MIG – VP: Negative current effect and proportion of electrode negative on the penetration aluminium weld bead

https://doi.org/10.56238/sevened2024.010-050

Leandro Rubén González[1], Arnaldo Ruben González[2], Rafael Ellwanger Pimentel[3] and Matheus Botega[4]

ABSTRACT

The MIG (Metal Inert Gas) process with variable polarity (VP) is a relatively new process that can be applied in the welding process industry with high deposition rates and competitive costs. The process uses curves composed of pulses in positive and negative polarities and presents as main benefits in relation to the conventional process, a high melting rate, combined with low thermal input, smaller deformations, and better control of penetration and dilution. The objective of this work is to analyze the effect of the negative current (In) and the proportion of negative electrode (%EN), of the typical current curve of the variable polarity process, on the penetration of the weld beads. For the study, three levels of In of -70 A, -50 A, and -30 A and four levels of %EN percentages of 20%, 30%, 40%, and 50% were used, applying a fully crossed factorial experiment design. Weld beads were made in the flat position (1G), depositing aluminum ER5356 on the free surface of the Al5052-F sheet. It is suggested that for the negative electrode proportion (%EN), the value of the negative current should be considered, in order to obtain a closer approximation to the effects of In and %EN on penetration. The effect of In on penetration is 13.1%, however, the effect of %EN is 71.6%, also the interaction (In and %EN) is statistically significant contributing with 11.0%. It was concluded that a decrease in negative current in modulus causes a reduction in penetration. Likewise, increasing the proportion of the negative electrode causes a decrease in penetration into the weld bead.

Keywords: MIG variable polarity, Negative Current, Proportion of negative electrode, Penetration, Aluminum welding.

[1] Master's student in Mechanical Engineering (UFRGS)
Institution: Federal University of Rio Grande do Sul (UFRGS)
E-mail: leorubengonzalez@gmail.com
[2] Doctor in Mining, Metallurgical and Materials Engineering (UFRGS)
Institution: Federal University of Rio Grande do Sul (UFRGS)
E-mail: ruben@mecanica.ufrgs.br
[3] Doctor student in Mechanical Engineering (UFRGS)
Institution: Federal University of Rio Grande do Sul (UFRGS)
E-mail: rafaellpimentel@hotmail.com
[4] Master's student in Mechanical Engineering (UFRGS)
Institution: Federal University of Rio Grande do Sul (UFRGS)
E-mail: matheusbotega94@gmail.com

INTRODUCTION

In manufacturing processes, after the consolidation of the large-scale production process, the need to join similar or dissimilar materials became imperative. In this context, welding technology has emerged as a great ally for the elaboration of projects and the creation of products that increasingly demand research and technology, especially in the area of metal joining.

Currently, in the industrial sector, there is a predominance in the use of electric arc welding processes, with the MIG/MAG process being the most widely used, both for coating and filling. The MIG/MAG process was patented in 1930 by Hobart and Devers and called GMAW (*Gas Metal Arc Welding*), according to (NASCIMENTO AND VILARINHO, 2006), and currently, it is widespread and widely applied, being the main welding method used, according to (MIRANDA AND FERRARESI, 2003). The MIG/MAG process has a range of advantages, such as a high deposition rate, a considerable and indisputable quality of the weld seam, combined with a moderate cost of production of the process.

Due to the constant increase in productivity demand, the need arose for the welding process to become more flexible and the optimization and constant improvement of the MIG/MAG process has made one of its variants the so-called Variable Polarity (PV) (MIG/MAG). This method is still not widespread in the production process and its main characteristic is the high rate of material deposition.

There is, on the other hand, a drawback in the MIG/MAG PV process, which is precisely the adjustment of the six parameters of the welding current curve, which generate weld seams in satisfactory conditions, this is basically done by the trial and error method until the point where a gap in parameter values that meet the desired characteristics is reached (DUTRA ET AL., 2015).

