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Dynamically-Flexible Arc – A Novel Interpretation for the High Performance GMAW

Regis Henrique Gonçalves e Silva[1], Jair Carlos Dutra[1], Mateus Barancelli Schwedersky[1],
Cleber Marques[1], Kauê Correa Riffel[1], Rafael Albino Bernardi[1]
LABSOLDA / UFSC – Welding and Mechatronics Institute, Mechanical Engineering Department, Federal University of Santa Catarina
Florianópolis, Santa Catarina, Brazil.

ABSTRACT

A number of versions of the MIG/MAG process has appeared in the market to cope with the welding of joints formed by high thickness sheets without the need for beveling. This originated in the 1980s under the designation of Transferred Ionized Molten Energy (TIME), whereas the 1990s saw the names Rapid Arc and Rapid Melt emerge and in early 2001 the technique was revisited under the name of Buried Arc. These developments did not reveal and do not reveal in principle any special version of the MIG/MAG, but rather showed technical implementations and the conjugation of variables and parameters to improve the geometric profile of the bead obtained, although some submitted patent applications. Recent modern product launches from 2010 on, in a huge profusion of new nomenclatures and many under the aegis that everything depends on a special technology embedded in the welding power sources have overwhelmed the users lately. This paper presents a new interpretation for what is really critical to achieve a high performance of the MIG/MAG process in terms of penetration. The welding power source may be based on the more conventional mode of the process, i.e. in the voltage control mode (CV). However, what the source effectively has to meet is a certain dynamic response in order to sustain a metastable equilibrium of the molten pool that is deepened in the joint in the form of a semikeyhole. The equipment must react very rapidly in the face of a physical contact between the wire-electrode and the weld pool and return to its steady state very slowly. This type of power source reaction is what some manufacturers obtain by the use of pulsed current, but without any correlation with the control of the metallic transfer, as claimed by these manufacturers. The present work presents practical results of both welding and the method to determine the required dynamic behavior of welding sources suitable for this technology.

KEY WORDS: Deep Penetration GMAW; Inductance Control; Current Dynamic; Voltage Control.

INTRODUCTION

Just over ten years ago, numerous commercial designations have appeared on the market for a GMAW application spectrum intended to meet a high melting rate, or to produce a special weld bead geometry. In the literature, these GMAW versions are treated as High Performance GMAW Processes (DVS Merkblatt 0909-1, 2000; DVS Technical Bulletin 0973, 2017). As examples, there are process versions which apply two or more wire-electrodes and variants that use an additional wire, such as the GMAW hot/cold wire (Ribeiro et al, 2015). However, the current propensity for the High Performance GMAW (HP-GMAW) designation directs the process to a penetration enhancement condition, generating process stability and more suitable weld geometries for thick plates in addition to providing a productivity increase.

As the proliferation of commercial offers on the market to meet such purpose is intense, each of them presents somewhat different justifications. Therefore, it has been a challenge for the end user to identify what is really behind each commercially marketed technology. So far, there are not enough scientific reports that explain or justify the different fundamentals presented by welding equipment manufacturers.

For example, some welding equipment suppliers justify their technology based on the use of pulsed current, although in an average current range in which the droplet transfer does not maintain a dependence on the current pulse value (Auenwald and Vollrath, 2009). In some cases, whereby even higher currents are adjusted in order to obtain higher penetrations, waveform analysis allows to verify that even the base current results in a range already above the spray transfer transition value, thus no longer characterizing the usual one drop per pulse condition, which then migrates more and more toward a pure spray transfer.

