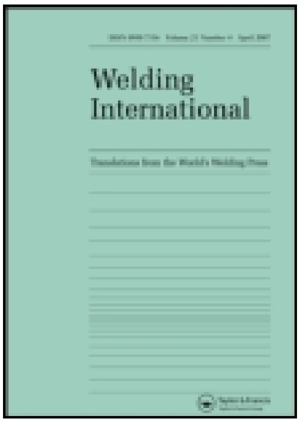

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Influence of welding current in plasma–MIG weld process on the bead weld geometry and wire fusion rate*

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One of the versions of the plasma–metal inert gas (MIG) process is basically a combination of a plasma arc with a MIG/metal active gas (MAG) arc in a single torch. With this association, the advantages of each arc are combined. The main characteristic of this is the independence between the heat input by the process and the deposited material, resulting in greater facility to control bead weld geometry. In the current literature, there is a shortage of information related to the process, and most of this goes back to the 1970s and 1980s when the technology available was not able to make the process viable for industry. However, in recent years, the use of the diffusion of new electronic power sources used in welding has sparked up again the interest in plasma–MIG process. In this context, this paper aims to contribute to the studies related to the influence of the MIG and plasma current balance on the geometry of the bead weld and wire fusion rate. Bead-on-plate welds were carried out with plasma and MIG/MAG current combinations at three levels each, keeping, by welding speed corrections, the bead volume the same. It was observed that the introduction of the plasma current over the MIG/MAG current reduces penetration and dilution and leads to convex beads. On the other hand, the use of plasma current increases the MIG/MAG wire fusion rate. However, it seems that the intensity of the plasma current is not the governing parameter of those changes.

Keywords: welding; plasma–MIG; hybrid arc

1. Introduction

In recent years, with the advance of new technologies available for the development of welding processes and the search for processes with greater production and productivity capacity, the so-called 'hybrid welding processes' arose, in particular, the metal inert gas (MIG)–laser and plasma–MIG.

This is the physical association of two processes with the aim of taking advantage of the most advantageous characteristics of each one[1].

As an advantage, the MIG/metal active gas (MAG) process offers a high rate of deposition and the possibility of adding material with different chemical compositions. However, in the MIG/MAG process, penetration is relatively small, normally requiring the confection of chamfers. This disadvantage is overcome by adding material. Yet, as with other processes with consumable electrodes, the welding current is strictly interconnected with the rate of addition metal feed, for a given welding condition (shielding gas, length and type of electrode, etc.). This fact is reflected in a strong dependence existing between energy inputs and the material of these processes, in other words, there is little margin to increase the current also without altering the amount of material to be deposited. As the geometry of a weld bead depends on the energy imposed and also on the amount of material deposited per unit of weld length, one of the main consequences of this dependency is the difficulty in freely controlling the geometry of the weld bead. Plasma on the other hand is a process with a very stable arc and in the wire feed mode, there is no strict dependence between its arc and the material fed.

One of the versions of the plasma–MIG welding process may be defined as a combination of plasma arcs of the MIG/MAG process in a single torch in which the addition metal is fed through the opening of the plasma nozzle. The process may be used both for welding and for coating[2]. It unites the advantages of high productivity of arc welding processes at lower equipment costs, provided by the possibilities of the combination between the current sources commercially available for plasma and MIG/-MAG[3] welding.

