INFLUENCE OF THE GAS FLOW ON THE WELD BEAD FINISHING IN PLASMA-MIG WELDING PROCESS USING CONCENTRIC ELECTRODES

André Alves de Resende, aaresende@gmail.com
Américo Scotti, ascotti@mecanica.ufu.br
Federal University of Uberlândia, Faculty of Mechanical Engineering, Group Laprosolda – Center for Research and Development of Welding Processes, Bloco 1O, Av. João Naves de Ávila, 2121, CEP 38400 902, Uberlândia-MG.

Abstract.
In various welding processes, the use of shielding gas is required. Thus the correct selection of type and flow of a gas is of fundamental importance for the proper functioning of the process. The Plasma-MIG welding process, using an annular copper electrode for Plasma and a concentrically fed MIG/MAG electrode, has appeared in the last years as a means of meeting the demand for competitive weld processes in the growing market. Plasma-MIG process requires supply of three gases simultaneously (External Shielding Gases, MIG/MAG and Plasma) at different and specific rates. Detailed studies on how the flow rate set for each gas affects the weld bead surface appearance have not been found in a recent bibliographic survey. Therefore, this work is a try to understand how the gas flow rate effect on the superficial aspect of the weld beads. Thus, some experiments were conducted using a mixture of Ar+8% CO_2 for all gases, maintaining the same welding parameters and varying only their flow rates. It was observed that the proportion of which each gas is fed affect significantly the weld bead appearance and that the Plasma gas is the most influent one. As results, was observed that a flow in l/min at a ratio of 8-2-10 to the Plasma, MIG/MAG and External Shielding gases respectively.

***Keywords**: Plasma-MIG, Shielding Gas, Flow, Weld Bead.*

1. INTRODUCTION

One primary function of gases utilized in welding is to ensure that the parties overheated by the welding arc (tip of the wire electrode and weld pool) become free from the harmful effects of the local atmosphere. An additional function, but not least, includes stabilization of the arc. When one talks about shielding gas for welding, the term "flow rate" comes out. Gas flow rate is a parameter that must be carefully selected so that the gas can exert their functions efficiently without damaging the weld bead; low flow rates cause weak protection and high flow rates can generate a turbulent flow. The consequences of an inadequate flow may be welds with porosity, undercuts, slag inclusions, irregular aspect of the weld bead and geometrical changes. As stated by Scotti & Ponomarev (2008), unfortunately there is not an appropriate way to decide the correct flow rate for each welding condition, the user must observe the behavior of weld and use his experience to define an appropriate flow rate.

Specifically in arc welding, the gas flow is led through a hose to a nozzle and from the nozzle end it flows freely through the atmosphere until it reaches the weld pool. In fact, the flow is not as free as mentioned, once magnetic field accelerates the ionized portion of the gas, forming an arc jet (Reis et al., 2011). The gas surrounding the plasma jet can be assumed as a shield to the arc and, by reaching the plate, to the heated plate. However, the gas inside the plasma jet reaches the weld pool at a very high speed and it is considered one of the factors determining the surface quality of the weld bead (as much as other factors, such as droplet impingement, mode of energy delivery, etc.). The pressure outside the gas nozzle can be considered to be at the atmosphere level. The speed of the plasma jet is likely to be not influenced by the income gas flow, but as they have surfaces in common (internal for the shielding gas and external for the plasma jet), the shielding gas flow becomes part of the system. In addition, the flow rate in which the shielding gas is provided must be enough to reach the plate before dissipating around the region of the nozzle end. Thus, the gas flow provided by the nozzle plays indirect role on the bead formation.

"Hybrids Welding Processes" are defined as a combination of at least two other conventional processes to obtain operational characteristics that would be impossible with other welding processes alone. The main advantage of such approach is the independence between the material feeding rate and the total energy used in the process. In last years, with the advances of new technologies available for welding processes development and the search for processes with higher production capacity and productivity, the so-called "Hybrid Welding Processes came to light, particularly the MIG-Laser and Plasma-MIG. They are a physical combination of two welding processes, in order to utilize the most attractive features of each one (Reis and Scotti, 2007).

