BEAD INSTABILITY IN ROBOTIC VERTICAL-UP GMA WELDING
(ESTABILIDADE DO CORDÃO EM SOLDAGEM MIG ROBOTIZADA VERTICAL ASCENDENTE)

Américo Scotti
Universidade Federal de Uberlândia
(PO Box 593, 38400-902, Uberlândia, MG, Brazil)

Jair Carlos Dutra
Universidade Federal de Santa Catarina
(PO Box 476, 88040-900, Florianópolis, SC, Brazil)

ABSTRACT

Automated welding (by robot) were carried out in a vertical-up position to compare the efficacy of GMAW process with pulsed current against short-circuiting transfer. The complexity for automation and operational requirements is commented and checked, with special emphasis placed on a bead instability phenomenon. Both versions of the process seem to demand a strict control of the initial arc length to avoid bead misshapening. Short-circuiting GMAW presented a wider tolerance range for parameter selection besides requiring less sophisticated equipment. On the other hand, bead finishing is more convex and the penetration rounded. The pulsed version, on the contrary, develops better bead finishing and less spattering, yet demands the use of automatic arc length control.
KEYWORDS: welding, GMAW, automation, robotic, bead instability, pulsed, short-circuiting

RESUMO

Soldagens automatizadas (por robô) foram realizadas para comparar a eficácia do processo MIG com transferência pulsada e por curto-circuito. A complexidade para automação e os respectivos requerimentos são comentados e verificados, com ênfase especial sobre o fenômeno de instabilidade do cordão. Ambas versões do processo parecem requerer um controle rígido do comprimento inicial de arco para prevenir má formação do cordão. MIG curto-circuito apresentou a faixa de tolerância mais larga para ajuste de parâmetros, além de requerer equipamentos menos sofisticados. Por outro lado, o acabamento do cordão é mais convexo e a penetração mais arredondada. A versão pulsada, ao contrário, resulta em melhor acabamento do cordão e menos respingos, mas requer o uso de um controle automático de comprimento de arco.
PALAVRAS-CHAVE: soldagem, MIG, automação, robótica, instabilidade do cordão, pulsada, curto-circuito

1.0 - INTRODUCTION

During the past few years, there has been a tremendous growth in the application of automated welding processes to achieve higher productivity. Despite considerable advances, a number of related problems have persisted. It is well known that most of the processes in automation are applied in either a flat or horizontal position [1]. In the particular case of the GMAW process, their application is mainly in the semi-automatic mode.

The advantages of GMAW, based on operational versatility (weld pool control for any position and metal thickness) and high production, are widely recognized. The operational versatility is due to the wide range of possible parameter combinations, such as shielding gas, electrode size and composition, arc length (voltage) and amplitude and type of current; there is always a proper combination for a given job. These combinations give rise to special characteristics, from which come the classes of the GMAW process, such as short-circuiting (dip) transfer, spray transfer and pulsed transfer.

Notwithstanding the reasonable balance between productivity and quality obtained by the semi-automatic GMAW process, full automation is still a goal. However, attempts to reach this objective have met some difficulties that discourage the application of the process in some particular situations, for instance, out-of-position and limited access grooves. In the specific case of robotics, the overcoming of these barriers becomes of key importance.

The experience gathered over many years in the application of the short-circuiting class (GMAW-CO_2) is surely one cause of its great utilization. Nevertheless, automation of the GMAW-CO_2 is considered risky due to lack of fusion, bead convexity and spattering. On the other hand, it is a technique utilized with no great equipment sophistication; special power supply is not necessary.

The use of more modern techniques, such as the pulsed GMAW, have a technological appeal based on the uniformity and easy control of the metal pool. Good finishing and little spattering are other advantages.

Contrary to short-circuiting GMAW, electronic power sources (constant current) supplied with automatic arc length control and a system for smooth arc striking are required (with conventional power supply, as in the case of the short-circuiting GMAW, this is unnecessary). Published data [2] has shown a better performance of the pulsed version over the short-circuiting as far as production is concerned.

Attempts to utilize the fully automated Pulsed-GMAW in a vertical up position have similarly shown problems of lack of fusion and penetration [3]. A bead instability phenomenon has also been observed and studied [4]. This instability is characterized by a self-increasing arc length during the welding, for obscure reasons, so that an initially regular bead becomes progressively misshapen (the weld pool collapses intermittently). This fact impedes a long stretch of welds to be developed up hill. In the semi-automatic mode, this phenomenon does not arise (the welder intuitively corrects the arc length).