Particularly, in this work, the MIG/MAG Variable Polarity welding process was chosen to carry out the weld seams, since it allows the accurate control of the characteristics of the seam. This process provides the best penetration control, less dilution and, as an advantage, less distortion, according to (BAUMGAERTNER, 2017) and (TONG ET AL., 2001).

OBJECTIVE

Considering the complexity of the selection of parameters, this work aims to analyze the negative current and the negative electrode proportion (%EN), varying the time of the negative current, in order to understand the variation of the negative current when applying the formulas of the proportion of negative electrode on the penetration of the weld bead, using the fully crossed factorial design.

THEORETICAL BACKGROUND

MIG/MAG WELDING PROCESS VARIABLE POLARITY

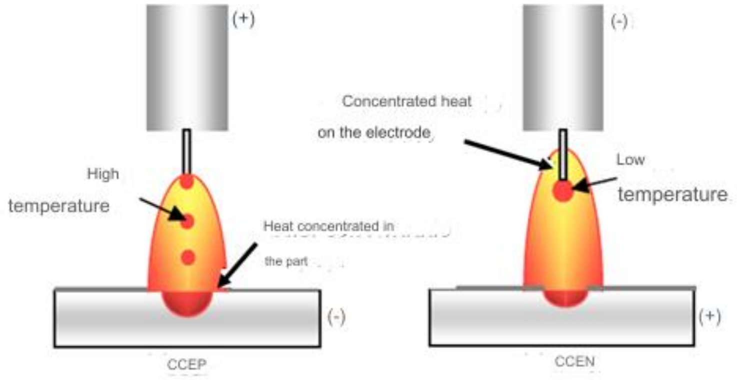
Currently, the MIG/MAG process is one of the most widely used welding processes for the production of weld seams in large extensions, such as surface coating, wear, corrosion, heat resistant, among others. However, some problems are usually found, especially in the coating made by welding, such as the high melting of the base metal that produces high dilution and distortions. The MIG/MAG welding process with the use of an alternating current would be ideal to solve some of the difficulties listed above, according to (TONG ET AL., 2001).

In the literature, two distinct nomenclatures are defined: pulsed alternating current (AC) or variable polarity (PV). (NASCIMENTO AND VILARINHO, 2006) mention that the two forms of nomenclature are related to the use of negative polarity in the welding process. However, the alternating current is linked to the sinusoidal waveform, where the positive and negative parts are very close, of equal magnitude. Therefore, the expression variable polarity is related to waveforms Rectangular with variation between the polarities, positive and negative in the welding current curve, and may contain greater time and intensity in its positive part, or, in the same way, in the negative.

The MIG/MAG Welding Process Variable Polarity (Figure 2) is used to describe rectangular waveforms (alternating in polarity) in which the ratio between the two polarities can be varied and used as a process parameter the "negative electrode ratio – %EN".

The negative polarity, direct current and negative electrode (CCEN), drastically alters the behavior of the MIG/MAG process, modifying the distribution of energies between the electrode and the part. In Figure 1 (KIM ET AL., 2007) they state that in the positive polarity, direct current and positive electrode (CCEP) process, the highest concentration of heat occurs in the part, consequently, the penetration is greater, and it is possible to work with several transfer modes. However, in negative electrode (CCEN), this situation is reversed, and a large part of the heat generated is concentrated in the electrode, and with this there is an increase in the melting rate, an increase in the voltage of the electric arc, a decrease in the temperature in the part and a reduction in penetration, it also affects the transfer mode, which in most cases is globular.

Figure 1 – Arc flash behavior in CCEP and ENCC.



Source: Adapted from ((KIM ET AL., 2007).