The Plasma-MIG welding process, in one of its versions, uses a copper Plasma annular electrode and a consumable MIG/MAG wire fed concentrically. Roughly speaking, this version of Plasma-MIG is the MIG/MAG welding process in which the arc formed between the electrode tip and the workpiece is involved (protected) by an ionized atmosphere sustained by the annular electrode (Plasma arc). In the conventional MIG/MAG, in contrast, the wire electrode and the arc formed between the electrode tip and the workpiece is protected by a cold gas. Unfortunately, there is no much information in current literature regarding the process and the most remotes from the 70s and 80s, when the available technology was not able to facilitate the process for the industry at that time.

A central peculiarity of the Plasma-MIG welding process is that it requires three gases (MIG/MAG, Plasma and External Shielding) to provide adequate arc operation and protection to the weld pool. A variety of combinations and forms of supplying theses gases can be obtained. According to Essers et al. (1981), there are four realistic possibilities of supplying gas in a Plasma-MIG process, namely:

1. Plasma, MIG/MAG and External Shielding Gases fed separately;
2. Plasma, MIG/MAG and External Shielding Gases fed by just one supply;
3. Combination Plasma with External Shielding Gas fed by just one supply and the MIG/MAG gas fed separately;
4. Combination Plasma with MIG/MAG Gas fed by just one supply and the External Shielding Gas gas fed separately.

For Essers et al. (1981), the first assumption possibility is the best solution, since the operator can set the composition and flow rate of each gas. This approach allow the user to prevent using active gases close to the plasma electrode, what would damage it, yet using for other areas of the torch (improving arc stability).

Table 1 shows some flow rates used by different authors. All of them have used 1.2-mm-diameter carbon steel wire, except Asai et al (2009), who welded with 1.2-mm-diameter copper wire. As seen, there is no consensus among researchers on the flow rate to be used for each gas. However, none of these authors mentioned the reason for choosing such set for each gas. They have neither worked on the effect of the gas flow on the welding performance. Essers et al. (1981) mentioned (but not demonstrate it in their article) that Plasma gas flow is highly critical. If the gas flow is not precisely regulated in each case, the Plasma arc becomes seriously disturbed and therefore unstable. This has an immediate effect on the weld quality: the weld has an irregular appearance. This effect was observed in welding and surfacing of steels and stainless steels and much more evident in welding of aluminum.

Table 1 - Flows in the literature for Plasma-MIG process

	External Shielding Gas (l/min)	Plasma Gas(l/min)	MIG/MAG Gas (l/min)
Kohei et al, 2009	10 (Ar + 20%CO_2)	10 (Ar)	5 (Ar)
Bica et al, 1995	30 (Ar + CO_2) (1)	15 (Ar)	not informed
Resende, 2009	10 (Ar + 8%CO_2)	5 (Ar)	5 (Ar)
Alaluss et al, 2007	18	10	5
Oliveira, 2006	10 (Ar + 4%CO_2)	5 (Ar)	5 (Ar)
Tanaka et al, 2008	15 (Ar + 20%CO_2)	15 (Ar + 20%CO_2)	10 (Ar)
Asai et al, 2009	10 (Ar)	15 (Ar)	10 (He)

(1) Proportion Unknown

Therefore, this work aims to clarify some aspects of the Plasma-MIG process by verifying as the flow rate setting of each gas affects the surface finish of the weld bead.