Figure 1 shows a plasma–MIG welding process torch in a schematic format highlighting the main components. A particular feature may be observed in the plasma electrode. Whilst the plasma–MIG process is made of copper and has a ring-shaped format, this is different from the one used in the conventional plasma process, which comprises tungsten and has a pointed shape. With the use of copper electrodes (emission per field and non-thermionic), the plasma part may operate in positive polarity with the tendency to promote greater stability in the MIG/MAG portion of the process. With this configuration, it is also possible to use mixtures of active gases since copper is less susceptible to degradation from the oxygen present in the active mixtures. Another point to

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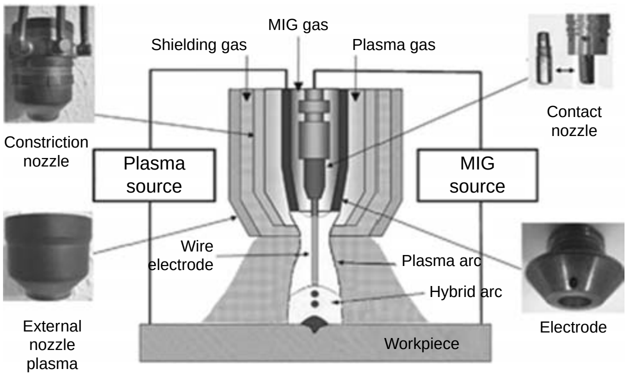


Figure 1. Schematic design of a torch for plasma–MIG welding highlighting the main components (adapted from Oliveira[5]).

be considered is that the copper electrode has a larger area to dissipate the heat and also counts on an auxiliary cooling system. Naturally, the constrictor nozzle of the plasma has a larger opening than the conventional process to enable the passage also in a concentric shape of the wire which results in a less concentrated arc.

In electric arc welding processes, the opening of the arc may be obtained artificially, basically in three ways: high-voltage differential, high-frequency–high-voltage, or short circuit. A high-voltage differential at a low frequency is unfeasible as it places operators at risk. High-voltage pulses (or high voltage at high frequency) are extremely damaging to electronic equipment (noise emissions). Finally, short-circuit opening generates an appreciable amount of splatter which may get into the vital parts of the torch, thus damaging it. Bearing these difficulties in mind, at the start of the 1980s, Essers et al.[4] proposed a new method of arc ignition for the plasma–MIG process called ‘soft start’. Using this arc ignition method, we used a wire electrode to generate a low intensity arc via which the formation of a plasma arc[5] occurs. With this method, the arc opening occurs practically free of splatter preventing vital parts of the torch from being damaged.

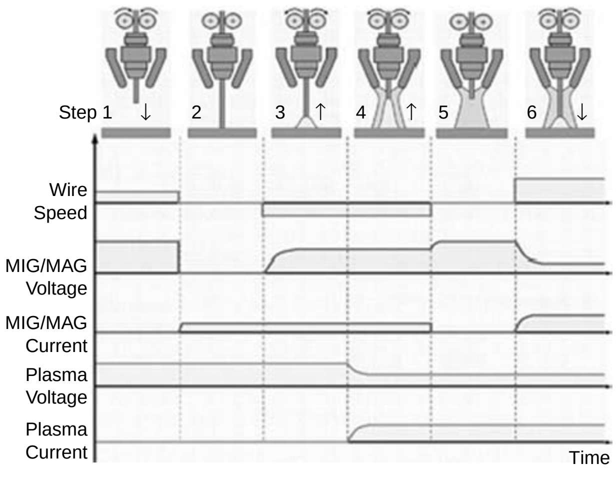


Figure 2. ‘Soft-start’ function scheme (adapted from Reis and Scotti[1] and Oliveira[5]).

Figure 2 illustrates the six basic steps involved in arc ignition using the soft-start method, namely:

> *Step 1.* The two sources have a voltage whilst empty and the wire electrode of the MIG/MAG portion of the process is fed in the direction of the workpiece.
>
> *Step 2.* When the wire touches the workpiece, its movement is interrupted and the source generates a low-current intensity arc (around 35 A) with no considerable fusion of the wire.
>
> *Step 3.* The wire feeder inverts the rotation and the wire retracts in the direction of the welding torch, progressively bringing the arc inside the torch until it is within the proximity of the plasma electrode.
>
> *Step 4.* As the plasma source already has a voltage whilst empty, the arc plasma immediately ignites due to the ionized atmosphere of the low-power MIG/-MAG.
>
> *Step 5.* After igniting the plasma arc, we extinguished the MIG/MAG arc (power cut-off) with the aim of preventing metal transfer and providing a pre-heating at the start of the joint solely with the energy of the plasma arc.
>
> *Step 6.* The wire again shifts the direction of the workpiece and as the MIG/MAG again has a voltage whilst empty and the area around it is ionized by the plasma arc, the spontaneous ignition of the MIG/MAG arc occurs, without the need for a short circuit (this ensures a splatter-free start to the weld bead) but with the current already regulated for the welding operation.

