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INITIAL TRIALS OF UNDERWATER WET WELDING USING MECHANISED FCAW PROCESS

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Abstract. *Wet welding is one of the most under rated and misunderstood welding processes in regular use. This may sound as strong words, but despite the advantages offered by underwater wet welding, such as speed, versatility, and cost effectiveness, it is still underused, especially when FCAW (Flux-Cored Arc Welding) process is applied. It has been used in pipelines, ships, shipyards/piers, nuclear power plants, waterfront structures, platforms and in general oil and gas applications. On the other hand, wet underwater MMA welding has been used as an underwater welding technique for a long time and is still being used. With recent acceleration in the construction of offshore structures underwater welding has assumed increased importance. This has led to the development of alternative welding methods like friction welding, explosive welding, and stud welding. Looking for traditional process, such as arc-welding ones, FCAW offers wide possibilities, versatilities and high productivity, which are inherent to the process. In fact, the advantages of the FCAW have been discussed in terms of cost reduction, where it has been shown cost reduction of the order of 50%. The FCAW is known for having two types: shielded and self-shielded. The logistics of handling shielding gas is always addressed, especially in offshore application. Thus, in the case of wet welding, the absence of the shielding gas would lead to gains of lead time, which underlines the use of self-shielded FCAW process. Moreover, the increase conscience of improving health and safety environment for divers has brought the high importance of mechanised process. Therefore, in this work it is presented initial trials on structural C-Mn steel with mechanised FCAW at shallow water depth with specially developed tubular wire. The final task is to achieve weld beads that can be classified according to the standard AWS D3.6M. The results showed the potentiality of the process, with the need of further investigation.*

Keywords*: Wet Welding, Mechanised, FCAW.*

1. INTRODUCTION

Wet welding is one of the most under rated, abused and misunderstood welding processes in regular use (Pett 2000). This may sound as strong words, but despite the advantages offered by underwater wet welding, such as speed, versatility, and cost effectiveness, it is still underused, especially when FCAW (Flux-Cored Arc Welding) process is applied (Rowe and Liu 2001).. However, wet FCAW can be used for repair and general manufacturing as well. It has been used in pipelines, ships, shipyards/piers, nuclear power plants, waterfront structures, platforms and in general oil and gas applications.

Wet underwater MMA welding has been used as an underwater welding technique for a long time and is still being used (Joshi 2008). With recent acceleration in the construction of offshore structures underwater welding has assumed increased importance. This has led to the development of alternative welding methods like friction welding, explosive welding, and stud welding. Looking for traditional process, such as arc-welding ones, FCAW offers wide possibilities, versatilities and high productivity, which are inherent to the process. In fact, the advantages of the FCAW have been discussed in terms of cost reduction (Lucas and Cooper 1999).

The FCAW is known for having two types: shielded and self-shielded. The logistics of handling shielding gas is always addressed, especially in offshore application. Thus, in the case of wet welding, the absence of the shielding gas would lead to gains of lead time, which underlines the use of self-shielded FCAW process. Moreover, the increase conscience of improving health and safety environment for divers (Nixon 2000) has brought the high importance of mechanised process.

Therefore, it is very important to dedicate special attention to this process applied to wet welding. The first step is to carry out a detailed literature survey on the subject. The focus is the self-shielded FCAW process mechanised operating in wet welding.

1.1. Literature Survey

The databases selected during the survey were the Weldasearch, Academic databases (such as Compedex, ScienceDirect, etc), Patents and Standards. Also, on-line documents (Web Search) were selected when strictly related to the subject.

The self-shielded FCAW in wet environment represents less than 0.5% of the total literature available for underwater welding. This outcome underlines the importance of this further investigation and research in this subject. Especially for academic databases, unfortunately, none results were obtained when looking specifically for the subject of wet FCAW. The best results came from with 76 hits for “underwater welding”. This result emphasises the technological focus of the subject rather than academic one. For the patent search, most “underwater welding” patents deal with electrode formulation and equipment (torches and power sources). Concerning standards, the most comprehensive standard relating to underwater welding it that developed by the American Welding Society, of which the lasts version was published in 1999 – AWS D3.6M:1999 (AWS 1999). This covers wet and hyperbaric welding, and all the conventional arc welding processes are included. Because arc welding is depth sensitive, the standard provides guidance indicating the depth range over which a qualification carried out at a specific depth can be considered valid. Salinity (salt water of fresh water – Table 5.2, Item 8f from the standard) is considered as nonessential variable. However, it has been shown that salinity plays an important role in the process performance (Kononenko 1989).

Most wet underwater welding is still carried out using covered electrodes, which have a waterproof coating varnished over its flux. Semi-automatic welding equipment has been developed and more recently mechanised process, including the development of self-shielded FCAW.

