Study of Humping Formation in the Conventional GMAW Process in Comparison to Dynamically Flexible Arc for Offshore Industry

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ABSTRACT

Welding technologies, especially the GMAW process, are well known and in great demand in the offshore oil and gas industry, especially for high thickness applications. As a result, technologies designated as high-performance GMAW variants have naturally emerged to meet certain specific quality and productivity requirements. Nevertheless, deeper understanding of the phenomena and effects responsible for their distinctive results is still lacking, which is needed for better application and customization for specific welding conditions. In this exploratory context, this work provides comparative analysis of one of these novel variants, called Dynaflex in relation to conventional GMAW. Process analysis via high-speed videography, macrography, oscillograms and IR thermography provided insights on the principles of the technology, its limitations and dependence on the welding power source.

KEY WORDS: welding defects, MIG/MAG, Dynamically Flexible Arc, high speed welding, high penetration, buried-arc, weld pool control.

INTRODUCTION

Offshore installations have been in increasing demand, consequently, the improvement of maintenance techniques plays an important role in meeting the industry's goals. After the rise in price of a barrel of oil in 1973, explorations were expanded offshore, boosting the need for structural repairs and fomenting research in the welding field for a number of purposes in offshore production and maintenance, as well as improving welding techniques and processes (Gondim et al, 2019).

GMAW is a well-known and widely used process. As a result, some so-called high-performance variants have naturally emerged to meet specific industry needs. The Dynamically Flexible Arc (Dynaflex) is one of these GMAW variants. In Dynaflex, the inductance of the current upslope and downslope can be adjusted electronically and independently, enabling the upholding of a metastable welding pool condition with reduced arc length, or buried arc, , (Gondim et al, 2019). Such technologies provide an arc with high current density, reduced spatter and high penetration (Stol, I. et al, 2006).

Previous works developed at Labsolda, such as the one by Schaeffer et al. (2022), where they applied Dynaflex welding on in-service pipelines, demonstrate the versatility of the process that can be used both for high penetration welding (buried arc) and for welding that demands greater control of the weld pool in an out of position condition (orbital welding, 5G welding position).

As in any process, in welding, attributes such as quality, productivity, and low cost are desirable. Some of the means to achieve a balance between these process metrics is to diversify some parameters, and when looking mainly at increasing productivity, a good alternative is to evaluate the effects of increasing the working speed and current, or reducing number of welding passes. In fact, time is a critical factor in the offshore industry, as exemplified by estimates made by RIO Analytics (2019), where the weekly cost of a well out of operation nears US $7 million.

The humping phenomenon is one of the most commonly observed geometric defects at high current and high welding speeds and was firstly documented by Bradstreet (1968) in spray metal transfer produced weld seams, in which he suggested that the defect is strongly influenced by oxygen presence during welding. Other authors mention the welding arc's high pressure, which provokes a gradual elongation of the molten pool and strong forced movement of liquid metal in the opposite direction of welding, as factors responsible for the humping defect (Dutra, J. et al, 2021; Mendez ,P.F, Eagar, T.W. 2003; Nguyen, T.C et al, 2005; Nguyen, T.C. et al, 2006; Savage, W.F. et al, 1979; Soderstrom, E, Mendez, P., 2006; Wang, L. et al, 2016).

The objective of this work is to study the effect of humping for high speed GMA welding, in order to broaden knowledge on its possible causes on the basis of a comparison between the Dynaflex GMAW and conventional GMAW, regarding the occurrence of humping.

EXPERIMENTAL PROCEDURE

Materials and Equipment

The experiments were performed with two set-up configurations. For Conventional GMAW welding a CLOOS thyristorized power source, a Tartílope V2f manipulator and a IMC data acquisition system (SAP), allowing for the acquisition of voltage, current and wire feed speed signals with a 5kHz frequency, were applied. For the Dynaflex GMAW experiments, the same peripherals were applied, except for the power source, which in this case was an transistorized, microcontrolled, IMC DIGIPLUS A7.