To understand the mechanisms with which thermal energy is transferred to the workpiece and the mechanisms which govern penetration in the plasma–MIG process, Essers and Walter[6] used the calorimetric technique and observed that there are differences between the energy absorbed by the workpiece for the MIG/MAG and plasma–MIG processes. The differences were explained by the fact that there are two anodes in the plasma–MIG process, one, the tip of the MIG–MAG electrode and the other, the tip of the plasma electrode, and in this case part of the heat generated in the plasma electrode is absorbed by the cooling system (a fact which results in the variation in the profile of the weld bead when compared). Jelmorini et al.[7] assessed the profile of the weld bead of the plasma–MIG process and demonstrated that the presence of the plasma current modifies the profile in the sense that it increases the width and promotes better wettability.

From that shown, the consensus appears to be that the association of the plasma and MIG/MAG currents may offer the possibility of acting on the geometry of the weld bead when varying the balance between the currents. However, the explanations given above and from the literature on the influence of plasma and MIG/MAG circuit currents on the geometry of weld beads are still vague and are little quantified, as well as mostly dating back to the 1970s and 1980s when the technology available was incapable of making the process viable for the industry at that time. In addition to this, the conception of the torch used at that time was different with a sharp-tipped plasma electrode resulting in a constricted arc different from the annular electrode used nowadays which produces a less concentrated arc. However, Oliveira[5] points out that in recent years the diffusion of new electronic sources used in welding enables better control over fusion and material transfer via the use of different forms of current waves, contributing in a decisive way to a resurgence in interest in the plasma–MIG process due to its major potential. Hence, there is a need to develop new technologies and knowledge for this process. In this context, this paper aims to increase studies associated with the influence of plasma and MIG/MAG circuit balances on the geometry of weld bead and wire fusion rates.

2. Experimental procedure

A total of nine experiments were performed to assess the influence of the currents of the plasma–MIG process on the geometry of the weld bead. When carrying out these experiments, we used a commercial torch for water-cooled plasma–MIG welding and two multi-process secondary key-type electronic sources. One of the sources was programmed to work in MIG/MAG mode and the other in plasma mode, both with static characteristics in a constant current to ensure current values in all comparative experiments. This way the values of feed currents and speed were regulated and voltages resulted from the load (characterized by each arc). As an arc start-up operation, we used the soft-start procedure (used to ignite the hybrid arc of the plasma–MIG process).

As the value of the feed speed varies with the plasma current and primarily the MIG/MAG current, we also adjusted the welding speed for each experiment. The feed speed was obtained in order to obtain an arc length approximately constant for the same weld speed/feed speed ratio. This regulation was performed by gradually increasing the feed speed until the wire touched the well (generating short circuits). From this point, we than slowly reduced the feed speed until the short circuits stopped occurring, with a drop transfer of the length of a small arc and approximately constant in all tests.

The test bench is presented in Figure 3. The plasma–MIG torch is hooked up to the sources normally used for the processes which originated it (plasma and MIG/MAG), requiring only a single command for both sources. A micro-processed interface controls the arc opening (soft-start) sequence and commands the pre-regulated parameters for the process. An item of great importance and worth pointing out is the cooling system (controlled temperature of the water, below room temperature), indicated in the figure as item 4. The temperature of the coolant water was regulated to remain at around 17°C. Use of only conventional coolant systems (water circulating via radiators) was shown not to be efficient at preventing damage to the torch, in particular to the constrictor nozzle and annular copper electrode.