One of the first published paper is due to Prof. Savich (Savich 1969). Afterwards his work was followed by Dr. Kononenko (Kononenko 1996; Kononenko and Korsun 2004), including a recent book on the subject (Kononenko 2006). After these first developments in The Paton Welding Institute, research was carried out in Germany (Hoffmeister, Kuster et al. 1992; Santos 1994), Japan (Ono and al 1997; Ogawa 1999) and Canada (Dorling, Huntley et al. 1985). Very focus and detailed investigation was carried out at TWI, where different approaches for underwater welding have been tried (Lucas and Cooper 1999; Woloszyn 2000; Perrett and Sketchley 2007).

Despite the benefits of wet welding has, such as versatility, less costly compared to dry welding, joint accessibility and small lead time, some drawbacks are cited in literature. The first limitation imposed to the process regards the high cooling rates by the surrounding water. Also, this high cooling rates combined to the large amount of hydrogen resulted from the dissociation of the water vapour in the arc region and plus the high carbon equivalent of the steels employed in the marine construction, led to a high hydrogen-induced cold cracking (HICC). Another issue concerning the hydrogen presence is its ignition in confined environments.

The pressure effect is always a concern in underwater welding, which leads to porosity. Other subjects have also been addressed, but few papers were found literature for wet welding, deal with metal transfer (Pokhonya and al 1989) and fitness-for-purpose (Watson 1994). Also no literature was found for topics like wild marine life, health and safety and environmental issues. Also the poor visibility is a major concerning, since it causes troubleshoots to tracking devices and, therefore, mechanisation.

One of the first comprehensive description about mechanised and automated system for underwater welding is available in. (Santos 1994). A FCAW system, known as A1660 type, was developed for semi-automatic machine (Asnis and Savich 1983), which means that a fully dedicated system for completely mechanised system applied to wet welding still needs to be developed and field applied.. This also opens another research field on the subject. Due to all the issues presented, this development is not an easy task and has to cope with to all of these issues (turbid water, hydrogen bubbling, high pressure, etc). In fact, sensoring is only first step for controlling the process, like the welder, when he “feels” the welding and feedback controls it.

There is a common consensus that the 100-m water depth is today limit for practical and profitable wet welding (Nixon 2000). In fact, until 2005 (Guerrero and Liu 2005), successful wet weld repairs have been conducted up to approximately 100-m-deep water. Deeper than this value, research in covered-electrode has been performed in USA, Mexico and Brazil to depths up to 150 m and out-of-position welds.

Considering that, in a specific application, costs for wet underwater welding were estimated to be about half the cost for hyperbaric welding (Lucas 1997) and also considering that the estimated costs are 80,000 per hyperbaric job, it is possible to state that each million invested in research is payback in 16 months (depreciation and inherent change of process and overhead costs were not included, but they act in favour of payback time reduction).

Therefore, the R&D&I in mechanised FCA wet welding have a high potential return of investment. The very first project on mechanised wet welding comes from the former Soviet Union, especially devoted to consumable development and semi-automatic machines. However, due to the lack of resources, the developments could not reach the levels desired by their researchers. A considerable project was developed in Japan, known as Mega-Float Project (Ono and al 1997), to build a very large floating structure to reduce damaging after earthquakes. A recent project, known as RobHaz (Gibson 2000), with a cost of 3.7 million euros in a 5-years project was developed by a European consortium of research institutions. It is estimated that a budget for R&D&I in mechanised FCA wet welding overcomes one million pounds for a non-commercial study and could triple this amount for a final-end technological product.

2. EXPERIMENTAL APPROACH

For the experiments, welding was carried out in a 1x1x1m water tank (Fig. 1) in fresh water at typically 0.7m water depth (Fig. 2.). In accordance with AWS D3.6:1999, this would allow qualification for water depths of 0.7 to 10.7m, though the effects of wave action when welding at shallow depths should be considered, as described in Section 5.6.2.3 of the standard. Although the most likely medium in practice is sea water, water salinity is defined as a non-essential variable in AWS D3.6:1999 (Table 5.2, 8f).

A conventional flat (voltage-current) characteristic power source is suitable for underwater wet FCAW, however the power source should be capable of an open circuit voltage of 60V for operating underwater with a current limit of typically 400A (60% duty cycle). ESAB Aristo feed 48 wire feeder and Aristo 500 MIG/MAG inverter power source were used for all runs.

For the mechanised welds, the torch was mounted on one-axis mechanised horizontal traverse. This provided control of direction and torch position and resulted in a consistent bead profile. The test pieces were located in a pre-set position by a jig, which held them at a water depth of approximately 0.7m. The welding torch was connected to the traverse; the power source and wire feed unit were located adjacent to the tank.