These facts encouraged the authors of this work to develop a program to allow fully automated GMAW welding, with use of robots and manipulators, in a typical condition where automation is required, that is, welding of long and thick plates vertically positioned. The objective is to compare the Pulsed-GMAW class with the short-circuiting class, so that users can have more assistance in process selection.

2.0 - EXPERIMENTAL PROCEDURE

To minimize the number of variables, it was decided to compare both classes of the process only in a vertical-up position, utilizing an adequate joint for high production automated welding (Figure 1). The process was automated by the use of a robot with 6 freedom degrees, which allowed synchronized longitudinal (vertical) and transverse oscillating movements of the welding gun (frequency = 1 Hz; amplitude = 3 mm ; lateral dwell time = 225 x 10^{-3} s).

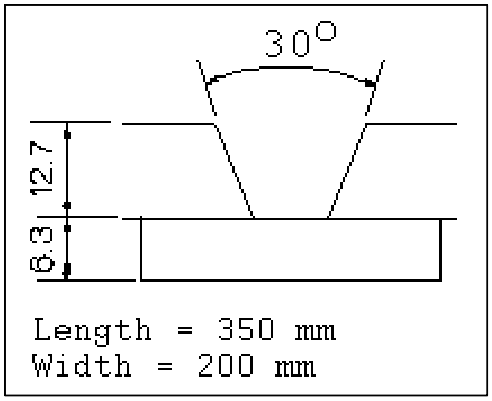

Figure 1 - Shape and dimensions of the test-plate joint (plain carbon steel)

A commercial secondary switched transistored power supply was used for the welding in both the short-circuiting and the pulsed modes. This source suffered some adaptations to permit the maintenance of the arc length (self-correction); should the arc length vary, the voltage is compared to a given reference and a signal is sent to the wire feeder, so that the wire speed is altered and the arc length recovered. In this study, this automatic control is called "external control".

Some welding parameters were kept constant along the work. The pulsed current pattern used was: peak current = 350 A; background current = 76 A; peak duration = 3.5 x 10^{-3} s; background duration = 9.8 x 10^{-3} s; mean current = 148 A. Contact-tip to work distance = 18 mm and travel speed = 14 cm/min were set for both the pulsed and the short circuit versions. The same wire was used in all welding (class AWS ER70S6, size 1.2 mm).

Mixture of Argon with CO_2 and O_2, obtained in a gas mixer, were used as shielding gas (12 to 15 l/min). The reference to these mixtures in this work is made by a code "AX", where "A" means the gas mixed to argon (C for CO_2 and O for O_2) and "X" indicates its content. For example, the gas C7 stands for a 93% Ar + 7% CO_2 mixture.

The welding were monitored by a data-logger board (8/12 bits, 25 kHz) installed in a PC computer and by a software for reading 3 channels (mean current, mean voltage and wire-feed speed). An "Hall effect" probe obtained the current signal. The voltage signal was proportionately reduced in order to be accepted by the data-logger. The wire-feed speed signal came out of a photoelectric sensor (encoder). Filtering or smoothing were not applied to any of the signals.

3.0 - TESTS AND RESULTS

A previous work [4] reported a bead instability phenomenon in some pulsed GMAW welding, occurring after completing a weld stretch. As the first step of this work, a series of test-plates (TP) was carried out in order to observe the repeatability of this phenomenon. Once it was confirmed, variation in shielding gas composition was applied to assess its effect. All welds were carried out with the above-mentioned conditions, except that the external control was disabled (there was no self-correction of the arc length). The initial arc length was adjusted as short as possible for each gas mixture by setting the wire feed speed. The results are shown in Table 1.

In all cases the arc stability seemed appropriate, decreasing a little in TP4 due to short circuits (arc too short). In spite of that, a self-increase of the arc length was always observed (and confirmed by voltage monitoring) along the welds. In an attempt to prevent this arc length increase, a second step of the work was planned. Now, the external control was turned on. Table 2 presents the results.

The results of Table 2 show that the external control was effective in keeping the arc length constant, and consequently the voltage, but, to do so, the wire-feed speed varied to compensate for the tendency of the self-increasing arc length. This effect is illustrated in Figure 2 (lower plot -TP9) in comparison with the voltage self-increasing phenomenon observed when the external control was off (Figure 2 - upper plot - TP10).

