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A Review on the Advanced High Performance GMAW Variants under the aim of the Dynaflex Technology

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ABSTRACT

Understanding the key differences between the High Performance Gas Metal Arc Welding – HP GMAW – variants and the conventional process variants and their conceiving and development scenario is paramount for their further evolution and customization for distinct heavy thickness joint welds or cladding applications, as found in the Offshore, Shipbuilding and Oil and Gas sectors. This paper aims to delineate the characteristics of the conventional GMAW process under high current conditions and thereby contrast the differences from the High-Performance variants (GMAW-HP) processes, emphasizing the group of processes identified by the German Welding Society - Deutscher Verband für Schweißen (DVS) as 'Modified Spray Arc'. Based on a literature review and supporting experimental work, the present paper explains and demonstrates the operational functionality of the GMAW variant called DynaFlex-Arc, highlighting the distinct features within this high-performance group of processes.

Keywords: high penetration MIG/MAG welding; high power GMAW; spray streaming; inductance control.

INTRODUCTION

According to the American Welding Society (AWS) (2004), the concept of Gas Metal Arc Welding (GMAW) was introduced in the 1920s, yet its development only took place between the 1940s and 1950s, evolving from invention designs to more robust versions suitable for industrial applications, as per some patents from that era (Kennedy, H., 1950; Lesnewich, A., 1958; Muller, A., 1950; Muller, A. et al., 1950). In summary, the system involved the use of an arc welding power source capable of adjustable values for voltage and wire feed speed, causing the current to naturally vary within a specific operational range, aiming to melt just enough material to maintain a constant arc length. Consequently, this setup facilitated stable metal transfer. Subsequently, the filler material was provided by a coiled electrode wire that continuously fed the molten pool, maintained under the atmosphere of an inert or active gas directed over it. Essentially, the foundation of what we now recognize as conventional GMAW (Júnior, R., 2002; Kah, P. et al., 2022; Egerland, S., 2015).

Over the years, welding power sources have evolved in terms of their internal constitution and can be classified into two groups: The first group comprises conventional sources, based on analog control architecture, conceived in the 1950s. These are further divided into static sources, primarily based on a transformer directly connected to the power grid, and rotary sources, based on motors that drove power generators. The second group consists of modern welding power sources, which began to be commercialized in the 1970s. These sources featured more robust electronics, initially based on thyristors. Subsequently, in the 1980s, came the transistorized inverter sources with faster response times, still extensively used by the industry today (Dutra, J., 2023).

Thanks to these technological advancements, still between the 1970s and 1980s, it became feasible to utilize a power source operating in current mode, with the electronic modulation of this waveform, enabling the programming of base and pulse parameters. Consequently, this allowed for a more precise control of the metal transfer throughout the welding process. In this way, it became possible to determine different times and current values, with improved repeatability of droplet formation and detachment cycles, thus resulting in more precise establishment of both transition ranges and operation modes of transfer.

With proper adjustments, it became possible to achieve a drop transfer per pulse in spray mode, with an average current, where only short-circuit transfer would occur in an operation under the same conditions but in non-pulsed mode. In other words, in the pulsed mode, it became feasible to execute a spray transfer below the transition current, consequently requiring less energy and producing fewer spatters compared to a short-circuit transfer, with the relevant advantage of a better joint fusion and wettability. The main roles of the puled waveform are providing heat for droplet melting and formation, as well as providing detaching forces to counterbalance the droplet retaining force. Two main theories are available for the free flight metal transfer, i.e. the Force Balance theory and the Pinch instability theory. Such roles of the pulsed waveform and free-flight metal transfer are discussed in numerous works, as in Scotti, A. and Ponomarev, V. (2014) and Amin, M., (1983). Thus, the variant of GMAW that is now recognized as Gas Metal Arc Welding Pulse (GMAW-P), or the pulsed operation mode, emerged. Later on, synergistic technology advancements contributed to the development of variants such as Cold Metal Transfer (CMT), as demonstrated by Mvola et al. (2017) and Galeazzi et al. (2022). Further recent studies tackle an array of advanced process variants, where influence of current waveform on droplet behavior, due to a more accurate modulation of welding energy, is further examined, such as those by Dutra and Silva (2009), Huang et al. (2023), and Norrish (2024).