Bead-on-plat (BOP) deposits were made in the downhand (PA/1G) position on the 10mm C-Mn steel plate (S355) with a Carbon-Equivalent (CE) of ~0.3 and chemical composition shown in Tab.1. Welding was carried out using direct current electrode positive (DCEP) polarity. The current and voltage were measured by acquisition system at 1 kHz per channel.

It was employed a FCAW wire specially developed by the E O Paton Welding Institute for the underwater welding, called PPS-AN1, with 1.6 mm of diameter, whose chemical composition is shown in Tab. 1 (analysis from the weld metal). The other welding parameters are shown in Tab. 2, which comes from a Central Composite Design (CCD) matrix, with face-centred design.

Figure 1. View of experimental rig (Copyright © TWI Ltd).

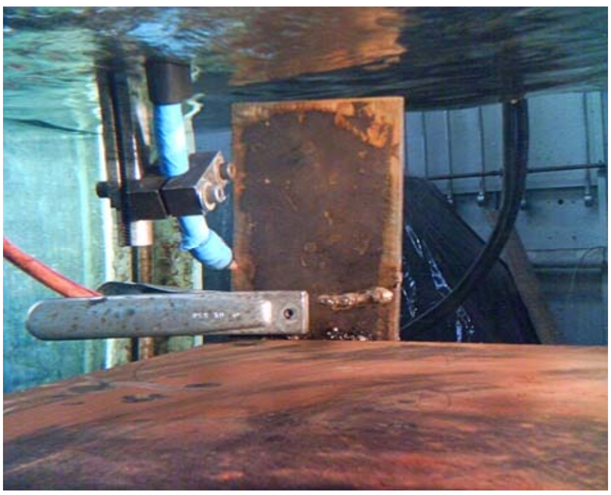


Figure 2. First view of the underwater initial trials in horizontal position (Copyright © TWI Ltd).

Table 1. Chemical analyses for the plate and wire.

Material	C	Si	Mn	P	S	Cr	Mo	Ni	Ti	V	Al	Cu	C.E.
S355*	0.15	0.01	0.84	0.009	0.010	0.014	0.012	0.011	0.001	0.001	0.039	0.019	0.297
PWI wire**	0.03	0.005	0.11	0.031	0.018	0.03	0.006	1.7	0.002	0.001	0.003	0.07	0.174

** It must be pointed out the C.E. is low for this steel and it was used only for these BOP trials..*
*** From the weld metal.*

Table 2. Results for CCD experimental design.

Run	Voltage [V]	WFS [m/min]	TS [cm/min]	Vmean [V]	Vrms [V]	Imean [A]	Irms [A]	100*(Vrms-Vmean)/Vmean	100*(Irms-Imean)/Imean
L01	26	3	10	25.509	25.983	139.15	151.37	1.857	8.784
L02	26	3	20	25.486	25.821	141.56	150.41	1.314	6.252
L03	26	5	10	24.972	25.432	216.73	229.09	1.844	5.701
L04	26	5	20	24.996	25.306	207.97	216.87	1.242	4.282
L05	30	3	10	29.602	30.218	138.47	147.60	2.081	6.595
L06	30	3	20	29.764	30.635	139.26	148.87	2.927	6.902
L07	30	5	10	29.297	29.612	215.10	222.25	1.075	3.326
L08	30	5	20	29.293	29.640	212.44	219.60	1.182	3.373
L09	26	4	15	25.462	25.838	180.77	187.36	1.476	3.643
L10	30	4	15	29.361	29.693	187.37	193.60	1.131	3.325
L11	28	3	15	27.540	27.975	139.78	148.49	1.580	6.232
L12	28	5	15	27.297	27.686	211.80	218.02	1.426	2.935
L13	28	4	10	27.299	27.581	179.40	187.30	1.033	4.406
L14	28	4	20	27.303	27.540	179.46	186.05	0.866	3.669
L15	28	4	15	27.151	27.403	180.25	187.15	0.930	3.825
L16	28	4	15	27.240	27.479	180.47	186.76	0.877	3.485

WFS: Wire feed speed; TS: Travel speed; Vmean: average voltage; Vrms: rms voltage; Imean: average current; Irms:rms current. Other parameters kept constant: Contact-Tip-Work-Distance (CTWD) = 18 mm; Pushing the electrode at 15^o; Flat Position; Inductance set at 10% in the power source scale.

3. RESULTS AND DISCUSSION

The first feature observed was the large volume of spattering (Fig. 3), calculated as 30% of the total wire mass. The final beads are shown in Fig. 4, just after welding (left images) and after manual brushing (right). The importance of keeping the brushing manual is to assess the slag detachability. In this case of flat position, the slag presents a very good detachability.

Figure 3. Large volume of spattering.