Table 1 - Assessment of the shielding gas composition on the bead instability phenomenon (first step - external control disabled)

TP	Gas	Wire-feed rate (m/min)	V_{mean} (V)	Bead Characteristics
2	C5	4.28	21.3	Good at the beginning, becoming irregular after 25 mm of weld
3	C7	4.30	21.8	Good up to 1/3 of the TP's length, becoming unstable, then changing into regular at the end
4	O6	4.20	19.4	Arc too short, but the bead is regular, mainly at the beginning

Table 2 - Assessment of the shielding gas composition on the bead instability phenomenon (second step - external control enabled)

TP	Gas	V_{mean} (V)	Bead Characteristics
5*	C5	21.1	Regular bead during the first 25 mm, becoming unstable ahead
7	C13	22.0	Regular bead all along TP, becoming progressively more convex
8	C5	20.5	Regular bead all along TP
9@	C10	21.0	Regular bead all along TP
10#	C10	21.4	Regular initially, misshaping at the end
11	O2	19.0	Regular bead all along TP
12	O2	18.1	Regular bead all along TP, but the arc was too short

* - *gun oscillation was not used for checking its influence.*
@ - *replicated.*
\# - *external control was disabled so that self-increasing arc length could manifest itself in the same condition as in TP9.*

As the initial arc length value (voltage) seems to be of fundamental importance, a third stage of the work was to step the external control reference voltage into 3 values along the test-plate; thus, three different arc lengths were step-by-step obtained. Utilizing reference voltages of 19 V, 20.5 V and 21.5 V, a weld was carried-out on TP16 (gas C7, I_{mean} = 148 A). The monitoring of the mean voltage and wire-feed speed gave (19.5 V - 4.42 m/min), (20.9 V - 4.21 m/min) and (21.9 V - 3.85 m/min) for each stretch as related to the respective reference voltages. The bead of the 1st stretch (smallest voltage) was regular, while that of the 3rd stretch (highest voltage) was totally irregular. The 2nd stretch appears to be the limit, since the bead tended to instability. Figure 3 illustrates the behavior of voltage and wire-feed speed during the welding of the TP16; as can be seen, the central stretch is more stable.

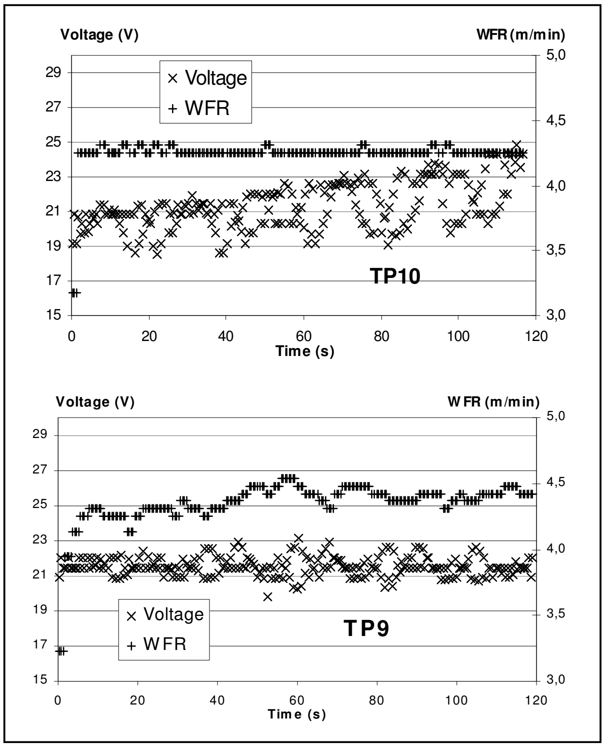

Figure 2 - Effect of voltage variation (TP10 - upper) and wire feed speed variation (TP9 - lower) along the welding stretches

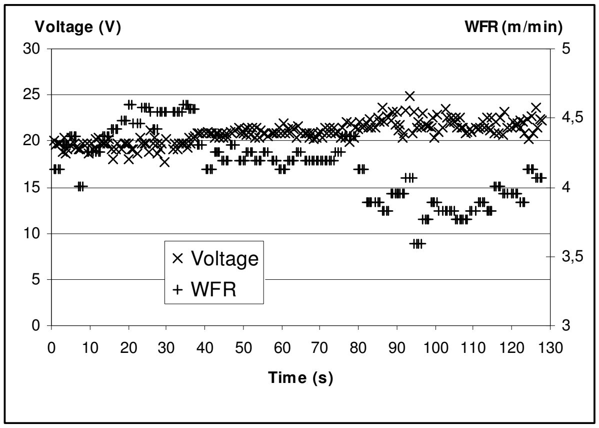

Figure 3 - Oscillograms of voltage and wire feed speed during stepped reference voltage variation by use of the external control in TP16

