

Underwater wet welding made simple: benefits of Hammerhead[®] wet-spot welding process

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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, eliminates the need for skilled welder-divers as well as traditional cleaning and preparation techniques normally associated with conventional manual metal arc (MMA) wet welding. In addition, the process also allows welding to be conducted in nil visibility, yet remains a MMA process, using a specially designed Fe–Cr–Ni–Mo electrode.

The process utilises a control device, which must be pre-set before the diver enters the water. Through this device, weld parameters are controlled and quality is maintained, thus the role of the diver is simplified to three steps: 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 regard to ease of use and 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.

Keywords: Hammerhead, welding, wet-spot, underwater, subsea, welder-diver

1. Introduction

Underwater wet welding has been employed for many years now, but has commercially been restricted to conventional manual metal arc (MMA) welding techniques (Keats, 2004, 1990; Association of Offshore Diving Contractors, 1985; American Welding Society, 1999; Hibshman and Jensen, 1933; British Standards Institute et al., 2002). The typical problems associated with under water MMA welding fall into two categories: mechanical/metallurgical quality, and skill and ability. It was with both these issues in mind that a new methodology of MMA welding was devised.

Underwater wet welding, accepted as a low cost, practical alternative to dry or hyperbaric welding,

can, however, suffer from quality issues mainly due to the rapid cooling (Keats, 2004, 1990; Association of Offshore Diving Contractors, 1985; American Welding Society, 1999; Hibshman and Jensen, 1933; Gretsikii and Maksimov, 1998; Bailey, 1987, 1991; Sadowski, 1980; Gooch, 1983a,b; Masubuchi, 1981; Abson and Cooper, 1998). 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 (Kralj et al., 2003; Gooch, 1983a,b; Grubbs, 1986). This new welding methodology, which has been developed by the author, provides a solution to both of these issues. The process is called Hammerhead wet-spot welding.

This process provides an alternative approach to welding, in which the role of the operator is minimised and is therefore no longer required to have hand-eye coordination skills. Rather, for this method, two materials are joined together by a spot or plug weld by 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 of weld slag. It utilises one electrode to produce each spot weld, which is localised through the thickness dimensions of the material.

The author has shown that the final mechanical weld qualities have been improved, as has the overall speed of joining when compared to conventional wet 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 role of the diver is reduced to simply that of an operator.

2. Experimentation and results

2.1. Design of apparatus

The Hammerhead MMA wet-spot welding method employs an electronic control device to control a



Fig 1: The control panel with isolation switch, amp/volt meters and the Hammerhead control device (bottom left)

number of key welding functions to produce a spot weld. These functions and features are:

- Main on/off switch
- First peak (high) current control
- Second background (low) current control
- Timer (up to 20s)
- High, low and auto current selector
- Amp and volt meter
- 400-amp dual pole isolation switch
- 110v power supply and remote control function cables.

2.2. 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 Fig 1). To ensure a suitable, safe current is available, the device is fitted with a transformer to adapt a 110-volt supply down to a more suitable and safe 9 volts, which is then rectified to direct current (DC). A reed switch is fitted to trigger a relay, which starts a timer when the arc is first struck. Two current control potentiometers 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 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 and is ready to make the next

spot weld, although a 5-second delay prevents the system resetting, should the diver accidentally break the arc.

LEDs 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 to the device, complete manipulation of the welding machine is provided. 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/voltage to the diver, which is required under Health and Safety Executive (HSE) regulations.

The setup of the device is quite straightforward. Prior to entering the water, the diver selects a suitable 'high' current (determined by eye) to allow for adequate penetration of the two materials to be joined. This high current time is recorded in seconds, and penetration is measured visually 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 and set, the operator now selects the 'low' current control. This function does not require the use of the timer and is set simply to provide a suitable current to complete the weld.

The device may now be set to automatic and is fully programmed to produce welds automatically. The diver can now enter the water and make any small adjustments as might be necessary for the given water type and working depth. After these adjustments are made, the device may be relied upon to give consistent and reproducible welding parameters, as programmed, for each and every weld. The device may also be set to manual mode, in which the diver can request either 'high' or 'low' only current values to be selected.

When under water, it is essential that the operator does not over penetrate the base materials. Should this occur, weld properties would be compromised by the effects of water 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 function. Excessive penetration is a combined function of both high current and arc time. By accurately controlling both functions, penetration control is 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. Thus, the device reduces the role of the diver to that of

Table 1: Composition of steel plates

Element	C	Si	Mn	P	S
% (max.)	0.2	0.55	1.6	0.035	0.035

Table 2: Carbon equivalent value of steel

CEV	0.35
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simply ‘pushing’ the electrode into the materials and ensuring that contact is maintained.

In operation, this requires no more than 5–10kgf and, provided the operator consistently maintains this force, poor visibility conditions will in no way affect the outcome or 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.

$$\text{Pressure N/mm}^2 \text{ or (MPa)} = \frac{\text{Force (kgf)}}{\text{Area (mm}^2\text{)}}$$

$$1\text{kg} = 9.80665 \text{ Newtons} \quad (1)$$

Although the core wire of the electrode measured 3.2mm, the outer flux coating also needs to be taken into account, which increases the diameter to approximately 6.0mm. Therefore, an applied force of 5–10kgf by the operator will ensure a pressure at the tip of the electrode of some 1.73–3.49N/mm² (MPa). The actual applied force each diver used whilst welding was clearly onerous. A ‘best estimate’ was made by each individual, but the applied force was based on the above calculation.