According to Matusiak and Pfeifer (2008) in the early 1990's the Swedish company AGA developed the trademarks Rapid Arc and Rapid Melt, with which Bengtsson and Skarin (1992) published demonstrative results in 1991. The (then) new developments did not reveal any innovative process in essence, rather they showed technical implementations, welding configurations and parameters conjugation aiming at welding procedures for increased productivity, either by increasing the wire melting capacity or by modifying the weld bead's geometric profile. The difference between the Rapid Arc and the Rapid Melt consisted only in the process operational range. Rapid Arc worked at a voltage and wire speed range lower than Rapid Melt. The latter would promote a deeper penetration compared to the former. According to reports, non-pulsating conventional power sources were used. Therefore, despite indications that the constant voltage mode was applied, there is no information about the type of power source (constant voltage or constant current) (Matusiak and Pfeifer, 2008).

Concurrently, other developments have appeared as, for example, the one designated as T.I.M.E. (Transferred Ionized Molten Energy), which was based, additionally to a higher current density, , in the use of a quaternary gas mixture (65,0Ar, 26,5He, 8,0CO_2, 0,5O_2) using a constant voltage power source (Church and Imaizumi, 1990; Stenke et al, 1991; Lahnsteiner, 1992).

In the year 2001 Stol et al. (2006) worked together with Alcoa in the development of aluminum welding procedures. It was the origin of what is recognized as buried arc, stating that neither special equipment nor specific wave formats are necessary, although they required a patent in the United States in 2004.

Hence, based on the information stated in the literature, it can be inferred that the technological basis to reach GMA weld beads with deep penetration profiles, as shown in Figure 1, is the adequate conjugation of the electrical variables, shielding gas and wire-electrode configurations, and weld speed. The core of the issue is the formation of a weld pool in the form of a stabilized crater, which enables the arc action in depth. If the arc and weld pool have an appearance similar as shown in Figure 1a, although with higher power than the condition in Figure 1b, the penetration will be deeper. Moreover, the risk of undercut on the weld bead's edge is higher. Fundamentally, a high pressure over the weld pool is necessary, which is dependent on a high current. On the other hand, the arc voltage exerts a conflicted energetic function, because if it is relatively high, it produces high power, but the weld bead's geometric configuration tends to Figure 1a. A situation as shown in Figure 1b has lower electric power, but reaches higher current density in addition to the buried arc effect and the deep crater. This crater generated in the molten pool has a similarity with the keyhole mode achieved in the High current Plasma and GTAW processes (Rosellini and Jarvis, 2009; Olivares et al, 2017). As for these processes, the welding current in GMAW is the main parameter governing the depth of the weld pool crater. However, there is a collateral factor that acts unfavorably to this, which is the inherent interdependence between the current and the wire melting rate. In other words, in order to achieve high current values, the fed wire-electrode amount must proportionaly high. However, much filler metal tends to close the crater. Thus, the key point of the GMAW technology that aims to obtain weld profiles such as in Figure 1b, is the appropriate conjunction of the whole parameters set, with a remarkable importance on the welding speed. I It must be adjusted in order to avoid large material accumulation between the arc and weld pool. The crater must be kept in a configuration as shown in Figure 2, which presents images captured by high speed videography carried out at UFSC's Mechatronics and Welding Institute - LABSOLDA, depicting a high penetration welding procedure in the buried arc mode. The strong arc pressure caused by high current value performs elevated base material melting while pushing the weld pool down.

EXISTING FUNDAMENTALS AND NEW KNOWLEDGE BASE OF THE HIGH PERFORMANCE GMAW

Keeping a continuously open crater, enabling the arc to act in depth, is not an elementary task. Citations in welding equipment advertisement highlight that high performance welding requires a large contact tip to work distance (CTWD), fact that is contradictory, since a higher CTWD acts in order to increase the melting rate, which hinders the deep arc. Then probably the reasons for a high CTWD are related to contact tip protection and torch heating reduction, so they do not suffer severe wear due to the high arc power and conditions remain constant, in addition to better accessibility in narrow joints.