2. EXPERIMENTAL PROCEDURE

A series of experiments was conducted to evaluate the influence of the gases flow rate on the weld bead appearance used in Plasma-MIG weld process. For conducting the experiments, two multiprocess electronic power sources, one set to work as MIG/MAG and the other one as Plasma process, was used (both of them operated in constant-current static characteristic and DCEP). This arrangement guarantees a same current value in all comparative experiments. For arc starting, the procedure 'Soft Start' was used (details of the procedure 'Soft Start' can be found in Resende, 2009). A commercial Plasma-MIG welding torch was employed, which position of the main elements is shown in Figure 1. The values of the plasma electrode set back distance (P-SBD) and the MIG/MAG electrode set back distance (M-SBD) are fixed and dependent on the torch model, being respectively 9 and 18 mm. The standoff distance (SOD) value can be regulated, but in this work was set at 10 mm, resulting in a 28 mm of contact tip-to-workpiece distance (CTWD).

For comparison purposes, all tests were performed using bead-on-plate welding. The specimens were prepared out of mild carbon steel plates (300 x 50.8 x 6.35 mm). A 1.2-mm-diameter AWS ER70S-6 electrode-wire was used. It was regulated the values of the currents at 75 and 260 A, respectively for Plasma and MIG/MAG, and the wire feed speed (MIG/MAG) at 10.2 m/min; the arc voltages is resultant of the load, characterized by each arc. The welding speed was set at 36 cm/min. This welding condition was previously assessed by means of high-speed filming and a spray transfer mode was observed.

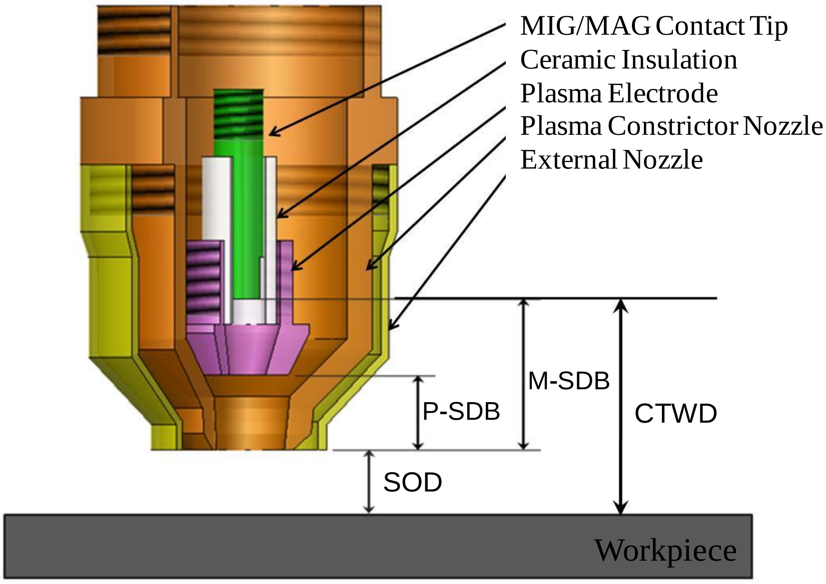


Figura 1 - Schematic view of the main elements of the Plasma-MIG torch (SOD = standoff distance; P-SBD = plasma electrode set back distance; M-SBD = MIG/MAG electrode set back distance; and CTWD = contact tip-to-workpiece distance)

The same gas blend (Ar+8% CO_2) was used for all tree gases (External Shielding, Plasma and MIG/MAG) to avoid variations in the final mixture composition, which could affect the interpretation of comparative results. Although the authors were aware that the use of CO_2 in contact with the copper electrode (electrode Plasma) would be harmful to it, as presented by Essers et al. (1981). However, the authors believe that this wear would become relevant only when the weld is performed for long time, in contrast to the present work, in which low number of short experiments were performed (there was no significant wear).

To achieve the aims of the work, it was proposed a 2^3 factorial design, where 2 is the number of levels assessed and 3 the factors (External Shielding, Plasma and MIG/MAG gas flow). The Factorial design allows checking whether there is some interaction among the factors evaluated. Combining the three variables (factors) on two levels has a total of eight possible combinations with their respective levels, which are listed in Table 2. It is noteworthy that the experiments were conducted in a random sequence rather than the identification of tests column.