For much of the welding operation, the electrode tip is deep within the wall thickness of the material, so no arc is visible, thereby minimising the diver’s influence on weld quality.

2.3. Weld samples

All welding was performed on plate that was 150 × 150 × 8.0mm. Material was restricted to low carbon steel having the composition as shown in Table 1, with CEV (IIW) as shown in Table 2. CEV formula calculated as:

$$C + \frac{\text{Mn}}{6} + \frac{(\text{Cr} + \text{Mo} + \text{V})}{5} + \frac{(\text{Ni} + \text{Cu})}{15} \quad (2)$$

The following weld IDs were assigned for each test plate: dry spot welds – D-1, D-2, D-3 and D-4; wet spot welds – W-1, W-2, W-3 and W-4.

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

2.4. Equipment, facilities and environment

All welding was conducted onsite in open air conditions, utilising the following equipment and facilities:

Table 3: Composition of Hammerhead electrodes

Element	Cr	Ni	C	Mo	Mn	Si	Nb
Min.	21	11	0.020	3	0.60	0.70	—
Max.	24	14	0.10	5	2	2	—

- A 400-amp Gen-Set diesel welding generator
- Piranha welding monitor/safety switch, fitted with the Hammerhead control system
- Underwater welding stinger
- Welding leads (50mm² copper) double-insulated
- Brass parallel closing earth clamp.

The 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. Full radio communications were also in place throughout, enabling welding data to be supplied and recorded. Welding was conducted in a freshwater dive tank, and working depth was 3m. The environmental conditions recorded during these experiments were as follows: air, –3°C (±1°) and water, 0°C (±1°).

2.5. Electrodes

The 3.2mm electrodes were used, having the chemical composition shown in Table 3. The electrode was designed specifically to allow for high dilutions while maintaining very short-arc conditions. These electrodes have the potential to allow for dilutions up to a maximum of 38% without the risk of martensite formation. To evaluate this potential fully, the Shaeffler diagram was used (Fig 2) to plot a dilution line based on the mean values, as shown in Equation 3.

$$\text{Cr}_{\text{Eq}} = \% \text{Cr} + \text{Mo} + (1.5 \times \text{Si}) + (0.5 \times \text{Nb})$$

$$\text{Ni}_{\text{Eq}} = \% \text{Ni} + (30 \times \text{C}) + (0.5 \times \text{Mn}) \quad (3)$$

The Hammerhead electrode provides for the following Cr and Ni equivalents, based on the following formula:

$$\begin{aligned} \text{Cr}_{\text{Eq}} &= 22.5\% \text{Cr} + (3.6) + (1.5 \times 1.1) \\ &+ (0.5 \times \text{Nb}) = 27.75 \end{aligned}$$

$$\begin{aligned} \text{Ni}_{\text{Eq}} &= 12.7\% \text{Ni} + (30 \times 0.045) \\ &+ (0.5 \times 0.8) = 14.45 \end{aligned} \quad (4)$$

As the Shaeffler diagram shows, the use of this electrode provides for a maximum dilution of 38.4%, without risking the formation of martensite in the body of the weld. It is accepted when using MMA welding, a dilution of around 25% can be expected. Under water, this is normally slightly reduced, due to ambient temperature and rapid cooling, to approximately 20% (Keats, 2004, 1990; Gooch, 1983a,b; Masubuchi, 1981; Abson and Cooper, 1998).

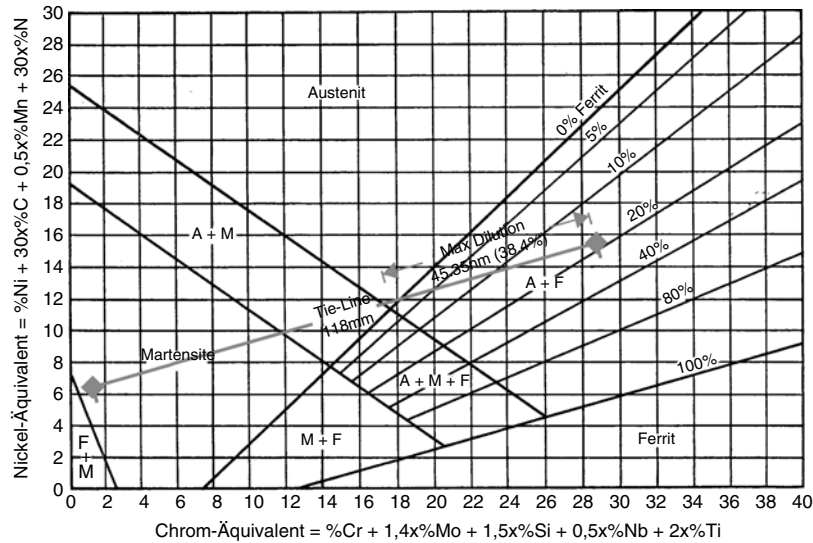


Fig 2: Maximum dilution possible without risk of martensite forming is 38.4%

2.6. 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 dry and one wet weld.