As mentioned, the in depth action of the arc requires a conjunction of factors in order to keep the crater opened. A metastable equilibrium is reached, in which the force created by the arc pushes the liquid metal away from arc's base, avoiding the crater to collapse. However, due to the system´s condition and weld pool´s dynamics, short-circuits are intrinsic to the process. Therefore, the weld pool in metastable equilibrium needs conditions to remain so, in case a short-circuit occurs. In addition to a harmonic parameters setting, the welding current must respond very quickly to any event that may break the metastable equilibrium. For that, welding equipment manufacturers conceive solutions and announce them as determinant features in their technology. They commonly work, although not for the reasons and explanations usually given. For example, some manufacturers apply pulsed current in their technology and infer that there is a metallic transfer (droplet transfer) control and that this is key for the high performance achieved. In fact, current pulsing in high frequencies causes a dynamic mechanical action against the physical contact between the weld pool and electrode's tip, which is liquefied.

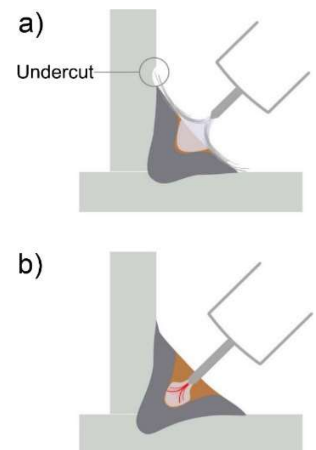

Figure 1 – Arcing configuration in two situations; a) Arc acting over the puddle; b) Arc acting inside a crater ("buried") (EWM Group- Force Arc).

In order to verify this assertion that the pulsation itself is not the reason for obtaining the desired results, in this work a transistorized welding power source was used, operating in the conventional GMAW mode (constant voltage). One of the distinctive features of the highly flexible, open architecture power source used is the possibility of adjustment of the welding current dynamics (inductance) in short-circuit events. This setting is electronic (provided by software) enabling an individual adjustment of the values relative to current up slope phase and to current down slope phase. In a series of experiments it was found that, to keep the metastable equilibrium, the power source should trigger its reaction promptly at the short-circuit moment in a high dynamic fashion for an accelerated contact break, but should not vary its output very rapidly after contact break, in the restoration phase to the regime condition. An inappropriate adjustment results in events such as presented in Figure 3, in which the physical contact between the wire-electrode's tip and weld pool implicates, due to a relatively long time period, in crater closing. This impairs the continuity of the deep penetration profile. Spattering increase is also a highly likely consequence. When the inductance is set to an elevated reaction capacity (low inductance), at the physical contact (short-circuit) instant, these tendencies are practically not observed, remaining a crater condition as shown in Figure 2.

Figure 2 – Crater created by arc pressure on the weld pool. Tests carried out in bead on plate conditions.

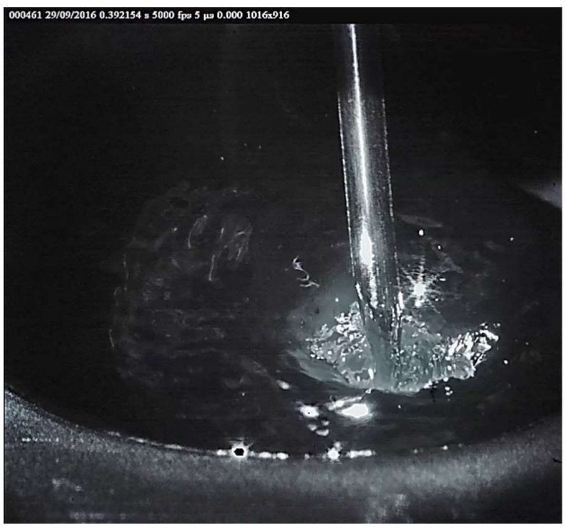

Figure 3 – Crater instability during short-circuiting due to an inadequate inductance adjustment (high speed video on LABSOLDA'S Channel on – https://youtu.be/zCr5Imyf4fM).

