compared to dry-spot welds

Table 2 - Reduction in wet-spot weld strength by 14.2%

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<tbody>
<tr>
<td>Load (kN)</td>
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<td>44.79</td>
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Table 3 - Further reduced from table 1 values by 23.56%

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<tbody>
<tr>
<td>Load (kN)</td>
<td>36.54</td>
<td>35.09</td>
<td>39.91</td>
<td>27.98</td>
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Table 4 - Adjusted for weld strength overvalue of 40.84 kN by 3%

<table>
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<td>\textbf{39.61}</td>
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</table>
**APPENDIX 1B**

**Select size and number of welds for given load based on 0.52kNmm² or 520N/mm²**

**Table 1 Assuming full weld Dia for Dry weld**

<table>
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<td>8mm</td>
<td>26.13</td>
<td>52.27</td>
<td>78.40</td>
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<td>130.67</td>
<td>156.80</td>
<td>182.93</td>
<td>209.06</td>
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**Table 2 Assuming full weld Dia for Wet welds (Strength reduced by 14.2%)**

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**Table 3 Adjusted for weld Dia for Wet welds (Strength reduced from table 1 by 23.56%)**

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<td>19.98</td>
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**Table 4 Adjusted for weld strength overvalue (Reduced from table 3 by 3%)**

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<td>348.84</td>
<td>392.44</td>
<td>436.05</td>
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</table>
APPENDIX 2 – CORUS REPORT

Welding developments for Speciality Welds Limited

Author(s):
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<td>Mr D Keats - Speciality Welds Ltd. (3)</td>
</tr>
<tr>
<td>Dr R Smith - The Welding Institute (2)</td>
</tr>
<tr>
<td>Namtec</td>
</tr>
<tr>
<td><strong>Swinden Technology Centre</strong></td>
</tr>
<tr>
<td>Mr B Gostelow</td>
</tr>
<tr>
<td><strong>Corus Construction</strong></td>
</tr>
<tr>
<td><strong>Crowthorne</strong></td>
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<tr>
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<td><strong>Shotton</strong></td>
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<td>Mr A R Davies</td>
</tr>
<tr>
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* Summary and circulation sent via e-mail

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Summary

Welding developments for Speciality Welds Limited

Author(s): A M Thompson, Knowledge Group Leader, Joining Technology

Reviewer(s):
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David Keats of Speciality Welds Limited, came to the 'Meet the Experts' event at STC. This event was organised within the TWI Joining Forces Programme, funded by Yorkshire Forward. David Keats came to explain the Hammerhead underwater welding process and ask whether Corus could evaluate and develop the process for use in air.

Corus undertook to test the process in air and assess its suitability for use in both the down-hand and vertical orientations to join a range of steel thickness from 1.6 mm to 15 mm. The evaluation revealed the following:

1. The Hammerhead welding process offers a rapid method of joining plates or sheets of a wide variety of thickness, in either the down-hand or vertical orientation.

2. Joints using the Hammerhead process can be made from one side only.

3. The correct degree of penetration can easily be achieved to ensure a weld of sufficient quality.

4. In certain cases connections, presently made by bolting, could be made by welding from one side.

5. Conventional stainless steel electrodes appear to be suitable for welding.

6. Small electrodes of approximately 2 mm need to be used for plate of a thickness below 4 mm.

7. Welds in thick materials in the vertical orientation will probably contain some defects, but would still be suitable for certain applications.

Customer: Third Parties
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Welding developments for Speciality Welds Limited

1. **Background**

David Keats of Speciality Welds Ltd. of the address below, came to the 'Meet the Experts' event at STC. This event was organised within the Joining Forces Programme, funded by Yorkshire Forward. David Keats came to explain the Hammerhead underwater welding process and ask whether we could evaluate and develop the process for use in air. The system was designed to be very user friendly and capable of use in conditions of very poor visibility. The welds were essentially modified MMA plug welds, which provide the ability to weld from one side only*.