The positioning distances of the main torch elements are presented in the scheme of Figure 4 in which DTP is the distance from the torch to the workpiece, RP the inset of the plasma electrode and RM the inset of the MIG/MAG contact nozzle. The values of RP and RM are fixed and depend on the construction characteristics of the torch they correspond to, 9 and 18 mm, respectively. Although the DTP value may be varied, for this paper, 9 mm was used resulting in a distance from the MIG/MAG contact nozzle to the workpiece (DBCP) of 27 mm. If the DTP values used were very small (to enable smaller DBCP), detachment of the cast metal drop may occur within the torch which may lead to problems with the deviation of these drops towards the torch.

For the purposes of comparison, we carried out all tests as simple bead-on-plate tests. Test plates were made from sheets of ABNT 1020 carbon steel measuring 300 × 50.8 × 6.35 mm. The wire electrode used in testing was an AWS ER70S-6 class of 1.2 mm in diameter. $Ar + 4\%CO_2$ as MIG/MAG gas at 5 l/min, Ar as plasma gas at 5 l/min, and Ar as shielding gas at 15 l/min. The

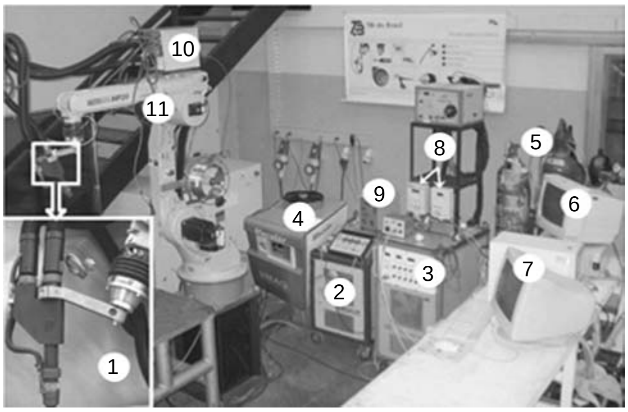


Figure 3. Test bench used, in which: 1, plasma–MIG torch; 2, MIG/MAG source; 3, plasma source; 4, water coolant unit; 5, gases for process; 6, control system for process; 7, electric signal acquisition system; 8, flow meters for plasma and MIG/MAG gases; 9, interface responsible for controlling feeder head; 10, feeder head; 11, robot.

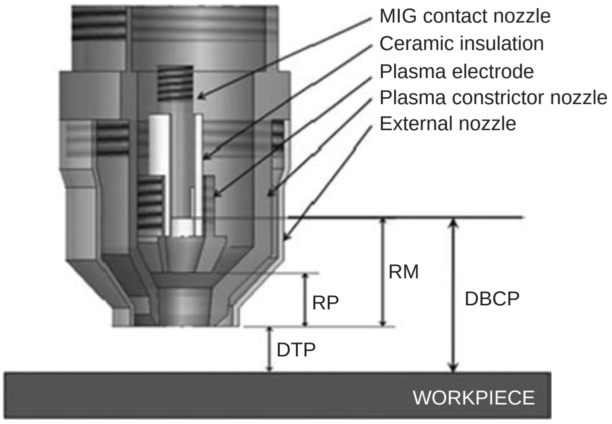


Figure 4. Schematic view of the positioning of the main elements of the plasma–MIG torch. Where DTP is the distance from the torch to the workpiece, RP the inset of the plasma electrode, and RM the inset of the MIG/MAG contact nozzle.

Table 1. Regulation parameters for tests.