Table 2 - Flows of gas and levels used in each test

Test	External Shielding Gas Flow (l/min)	Plasma Gas Flow (l/min)	MIG/MAG Gas Flow (l/min)
1	5 (-1)	2 (-1)	8 (1)
2	10 (1)	2 (-1)	8 (1)
3	10 (1)	2 (-1)	2 (-1)
4	5 (-1)	2 (-1)	2 (-1)
5	5 (-1)	8 (1)	2 (-1)
6	10 (1)	8 (1)	2 (-1)
7	10 (1)	8 (1)	8 (1)
8	5 (-1)	8 (1)	8 (1)

As complement of the experiments presented in Table 2, it was also done a scan around the parameters of the best flow rate combination. For this condition, only one gas flow rate was varied at a time to values above and below the one found as the best. This step was performed in 10 tests. Thus, a total of eighteen experiments were conducted.

3. RESULTS AND DISCUSSION

Table 3 presents the voltage and current values monitored during the tests of Table 2 for the Plasma and MIG/MAG circuits. By means of the low standard deviations observed, the process was quite stable (in the Plasma circuit, the deviation is intrinsically low, while in the MIG/MAG circuit, despite metal transfer, the standard deviation values were also low, characteristic of a spray metal transfer).

Table 3 – Plasma and MIG/MAG circuits monitored current and voltage (average values and their respective standard deviations)

Test	Plasma Current [A]	Plasma Voltage [V]	MIG/MAG Current[A]	MIG/MAG Voltage[V]
1	$72{,}5^{\pm 2{,}0}$	$44{,}2^{\pm 2{,}0}$	$261{,}0^{\pm 3{,}7}$	$29{,}6^{\pm 1{,}0}$
2	$72{,}7^{\pm 1{,}9}$	$45{,}9^{\pm 2{,}0}$	$260{,}6^{\pm 3{,}6}$	$30{,}3^{\pm 1{,}2}$
3	$72{,}8^{\pm 1{,}8}$	$47{,}0^{\pm 1{,}0}$	$260{,}6^{\pm 3{,}7}$	$32{,}9^{\pm 1{,}2}$
4	$72{,}7^{\pm 1{,}8}$	$46{,}7^{\pm 1{,}2}$	$260{,}7^{\pm 3{,}7}$	$32{,}1^{\pm 1{,}0}$
5	$72{,}8^{\pm 1{,}9}$	$45{,}9^{\pm 1{,}6}$	$260{,}7^{\pm 3{,}7}$	$31{,}1^{\pm 1{,}3}$
6	$72{,}7^{\pm 1{,}8}$	$45{,}5^{\pm 1{,}2}$	$260{,}7^{\pm 3{,}7}$	$30{,}5^{\pm 1{,}0}$
7	$72{,}7^{\pm 1{,}8}$	$46{,}6^{\pm 0{,}2}$	$260{,}6^{\pm 3{,}5}$	$30{,}3^{\pm 0{,}8}$
8	$72{,}7^{\pm 1{,}8}$	$46{,}7^{\pm 1{,}8}$	$260{,}7^{\pm 3{,}6}$	$30{,}5^{\pm 1{,}0}$

After performing the tests indicated in Table 2, four engineers with some experience in welding processes were invited for visual assessment of each weld bead appearance (without communication amongst them and not knowing the parameters used in each test). They were instructed to assign scores from 0 to 5 for the visual aspect of each weld bead. Table 4 presents the scores gave by each engineer and Figure 2 illustrates the surface appearance of each bead with the sum of the scores awarded.