In addition to the advantages mentioned earlier, from a weldability standpoint, it is worth noting that GMAW-P also promotes metallurgical improvements in the weld. According to experiments conducted by Barra (2003), it was observed that there is a relationship between the frequency and shape of the pulses, the average current and the cooling time of the weld and resulting microstructure. When compared to conventional GMAW under similar conditions, a reduction in grain growth can be achieved, also helping to prevent hot crack formation.

With the improvements integrated into power source systems such as enhanced electronics (notably the evolution of microcontrollers), faster dynamics, and the capability for real-time measurements of parameter variations like electrical transients and wire feed speed changes, coupled with the processing of this information in timely responses, it became possible to conceive two additional modes of power source operations: the synergic and adaptive modes. The so-called synergic modes consist of electronic sources operating based on predefined algorithms, fueled by previously tested parameters. These algorithms are used to control metal transfer across various welding jobs, varying according to electrode diameter, material, welding speed, among other factors (Filho, D., 2014). On the other hand, adaptive modes rely on real-time process monitoring, spanning from input parameters to the stability of metal transfer and the final appearance of the weld. Thus, the system is fed back, automatically making necessary adjustments to welding parameters based on algorithm operation responses. This ensures process stability and, consequently, enhances the quality of the welded joint (Quites, A., 1989).

Furthermore, it's worth highlighting that operation modes can also be operated in a mixed manner, as seen in the case of Synergic Pulsed GMAW (Amin, M., 1981; Mvola, B. et al., 2013) and Controlled Short Circuit (CCC) (Dutra, J. et al., 2007; Silva, R. et al., 2021).

In conjunction with the technological development of both hardware and software in power sources, it's also necessary to conduct research that enables a better understanding and refinement of the effects that all this technology can promote in the electric arc (Lemes, J. et al., 2017). In this sense, and now from a more specific perspective, studies regarding the influence of inductance on welding current have been developed with the aim of enhancing the stability of welding processes (Lara, M. et al., 2020; Kah, P. et al., 2022). It's important to note that inductive circuits represent a settled subject within the field of electrical engineering, as per the literature (Alexander, K. and Sadiku, M., 2016), however, the effects of current variation caused by inductance on the stability of metal transfer concerning spatter occurrence, bead geometry, and mainly the potential to enhance deposition rate efficiency, still stand as a topic under discussion within the field of welding engineering.

With the aim of setting the basis for understanding the origin scenario and subsequent development of the HP GMAW, and hence contribute to its further development and customization for different applications and welding conditions, a literature review is presented, complemented with a practical application example. For this, the paper shows DynaFlex-Arc´s performance on achieving welding speeds of approximately 60 cm/min, wire feed rates around 15 m/min, allowing versatile application for welding both 9.52 mm thick steel plates using ER70-S6 wire and for overlaying using Inconel 625 wire, enabled by refined inductance control. DynaFlex-Arc differs from conventional GMAW, not only due to a more robust dynamic of the power source in the presence of an arc condition that would induce instability but also because of the capability to achieve varying rates of current rise and fall with different values throughout the welding process. Furthermore, the source's architecture allows for independent adjustments of these current variation rates, even during the welding operation.