Test	$I_{MIG/MAG}$ (A)	I_{plasma} (A)	Weld speed (m/min)	Feed speed (m/min)	(Weld speed/feed speed) × 10^2
1	200	0	0.30	5.0	6.0
2	200	60	0.42	7.1	5.9
3	200	100	0.45	7.4	6.1
4	240	0	0.44	7.3	6.0
5	240	60	0.65	10.8	6.0
6	240	100	0.67	11.2	5.9
7	280	0	0.53	8.8	6.0
8	280	60	0.77	12.7	6.0
9	280	100	0.80	13.0	6.1

choice of gases and flow were made subjectively, with an indication of the appropriateness in exploratory tests (no optimization or the study of influence was intended in this parameter). The option was made to work with MIG/MAG current values higher than the globule–droplet current transition typical for the conventional MIG/MAG process, on three levels (200, 240, and 280 A). For the plasma current, three levels were also assessed (0, 60, and 100 A). Tests included a combination of currents as shown in Table 1. Welding speed was regulated to maintain the same welding speed to feed speed ratio with the aim of obtaining the same quantity of deposited material per unit of length and compare the effect of variables on the weld bead profiles.

Tests 1, 4, and 7 were performed with no current passing through the plasma circuit, in other words, MIG/MAG welding with a constant current using a plasma–MIG torch. These tests are reference points to verify the influence of the plasma current on the process and primarily on the geometry of the bead. These tests in particular were carried out with the plasma source turned off and as a result the soft-start procedure was not used and the MIG/MAG parameters were regulated directly on the control panel of the source. This procedure was performed to ensure that the MIG/MAG current only circulated via the MIG/MAG arc, since if the soft-start procedure was used with the plasma current regulated to 0 A (zero A) the plasma source would remain at zero voltage throughout welding and a small part of the MIG/MAG current would circulate through the plasma current. The other tests were performed with the current passing through the plasma circuit and use of the soft-start procedure.

To acquire the current, we used a Hall sensor as a signal transducer/conditioner and a voltage divider to acquire the welding tension. Both supply and signal voltage in the range of ± 10 V which corresponds precisely to the measurement range of the 14-bit resolution measurement plate were used. For the Hall sensor measurement range of ± 500 A, the resulting measurement resolution, calculated by the ratio (Hall sensor measurement range/plate resolution) was 0.06 A for the current. Similarly, the measurement range of ± 100 V of the voltage divider resulted in a measurement resolution of 0.01 V for voltage.

The effect on geometry was studied using the conventional techniques of macrography on cross-sections taken from the welded test plates (250 mm bead). For each test plate, two cross-sections were cut, one approximately in the middle and one close to the end of the bead (20 mm from the edge). The two geometric parameters were taken using digital imaging with a resolution of 20 pixels/mm which resulted in a measurement resolution of 0.05 mm for the geometric parameters.

3. Results and discussion

In Table 2, the voltage and current values monitored during the tests for the plasma and MIG/MAG circuits with their respective standard deviations are given. In Table 3, the cross-sections representative of each of the welded test plates are shown. For each test plate, two cross-sections were removed; one approximately in the middle and one close to the end of the bead. The average values of the respective standard deviations of the respective geometries of the beads are presented in Table 4.

Figure 5 presents the variation in penetration, cast area, and dilution with the welding currents. It is important to remember that the increase in current was accompanied by a proportional increase in welding speed. In Figure 5(a), one notes an increase in penetration with an increase in MIG/MAG current justifiable due to the increase in pressure which the arc exerts on the cast well due to the higher concentration of the magnetic fields. Another fact, observed by Scotti and Rodrigues[8] is that higher currents result in drop in higher speeds, which may contribute via momentum to greater penetration.

Table 2. Average values of current and voltage signals monitored for the plasma and MIG/MAG circuits.