2.7. Welding procedures

To ensure accurate data collection, all welding operations were recorded. Applied arc energy was calculated by use of the standard formula given in Equation 5:

$$\text{Arc energy} = \frac{I \times V \text{ (total power in watts)}}{*ROL \text{ (mm)}/\text{time in seconds}} \quad (5)$$

where I is current, V is volts and $*ROL$ equals run out length of the electrode (in this case ROL referred to the burn-off rate of the electrode).

No specification exists for wet-spot welding, thus in order to determine how many welds may be required to bear a given load, the formula shown below was used. 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.

$$\text{Max load} = \frac{\pi d^2}{4} \times \text{shear strength} \quad (6)$$

(neglecting any bending moment)

In calculating the shear strength for plain carbon steel, it is common industrial practice to assume this to be ~80% of the ultimate tensile strength. The Hammerhead electrode offers a tensile strength of 650MPa (all-weld ‘dry’ test); based on this assumption, shear strength becomes 520MPa.

Thus, load carrying area (mm^2) is $\frac{\pi d^2}{4}$ where d is the spot diameter (mm), so for a 10.0mm spot weld, the area is $\frac{\pi 100^2}{4} = 78.54\text{mm}^2$. Max design shear stress for a 10.0mm spot weld is therefore 40.84kN. The number of 10mm diameter welds required can be calculated using Equation 7:

$$N = \frac{\text{total shear load (kN)}}{40.84} \quad (7)$$

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.

$$\text{Shear Stress (X) kN mm}^2 = \frac{40.84 \text{ (kN)}}{78.54 \text{ (mm}^2)} \quad (8)$$

Thus shear stress equals 0.52kN/ mm^2 . The total spot weld area required for a load of 45kN is therefore 86.54 mm^2 . The actual test results obtained for all wet and dry spot welds are shown in Fig 3. The results presented in Fig 4 show the desired joint strength against a specific number and/or size of individual spot welds, based on the calculations discussed.

2.8. Spot welds

The welding parameters and techniques for all welds were pre-set and recorded as follows:

- Amps: primary value 250–260, secondary value 150–160
- Timer: 5–6s for peak (primary) current value

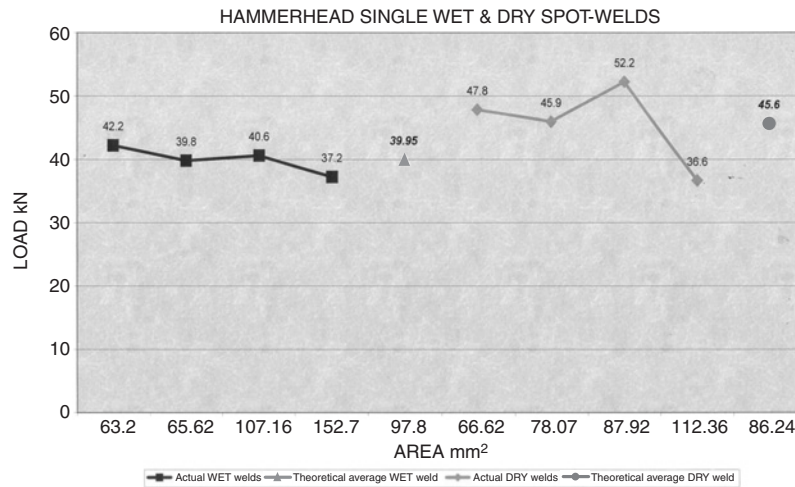


Fig 3: Results of the actual wet and dry spot welds produced

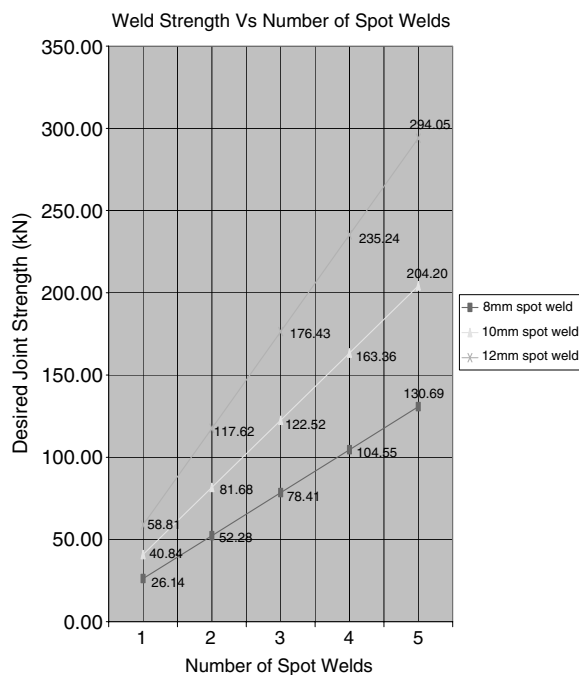


Fig 4: Number of welds required against desired weld strength, based on the calculations discussed

- Volts: 25–35
- Polarity: DC-Ve electrode
- Electrode angle: 90°, ±10°
- Pressure applied: constant 5–10kgf
- Material thicknesses: 2 × 8.0mm plates
- Electrode: 3.2mm Hammerhead
- Position: flat
- Weld time: 25–27s

Prior to welding, plates were simply clamped together to prevent relative movement. No cleaning or other joint preparation was used. Welding was conducted on plates in as-delivered condition. At the time of welding for Welder A, visibility was moderate at approximately 30–45cm.