The weld beads with a length of about half the plate's length, 100 mm were deposited using a common steel wire-electrode (ER70-S6) with 1.2 mm diameter, a mixture of Ar+8%CO_2 was used as a shielding gas with flow rate of 20l/min over SAE 1020 steel plates with 12.7 mm x 75 mm x 200mm as base metal. In order to mitigate influences of the surface condition that could affect weld pool surface tension (as oxidation and lamination remnants), and hence foster experimental repeatability, the plate surface was finished with a grinder along its entire length. Workpieces were cooled in water after each bead, in order to uphold a homogeneous weld start temperature for each bead, as multiple beads were deposited over the same plate. The welding experiments were performed as single pass beads, on top of the steel plates with the torch positioned at a 90 degrees angle from the table and the welding trajectory. For each condition, the beads were welded with a different welding speed, starting at 0.6 m/min and adding 0.1 m/min until the humping phenomenon occurred. The parameters adopted can be seen in Table 1, for both power sources and all welding conditions.

Table 1: Welding parameters.

Parameters	Conventional	Dynaflex
Procedure variant	Spray	DynaFlex-Arc
Wire (mm)	1,2	1,2
Power Source	CLOOS	IMC DiGIPlus A7
DBCP (mm)	18	18
Voltage (V)	30	30
Current (A)	295	400
Wire Speed (m/min)	15	15
Dynamics (Ks/Kd)	-	100/1
Work Angle	90°	90°
Power (W)	9330,5	13000
Shielding Gas	Ar+8%CO_2	Ar+8%CO_2

After welding and determining the welding speed limit for the humping defect to be formed, high-speed videography was performed with the IDT MOTION PRO Y4-S2 camera and the CAVILUX 500W 800 nm LASER illumination system, in order to observe how the defect is formed in the most critical welding condition. The images were also used to measure arc length. Subsequently, thermal images were taken with the FLIR SC 7000 IR thermographic camera, in order to gather information on the relationship between temperature, GMAW variant and humping formation conditions.

RESULTS AND DISCUSSION

Acquired Data

The welding parameters were adjusted to ensure the transfer mode is predominantly spray transfer, with 30 V defined as welding voltage. Once the analog adjustments were performed on the thyristorized power source (conventional GMAW), the same conditions were analogously adjusted on the electronic power source (Dynaflex GMAW). The monitored parameter values are seen in Table 2 (Ks/Kd=indirect inductance control for current up- and downslope; CTWD=contact tip to work distance).

With the acquired data the disparities in current between the two systems is evident, where Dynaflex presented currents at least 100A higher than the conventional, resulting in higher power. This result is power source dependent, but is useful in drawing conclusions regarding process behavior under the different working conditions of the Dynaflex GMAW and the conventional GMAW. The capacity of the electronic transistorized power source in maintaining a higher current (and higher power) for 30 V adjusted voltage leads to higher melting and higher arc pressure, and hence to a wider and deeper weld pool crater (buried arc condition. This results in higher penetration (with proper molten pool stability, as shown by Dutra et al., 2021), as will be described ahead. The oscillograms presented in Figure 1 shows the voltage and current behavior during 1 second, and depict the oscillographic conditions for lower welding speeds and for the limit welding speed for humping formation, for both GMAW technologies.

For welding speeds under the speed limit for humping formation, the welding presented stable behavior for both systems, pointing to a metal transfer regime that occurs by a filament / streaming of molten material without the occurrence of droplet formation and few insipient short circuits. It can be seen that the inductance control of the Dynaflex acted (more intensely at lower speeds), in order to avoid violent short circuiting and crater collapse (as described by Dutra et al, 2021).

Table 2: Parameters acquired for conventional GMAW (C samples) and Dynaflex GMAW (D samples) welding (S=sample; U= welding voltage; Ws=Welding speed; I= welding current; Wfs=wire feed speed; Ks/Kd =adimensional inductance index; CTWD: contact tip to work distance; P=welding power).