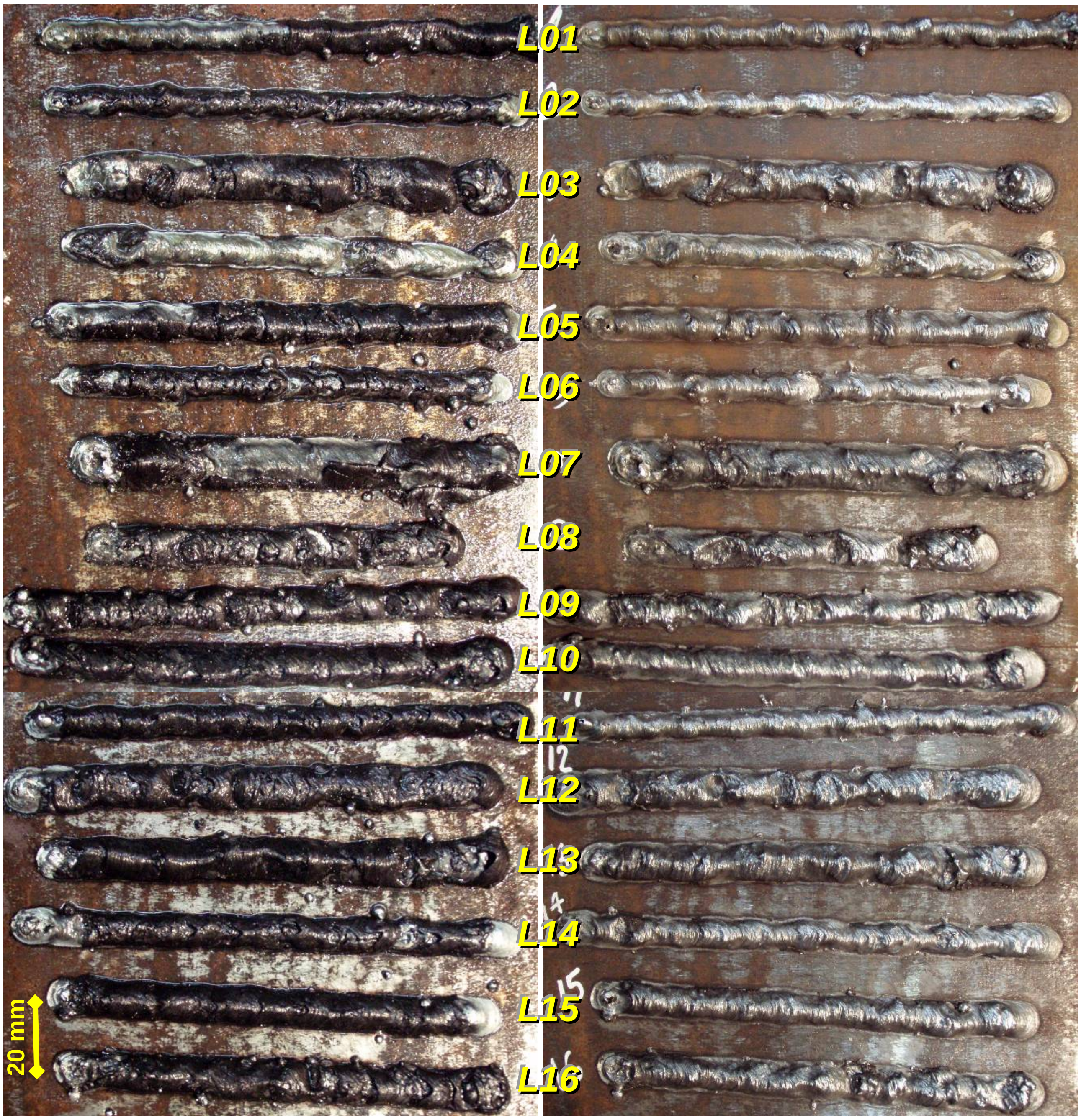


Figure 3. Bead appearance just after welding (left) and after manual brushing (right) (Copyright © TWI Ltd).

The recorded electrical signals are shown in Fig. 5 and 6, whereas the measured values of voltage and current (both average and rms) are shown in Tab. 2. These two figures represent process where there were more (Fig. 5) and less (Fig. 6) fluctuation observed by the authors during the welding, what can be verified by the voltage fluctuation (although the static characteristic of the power source is constant voltage).