Welder B was permitted a short practice period for familiarisation. The welding parameters and techniques for Welder B were exactly the same as for Welder A. At the time of under water welding, visibility was very poor at <25cm.

Welder C was asked to produce his welds after a brief introduction of the technique. At the time of under water welding, visibility was very poor at <25cm.

Welder D was asked to produce his welds completely unaided and without any opportunity to practice, in a bid to demonstrate the feasibility of a no-skill process. At the time of welding, visibility was completely nil and all welding was carried out by touch.

3. Results

3.1. Visual appearance

The overall quality of welds produced for both wet and dry was surprisingly similar, especially when one considers the visibility factor. Equally, there was no substantial difference between welds made by the skilled welders over non-welders. 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 results 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 did exist between wet and dry. Wet spot welds had a somewhat untidy appearance and failed to blend in well with the top plate surface, unlike the dry welds. This appearance was due to the existence of a more restricted weld puddle. Also, as the operator was discouraged

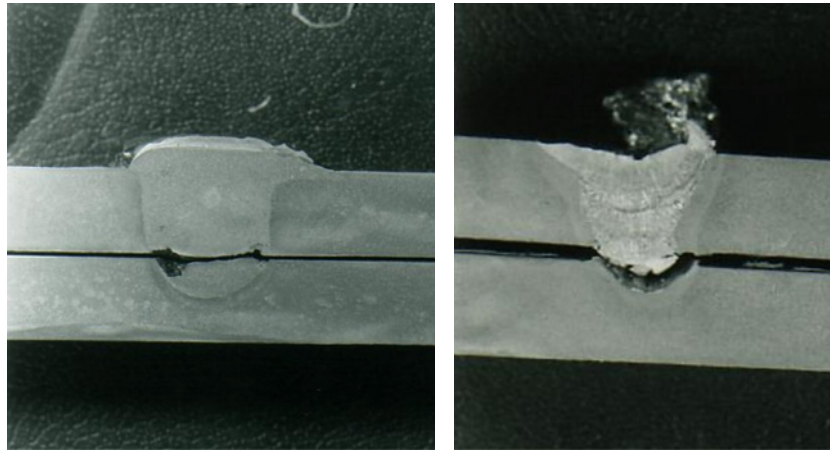


Fig 5: Macro-photograph for welds D1 (left) and W1 (right) conducted by Welder A

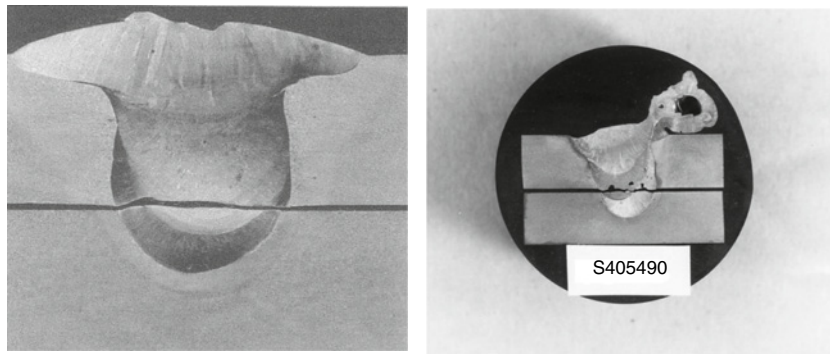


Fig 6: Macro-photograph for welds D2 (left) and W2 (right) conducted by Welder B

from manipulating the electrode. It was possible, however, to manipulate the electrode for the dry spot welds during the final stages of welding, which did assist in working/wetting out the weld puddle. This manipulation produced a smoother, more blended appearance, and as a result, dry welds did not show the 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, resulting from additional electrode weld metal, causing 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 with 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 visual method of establishing whether adequate penetration had occurred. Where no heat mark was present, 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 14.39mm for that of a wet weld. Wet welds on average were nearly 50% smaller in diameter (49.27%) compared to dry welds made under similar current/voltage conditions. This increase in diameter appeared to be mainly due to operator manipulation of the electrode, despite being requested not to do so, and may also be due in part to the input energy vaporising the water. This can be seen from studying the weld shapes more closely in the macro-photographs shown in Figs 5–8.

3.2. 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 the individual test results for wet and dry spot welds.

The average failure load of each weld type was 45.63kN for dry spot welds and 39.95kN for wet spot welds. A difference of 5.68kN between wet and dry was found. Thus, the average dry spot weld offered a 14.2% strength improvement over the average wet spot weld. The average cross-sectional area (CSA) of weld nuggets for all welds was 86.24mm² for dry spot welds and 97.17mm² for wet spot welds.