S	U (V)	Ws (m/min)	I (A)	Wfs (m/min)	Ks/Kd	CTWD (mm)	P (kW)
C1	30,6	0.6	296,9	15	-	18	9,088
C12	30,4	1.7	309,7	15	-	18	9,422
C20	30,4	2.5	292,4	15	-	18	9,045
D1	29,8	0.6	426,0	15	100/1	18	12,706
D12	29,1	1.7	430,9	15	100/1	18	12,541

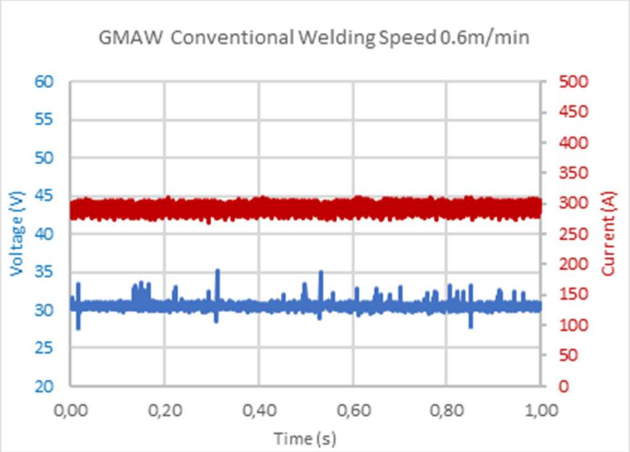


Figure 1. Oscillogram and average parameters in conventional GMAW and Dynaflex GMAW for different welding speeds.

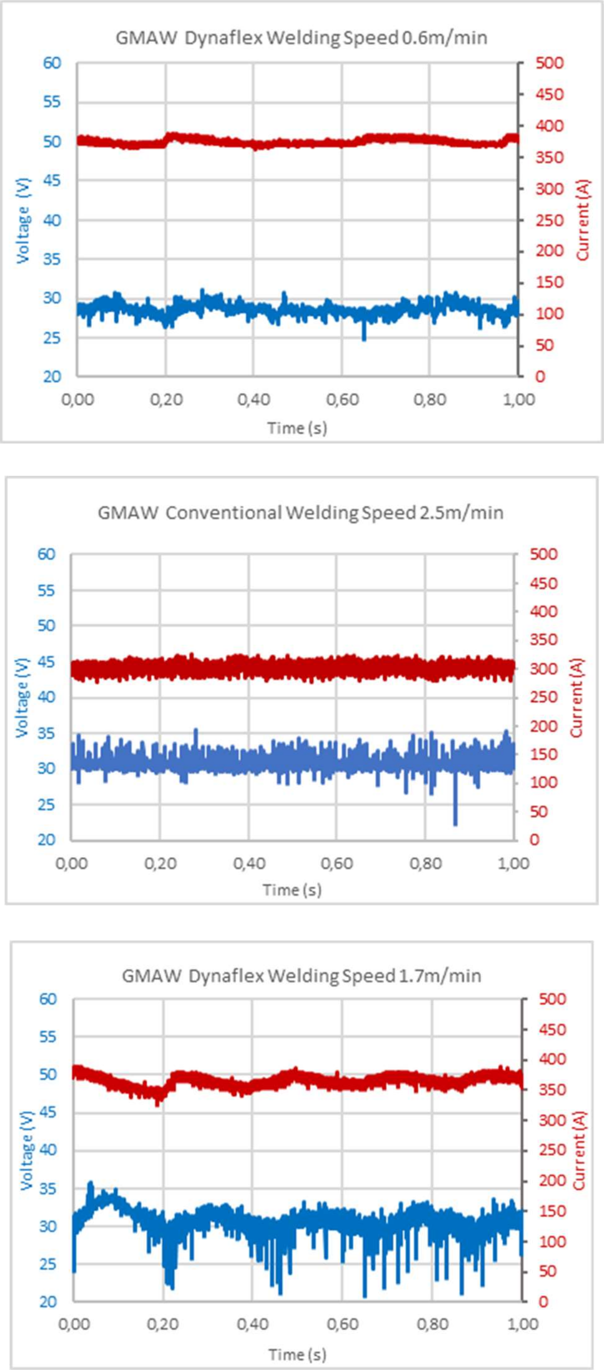


Figure 1. (cont.) Oscillogram and average parameters in conventional GMAW and Dynaflex GMAW for different welding speeds.

High-speed videography

High-speed videography (filming and synchronized welding data acquisition) allowed for a more accurate analysis of the process, making it possible to geometrically measure the arc length and observe the process itself.