2. **Portability and application**

Speciality Welds developed the Hammerhead single sided welding process, to require only a very low level of skill and to be very portable. The equipment comprises an 8 kg attachment to a MMA welding machine (DC). In essence, a MMA electrode is forced through a front plate into the backing plate, at high current and then withdrawn slowly at a lower current, such that the hole created by the arc is re-filled. The steady pressures required can be taught very easily to a non-skilled operator and the machine is preset with the current levels and welding duration time settings, depending on the thickness of materials to be welded. Even changing the numbers and symbols on the knob to talk the language of plate thickness rather than amps and seconds has been considered.

The standard machine is built around the Mahe 360A, weighs approximately 16.5 kg in total and will cost approximately £3000.

This is shown in Fig. 1.

---

* Speciality Welds Limited
Suite 18, Moorlands Business Centre,
Bailme Road,
Cleckheaton,
West Yorks,
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(a) Mahe welding power source

(b) Hammerhead control unit
The process was developed for underwater welding and as such could easily be undertaken in either the down-hand or vertical position. The vertical position was facilitated by the effect of the metal freezing on contact with the water below the weld and hence, the metal was held in the weld. Also, the surrounding water kept the electrode cool during welding at high current.

3. **Work undertaken by Corus**

Until Corus undertook the evaluation, the Hammerhead process had only been developed for use underwater. Corus undertook to test the process in air and assess its suitability for use in both the down-hand and vertical orientations to join a range of steel thickness.

The potential for extending the thickness range of steels that can be welded was evaluated according to Table 1. All weld numbers were done under the Corus QA code 5WH73, such that the full codes were 5WH73-D1 for Downhand 1 etc.
Table 1: Evaluation undertaken by Corus

<table>
<thead>
<tr>
<th>Welding position</th>
<th>Back plate (mm)</th>
<th>Front plate (mm)</th>
<th>Electrode</th>
<th>Weld QA number 5WH73</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downhand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>5</td>
<td>Hammer-head 3.25</td>
<td>D1</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5</td>
<td>Hammer-head 3.25</td>
<td>D2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>Avesta 316/SKR 2.5</td>
<td>D3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.6 (G)</td>
<td>Avesta 316/SKR 2.5</td>
<td>D4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>Avesta 309L 2.0</td>
<td>D5</td>
</tr>
<tr>
<td></td>
<td>1.6 (G)</td>
<td>1.6 (G)</td>
<td>Avesta 309L 2.0</td>
<td>D6</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>5</td>
<td>Hammer-head 3.25</td>
<td>V1</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5</td>
<td>Hammer-head 3.25</td>
<td>V2</td>
</tr>
<tr>
<td></td>
<td>4</td>
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<td>Avesta 316/SKR 2.5</td>
<td>V3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.6 (G)</td>
<td>Avesta 316/SKR 2.5</td>
<td>V4</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>Avesta 316/SKR 2.5</td>
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<tr>
<td></td>
<td>1.6 (G)</td>
<td>1.6 (G)</td>
<td>Avesta 309L 2.0</td>
<td>V6</td>
</tr>
</tbody>
</table>

(G) - Galvanised

Fig. 2: Photograph of welds made

The back plate is that onto which the front plate is welded. Hence, required penetration is approximately the sum of the front plate and several millimetres of the back plate. The range of materials welded is shown in Fig. 2. This is a significant extension to tests of the existing hammerhead process, which to date have only used 3.2 mm electrodes to weld steels in the thickness range of 8 mm to 15 mm. To facilitate welds in the thinner plates a 2.0 mm or 2.5 mm stainless steel electrode was used. (Table 1, column 3.)
4. Results for a variety of thickness and orientation

The twelve welds described in Table 1 were all welded without insurmountable problems. The problems that did arise were as follows:

- Weld metal tended to run out of the welds made in the vertical position. However, this was not expected to significantly reduce the strength.

- The current needed to be very low for the thin material and at such power levels the controller was not stable. This is because it was designed for higher currents and it is believed that the sensitivity can be improved.

- The thicker welds made in the vertical position contained porosity and lack of fusion unless the electrode was manipulated to force the arc to the top of the molten pool.