A new series of test-plate welding (step four) was then carried-out using the pulsed current and with the external control enabled. Some shielding gas variation was applied to confirm the useful range for reference voltage, that is, the voltage range for sound welds. Table 3 presents details of each weld, highlighting the wire-feed speed variation to make up for the arc length self-increase. All test-plates demonstrated good bead finishing, as illustrated in Figure 4.

Table 3 - Assessment of reference voltage on the bead instability phenomenon (fourth step - external control enabled)

TP	Gas	Reference voltage (V)	Mean Voltage (V)	Δ Wire-Feed speed (m/min)
17	C13	21.5	22.0	4.10 to 4.35
18	C5	20.0	20.7	4.04 to 4.30
19	C10	21.0	21.5	4.10 to 4.60
20	02	18.0	18.1	3.91 to 4.46

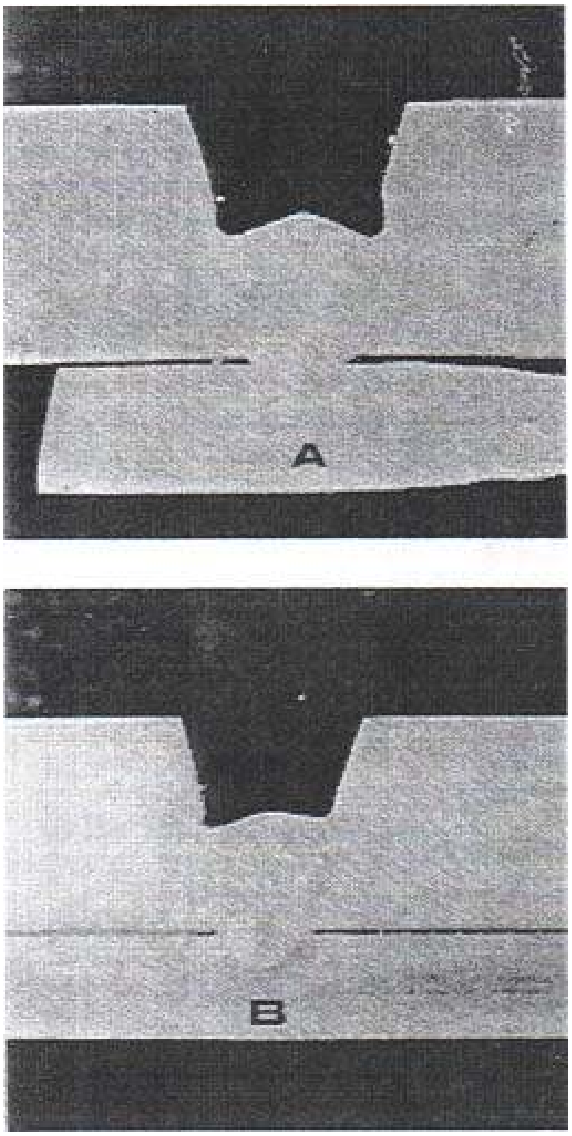

Figure 4 - Test plate sections welded by the automatic (robot) pulsed GMAW: (a) TP16; (b) TP20

The TP20 was then replicated (denoted TP21) with a reference voltage of 19 V. The arc length caused by this voltage shown to be too long and the bead destabilized itself.

In a 5th step of the work, an analog procedure to the TP16 was implemented for the short-circuit GMAW class (100% CO_2 as shielding gas), aiming to see the effect of initial arc length under the short-circuiting mode, too. A TP22 was carried-out by changing the power supply to the constant voltage mode and disabling the external control (it is important to recall that in constant voltage mode the arc length is always kept constant by an intrinsic fusion rate control, known as "internal control"). The wire-feed speed was adjusted to 4.3 m/min, which corresponded to a current of approximately 148 A. The open circuit voltage of the power supply was regulated to steps of 22, 23.5 and 25 V in each stretch of the test-plate. Voltage, current and wire-feed speed were also monitored; the 1st stretch presented (18.5 V - 166.2 A - 4.26 m/min), while the 2nd presented (21.3 V - 159.6 A - 4.27 m/min). The 3rd stretch presented (25.1 V - 151.9 A - 4.25 m/min).