Figure 2 (a) and (b) depict the conditions for 0.6 m/min welding speed, whereby the arc lengths were 0.8 mm for conventional and 1.0 mm for Dynaflex. Figure 2 (c) and (d), show the speed limits where humping occurred, the higher speed destabilized the molten pools crater and it is possible to notice an increase in short circuit occurrence. From the pictures in Figure 2 it is also possible to identify aspects of the mechanism of humping formation. Right hand side of Figure 2 (c) and (d) show the arc over the molten pool crater (depression) and in the center of these pictures one can see the hump formed by the molten metal that is pushed downwards (under the arc) and then backwards. The volume of the backwards molten metal flow and its speed is determined by the welding current. Due to the high speed of this flow and the increasing welding speeds, the molten metal accumulates and solidifies, forming the humps (humping defect). Due to the higher welding speeds of the unstable conditions where humping occurred, and consequent less molten metal under the arc, the arc lengths become slightly higher than in the lower speed cases, averaging 1.4 mm for conventional and 1.6 mm for Dynaflex.

Figure 3 shows three video frames of an experimental footage, (a) right after arc extinction, (b) liquid metal accumulating on the bead (center of the picture), (c) hump formed / solidified (center of the picture).

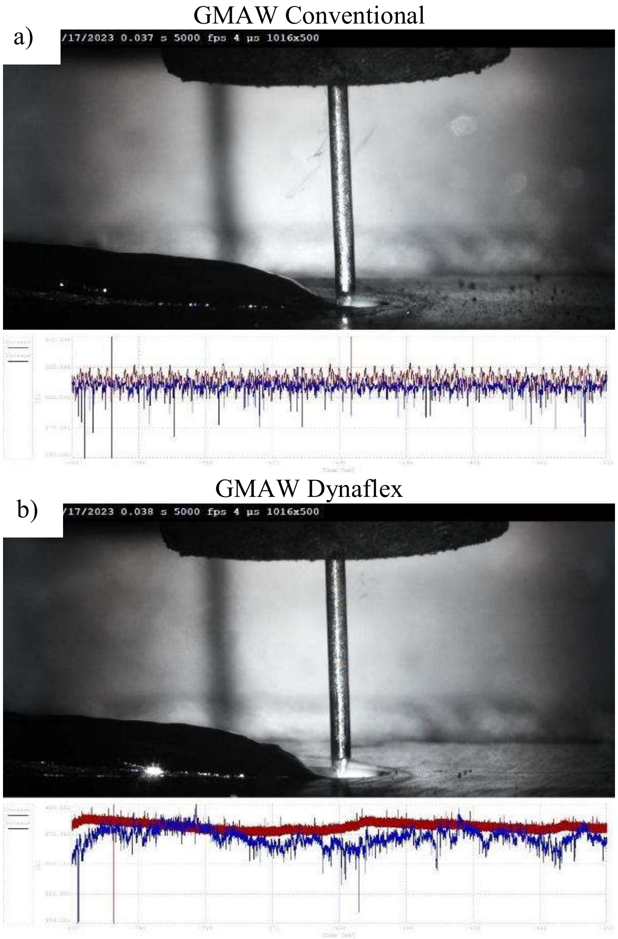
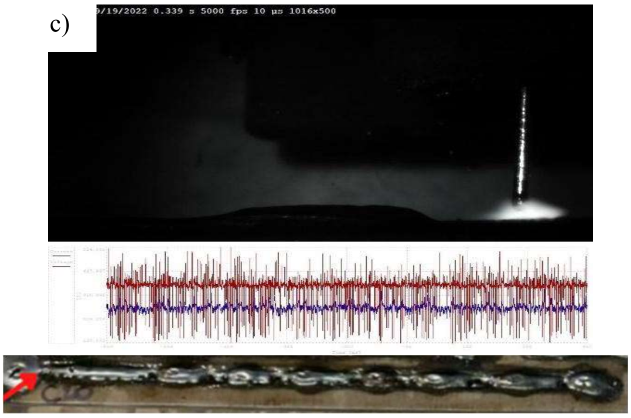


Figure 2. High-speed conventional GMAW and GMAW Dynaflex footage and respective current (red) and voltage (blue) oscillograms, (a) ,(b) Welding Speed 0.6 m/min; (c) humping: Welding Speed 2.5 m/min for conventional GMAW and (d) humping: 1.7 m/min for GMAW Dynaflex (respective speed limits for humping formation).