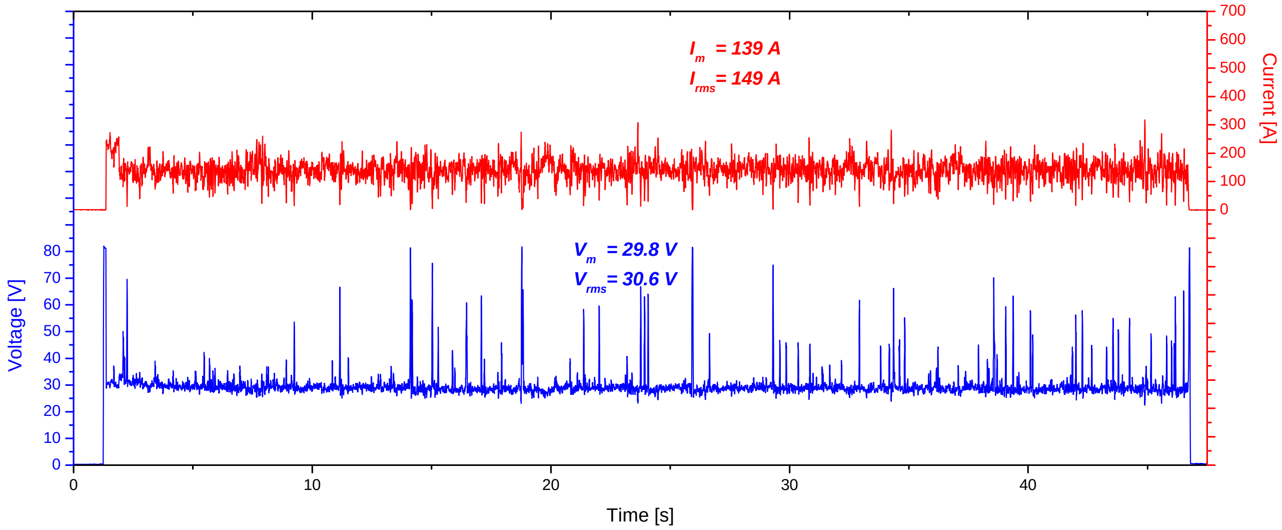


Figure 4. Electrical signals for the run L06 (Copyright © TWI Ltd).

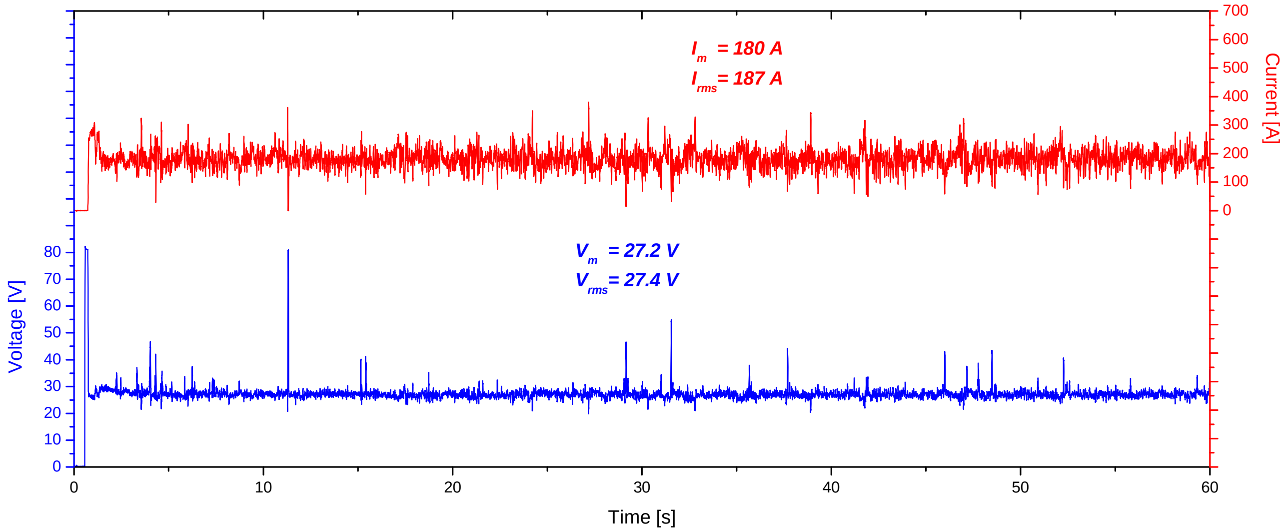


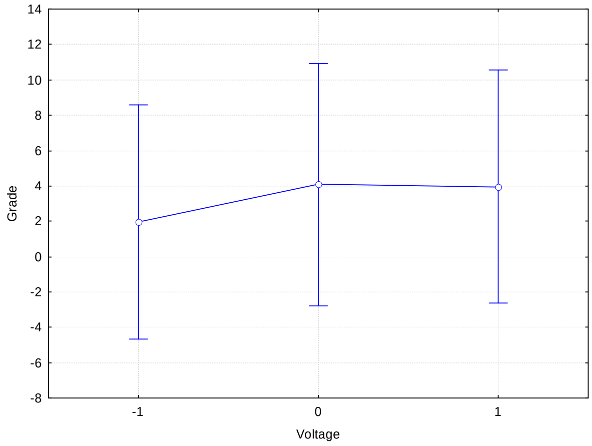
Figure 5. Electrical signals for run L15 (Copyright © TWI Ltd).