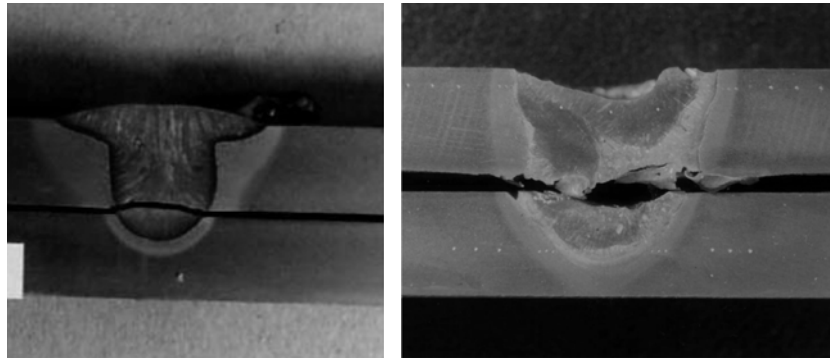


Fig 7: Macro-photograph for welds D3 (left) and W3 (right) conducted by Welder C

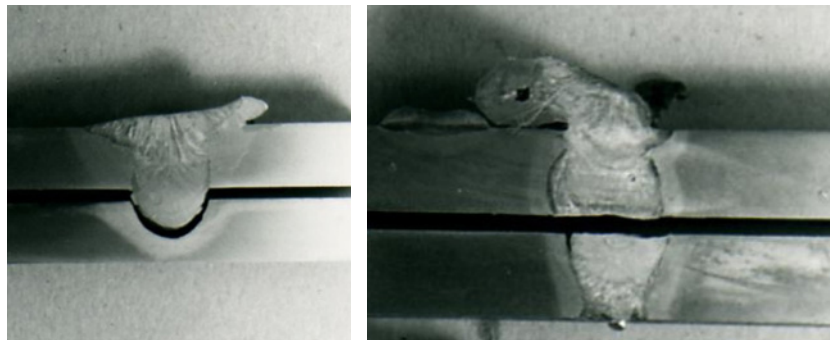


Fig 8: Macro-photograph for welds D4 (left) and W4 (right) conducted by Welder D

Table 4: Tensile test results for dry spot welds

Welder – weld No.	CSA of weld (mm ²)	UTS (MPa)	Failure load (kN)
Welder A – D1	66.62	717	47.8
Welder B – D2	78.07	587	45.9
Welder C – D3	87.92	594	52.2
Welder D – D4	112.36	326	36.6
Average	86.24	548.5	45.63

Table 5: Tensile test results for wet spot welds

Welder – weld No.	CSA of weld (mm ²)	UTS (MPa)	Failure load (kN)
Welder A – W1	63.20	668	42.2
Welder B – W2	65.62	607	39.8
Welder C – W3	107.16	379	40.6
Welder D – W4	152.7	244	37.2
Average	97.17	474.5	39.95

Wet welds, therefore, showed an increase of 10.93mm², thus increasing the CSA of deposited weld metal by 12.67% (12.7) even though the actual diameters were far smaller than any of the dry welds. By factoring in this percentage change in the CSA of wet welds to match the CSA of dry welds, a new load required 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 5 for more details.

Clearly, the effects of rapid cooling on welds made under water should have caused a change in the mechanical strength of the weld, due to the faster cooling rates. To better understand these

results, hardness surveys and weld macros/micros were also examined. Unfortunately, however, these particular tests were carried out after shear testing and thus may have obscured any minor defects. 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. It should also be appreciated that the visibility conditions for making the wet spot

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

	Parent	HAZ	Weld
Welder A – D1			
Traverse 1 (top)	117	183	272
Traverse 2 (bottom)	123	182	282
Welder B – D2			
Traverse 1 (top)	149	168	237
Traverse 2 (bottom)	138	172	458
Welder C – D3			
Traverse 1 (top)	154	197	188
Traverse 2 (bottom)	148	176	189
Welder D – D4			
Traverse 1 (top)	125	165	215
Traverse 2 (bottom)	122	173	401
Combined average	135	177	280

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

	Parent	HAZ	Weld
Welder A – W1			
Traverse 1 (top)	124	208	134
Traverse 2 (bottom)	122	248	217
Welder B – W2			
Traverse 1 (top)	139	223	276
Traverse 2 (bottom)	164	224	284
Welder C – W3			
Traverse 1 (top)	147	308	274
Traverse 2 (bottom)	147	220	281
Welder D – W4			
Traverse 1 (top)	116	199	132
Traverse 2 (bottom)	120	181	262
Combined average	135	226	233

welds – especially for Welders B and C – was poor and completely nil for Welder D.

3.3. Hardness survey

A number of hardness surveys were carried out in accordance with BS EN 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 for welds D2 and W3. Table 6a shows the average results for all dry spot welds, whilst Table 7a shows the average results for all wet spot welds. An additional hardness survey was undertaken on welds D2 and W3 running down the weld centre from top to bottom. Its purpose was to better understand the microstructural changes taking place within the weld body at different intervals from the interface to the weld cap (see Tables 6b and 7b).

When considering the combined average values for Tables 6a and 7a, it was seen that wet results was similar to the dry welds. Somewhat surprisingly,

Table 6b: Individual hardness survey of dry weld (D2); weld-metal only, running from top weld centre to weld bottom

Distance from weld cap (mm)	Hardness Hv1kg
0.3	312
1.0	208
2.0	205
4.0	373
6.0	205
8.0	364
9.0	454
10.0	482
11.0	449
12.0	468
13.0	472

Table 7b: Individual hardness survey of wet weld (W3); weld-metal only, running from top weld centre to weld bottom

Distance from weld cap (mm)	Hardness Hv1kg
0.3	210
1.0	206
2.0	194
3.0	196
4.0	261
5.0	419
6.0	283
9.0	215
10.0	386
11.0	370
11.7	378

however, was that the wet welds produced lower hardness values than the dry welds. This is contrary to what might be expected with conventional under water welds cooling more rapidly, thus resulting in harder weld and heat-affected zone (HAZ) metal (Keats, 2004, 1990; Gretsii and Maksimov, 1998; Gooch, 1983a,b; Masubuchi, 1981; Abson and Cooper, 1998; West et al., 1990).