GMAW Conventional



GMAW Dynaflex

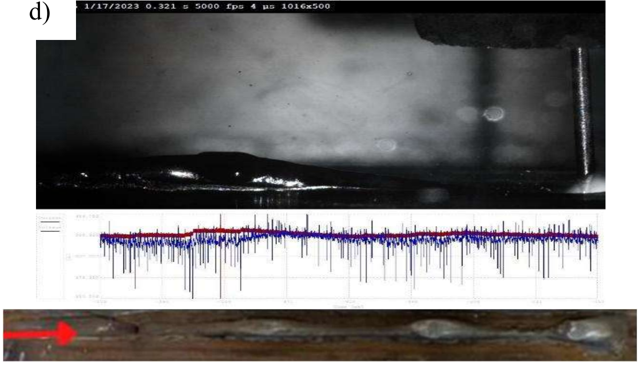


Figure 2. (cont.) High-speed conventional GMAW and GMAW Dynaflex footage and respective current (red) and voltage (blue) oscillograms, (a) ,(b) Welding Speed 0.6 m/min; (c) humping: Welding Speed 2.5 m/min for conventional GMAW and (d) humping: 1.7 m/min for GMAW Dynaflex (respective speed limits for humping formation).

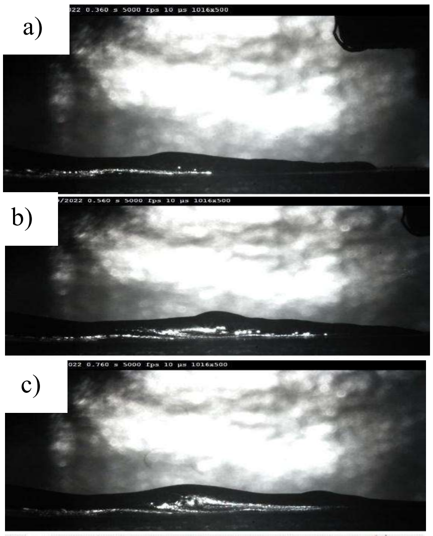


Figure 3: High-speed footage frames for different hump solidification stages (a) right after arc extinction, (b) liquid metal accumulating on the bead, (c) hump formed / solidified.

Macrography

Macrography analysis was performed for the tests described, for measuring of bead geometric features. Figure 4 shows the results for the conventional GMAW, (a) 0.6 m/min, (b) 2.5 m/min (speed limit for humping formation).

Sample C1 (see Table 2), seen in Figure 4(a) shows good penetration (6.2 mm). Despite a good wettability on the bead toes, the bead reinforcement is considerably high. Excess reinforcement is a normal feature of experimental bead-on-plate tests for process related investigations for high-performance (buried arc) GMAW. Real joint applications would require a bevel (even if far smaller than for conventional GMAW conditions), resulting in acceptable low reinforcements (Dutra et al, 2021). Further increase in current led to the direction of a "ballooning" effect, as proposed by Bradstreet (1968), whereas neck geometry is formed between the base and added material. As the welding speed reaches 2.5 m/min, (sample, C20), the humping defect effectively occurs, forming subsequent humps and valleys (Figure 4 (b) shows the cross section of a valley and a hump on the background). The significant decrease in penetration and apparent lack of material is noticeable, caused by the forced displacement of molten material.