After the manual brushing of the weld beads, four International Welding Engineers (IWE), certified by the International Institute of Welding (IIW), were asked to give grades for each bead, basing only the visual appearance. The results and the sum of the grades received by each bead are shown in Tab. 3. From this table, an ANOVA was carried out and the final statistical results are shown in Fig. 7.

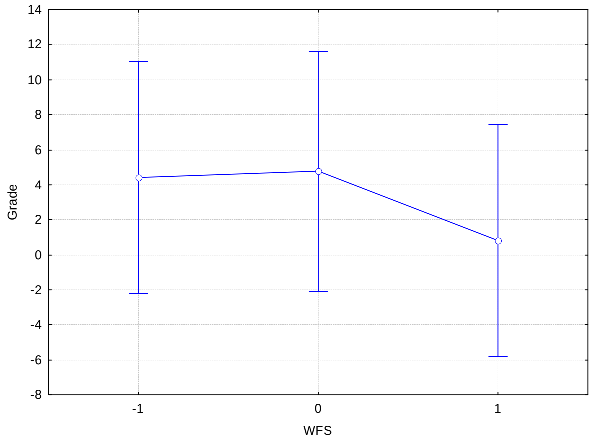
In order to maximize the grade by choosing individually each factor, the logical selection would be selecting the levels that provide the highest grades, i.e., voltage equals to 28 V (level 0); WFS equals to 4 m/min (level 0) and travel speed equals to 15 cm/min (level 0). This represents the run L15, which received the highest grades according to Tab. 3. This is a good indicative of the correct procedure. However, the bead from run L16 was carried out under the same conditions and was not selected as one of the best. This is an indicative of the lack of robustness of the process. During the welding the feedability of the wire was a constant concern. In general, FCAW wires are not rigid as the solid wires, because it is filled with powder. In the beginning of the bead L16, instability happened during the feedability problem, leading to a poor bead profile. However from half of it onwards the visual quality is similar to the L15 bead. The run L16 was not repeated once again in order to reinforce the feedability concern that is present in the process.

Table 3. Results for CCD experimental design in terms of grades.

Run	Welding Engineer 1	Welding Engineer 2	Welding Engineer 3	Welding Engineer 4	Welding Engineer Sum
L01	-	-	-	-	0
L02	2	1	-	2	5
L03	-	-	-	-	0
L04	-	-	-	-	0
L05	-	-	-	-	0
L06	-	-	-	-	0
L07	-	-	-	-	0
L08	-	-	-	-	0
L09	-	-	-	-	0
L10	5	2	4	4	15
L11	3	4	3	3	13
L12	-	-	-	-	0
L13	-	-	-	-	0
L14	1	3	2	1	7
L15	4	5	5	5	19
L16	-	-	-	-	0



(a)



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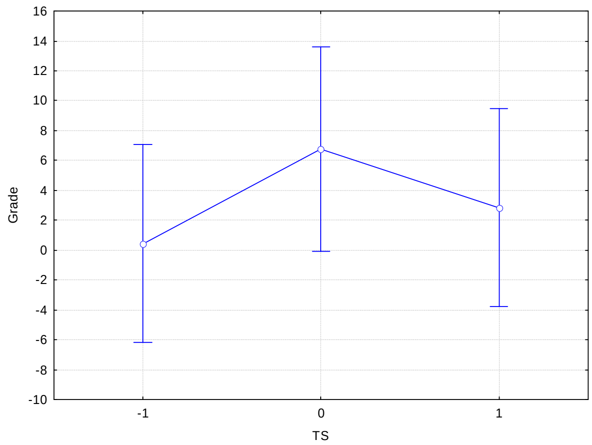


(c)

Figure 6. ANOVA of the grades from the welding engineers for Voltage (a), WFS (b) and TS (c) (Copyright© TWI).

Despite the procedure so far presented relies on the expertise of four certified welding engineers, it is important to provide other approach to identify the most suitable condition. Therefore, a stability index was search in the voltage signal, since Figs. 5 and 6 show that there is more or less voltage fluctuation according to the parameters selection.

Therefore, it is proposed here an index based on Eq. 1, which can be straight implemented as an algorithm in any software and the lower the index, the higher the process stability.

$$Index = \frac{Number\ of\ points\ where V_i \geq V_{cut}}{Total\ number\ of\ points} \cdot \frac{V_{ref\_\min}}{V_{ref}} \quad (1)$$

where, V_i is the voltage values acquired; V_{cut} is the voltage level above which is instability is considered; V_{ref_min} is the minimum reference voltage set in all the experiments (in this case 26 V) and V_{ref} is the reference voltage for the run from which the index is being calculated.