From the aforementioned and discussed factors, it becomes clear that a characterization of the dynamic behavior of the welding power source is paramount. Normally, when at all available, the adjustment of the dynamic behavior of the power sources is performed indirectly, by means of indicative indexes, and not the actual physical quantity, which is inductance. In order to characterize and quantify the dynamic behavior of the power source used in this work, an electrolysis procedure using a carbon electrode submerged in a saline solution with sodium chloride ($NaCl$) and water (H_2O) was carried out. The cathode and anode were connected as shown in Figure 4. This procedure allowed for the verification of the current dynamics with the advantage of not requiring an open arc welding test. In order to reach a saturated electrolytic solution, a ratio of 36 g of NaCl for each 100 g of water was adopted.

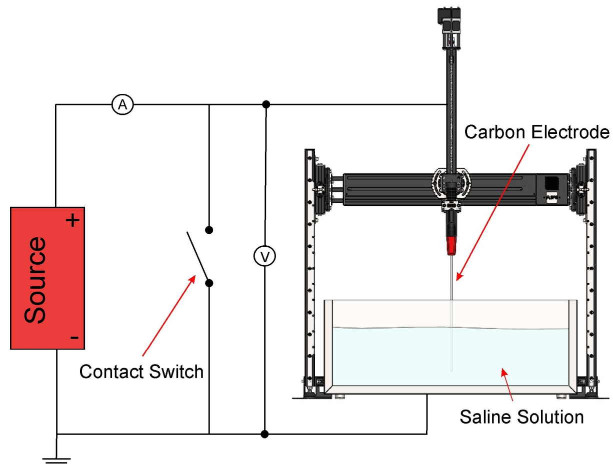

Figure 4 – Electric connections and experimental rig layout for power source dynamic response experiments.

The power source was set up in constant voltage mode and adjusted value of 32,5 V (the same value applied to welding tests), which renders the welding current dependent on the solution´s electric conductivity. This, in turn, can be adjusted through the amount of NaCl and the distance between cathode and anode inside the water container (plunge depth of the carbon electrode). When the desired current intensity (same value achieved in welding tests, around 350 A) is reached, a temporary short-circuit was induced through a circuit parallel to the saline solution, connecting the power source's poles directly, as represents the switch in Figure 4. Thus, the current reaction before and after a short-circuit event was measured to the condition applied in welding tests. Figure 5 presents the graph that corresponds to the welding current dynamics setting found most favorable to maintain the metastable equilibrium with a buried arc during the welding process parameterization phase (Table 1 shows the established parameters and Figure 6 depicts the resulting metal transfer and weld pool profile). The dI/dt (current rate per time rate) was approximately 70000 A/s in the upslope phase and 300 A/s in the downslope phase.