REVIEW

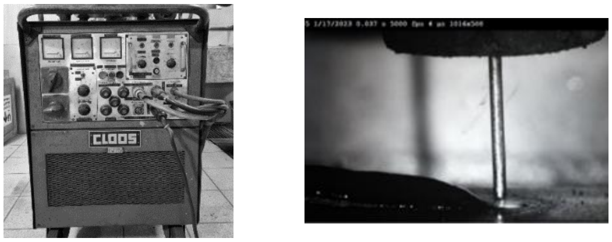
Within this context, it became possible to provide conditions for the development of processes known as high-performance or advanced processes. The development of these variants was made feasible through technological refinements in electronics, mechanics, and computing (especially the increase in processor speeds and the utilization of artificial intelligence-based analysis systems such as genetic algorithms and neural networks). The primary aim was to promote higher material deposition rates, greater control of metal transfer, and thus ensure specific weld geometries as envisaged in projects (Mvola, B. et al., 2018; Kah, P. et al., 2012). Throughout this evolutionary movement, many companies commercially branded their high-performance GMAW processes (GMAW-HP) with names suggesting high power or high penetration, as ForceArc, Deep Arc and DeepMIG.

According to the Deutscher Verband für Schweißen (2000, 2003), the high-performance variants of GMAW, operating with equipment using torches with only one wire, with diameters of 1.0 and 1.2 mm, were defined by processes where wire feed speeds start from 15 m/min, or when using larger wire diameters, achieving deposition rates exceeding 8 kg/h. Based on this premise, ten families of variants were characterized, focusing on different source control methods and electrical arc behavior, aiming for specific benefits both in terms of the process and the weld (DVS, 2017).

Simultaneously, according to AWS, Volume 2 of its Handbook (2004), they address the GMAW process based on source control modes and metal transfer modes. It also describes ways to optimize welding performance, including adjustments to source inductance. However, unlike DVS, it doesn't classify or establish a grouping for high-performance variants.

However, it's worth noting that according to Dutra (2023), more recent research lines demonstrate that high-performance processes aim not only for high deposition rates but also for increased penetration and the capability to weld thick plates. A prime example is the recent experiments conducted by Zhifeng and Xia (2023), where they tested the GMAW process using a buried arc configuration, which they referred to as Super Spray Mag Welding, to join plates with a thickness of 40 mm.

On the other hand, experiments conducted by Silva et al. (2023) using a 1970s thyristor-based CLOOS power source Fig. 1 (a), demonstrated the possibility of performing welds at wire speeds around 15 m/min in a buried arc condition Fig. 1 (b), in a voltage mode without major process control refinements. Although this type of power source can operate under these conditions, albeit in much narrower ranges and with less robustness compared to modern commercial sources, it doesn't fall under the high-performance variant category. Another similar condition was described by Dreveck et al. (2020), where a transistorized power source, in a voltage mode, operated in a buried arc with streaming spray transfer, achieving high deposition rates but limited to a welding speed range of 1.0 m/min due to observed defect formation above this value.



(a) (b)

Fig. 1 In (a) CLOOS power source; (B) Buried arc condition (Silva, R. et al., 2023). Video available at: https://youtu.be/3kJIyAdYBYY

Despite the advantages of GMAW-HP mentioned earlier, it is worth noting that its utilization, however encompassing a range of applications in the industry, still entails certain limitations inherent to conventional GMAW. For instance, logistics for the use of gas cylinders for on-site repairs pose a challenge, as is the case in the oil and gas industry, in comparison for example, with Shielded Metal Arc Welding (SMAW) or Innershield Flux Cored Arc Welding (I-FCAW). The presence of slag also provides the latter two process with improved performance against surface contaminants, under certain conditions. The higher overall productivity and lower costs of GMAW-HP, with narrower grooves (less volume of material needed) and unnecessity of slag removal, is expected to overcome limitations. Additionally, despite SMAW and I-FCAW are still widely used due to their robustness in windy outdoors conditions, the GMAW-HP's very low arc length is expected to perform just as well. More studies are needed in this regard.