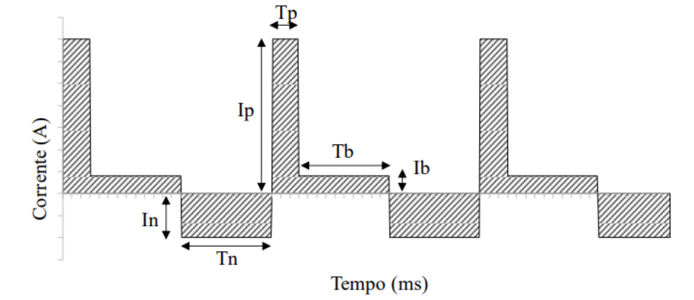
(TONG ET AL., 2001) conducted studies using CCEN compared to conventional MIG/MAG (CCEP), with CCEN showing lower temperature values in the specimen. As a result, they saw a reduction in the deformation of the final part, as well as less penetration and dilution. This benefit was also proven by (PARK ET AL., 2009), who verified the reduction in the temperature of the welded part with the increase in the use of the negative electrode.

In the MIG/MAG PV process, it is possible to obtain a higher melting rate, combined with the low temperature in the base metal, generating great instabilities in the electric arc and in the transfer of the metal from the tip of the electrode to the weld pool, in the vast majority of situations making it impossible to use CCEN in the MIG/MAG process. The instability is explained by (TALKINGTON, 1998), mainly by the mode of transfer of the metal, which is limited to the globular mode for NCCC. But in order to minimize the instability of the arc and thus use the benefits of the negative electrode, such as reduced penetration, reduction of temperature in the base metal, the positive electrode is applied to the process, which brings with it the stability of the electric arc. According to (JOSEPH, 2003), each polarity has a heat balance, but combined they allow the control of the heat of the part and electrode, as well as the control of penetration, and according to (DUTRA, 2015), this combination generates low temperatures combined with increases in the melt rate (productivity) in the welding process.

The current curve used in this work of the Variable Polarity MIG/MAG process has three parts: positive pulse, positive base and negative pulse. As shown in Figure 2, the waveform of the MIG/MAG PV welding process is formed by the positive part, which contains four parameters: peak current (Ip), peak time (Tp), base current (Ib), base time (Tb), and the negative part: negative current (In) and negative current time (Tn).

Figure 2 – MIG/MAG-PV waveform and its parameters.

Ip = Positive current - energy to blow and detach the drop
Tp = Positive current time - time required to ensure full melting
Ib = Base current - current that ensures non-extinguishing of the arc
Tb = Base current time - assists in cooling the part
In = Negative current - increases electrode melting rate
Tn = Negative Current Time – determines penetration and helps with cooling



Source: Author (2024).

According to (TONG, 2001), a positive base current lasting approximately 1.5 ms before or after the detachment pulse (positive peak current), recommended for welding aluminum, is a mechanism that allows the droplet to reach the weld pool free of repulsive forces, thus minimizing or avoiding splashing. The step of the base current, before and/or after the detachment pulse, helps to mitigate the rapid reversal of polarity and stabilize the electric arc, according to (NASCIMENTO, 2011).

NEGATIVE ELECTRODE RATIO (%EN)

Along with the use of the equation for the negative electrode ratio, the following authors: (FARIAS, 2005; MONTEIRO AND SCOTTI, 2013; NASCIMENTO, 2011; SO ET AL., 2010; TONG, 2001) use penetration as an object of study, seeking improvements in processes, for example, to improve root passes, closing openings between plates or welding for coating, where there is a need for greater control of penetration in the welding process. And the understanding of the effects of the negative electrode through only one factor (%EN), would facilitate the application of variable polarity at the industrial level.

The current curve in Figure 2 consists of rectangular pulses formed by six different parameters. The choice and understanding of these six different parameters make the process quite complex to parameterization, that is, the appropriate combination of parameter values for the desired response. For this reason, many authors use a factor that represents the percentage of negative polarity in relation to the total current curve, called the negative electrode ratio (%EN), which is used to understand the variation of negative polarity in relation to the variables of the welding process, such as penetration, dilution, temperature, etc. among others. The %NE ratio is found in the literature in two different forms of calculation according to the Eqs. (1) and (2).