Table 4 - Scores assigned by each evaluator and sum of scores for each test

	Evaluators Scores				
Test	***1***	***2***	***3***	***4***	**TOTAL**
1	3	3	2	2	**10**
2	3	2	3	4	**12**
3	1	1	1	2	**5**
4	0	0	0	0	**0**
5	3	4	3	3	**13**
6	5	5	5	5	**20**
7	2	4	4	5	**15**
8	3	3	3	3	**12**

To determine the factors (External Shielding, Plasma e MIG/MAG gas flow) that affect more the response (sum of scores - Table 4), an analysis of variance was carried out using the software Statistica®. The test uses the F-distribution (probability distribution) function and information about the variances of each population (within) and grouping of populations (between) to help decide if variability between and within each populations are significantly different. If the P-value if greater than the alpha level of significance, then there is not reason to reject the null hypothesis that all the means are the same.

The Table 5 presents the effects of each gas flow rates (External, Plasma and MIG/MAG gas flow) calculated from the response of the experimental design, considering the dimension levels (-1,1) of the independent variables. This table indicates that the gas flow rates of the three gases have significant effect on the weld bead appearance, even though the intercept presented very significant *"p-value"* and a high "*Effect*" value (coherent results, considering other factors affecting bead appearances not controlled in the experiments, such as metal transfer, pool volume, etc.). Plasma gas flow rate is clearly the most influence, considering its high "*Effect*" and low "*p-value*". For the external and MIG/MAG gas flows it is not so obvious which one presents the greater effect.

Table 5 – Effects and p-values obtained by ANOVA over the effect of the gases in the Plasma-MIG on the weld bead appearance

	Mean/Interc.	**(1) External**	**(2) Plasma**	**(3) MIG/MAG**	**1 by 2**	**1 by 3**	**2 by 3**
***p*-value**	0,007	0,037	0,019	0,057	0,204	0,090	0,027
Effect	10,87	4,25	8,25	2,75	0,75	-1,75	-5,75

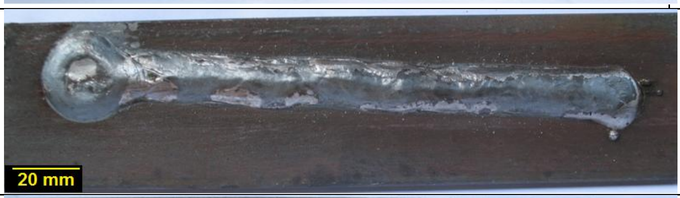
Test	Image of specimens	External Shielding Gas Flow [l/min]	Plasma Gas Flow [l/min]	MIG/MAG Gas Flow [l/min]	Sum of scores
1		5	2	8	10
2		10	2	8	12
3		10	2	2	5
4		5	2	2	0
5		5	8	2	13
6		10	8	2	20
7		10	8	8	15
8		5	8	8	12

Figure 2 – Top view, gas flow rate combinations and evaluation scores of the bead appearances

As shown in Table 4 and Figure 2, the best performed bead was the test 6 and test was 4 the worst. The test 6 (10, 8 and 2 l/min, respectively for the External Shielding, Plasma and MIG/MAG gases) have possibly provided a profile of gas flow more uniformly toward the weld pool. In test 4, in which it was obtained the worst performance, it was employed 5, 2 and 2 l/min, respectively for the External Shielding, Plasma and MIG/MAG gases. Observing the weld bead appearance of this test in Figure 2, some porosity can be observed, indicating that the shielding gas may have been insufficient.

Taking into consideration now only the Plasma gas and making a comparative analysis between tests, one can directly observe in Figure 2 that tests 1 to 4 (Plasma gas flow of 2 l/min) showed inferior appearance when compared to tests 5 to 8 (8 l/min). This finding is in accordance to Essers et al (1981), who mentioned the plasma gas as the highest critical. Considering now only the External Shielding gas for analysis, comparing the pairs of tests 1 and 2, 3 and 4, 5 and 6, 7 and 8 (Plasma gas flow rate of 5 and 10 l/min, respectively, at each pair, but keeping Plasma and MIG/MAG gas flow rates constant). From these tests, it is observed that a flow of 10 l/min gas gave always better results. Considering finally the MIG/MAG gas, comparing the pairs of tests 1 and 4, 2 and 3, 8 and 5, 7 and 6 (MIG/MAG gas flow rate of 8 and 2 l/min, respectively, at each pair, but keeping Plasma and External Shielding gas flow rates constant). From these tests, it was not possible to identify any trends view an expressive difference on weld bead appearance, this may be related to the interaction with the External Shielding and Plasma gases flow observed in Table 5.