Test	$I_{MIG/MAG}$ (A)	$U_{MIG/MAG}$ (V)	I_{plasma} (A)	U_{plasma} (V)
1	200.7 ± 4.0	30.4 ± 2.0	*	*
2	202.1 ± 3.8	27.6 ± 3.1	55.1 ± 7.6	37.5 ± 3.6
3	201.4 ± 3.9	29.6 ± 2.9	93.2 ± 7.7	33.1 ± 4.7
4	240.4 ± 3.9	26.7 ± 1.9	*	*
5	241.6 ± 3.7	27.7 ± 4.8	54.8 ± 5.1	36.4 ± 6.7
6	242.1 ± 3.8	22.5 ± 3.5	94.2 ± 7.5	30.8 ± 2.1
7	279.3 ± 3.9	28.9 ± 1.5	*	*
8	281.5 ± 3.8	25.0 ± 2.4	55.3 ± 4.8	33.4 ± 2.0
9	281.1 ± 3.8	24.1 ± 2.0	94.2 ± 4.9	30.8 ± 2.0

Note: Values marked with an asterisk (*) correspond to welds with plasma source switched off.

Table 3. Cross sections of welded test plates (for effect of scale, plate thickness is visible and corresponds to 6.35 mm).

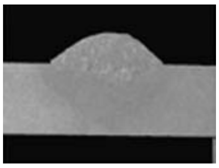
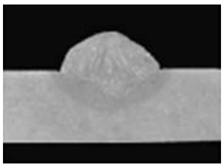
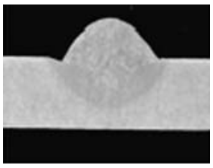
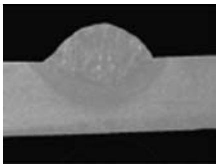
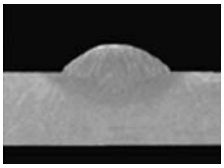
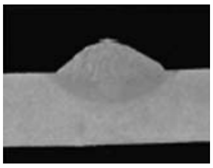
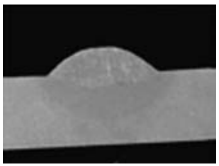
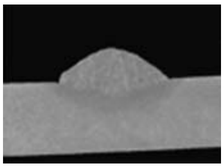
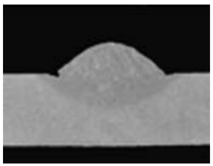
	$I_{\mathrm{MIG/MAG}} = 200\,\mathrm{A}$	$I_{\mathrm{MIG/MAG}} = 240\,\mathrm{A}$	$I_{\mathrm{MIG/MAG}} = 280\,\mathrm{A}$
$I_{\mathrm{plasma}} = 0\,\mathrm{A}$			
$I_{\mathrm{plasma}} = 60\,\mathrm{A}$			
$I_{\mathrm{plasma}} = 100\,\mathrm{A}$			

Table 4. Geometric parameters measured for weld beads.

Test	Width (mm)	Reinforcement (mm)	Penetration (mm)	Cast area (mm^2)
1	9.25 ± 0.10	2.83 ± 0.04	1.66 ± 0.13	8.66 ± 0.23
2	9.62 ± 0.16	2.50 ± 0.14	1.41 ± 0.13	9.05 ± 0.61
3	9.78 ± 0.11	2.30 ± 0.17	1.14 ± 0.06	8.06 ± 0.39
4	8.35 ± 0.35	2.92 ± 0.26	2.60 ± 0.13	11.85 ± 0.49
5	9.28 ± 0.11	2.43 ± 0.17	1.73 ± 0.11	8.04 ± 0.65
6	9.39 ± 0.31	2.59 ± 0.11	1.48 ± 0.24	7.02 ± 0.37
7	8.39 ± 0.12	3.29 ± 0.15	3.00 ± 0.28	12.19 ± 2.41
8	9.19 ± 0.08	2.57 ± 0.10	2.23 ± 0.04	8.81 ± 0.62
9	9.47 ± 0.16	2.62 ± 0.26	2.18 ± 0.12	9.20 ± 1.48

Note: Cast and penetration area refer to measures taken in the region below the test plate surface.