A Eq. (1) considers only the times between polarities, having as a response the proportion of the negative current time (Tn) in relation to the total pulse period (T), which is the sum of the positive base current (Tb) and peak time (Tp) and the negative current time (Tn). This calculation method was used by the following authors: (CIRINO, 2009; DUTRA ET AL., 2015; MONTEIRO AND SCOTTI, 2013; NASCIMENTO ET AL., 2008; NASCIMENTO, 2011; SANTOS, 2008; VILARINHO ET AL., 2009).

$$\%EN = \frac{Tn}{Tn + Tp + Tb} \times 100\% \quad (1)$$

However, a second way of calculating the percentage of negative electrodes can be found in the literature. The proportion calculated according to Eq. (2) Considers the time composition and the intensity of the negative current in relation to the total current wave in the period. In summary, the term %EN' compares the area of the current curve as a function of the time (I x T) of the current in the negative part with respect to the total area of a pulse cycle. This type of calculation was used by the following researchers: (FARIAS, 2005; KAH, SUORANTA & MARTIKAINEN, 2013; KIM ET AL., 2002; KIM ET AL., 2007; PARK ET AL., 2009; SO ET AL., 2010).

$$\%EN' = \frac{In \times Tn}{(In \times Tn) + (Ip \times Tp) + (Ib \times Tb)} \times 100\% \quad (2)$$

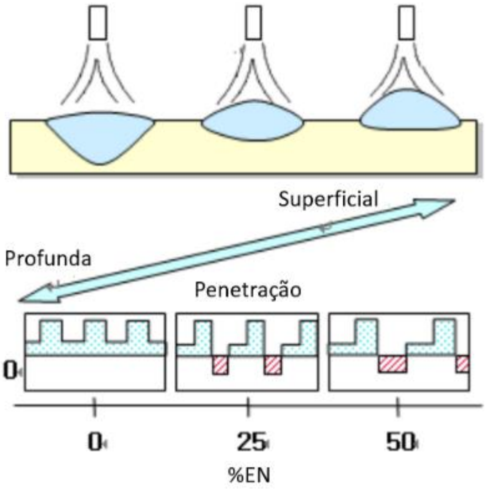
Essentially, the difference between the two forms of calculation is as follows: in Equation (1) only the times (Tn, Tp, Tb) of application of currents are considered and not their respective intensities (In, Ip, Ib), while in Eq. (2) The %EN is calculated considering the six parameters of the current curve. Considering an arbitrary set of values of these six parameters, depending on whether Eq. (1) or Eq. (2), different %EN values can be arrived at.

However, as presented by (FARIAS, 2005) and (KIM ET AL., 2002), who used Eq. (2), or as demonstrated by (NASCIMENTO, 2008), using Eq. (1), the higher the value of the negative electrode ratio (%EN), the lower the values obtained from penetration.

In general, the increase in the percentage of negative polarity in the current curve generates a reduction in penetration into the weld seam geometry. This condition is represented by (KIM ET AL., 2002) in Figure 3, where the increase in the percentage of negative polarity, considered by the %EN value between 0% and 50%, is illustrated, and in turn the effects on the penetration and characteristic of the weld bead.

Experiments were carried out by (KIM ET AL., 2002) with aluminum wires and pure argon shielding gas, on thin aluminum sheets of 1 to 2 mm thickness, varying the %EN between 5% and 40%, in order to control the penetration in the welding process. The results of the cross-sections of the weld seam show that increasing the electrode ratio reduces the penetration of the weld seam.

Figure 3 – Effect of %EN on Penetration.



Fonte: Adaptado de (KIM ET AL., 2002).

FULLY CROSS-FACTOR EXPERIMENT DESIGN

Experiment designs have had an important impact on manufacturing industries, including the design of new products and the improvement of existing ones, the development of new manufacturing processes, and process improvement.

Factorial designs have several advantages. They are more efficient than experiments performed by varying only one factor at a time. In addition, factorial planning is necessary when interactions may be present to avoid misleading conclusions.

Finally, factorial designs allow the effects of one factor to be estimated at various levels of the other factors, generating conclusions that are valid under a variety of experimental conditions.

According to Montgomery, 2009, the simplest types of factorial experiments involve only two factors or sets of treatments. There are factor A levels and B factor B levels, and these are arranged in a factorial design; That is, each replicate of the experiment contains all combinations of AB treatment. In general, there are *n* replicas.