Considering the aforementioned, for the purpose of characterizing DynaFlex-Arc, the classification from DVS will be utilized, always seeking alignment with AWS definitions in accordance with its general context. Thus, as per DVS Report 0973 (2017) this high-performance variant falls under family five, titled: 'Modified Spray Arc', describing the operation of a short arc with spray metal transfer. This classification is established due not only to static characteristics and electro-electronic components but primarily to dynamic effects from variations in source inductance, efficiently responding to imminent instability occurrences and maintaining the process in a stable operational regime. Furthermore, this setup allows, at the same voltage typically suited for spray transfer in the conventional mode, for the operation of the process at higher currents and welding speeds, as depicted in the graph in Fig. 2, promoting a streaming spray transfer, as demonstrated in experiments conducted by Dutra et al. (Dutra, J. et al., 2020).

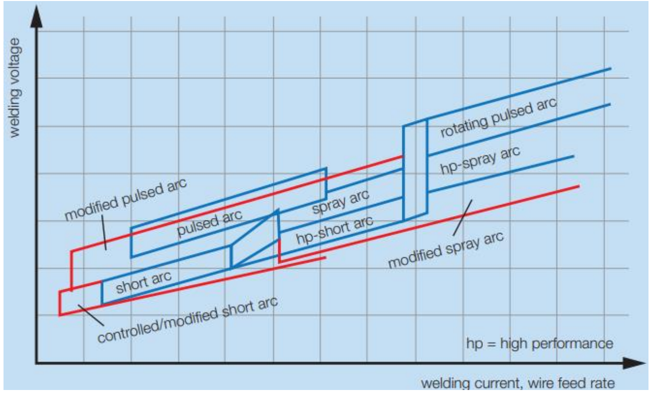


Fig. 2 Chart displaying, in red lines, the extension of operating ranges by high-performance variants of the GMAW process (DVS, 2017).

In this family, the variants are classified under the following commercial names: RapidWeld, ForceArc, Puls Controlled Spray Arc (PCS), NewArc, SpeedArc, DeepArc, FOCUS.ARC, Rapid MIG/MAG Technology (RMT), and High Penetration Speed (HPS). Below, three examples of these mentioned variants will be discussed for a better understanding of their definitions:

- The RapidWeld is characterized by a short arc with streaming spray metal transfer, capable of welding thick plates from 6 mm onwards. The manufacturer does not specify the control method but mentions that 'special controls' and 'special electrical parameters' enable high wire feed speeds. (CLOOS, 2023; Brabec, J. et al., 2021).

- The ForceArc can be described as a variant operating in spray transfer mode, utilizing low voltage, thereby promoting a short arc. This process is suitable for thick plates due to its strong penetration owing to the arc pressure. The molten pool is considered highly stable and generates minimal spatter. Thanks to the high dynamics of the power source, most short circuits are avoided, and even when they occur, they are quickly stabilized (Chen, J. et al., 2011; Dompablo, M., 2013; EWM, 2023).

- The SpeedArc is a synergic process that performs well across operating ranges, from short arc to spray arc transfer. When operating in spray arc mode, it achieves excellent penetration with exceptional stability. Its flexibility stems from the power source's dynamic control capabilities (LORCH , 2019; Wei, W. et al., 2019; Leilei, W., 2019).

In summary, these three variants were classified by DVS not only due to the dynamic response of the power source but also their similar characteristics concerning metal transfer and the operation of a short electric arc in the molten pool when operating in a spray arc condition, as depicted in Fig. 3.

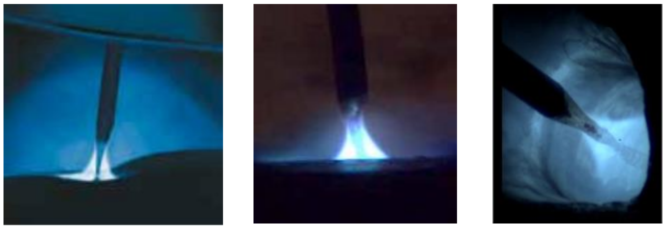

(a) (b) (c)

Fig. 3 Examples of metal transfers in high-performance Modified Spray Arc processes. In (a) RapidWeld (CLOOS, 2023); (b) ForceArc (EWM, 2023); (c) SpeedArc (LORCH, 2019).