The reason for the correction suggested as V_{ref_min}/V_{ref} is due to the fact that higher references voltages naturally produce higher voltage levels that can overcome V_{cut}, but not necessarily meaning higher instability.

Using the gathered data from the experimental matrix, the index was calculated for each run and it is shown in Tab. 4. Three different levels of V_{cut} were selected: 45, 50 and 60 V. Moreover, it was also included in the index before and after the suggested correction (V_{ref_min}/V_{ref}), so its importance could be notice. At last, it was also calculated the index in the face of filtering the signal (third row of Tab. 4) for V_{cut} = 45 V.

The trends of Tab. 4 are better visualised in Fig. 8 and 9. Although, great discrepancies were not notices on these trends, differences can be observed for runs L01, L02 and L03. Using the previous knowledge from the welding engineers it is expected that the best bead is the L15, which indeed has one of the lowest indexes. If a carefully look is taken on Figs. 8 and 9 and Tab. 4, between runs L15 and L16 indexes, the index with V_{cut} = 45 V, corrected and not filtered assures that the index for L15 is lower than for L16. Therefore, this index will be used here.

Table 4. Results for CCD experimental design in terms of indexes.

Run	Index45	Index45Filt	Index45Corr	Index50	Index50Corr	Index60	Index60Corr
L01	0.582	0.238	0.582	0.365	0.365	0.222	0.222
L02	0.421	0.363	0.421	0.327	0.327	0.299	0.299
L03	0.547	0.320	0.547	0.361	0.361	0.190	0.190
L04	0.788	0.775	0.788	0.707	0.707	0.667	0.667
L05	1.968	1.634	1.705	1.520	1.317	1.135	0.984
L06	2.235	2.180	1.937	1.960	1.698	1.674	1.450
L07	0.657	0.573	0.570	0.500	0.433	0.365	0.316
L08	0.708	0.626	0.614	0.559	0.485	0.494	0.428
L09	0.448	0.365	0.448	0.387	0.387	0.335	0.335
L10	0.691	0.665	0.598	0.577	0.500	0.469	0.407
L11	0.766	0.650	0.712	0.596	0.554	0.503	0.467
L12	0.660	0.623	0.613	0.555	0.515	0.490	0.455
L13	0.468	0.276	0.435	0.312	0.289	0.192	0.178
L14	0.320	0.320	0.297	0.285	0.265	0.225	0.209
L15	0.329	0.274	0.306	0.282	0.262	0.204	0.189
L16	0.372	0.240	0.346	0.273	0.253	0.185	0.172

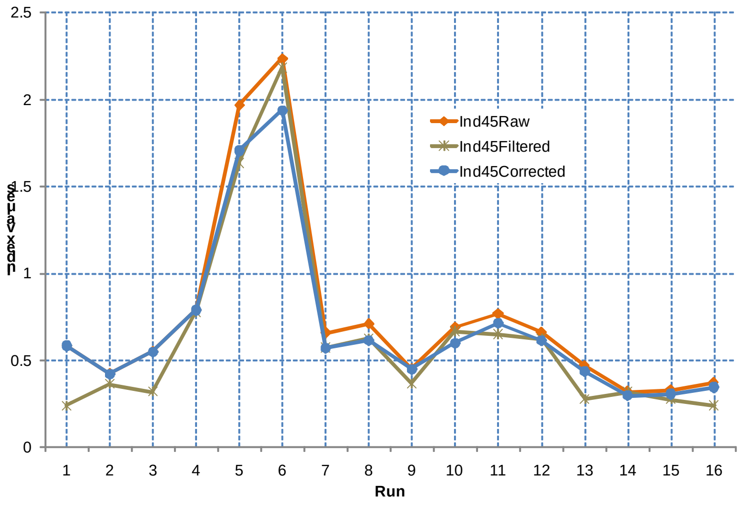


Figure 7. Comparison for the indexes with a 45 V reference (Copyright © TWI Ltd).