In the case of the dry spot welds (Table 6a), this appeared due to two anomalously high readings 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 effects of plate cooling caused the formation of martensite. This is evident from the results shown in Table 6b for weld D2 (weld metal only).

A similar picture was also evident for weld W3 (Table 7b). As far as HAZ results were concerned, although wet spot welds did show higher hardness

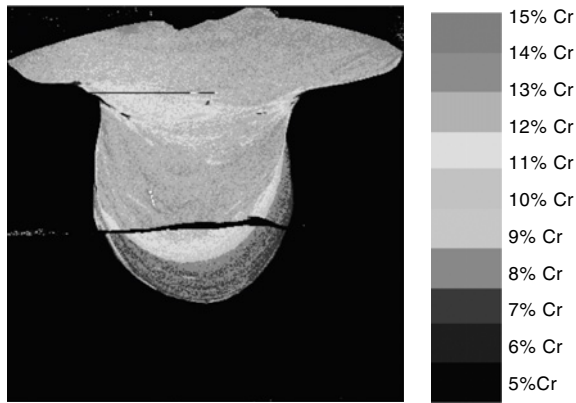


Fig 9: Quantitative map plotted for Cr in weld D2

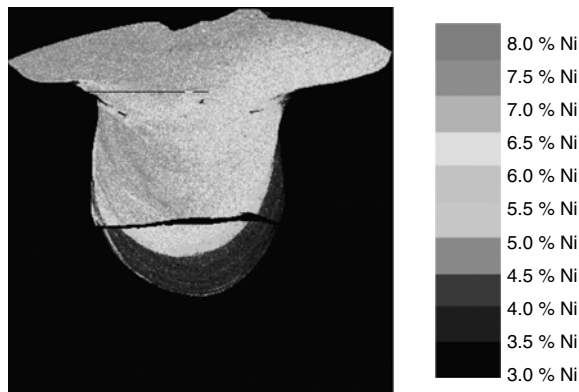


Fig 10: Quantitative map plotted for Ni

values than dry spot welds, their values were still acceptable under BS EN ISO 15614-1 (2004) and AWS D3.6 (1999) and did show some improvements over conventional wet MMA fillet welds (Keats, 2004, 1990; Masubuchi, 1981; Abson and Cooper, 1998; West et al., 1990).

3.4. Macro/microscopic survey

To better understand what has actually happened to weld D2 (highest hardness dry weld) and wet weld W3, a series of microphotographs were taken to study the microstructures present. Weld D2 was also scrutinised under a Cameca SX50 EPMA electron microscope to map the weld area (see Figs 9–11). 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 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 than weld W3.

Microphotographs for weld D2 apparently confirmed this effect and showed that higher carbon martensite existed, as did numerous spherical carbide particles. Martensite and carbides were evident to some degree throughout the whole weld

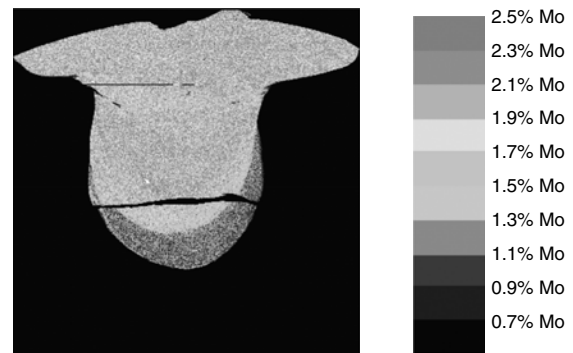


Fig 11: Quantitative map plotted for Mo

body, as was the occasional isolated globular oxide. 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.

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 that may have caused such a defect. This may be explained by the pronounced loss of material that occurred from the weld nugget, which appeared to show a ductile break. In addition, it was clear that the material for welds D2 and W3 were not the same, despite the material specification (shown in Table 1).

Weld D2 clearly had a higher carbon content, as shown by the ferrite and pearlite content, which may be as high as 0.25% (see Fig 12). Weld W3 showed a lower percentage of pearlite (smaller and less carbide platelet formation). This may more accurately reflect a material composition closer to 0.15% carbon (see Fig 13).

4. Discussion

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

$$\text{Stress (UTS)} = \frac{\text{Force (load)}}{\text{Area}} \quad (9)$$

The dry results, as shown in Table 4 and Fig 3, reveal the average CSA for dry spot welds was 86.24mm² with the average load to failure being calculated at 45.63kN, whilst the average ultimate tensile stress (UTS) was 548.5N/mm². The wet tensile results in Table 5 and Fig 3 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 by comparison, the average dry spot weld CSA was 10.93mm² smaller than the average wet spot