In this context, DynaFlex-Arc was developed to showcase the possibility of welding in a buried arc configuration, as shown in Fig. 4 (a), for joining thick plates with high penetration, without the need for complex synergic programs or devices for monitoring and integrating adaptive systems (Dutra, J. et al., 2020; Dutra, et al., 2021; Bernardi, R. et al., 2017). However, through ongoing studies and conducted tests (Silva, R. et al., 2022), its flexibility has been demonstrated with potential applications in orbital welding for API tube repairs in operation. More recently, experiments have been conducted to assess its capability in executing cladding welding, as illustrated in Fig. 4 (b), using Inconel 625 wire in the vertical position with a downward oscillatory movement (Schaeffer, et al., 2024).

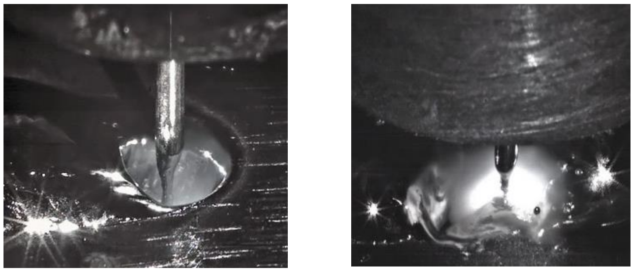

(a) (b)

Fig. 4 DynaFlex-Arc: In (a) In buried arc with 30 V, 430 A , wire feed of 15 m/min, and welding speed of 170 cm/min (Silva, R. et al., 2023); (b) In cladding with 32.5 V, 270 A, wire feed of 13.5 m/min and welding speed of 60 cm/min (Schaeffer, et al., 2024).

In terms of the process, this arc flexibility to operate in an extremely critical condition, offering a constant risk of short-circuit occurrences, is only possible due to the dynamic response of the IMC power source (IMC, 2015). It promptly acts before instability events occur, or if they do occur, it can swiftly restore the working condition before the metal transfer regime is disrupted. Moreover, not only the regulation of inductance but also, and primarily, the adjustment of intensity, which controls the rate of change of both current rise and fall over time (di/dt), with the possibility of adjusting different values from each other, enables these variations in both position and application of the process. To make this adjustment, the rise inductance (Ls) and fall inductance (Ld) values used by the source are based on the reference inductance (Lr) of the insulated-gate bipolar transistor (IGBT) input and the setup value of the rise divider (Ks) and fall divider (Kd), as per Equation 1 and 2.

$$Ls = \frac{Lr}{Ks} \quad (H) \tag{1}$$

$$Ld = \frac{Lr}{Kd} \quad (H) \tag{2}$$

Thus, the values of Ks and Kd can be programmed on a dimensionless scale ranging from 1 to 600, with a resolution of 1, to change the IGBT switching frequency to emulate the performance of different Ls and Ld. In other words, adjusting the inductance in real time (Júnior, R., 2002). An example of a portion of an electrical diagram, applied in welding and based on the logic described above, can be observed in Fig. 5.

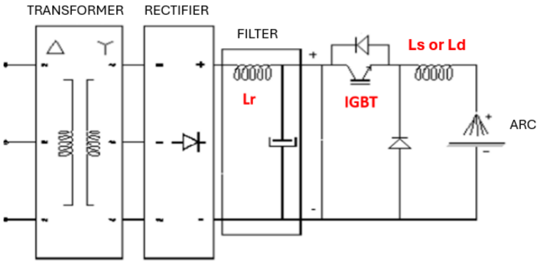


Fig. 5 Example of a section of an electrical diagram applied to welding, featuring inductance control via IGBT (IMC, 2015).