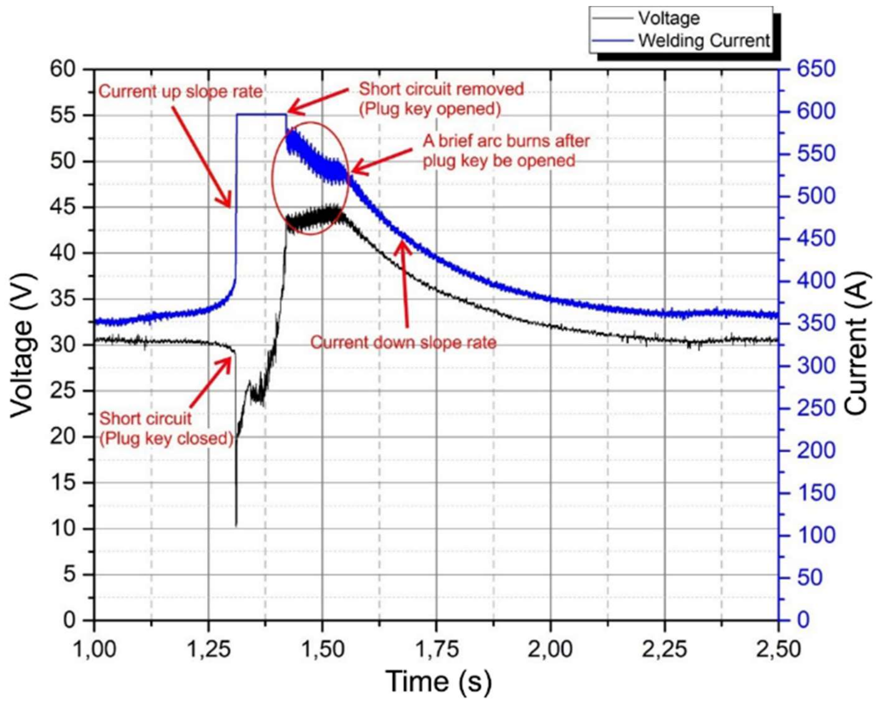

Figure 5 – Source response (current's up and down slopes) in a short-circuit event for an adequate inductance regulation.

Table 1 – Welding parameters set on IMC DIGIPLUS A7 power source.

Parameter	Value
Average Voltage	32.5 V
Average Current	370 A
Wire Speed	13 m/min
Welding Speed	0.45 m/min
Dimensionless parameter Ks (dI/dt up slope period)	100
Dimensionless parameter Kd (dI/dt down slope period)	1

The real inductance value is calculated by the following equation:

$$L = \frac{0.02}{K}\ (H)$$

Therefore, in order to keep the process in a metastable equilibrium, and then stability and constant penetration, the source must react relatively rapidly after a short-circuit event and smoothly in the arc re-stabilization, provided by flexibilization of the arc's dynamics. In this context, this GMAW version was designated as *Dynamically Flexible Arc (DynaFlex-Arc)*.

WELDING CURRENT MODE COMPARATIVE ANALYSIS FOR HP GMAW

For the conditions applied in this work, the metallic transfer takes place through a continuous filament of melted material at the wire-electrode´s tip, without single well defined droplet formation (Figure 6). The literature cites the use of pulsed current with single or multiple drops formation during each pulse period, such as in paper describing the *Speed Pulse* version (Jaeschke, 2009), as well as can be seen in the *Rapid Arc* version (Figure 7).

Aiming to present a comparative performance analysis between HP GMAW welding current modes and the respective dynamic behavior in the face of short-circuit events, the current up slope for *Rapid Arc* GMAW versus the one for the version proposed in this work (*DynaFlex-Arc*) were monitored. Figure 8 shows both oscillograms. Even though a markedly higher current dynamic is observed for the *Rapid Arc*, in a buried arc condition, mentioned relevant benefits in penetration and weld geometry could not be established. Neither could stability gains be inferred, as shown in Figure 9 with the respective voltage oscillograms (voltage's dynamic behavior / regularity is an index of process stability (Hemans, 1999)). As a matter of fact, the oscillograms in Figure 9 and the HSV frames in Figures 6 and 7 show much intenser impact of the short-circuits on the electrical behavior (process stability) for the pulsed version. These facts indicate that the pulsed current mode with extra high current dynamics is not necessary, as these existing in pulsed versions for high performance welding. For satisfactory welding results, features required from the power source are the capability to react promptly and discretely (only when the metastable equilibrium is affected by crater closing tendency due to short-circuits) and to provide a sufficiently rapid current dynamics for a determinate condition.

Figure 6 – Crater formed in the *DynaFlex-Arc GMAW* (high speed video on LABSOLDA's Channel on - https://youtu.be/RkpVX2cv1qc).