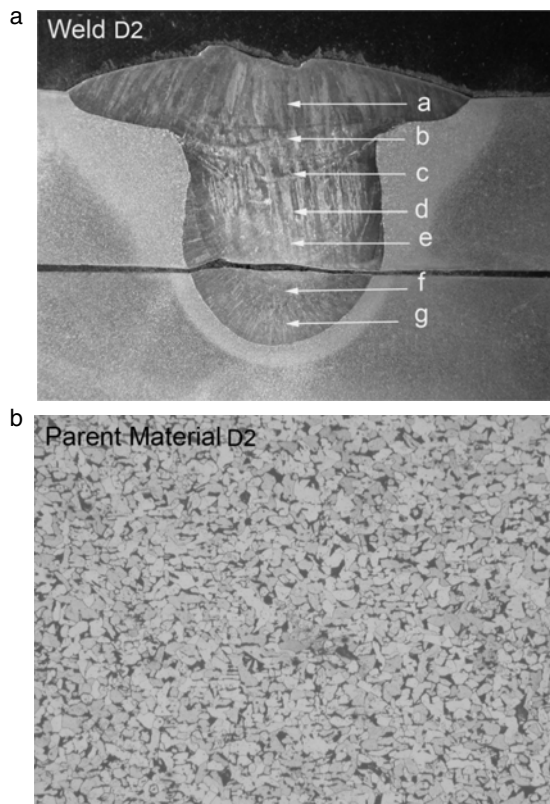


Fig 12: (a) Weld macro of weld D2 (dry weld) conducted by Welder B; (b) parent material comprising predominantly ferrite and pearlite

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 a UTS of 408N/mm² (as shown in Fig 4), the actual weld deposited offered a slight reduction of 0.85kN or 2.1%. When calculating the reduction in CSA that equated to 2.83mm², however, the strength reduction became 2.9%. Thus, the design principle that predicts a given number of spot welds for a given load would appear to overvalue wet weld strengths by approximately 3%. Nevertheless, this approach demonstrates that simple calculation would provide a reliable base method for determining the number of spot welds necessary to carry a given load (see Appendix 5 for more details).

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

The average hardness values shown in Tables 6a and 7b for wet and dry spot welds were acceptable, showing no particular hardness concerns. In fact, considering the average values between wet and

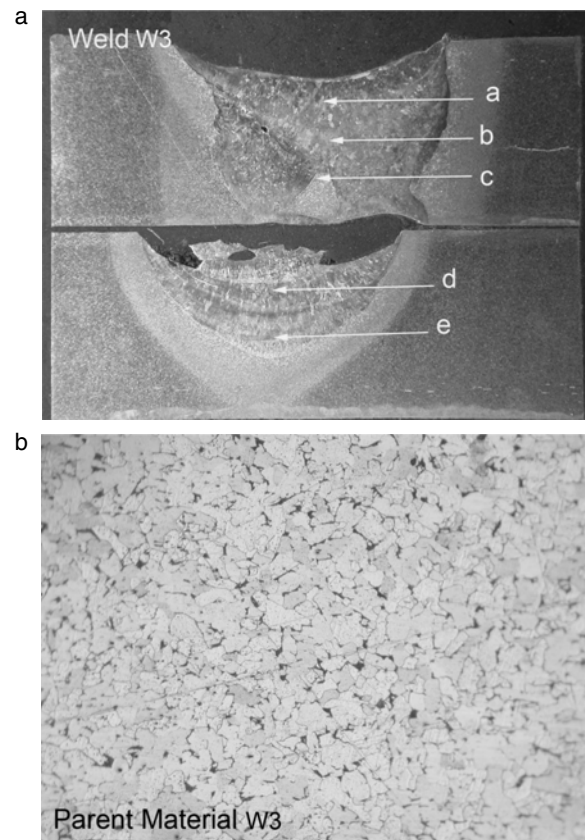


Fig 13: (a) Weld macro of weld W3 (wet weld) conducted by welder C; (b) parent material comprising predominantly ferrite with a small amount of pearlite (carbon content appears to be approximately 0.10–0.15% based on the pearlite present)

dry (excluding D2 and D4), the difference was so minimal as to be irrelevant. It should be appreciated, however, differences in material carbon content for welds D2 and W3 could alone be sufficient to show a difference in the hardness readings obtained. The hardness results shown in Tables 6b and 7b for welds D2 and W3 clearly shows a significant difference in the overall hardness on weld metal, with the dry weld (D2) suffering from increased carbon dilution as compared to the wet weld (W3).

The weld macros showed that weld quality was similar between wet and dry, though not defect-free, and no significant 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 effect on the results obtained. Nevertheless, the quality of wet spot welds produced showed that this method of welding can be relied upon to produce under water welds, at the very least, as effective as those described in the referenced literature for conventional wet fillet

welds (Bailey, 1987, 1991; Sadowski, 1980; Gooch, 1983a,b; Masubuchi, 1981; Abson and Cooper, 1998; West et al., 1990). It is accepted, however, martensite is likely to exist at the interface (root) area of any welds produced using this method.

No weld cleaning or joint preparation was performed prior to welding, unlike that of conventional wet fillet welding, thus welding efficiency was significantly increased, with a completed weld being produced in less than 30 seconds. The control device 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. The presence 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 that eliminates the need for skilled welders, as well as all conventional cleaning/preparation methods. Furthermore, successful wet welds were produced under conditions of nil visibility.

5. Conclusions and further work

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.

The experiments demonstrated that the spot welding method tested was more than capable of making an effective mechanical fixing under water. It also provided 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 for both dry and wet spot welds.