An example of the effects caused by varying values of rise and fall inductance can be observed in an experiment conducted by Dutra et al. (Dutra, J. et al., 2020), They simulated a short circuit on a test bench where different Ls and Ld values resulted in a rise di/dt of 70 A/ms and a fall di/dt of 0.3 A/ms. This experiment demonstrated the power source's behavior in a short-circuit condition, illustrating the current curve controlled by different inductance values in a single instability event, as shown in Fig. 6. Consequently, upon encountering a short circuit (voltage drop), a rapid rise in current occurs, followed by a slow return to the operational regime after the short circuit is cleared.

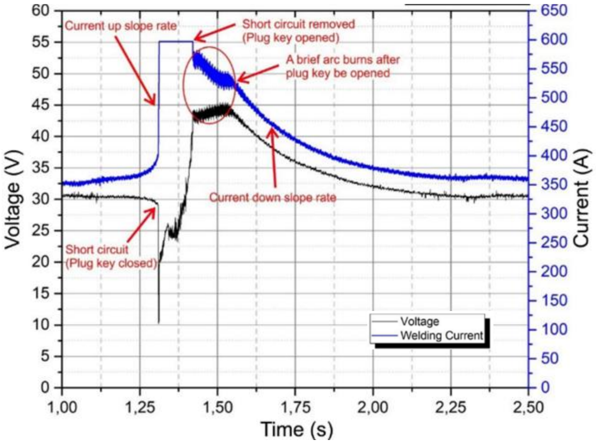


Fig. 6 Graph illustrating the effects on the current curve caused by different Ls and Ld values. (Dutra, J. et al., 2020).

Based on these definitions, experiments conducted by Bernardi et al. (2017), using DynaFlex-Arc, demonstrated the behavior of the current curve with three different Ks and Kd configurations, as shown in Fig. 7. They confirmed that, for the parameters used, the most stable condition was achieved with the ratio Ks = 100 and Kd = 1, as shown in Fig. 7 (c).