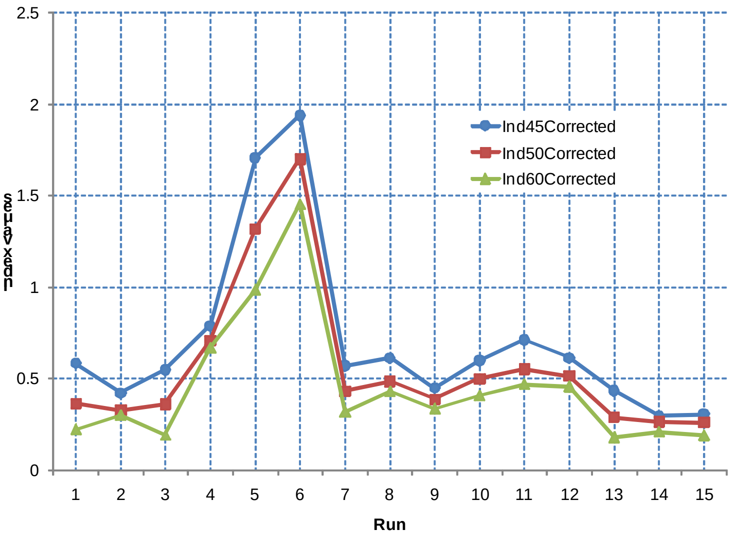
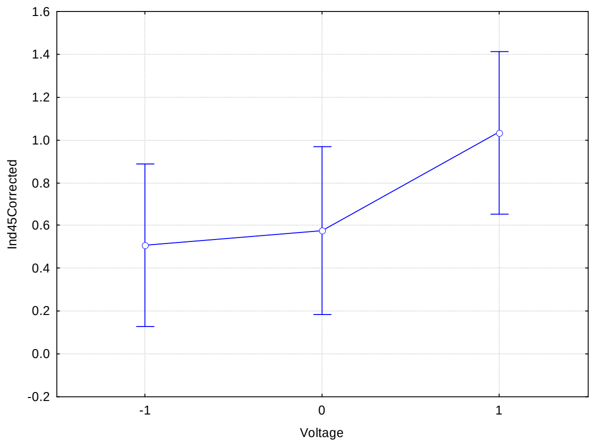


Figure 8. Comparison for the indexes with different voltages as reference (Copyright © TWI Ltd).

As the same case of the grades received by the beads, the index values were analyzed using ANOVA in the CCD design and the results are summarized in Fig. 10. The first approach to obtain the best combination of parameters is to select the lowest index values, i.e., voltage equals to 26 V (level -1); WFS equals to 4 m/min (level 0) and travel speed equals to 15 cm/min (level 0). This parameter combination was not performed. However, it differs from run L15 on the voltage level (28 against 26 V). Therefore, a refinement of the index must be done between 26 and 28 V. This indicates that the proposed stability index is a good indicative, but needs to be further investigated.



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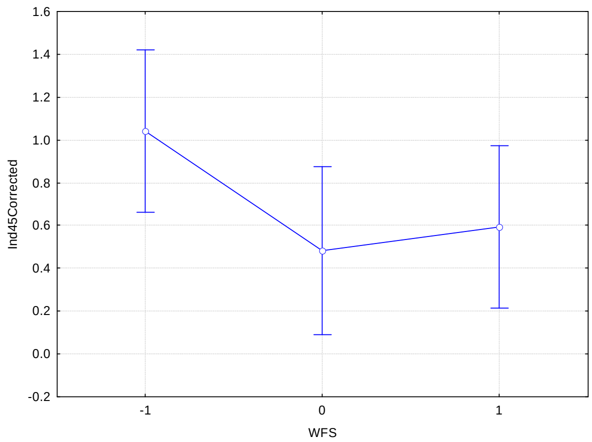

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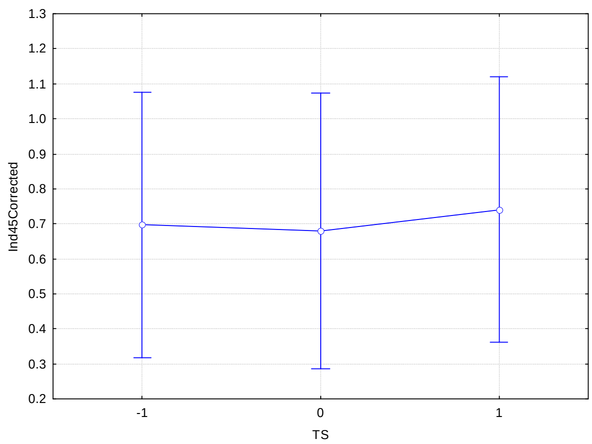

(c)

Figure 9. ANOVA of the Index45 corrected for the factors Voltage (a), WFS (b) and TS (c) (Copyright © TWI Ltd).

4. CONCLUSION

The self-shielded FCAW for wet welding has proved all its potentiality. For bead-on-plate deposits the best parameters selection was 28 V; 4 m/min and 15 cm/min. The set led to best bead appearance and lower fluctuation in the voltage level, which makes possible to create a mathematical index to assess the process stability. The index showed correlation to the bead appearance, assessed by for certified welding engineers.

5. ACKNOWLEDGEMENTS

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