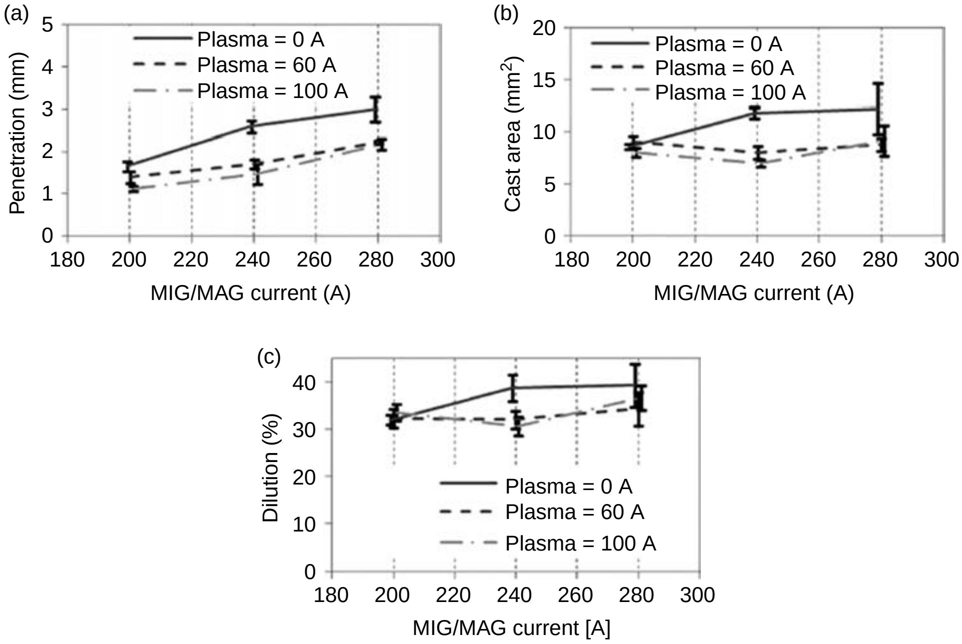


Figure 5. (a) Penetration, (b) cast area, and (c) dilution of the weld bead as a result of the MIG/MAG current for three levels of plasma current.

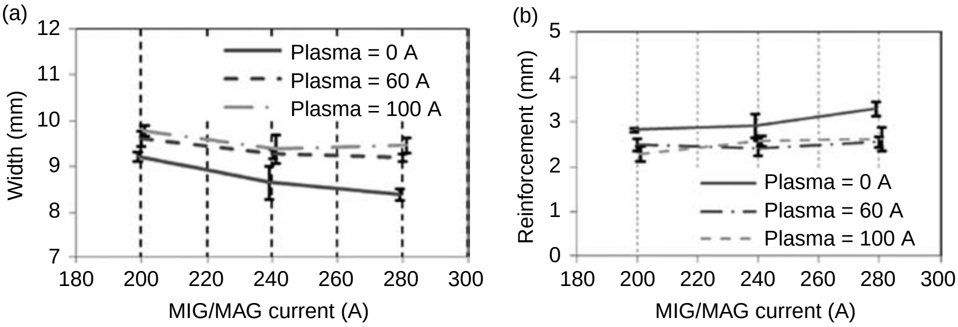


Figure 6. (a) Width and (b) reinforcement of weld bead as a result of MIG/MAG for three levels of plasma current.