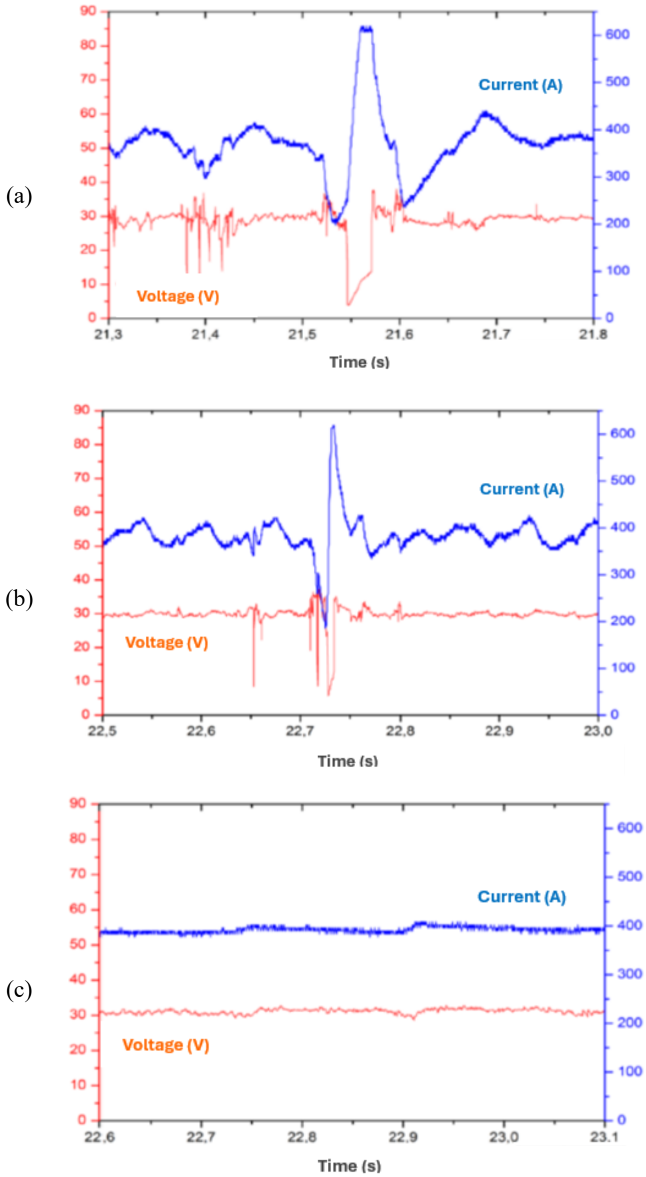


Fig. 7 Oscillograms demonstrating the behavior caused by different Ks and Kd values. In (a) Ks = 25 and Kd = 100; (b) Ks = 100 and Kd = 100; (c) Ks = 100 and Kd = 1.

In conjunction with the refinement of Ks and Kd values aimed at optimizing process stability, Dutra et al. (2020) also conducted experiments to demonstrate the differences caused by process gases. They utilized 100% Argon, Argon with 8% CO2, Argon with 25% CO2, Argon with 50% CO2, 100% CO2, and a quaternary mixture of Ar, He, CO2, and O2 used in the Transferred Ionized Molten Energy (T.I.M.E.) process. As depicted in Fig. 8 (a), it was observed that the transfer was more stable when utilizing the Argon with 8% CO2 mixture. However, the Argon with 25% CO2 mixture and the quaternary mixture exhibited a smoother current drop following the reaction to imminent short circuits, as shown in Fig. 8 (b).