All results of the evaluation, including photographs are shown in Table 2. It is evident that the range of thickness, which can be welded using this process could easily be extended down to 1.6 mm thick steel. Plates were not cleaned, nor was the surface removed from the galvanised plates. Hence, the process was robust and demonstrated that it was capable of welding through scale, light rust or a galvanised surface.

The results of the Hammerhead welding process trials are shown in Table 2.

The Hammerhead process, generally produced welds of high quality in the downhand position. No defects were discovered in these welds.

In the vertical orientation weld quality was variable. The most consistent problem was the tendency for the molten steel to run out of the weld. At the greater thickness of 8 mm front plate, there is also a tendency for the formation of voids. Generally however all joints contained large fused regions providing what would be expected to be a strong joint.

The 1.6 mm galvanised steel could be welded to produce joints with high mechanical integrity. Indeed, the photograph for weld 5WH73-V6 shown in Fig. 3, shows how the weld nugget has pulled out of the parent material, with significant plastic deformation.
There was insufficient time to study the size of gaps between plates that could be accommodated by 'bridging' with the weld, but a couple of welds where imperfect fit up had been achieved, creating a gap of approximately 1 mm, did not appear to lack weld quality.
<table>
<thead>
<tr>
<th>Welding position</th>
<th>Back plate (mm)</th>
<th>Front plate (mm)</th>
<th>Electrode/diameter (mm)</th>
<th>Weld number</th>
<th>Photographs top and cross-section</th>
<th>Welding parameters</th>
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<td></td>
<td>8</td>
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<td>SWH73-V2</td>
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<td>2.3</td>
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</table>
5. Suggestions for modification of welding kit

The Hammerhead process is currently an open arc process and for many applications open arc welding is perceived to be dangerous and dirty. Corus suggests that Specialist Welds should consider enclosing the arc within a shroud, with an extraction system attached. This could also be fitted with a safety contact so that the shroud needs to be in place before welding can commence. Such a system would be less likely to have perceived disadvantages in comparison with mechanical riveting to clinching. However, it would have a great advantage from only requiring access from one side. Such a development may be of particular interest for applications involving plate less than 8 mm thick.

A further development could be to automate the pressure by means of a pneumatic or hydraulic ram. Such a development would result in operators merely placing the system in the correct location and pressing a button. The skill level would become very low indeed, safety very high and the quality and consistency of weld very high.

6. Replacement of bolts with welds

For certain applications there is a desire to be able to fix a component from one side only. In such cases, a bolted assembly requires advanced planning and precise alignment. The Hammerhead technique facilitates a rapid, single sided attachment without precise alignment. Also, in many instances a weld would be quicker to make than a bolted assembly joint.

Testing had been undertaken, previously, to demonstrate good mechanical properties from typical welds in 15 mm thick plate made underwater and the results are recorded [1]. Hence, in this evaluation only the weld profiles were examined to assess whether a weld, of at least comparable quality to with those tested could be produced.

The weld profiles generally contained a high proportion of fused interface and the assessments made suggested that the welds should be of equal mechanical performance to those previously tested [1].

7. Conclusions

1. The Hammerhead welding process offers a rapid method of joining plates or sheets of a wide variety of thickness, in either the down-hand or vertical orientation.
2. Joints using the Hammerhead process can be made from on side only.
3. The correct degree of penetration can easily be achieved to ensure a weld of sufficient quality.
4. In certain cases connections, presently made by bolting, could be made by welding from one side.
5. Conventional stainless steel electrodes appear to be suitable for welding.
6. Small electrodes of approximately 2 mm need to be used for plate of a thickness below 4 mm.
7. Welds in thick materials in the vertical orientation will probably contain some defects, but would still be suitable for certain applications.

8. **Recommendations**
   1. The Hammerhead welding process should be evaluated for a range of applications and especially those where single sided joining is required, but precise fit up cannot be achieved easily.
   2. Use of a shrouding mechanism should be considered, to fully enclose the welding and prevent the escape of fumes.

9. **Further work**
   1. Trials should be undertaken using conventional steel electrodes on plates within the same range of thickness.
   2. The maximum gaps that can be 'bridged' between plates should be evaluated.
   3. A shrouding device should be designed to enable the welding to be fully enclosed.

10. **Reference**