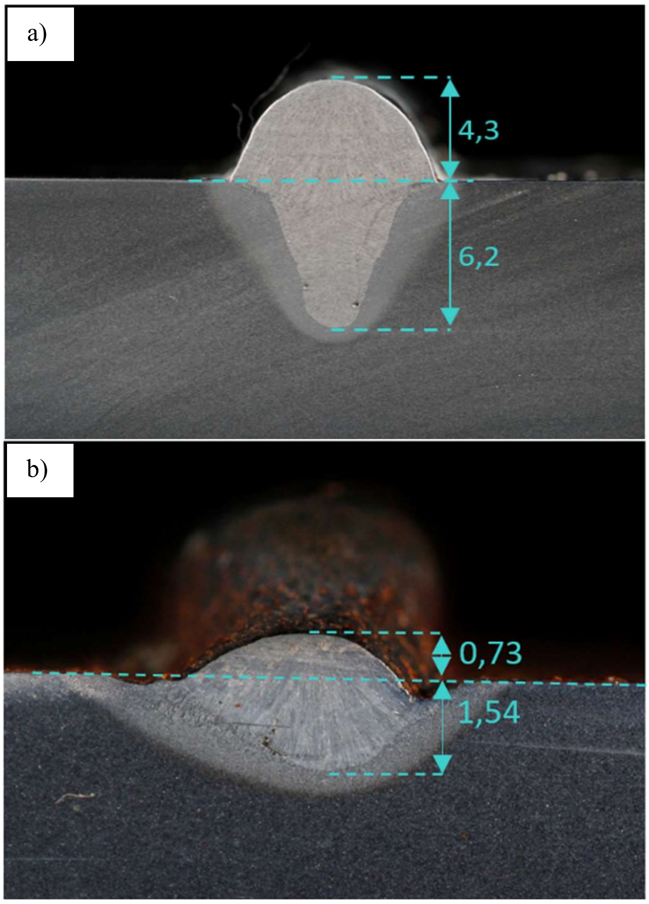


Figure 4: Macrographs, (a) Weld bead C1, Vs = 0.6 m/min; (b) Weld bead C20, Vs = 2.5 m/min.

The discontinuities observed for a current of ~300A in conventional GMAW process tend to corroborate what was suggested by Bradstreet (1968), that humping is accompanied by more than one discontinuity and defects, such as undercut, porosity and lack of fusion. Nguyen, et al

(2005), however, states that for the referred current the undercut defect should not be present.

Macrographic images of the transverse cross section of Dynaflex GMAW beads can be seen in Figure 5.

It is possible to notice that in the D1 sample (see Table 2), at 0.6 m/min (Figure 5(a)), there is a distinct bead morphology from the conventional process at the same speed (Figure 4(a)), with a slightly more convex appearance, with good toe wettability, and higher penetration (7.1 mm). Further increase in welding current led to "ballooning" effect and, ultimately, in sample D12, at 1.7 m/min welding speed, a transversal cut of a hump arose (Figure 5 (b), setting the welding speed limit for humping formation. The bead morphology presented is irregular, with a great penetration decrease, when compared to the other beads, and wide undercut formations on the toes. The geometry of this bead is representative of the irregular and unusual formation that occurs during humping.

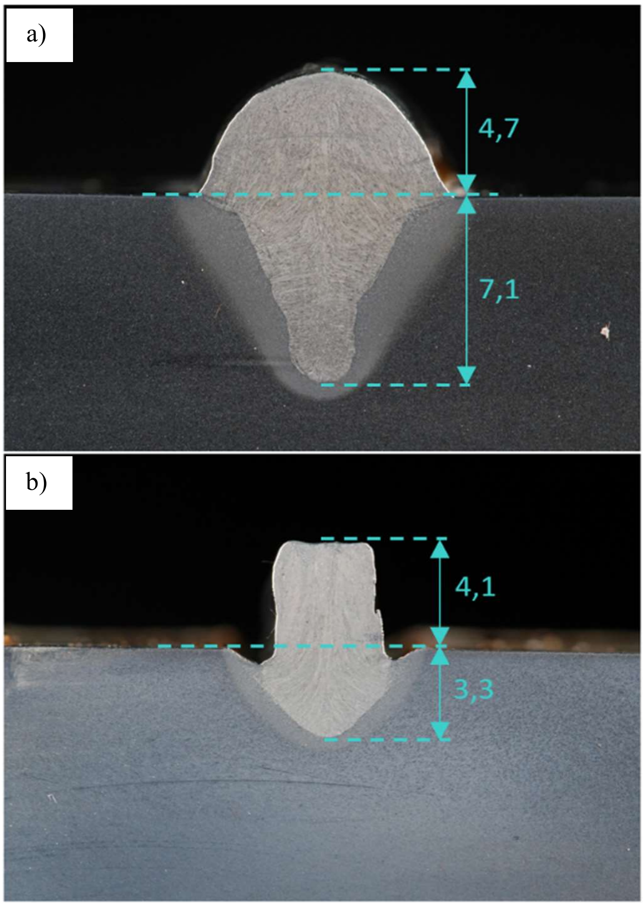


Figure 5: Macrographs, (a) Weld bead D1, Vs = 0.6 m/min; (b) Weld bead D12, Vs = 1.7 m/min

IR Thermography

Due to difficulties of determining molten metal emissivity, the technique was applied qualitatively, with an arbitrary emissivity, with the aim of highlighting temperature differences and not absolute temperature values. For this reason, temperature values on the molten pool below the arc are shown to be lower than steel melting temperature. The analysis of the two welding processes is presented in Figure 6. Using similar welding parameter adjustments and a welding speed of 0.6 m/min, an attempt was made to comparatively thermograficaly evaluate the molten metal pool in regime.