The 1st stretch showed a regular bead, yet too convex (Figure 5 - (a)). The 3rd stretch presented an acceptable bead at the beginning, but unstable afterward. However, the 2nd stretch had a nice bead. As in for the pulsed version, the arc length seems to influence the short-circuiting welding. A new test-plate (TP23) was then carried-out with 22.5 V of open circuit voltage and 4.3 m/min of wire-feed speed to confirm the hypothesis that bead instability also occurs in the non-pulsed current condition. A mean voltage of 19 V and a mean current of 167 A was registered. The bead was slightly convex, but with good aspect. As expected for constant voltage power sources (internal control), there was no self-increasing arc length (voltage) along the welding.

Next, the procedure of the experiment TP22 was replicated, but the external control was enabled at this time (TP24). By doing that with a constant voltage power supply, the external control matched the arc voltage with the reference voltage (in this case, 21.5 V), despite the stepped changes of the open circuit voltage. This was possible through an automatic variation of the wire-feed speed (consequently of the current) to adjust to the different arc voltages (similar to a synergic control). Mean voltage, current and wire-feed speed were monitored as (21.7 V - 124.6 A - 3.05 m/min) during the 1st stretch, (21.6 V - 157.9 A - 4.05 m/min) during the 2nd stretch and (21.9 V - 198.1 A - 5.80 m/min) during the 3rd stretch of the test-plate.

Bead appearance was very good in the 1st and 2nd stretches (Figure 5 - (b)), changing into convex and leading to collapse in the 3rd stretch (Figure 5 - (c)), due to the excessive current. Accordingly, the arc length was demonstrated to be the main parameter for controlling bead instability (21.5 V is within the useful range predicted by TP22).

4.0 - DISCUSSION

The self-increasing arc length became evident by the 1^{st} experimental step (Table 1). The bead gets unstable if the arc length goes over a certain level. The external control, however, demonstrated the ability to keep the arc length constant (Table 2) at the expense of the wire feed rate variation. Moreover, the 3^{rd} and 4^{th} experimental steps confirmed the existence of a useful range for the reference voltage, which must be followed to obtain sound welds in vertical-up position using the pulsed GMAW. The upper limit concerns bead instability, while the lower limit is related to excessive short-circuits, even with pulsed current.

These results parallel the experimental observations in Scotti's previous work [4] very well, regardless of differences in equipment and conditions. It was verified that gas type has no great influence on the phenomenon, but it can restrict the operational range. The range for reference voltages of the external control (for the given groove, electrode, shielding gases and mean current) appears to be from 19 to 20 V, or even smaller (gas O_2). This represents a quite narrow tolerance for the pulsed equipment set-up. A useful voltage range for short-circuit GMAW also seemed to exist (5^{th} work step). It may be said that this extends from 19 to 24 V for the given electrode and wire-feed speed. This range is significantly wider than that for the pulsed condition.

Nevertheless, the reason for the self-increasing arc and bead instability is still uncertain. A hypothesis based on plate thermal stability was rejected in the previous work [4]. Now, a new hypothesis comes up toward a thermal stability of electrode and contact-tip; there would be a set time for the heat stabilization of these parts. This is supported by the wire-feed speed increase up to the point of stabilization, when the fusion rate is higher. More evidence is required.

Another interesting comparison between the two classes of the process concerns bead geometry. While the pulsed current provides finger like penetration (Figure 4), constant current with CO_2 is prone to a narrower and rounded penetration (Figure 5). However, one cannot say which penetration is better since there was no evidence of lack of fusion in both conditions. Nevertheless, beads showed themselves to be more convex for the short-circuit condition, that can lead to worse conditions during the second run. Additionally, spattering is higher and this can block the torch nozzle. This fact can be a nuisance mainly in robotic welding, when cleaning is demanded.

5.0 - CONCLUSIONS

On the whole, bead instability during automatic pulsed welding in a vertical-up position has been confirmed. This instability is caused by a self-increasing arc length phenomenon, which can be avoided by using power supply with external control.