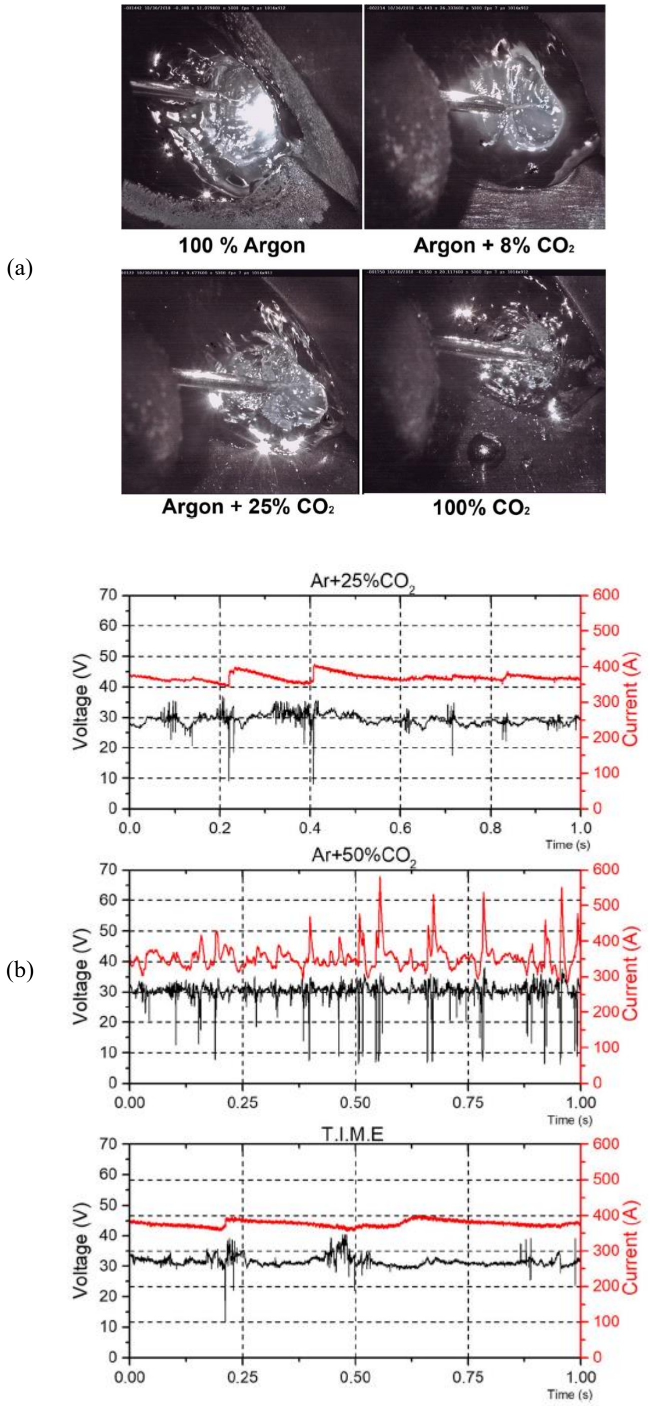


Fig. 8 In (a) Crater profile and metal transfer for different compositions of gases for a fillet joint, wire feed of 250 mm/s (15 m/min); (b) Oscillograms obtained with different gas mixtures highlighting the different current responses depending on the gas employed.

Conclusively, they also determined that with electronic control of the intensity of Ls and Ld, it's possible to conduct welding with a penetration of 10.3 mm, in a buried arc condition, with a more stable streaming spray transfer, resulting in fewer spatters and, consequently, better quality welding, as depicted in Fig. 9 (a). In this same line of research, Dutra et al. (2021) e Silva et al. (2019) respectively demonstrated the possibility of joining 9.52 mm plates with a V-groove, as shown in Fig. 9 (b), and a fillet 'T' joint (without groove preparation), as displayed in Fig. 9 (c).

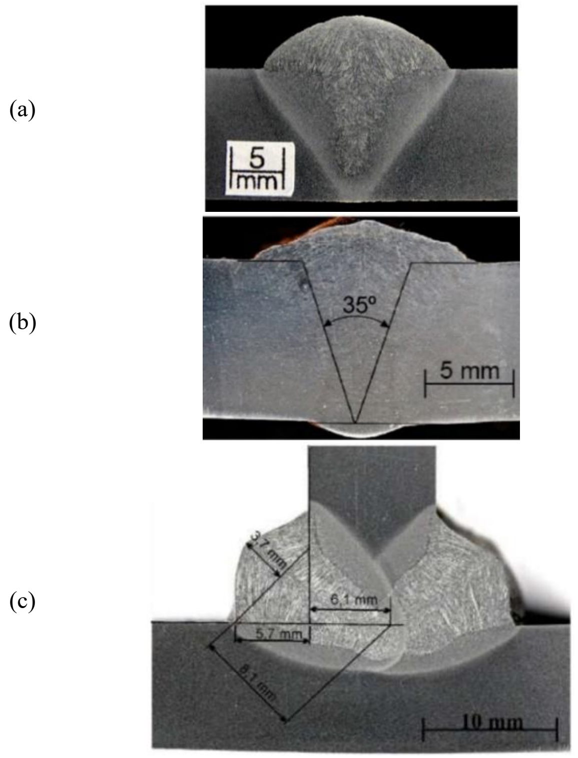


Fig. 9 Examples of welds performed with DynaFlex-Arc: In (a) Plate deposition; (b) V-groove butt weld; (c) 'T' fillet joint.

FINAL CONSIDERATIONS

From the dynamic perspective of the power source, it is not the different inductors and the various inductance settings that determine whether a GMAW variant is high performance or not. There is no specification or standard that defines an inductance operating range or specific di/dt values for conventional GMAW to categorize it as high performance. Consequently, the market presents a variety of welding power source architectures and models with different inductor specifications for conventional GMAW applications. Therefore, it can be affirmed that different welding power sources, even when operating with identical welding parameters, exhibit different di/dt values for various reasons extending beyond the differences in inductors. Factors such as cable arrangement and setup layout also influence these variations.

In conclusion, DynaFlex-Arc differs from conventional GMAW not only due to a more robust power source dynamic but also because of the capability to program different values for Ks and Kd. These values consequently control inductance throughout the welding process. This feature allows for the creation of varied current rise ramps combined with different current fall ramps, aiming to prevent or minimize arc instability occurrences during welding. Additionally, the power source architecture enables independent adjustments of Ks and Kd even during the welding process.

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