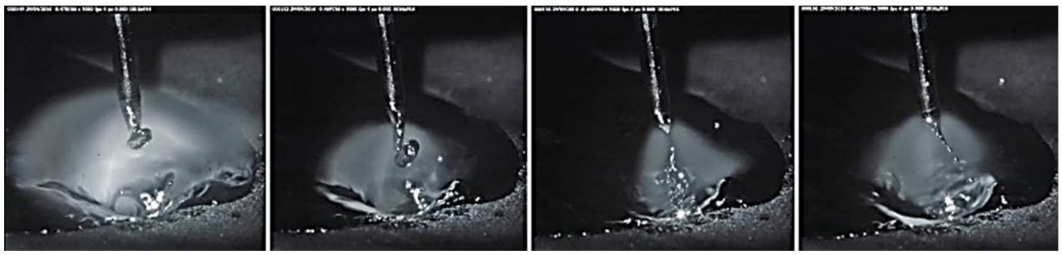

Figure 7 – Rapid Arc's metallic transfer- multi-drops formation during the pulse period. (high speed videos on LABSOLDA's Channel on - https://youtu.be/OAD3HNoIRX4).

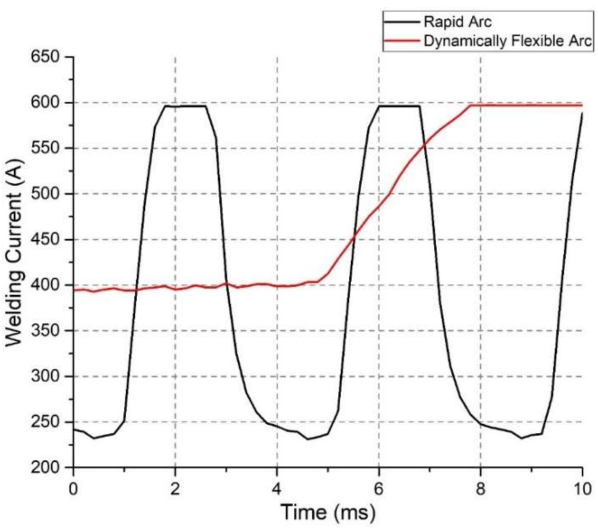

Figure 8 – Comparative oscillograms for proposed system (*DynaFlex-Arc*) in response to a short-circuit event versus the *Rapid Arc* pulsed wave form.

VERIFICATION AND VALIDATION TESTS FOR THE PROPOSED *DYNAFLEX-Arc* GMAW VERSION

In the welding tests for verification and validation of the optimized inductance technique that characterizes the *Dynamically Flexible Arc* GMAW version (DF-Arc), fillet welding joints ("T" type) of carbon steel plates 3/8" thick were performed in the horizontal position, without groove or gap, as the scheme in Figure 1. The wire feed speed was 15 m/min (ER 70S-6, 1,2 mm of diameter) and the voltage was set in 32.5 V. The first choice for shielding gas was an Ar+8%CO_2 gas mixture. Even though process stability was excellent, porosity was detected (Figure 10a). In an attempt to improve the welding quality, experiments were carried out with an Ar+25%CO_2 mixture. In spite of a slight reduction of process stability and spattering occurrences, pore free high penetration profiles (Figure 10b) were obtained. This can be a consequence of a higher heat input due to increased CO_2 content, resulting in higher solidification time and facilitating outgassing (Irving, 1994; Ebrahimnia et al, 2009).

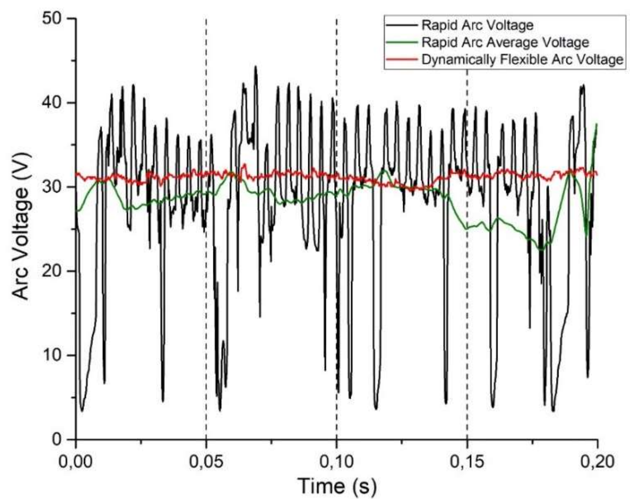

Figure 9 – Voltage oscilograms measured in buried arc condition for *Rapid Arc* and *DynaFlex-Arc*.