The camera was positioned horizontally approximately 0.5 m away from the bead, with a perpendicular angle to the welding trajectory and the camera focused on the region where the electrode touches the base metal. For the treatment and analysis of the footage the software Altair was used.

Figure 6 (a), conventional GMAW, shows a smaller high temperature area in the arc / molten pool region, in comparison to the Dynaflex GMAW (Figure 6(b). This can be attributed to the lower current and lower molten pool volume of the conventional process. Also, there is a longer temperature gradient on the back part of the molten pool (green, yellow region) of the Dynaflex GMAW in comparison to the conventional GMAW. This can be a result of the higher volume of molten metal pushed backwards and accumulating (forming the hump) by the higher pressure of the higher welding current of the former. The blue intermediary region between the arc and the humps (green,yellow regions) for both process variants have higher temperatures and, thus, lower emissivities (Goett et al, 2013). The hot spot in Figure 6 (b) is hypothesized as being a silica island. This feature is still to be studied in future works.

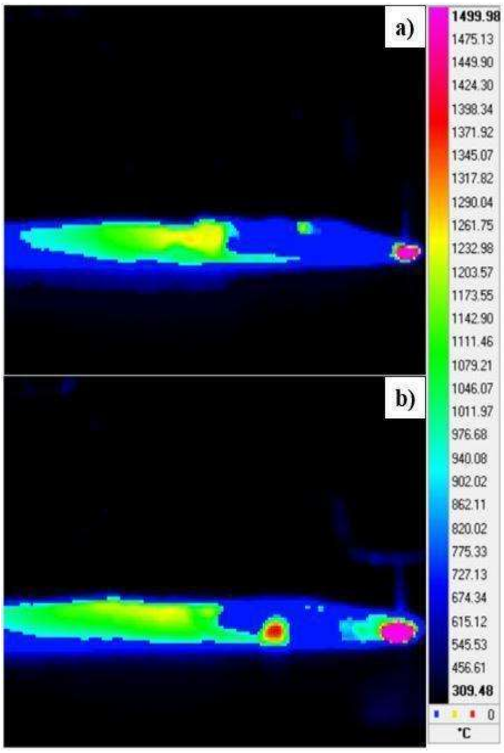


Figure 6: Thermal filming, (a) conventional GMAW ;(b) Dynaflex GMAW.

CONCLUSIONS

Upon considerations and analyzes of the carried out experiments and results, following conclusions can be drawn:

- High performance GMAW (buried arc) conditions depend on the technology of the welding power source. The conventional power source stabilizes the arc in a lower power than the Dynaflex enabled power source allows. This limitation of the conventional power source then melts the same wire speed (melting rate), but at a lower current and longer stickout (more resistive heating is needed);

- Power characteristics of the Dynaflex GMAW variant provided for higher penetration, despite having lower limit speed for humping formation, with pool stability provided by the independent electronic current upslope and downslope inductances control. It is hypothesized that the Dynaflex GMAW´s penetration advantage can be even higher for real beveled applications, and such comparison will be the focus of future studies, under several different welding conditions found in the offshore industry;

- Due to the higher arc pressure in the Dynaflex GMAW condition, humping formation was observed at lower speeds than in the conventional GMAW condition. The weld pool is more intensely "pushed" downward and backward, resulting in intenser molten metal flow to the rear of the elongated molten pool, leading to mass accumulations that solidify as humps and are known as humping, a welding defect.

- High performance GMAW (Dynaflex GMAW; buried arc) conditions are only achieved as a result of integrated parameterization. The trinomial welding current-inductance control-welding speed is especially to be considered. Future work will target developments on Dynaflex GMAW parameterization and overall welding configuration for higher speeds.

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