To select the best set of parameters, it was used the Statistica® software for plotting graphs of predicted values and desirability, as shown in Figure 3. It can be observed that the best results of surface finishing values were obtained for maximum external shielding gas rate, minimum MIG/MAG gas rate and maximum Plasma gas flow rate. In addition, from this figure it is possible to quantify the highest sensitivity of the Plasma gas flow rate.

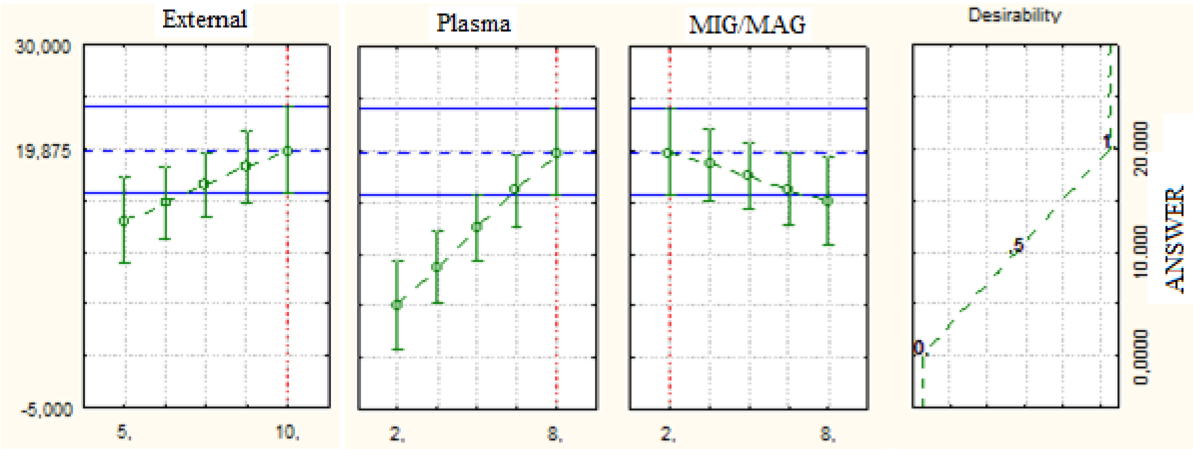


Figure 3 – Predicted values and Desirability

Taking as standard the best welding condition provided by factorial design (10, 8 e 2 l/min respectively for External, Plasma e MIG/MAG), it was looked separately for the effect of each gas using the one-step-at-a-time approach. First, the External Shielding and MIG/MAG gases flow rates was kept invariable and the Plasma gas flow was varied from 6 to 12 l/min (Plasma gas flow was evaluated first because of its greatest effect on the process). The outcome can be seen in Figure 4, in where one can observe that test 9 (corresponding to a replication of test 6) was already an optimized condition, since values below and above 8 l/min for the Plasma gas flow rate resulted in weld beads with inferior superficial aspect.

Similarly, Figure 5 presents the results for the MIG/MAG gas flow optimization. Increases in the MIG/MAG gas flow (test 14) impair the weld bead appearance. The likely cause is that an increase in the gas flow rate causes an augment in the gas velocity, the pressure on the weld pool and its consequent disturbance became higher, which would result in irregular weld beads. In addition, a test was also performed without the presence of MIG/MAG gas (test 15) and and no impairment in superficial weld bead aspect compared to the tests 9 or 6 was observed. This is a very interesting result, since it indicates the possibility of working with the Plasma-MIG welding process with the supply of only two gases, Plasma and External Shielding (it must, however, be evaluated the effect of the MIG/MAG gas on the torch components life).