Also in Figure 5(a), one notes a clear trend towards the reduction in the penetration of the weld bead when the current is inserted into the plasma circuit. Whilst in Figure 5(b) and (c), one notes a clear trend towards the reduction in cast area (below the line which delimits the surface of the plate, not including the area relating to the deposited material) and dilution (correlated factor) of the weld bead when the current is inserted into the plasma circuit. As presented above, the hybrid arc has a wider contact area with the workpiece and as a result a larger heated area, increased wettability, and greater bead width. With the imposition of the current in the plasma circuit, the volume of the hybrid arc increases considerably in relation to the MIG/MAG arc (plasma = 0 A), and the pressure caused by the magnetic fields may be reduced as the current is less concentrated, resulting thus in lower speed drops. An indication for this reduction in the concentration of the current is quoted in the paper of Ton[9] who, by way of optical spectroscopy techniques, verified that the greater part of the current which passes through the wire (MIG/MAG current) flows through the periphery of the hybrid arc. Essers and Walter[6] observed, using high-speed photography techniques, that for high-current values (over 170 A) in the wire, there is a tendency for the electrode tip to rotate though not enough to characterize transfer of a rotational type. This makes the drops be transferred to the fusion well but in a less concentrated way which may as a result reduce penetration and increase bead width. Hence, an explanation for the reduction in penetration would be the reduction in momentum (mass versus speed) of the drops spattering on the well. One also notes from the figure mentioned (Figure 5(a)) that greater penetration differences occur for higher currents, confirmed by the behaviour of the cast area (Figure 5(b)) and dilution (Figure 5(c)).

Figure 6 presents the variation in width and reinforcement with welding currents. One notes a tendency to increase weld bead width and reduce reinforcement when inserting current into the plasma circuit. This effect can be attributed to the increase in the contact area of the hybrid arc with the workpiece in comparison with the MIG/MAG arc which as a result increases the surface area of the heated plate, increasing the wettability of this, resulting in wider and shallower beads (remember that the volume was the same). On the other hand, an increase in the plasma current from 60 to 100 A did not provoke a significant alteration in width and reinforcement. Probably the effect was slight because the volume of ionized gas corresponding to the hybrid arc is already relatively large and an increase 40 A in plasma current to is incapable of providing a significant increase in the volume of the hybrid arc and consequently on the contact area of this with the workpiece. Hence, most of the heat that is inserted with the increase in plasma current is lost to the environment reducing the contribution of this current increase in the fusion of the plate.

Figure 7 shows the ratio between feed speed and weld current. One notes a significant contribution of the plasma arc: in the fusion of the electrode for a 60 A plasma current, there was a gain of almost 3 m/min in wire feed speed. This result was similar to that obtained by Oliveira[5] welding with pulsed plasma–MIG. On the other hand, the increase in plasma current from 60 to 100 A did not result in any significant increase in feed speed. This trend also coincides with that observed by Oliveira[5] who states that the increase in the fusion rate of the wire caused by the plasma arc depends on the capacity of the wire electrode to absorb the energy made available by the plasma arc and that this absorption occurs by way of three heat transfer mechanisms: radiation, convection, and conduction.

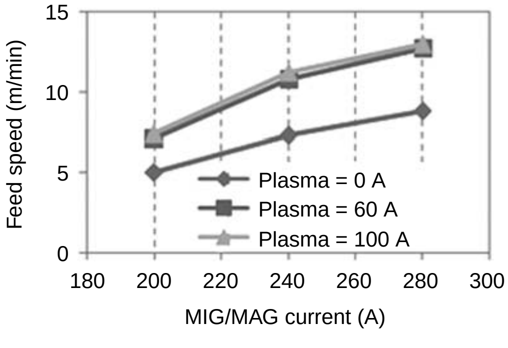


Figure 7. Wire feed speed as a result of the MIG/MAG current for three levels of plasma current.

4. Conclusions

For the welding conditions and parameters used in this paper, one can conclude that

- different combinations of plasma currents and MIG/MAG produce beads of different sizes which have the tendency to reduce penetration, the cast area, and dilution (contrary to user expectations due to the presence of the term plasma in the name of the process) and the increase in width and reduction in reinforcement when the plasma current is introduced, indicating that the process has a potential to be applied in operations which require less dilution such as for example in coatings and the welding of fine plates;
- the use of the plasma current also increases the wire fusion rate for the same MIG/MAG current indicating the possibility of increasing the capacity of the production process;
- the value of the plasma current itself for the values studied does not appear to be the governing factor of these changes but the use of the plasma current.

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