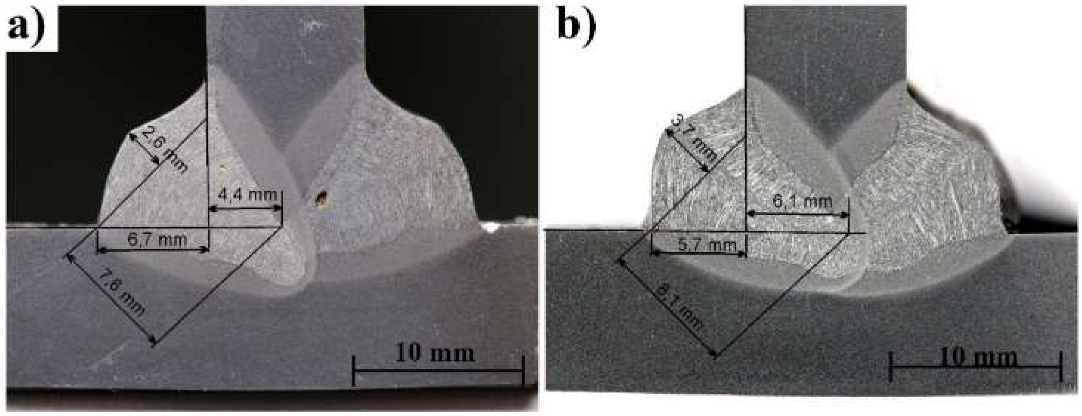

Figure 10 – Fillet joints welded through buried arc methodology and inductance control (*DF-Arc*). In a) Ar+8CO_2 gas moisture; b) Ar+25CO_2 gas moisture.

CONCLUSIONS

In spite of the first works approaching high penetration GMAW having mentioned that welding power sources with special characteristics as pulsed current, different wave formats and control methods (and therefore, more expensive) are not necessary for the intended results, the disconnection between the past and the new technologies, launched and announced as innovations by some manufactures, have conducted to an inaccurate interpretation of the reasons for which high penetration profiles are reached. The molten pool´s metastable equilibrium, needed for keeping the created liquid crater stable, is maintained by means of rapid power source electrical reactions in the eventual instants of short-circuiting. On arc restriking, the welding current restoration to its regime value must run slowly. It is believed that some equipment manufacturers when launching new power sources for the aforementioned application with the utilization of pulsed current are indeed performing a much more complicated (and likely more expensive) way than the welding process´s physics really requires. The waveform of these sources, as they change from base to pulse current, really do it faster than when reducing from pulse to base. If the metastable equilibrium is lost there is always an imminent current pulse with an acceptable dynamic and posteriorly a slow current down slope. But the fact is that the periodic pulses are most often not required because the metastable equilibrium of the pool tends to be maintained.

This work demonstrated that a power source just needs to provide dynamic characteristics only sufficient to maintain the puddle in a metastable equilibrium in a form similar to a keyhole, so that the arc acts continuously in depth. Independent dynamic characteristics (inductance) adjustment enables optimization of the welding current upslope and downslope for distinct welding conditions. For the welding conditions of this work, the high penetration GMAW technique was enabled by a current up slope rate of 70000 A/s, while the current down slope rate was 300 A/s, method that was called *Dynamically Flexible Arc (DynaFlex-Arc or, for short, DF-Arc)*. Ar+25%CO_2 as shielding gas resulted in better macroscopic results than Ar+8CO_2.

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