Dry welds were produced as a baseline comparison to compare weld quality and highlight any differences in mechanical and metallurgical qualities. This work was limited to welding low carbon structural steel plate (8.0mm) in fresh water at a depth of 3m using a specially designed control device. The experiment had not taken into account the possible effects of welding in seawater, nor did it consider other welding positions (Keats, 2004, 1990; AWS, 1999; Hibshman and Jensen, 1933; BS/EN/ISO, 2002; Gretskii and Maksimov, 1998; Bailey, 1987, 1991).

Welding was restricted to the use of a single Fe-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, including different sizes of electrodes, welding positions and water type and depth, together with different grades of structural steel. All under water welding was conducted in poor and/or nil visibility conditions using both skilled and non-skilled welder-divers. Although only a few welds in total were produced, which were insufficient to provide for a comprehensive outcome, the evidence supports that divers with little or no welding skills/knowledge were able to produce acceptable spot-welds just as easily as the skilled welders. It was shown that visibility had no effect on performance or weld quality, nor did the lack of weld preparation or cleaning appear to affect final weld quality.

Although not a fully automatic welding method, the control device proved suitable to manage the welding parameters essential to produce quality welds repeatedly. It was axiomatic that each individual diver must ensure suitable pressure is applied to the electrode for an acceptable weld to be produced. The wet spot welds provided suitable weld quality in terms of strength, with properties closely matching those of dry spot welds. Due to the metallurgy, however, the process is likely to be limited under water to welding non-load bearing joints (e.g. anodes). During testing, 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 joint preparation or cleaning of the material/weld, so 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 work (1980) involved automatic fixed welding heads working in hand-deep test tanks only. In contrast, the Hammerhead process is used by a diver being fully submerged under water. The welding process is designed as a one-spot process – i.e. one electrode produces one spot weld, thereby eliminating the need to make a second weld over the first, as well as inter-run cleaning and the need for a second pass (Abson and Cooper, 1998).

The Hammerhead welding method appears to lend itself to automation and may well prove to be of great interest, as presently there remains a level of control required by the diver to apply pressure to the electrode during welding. It was reported by Gooch (1983a,b), Masubuchi (1981), and West et al. (1990) that the use of austenitic electrodes to produce conventional fillet and butt welds under water often produced cracking in the weld root and hot pass zone. Abson and Cooper

(1998) also found when using this type of electrode cracking so extensive that it prevented any useful mechanical testing from being undertaken.

With the exception of a small micro-crack ($\leq 0.3\text{mm}$) in zone E on weld W3, no other cracking was observed in the weld or the HAZ. Although this crack may be metallurgical in nature, it was more likely to be as a result of the mechanical 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 (1998) also stated that martensite was severe, particularly in the root area, where contact with the parent material produced high dilutions. Nevertheless, martensite was observed throughout the whole weld body. Although martensite was present in the weld body of the Hammerhead spot welds, it was not as severe as reported by Abson and Cooper (1998).

The hardness values reported also showed a significant increase over those produced by the Hammerhead process, whose values (as shown in Table 7b) are considerably lower and thus clearly suggest evidence of an improved welding process. The average shear strength values, as reported by Gooch (1983a,b), suggest that the Hammerhead process provided equally effective mechanical strength properties.

Van der Brink and Boltje (1983) also demonstrated that the moisture content of the electrode flux covering was critical to avoid hydrogen cracking. The experiments detailed herein were conducted on a specially developed electrode, manufactured specifically to minimise moisture pickup. Furthermore, the number of electrodes taken into the water at any one time was limited also to minimise moisture pickup and thus help prevent hydrogen cracking. Szelagowski (1991) reported that the type of waterproof coating could also have a significant effect on chemical composition of the weld deposit, though no evidence of this was observed on the welds produced in this work. Clearly, further work in this regard would be beneficial. The waterproof coating used for the Hammerhead electrode was a specially formulated vinyl lacquer.

According to Grubbs (1986), conventional wet fillet welds using ferritic electrodes can be successfully made in accordance with AWS D3.6 (1999) Class B at depths down to 60m. The opportunity to test the Hammerhead process at these depths was not available for 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. From the results obtained for the Hammerhead process, evidence suggests that further additional alloying of the

electrode may be beneficial, in order to help reduce martensite in the central weld body area. This, however, is unlikely to offer any benefits at the joint interface (root) zone, where the highest dilution was recorded.

The work undertaken by Corus (Thompson, 2005) demonstrated that the welding methodology to be valid, even for above water applications, and that it was more than capable of joining a wide range of material thicknesses. The process offered a rapid method of joining plates and sheet steel in both very thin and thick materials (1.6–15.0mm) and the device-controlled penetration quite satisfactory. Welding was performed in both the flat and vertical orientation, and no significant weld defects were reported, though some voids were present 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 gap tolerance, as no gap was present or pre-set during the initial trials. This is recognised to be an area of extreme interest and significance. (The full Corus report is available as a separate report.)

Appendix 1

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

Load (kN) 40.84

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

	1	2	3	4	(Average)
Load (kN)	47.8	45.9	52.2	36.6	45.63

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

	1	2	3	4	(Average)
Load (kN)	41.01	39.38	44.79	31.40	39.15

Table 3: Further reduced from table 1 values by 23.56%

	1	2	3	4	(Average)
Load (kN)	36.54	35.09	39.91	27.98	34.88

Table 4: Adjusted for weld strength overvalue of 40.84kN by 3%

Load (kN) 39.61

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