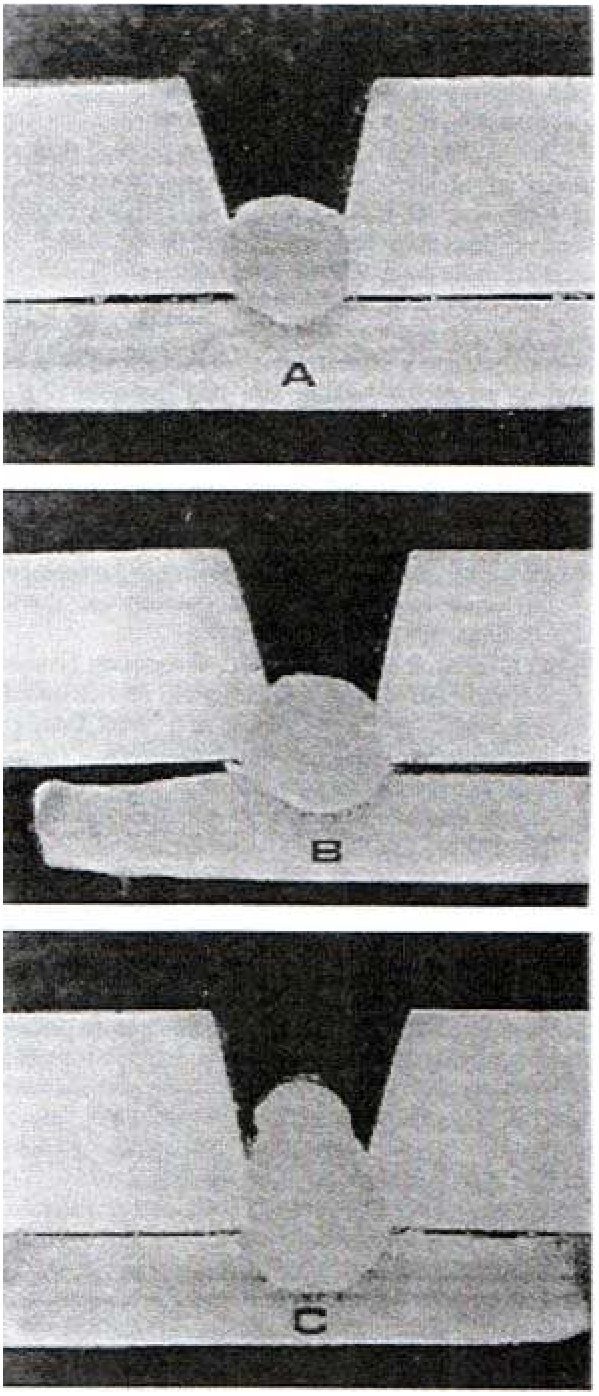

Figure 5 - Test plate sections welded with the automatic (robot) short-circuit GMAW: (a) TP22 - 1st stretch; (b) TP24 - 2nd stretch; (c) TP24 - 3rd stretch

It was also concluded that difficulties originating from automation of the GMAW process, in particular with robots, can be overcome when appropriate equipment and strict control on the parameter set-up is applied.

On the one hand, the short-circuit process class is cheaper and simpler, as far as equipment and shielding gas are concerned. The set-up tolerance is also wider. However, spattering and bead finishing can make its automatic application difficult.

More stable arcs and flat bead finishing, on the other hand, characterize the pulsed GMAW. However, this version demands a stricter initial arc-length setting. In addition, automated welding are only possible if the equipment is provided with arc-length control (external control, for instance).

6 - REFERENCES

[1] AWS. *Welding Handbook - Welding Technology.* (Chapter 10 - Automation and Control). vol. 1, 8th. Edition, 1991, AWS, USA, 637 p.

[2] SCOTTI, A. & PEREIRA, W.A., Comparison between Pulsed MIG and Short-Circuit MAG on Economical Aspects for Structural Building, In: 15th Int. Conf. on Offshore Mechanics and Arctic Engineering - Volume III: Materials Engineering, Florence, Italy, 16-20 Jun 1996, pp. 73-80.

[3] HERRIDGE, B.J. *An Investigation of Weave Parameters in Multi-Pass Orbital MIG Welding*. MSc. Thesis, Cranfield Inst. of Tech., UK, 1988, 109 p.

[4] SCOTTI, A. et al., Bead Instability of Mechanized P-MIG Welding in Vertical-Up Position. *The International Journal for the Joining of Materials*, 3 (1), Mar 1991, pp. 18-24.