Figure 6 shows the optimization results for the External Shielding gas flow. Using the test 9 as standard, for both, increasing and decreasing of the External Shielding gas flow rate, the weld bead superficial aspect got worse. To further analysis, it was also performed test 18 at much higher External Shielding gas flow (15 l/min) and with no MIG/MAG gas. Comparing this condition to tests 16's, it is observed an improvement in the appearance of the weld bead when the gas MIG/MAG is suppressed; reinforcing what was presented in the previous paragraph.

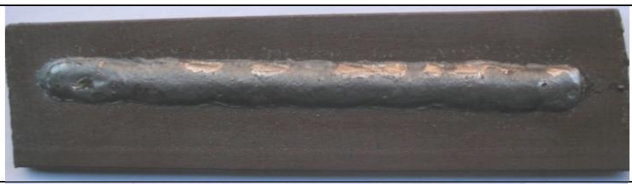
Test	Image of specimens	External Shielding Gas Flow [l/min]	Plasma Gas Flow [l/min]	MIG/MAG Gas Flow [l/min]
9 (Replication)		10	8	2
10		10	6	2
11		10	10	2
12		10	12	2

Figure 4 - Top view, gas flow rate combinations and evaluation scores of the bead appearances for the Plasma Gas Flow optimization

Test	Image of specimens	External Shielding Gas Flow [l/min]	Plasma Gas Flow [l/min]	MIG/MAG Gas Flow [l/min]
9 (Replication)		10	8	2
14		10	8	5
15		10	8	0

Figure 5 - Top view, gas flow rate combinations and evaluation scores of the bead appearances for the MIG/MAG Gas Flow optimization

Finnaly, taking now the best welding condition, maximum gas flow rates for Plasma and External Shielding and minimum one for MIG/MAG gas, it can be established a direct relationship with the conventional Plasma welding process. In this process, the final weld bead appearance is directly related to Plasma gas flow and the External Shielding gas plays the hole of offering an additional protection to weld pool and hot parts of workpiece. In the Plasma-MIG welding process, the experiments here showed the same relationship, i.e., the flow of Plasma gas has direct influence on surface appearance of the weld bead and the External Shielding gas provides a complementary protection to the weld pool. In this case, the gas MIG/MAG would act only as part of the Plasma gas, and it could even be removed from the process if the other two gases are well set to the process, as happened in tests 15 and 18.

Test	Image of specimens	External Shielding Gas Flow [l/min]	Plasma Gas Flow [l/min]	MIG/MAG Gas Flow [l/min]
9 (Replica-tion)		10	8	2
16		15	8	2
17		5	8	2
18		15	8	0

Figure 6 - Top view, gas flow rate combinations and evaluation scores of the bead appearances for the External Shielding Gas Flow optimization

4. CONCLUSIONS

For the conditions and welding parameters used in this work, it was concluded that:

- when was used higher flow rates for External Shielding (10 l/min), smaller flow rates for MIG/MAG (2 l/min) and intermediate for Plasma gases (8 l/min), the best weld beads was obtained;
- The Plasma gas flow influences most the weld bead surface appearance, similar to what occurs in the conventional Plasma Weld Process;
- External Shielding gas flow has intermediate influences on the superficial aspect of the weld bead, and its main effect is concentrated on ensuring a complete protection to weld pool;
- When the External Shielding and Plasma gases are sufficient to ensure a complete protection of the weld pool, MIG/MAG gas can be not used (except concerning maintaining the life of the torch). When choose to use a gas in MIG/MAG circuit, this should have a low flow.

5. ACKNOWLEDGEMENTS

The authors wish to thank all members of the Laprosolda (Center for Research and Development of Welding Processes at Federal University of Uberlandia, Brazil), for infrastructure support and advices. Thanks to TBi company for supporting the project. The authors also extend thanks to FAPEMIG and CAPES Foundations for the financial support.

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