The following is a general case of a two-factor factorial design, where y_{ijk} is the response observed when factor A is at the ith level (i = 1, 2, ..., a) and factor B is at the *jth* level (j = 1, 2, .., b) for k-th replication (k = 1, 2, ..., n). The sequence in which the *abn* observations are made is randomly selected for the treatments of the fully crossed factorial design.

Observations in a factorial design can be described by Eq. (3) By a model of effects:

$$y_{ijk} = \mu + \tau_i + \beta_i + (\tau\beta)_{ij} + \epsilon_{ijk} \begin{cases} i = 1, 2, \dots, a \\ j = 1, 2, \dots, b \\ k = 1, 2, \dots, n \end{cases} \qquad (3)$$

Where μ is the overall mean effect, τi is the effect of the *ith* level of the line factor A, βj is the effect of the j-th level of the column factor B, $(\tau\beta)_{ij}$ is the effect of the interaction between τi and βj, and ε_{ijk} is a random error component.

MULTIPLE COMPARISON OF MEANS – TUKEY'S TEST

When ANOVA indicates that row or column averages differ, it is often interesting to make comparisons between individual row or column averages to find out the specific differences. There are several methods of multiple comparison, e.g., Scheffé's method, Fischer's method of least significant difference (LSD), Dunnett (1964), Duncan, and Tukey (1953) that are useful in this regard, according to (Montgomery, 2009).

In many practical situations, it is necessary to compare only pairs of averages. Often, it can be determined which averages differ by testing the differences between all pairs of treatment averages

When there is interest in comparing all the pairs of means of a treatment and the null hypotheses to be tested is H0 :μi = μj for all $i \neq j$. There are several procedures available for this problem, but in this work the Tukey test will be applied.

Tukey's Test

Suppose that, after an ANOVA in which the null hypothesis of equal treatment means is rejected, the goal is to test all comparisons of paired means:

$$H_0 : \mu_i = \mu_j$$
$$H_1 : \mu_i \neq \mu_j$$

for all $i \neq j$. According to (MONTGOMERY, 2009), Tukey (1953) proposed a procedure for testing hypotheses for which the overall level of significance is exactly α when sample sizes are equal and at most α when sample sizes are unequal. Its procedure can also be used to construct confidence intervals on differences across all pairs of means. For these intervals, the simultaneous confidence level is 100(1− α) percent when sample sizes are equal and at least 100(1− α) percent when sample sizes are unequal. Tukey's procedure uses the error from the experiment at the selected level of α. This is an excellent data evaluation procedure when interest is focused on pairs of means.

Tukey's procedure makes use of distribution statistics:

$$q = \frac{\bar{y}_{max} - \bar{y}_{min}}{\sqrt{MQE/n}} \qquad (4)$$

Where and are the highest and lowest sample means, respectively, of a group of $\bar{y}_{max}\bar{y}_{min}p$ sample means. From the literature (MONTGOMERY, 2009), one can find values of *qα (a, f),* the upper α percentage points of *q*, where *f* is the number of degrees of freedom associated with the mean square of the error term (MQE). For equal sample sizes, Tukey's test states that two means are significantly different if the absolute value of their mean differences exceeds the $T\alpha\ value$ calculated by Eq.(5).

$$T_\alpha = q_\alpha(a, f)\sqrt{\frac{MQE}{n}} \qquad (5)$$

Where, *MQE*: Mean Square of the Error term (from ANOVA); *a*: Number of treatments; *f*: Degrees of Freedom from Error; *n*: Number of repetitions; *α*: Level of significance.

MATERIALS AND METHODS

The experimental part was developed at the Laboratory of Welding and Related Techniques of the UFRGS Technology Center. The welding source used was the DIGIPlus A7 450. To drive the torch, a MOTOMAN robot (Yaskawa) was used to ensure the advance and speed control, as well as the maintenance of the contact nozzle-piece distance (DBCP), everything was properly aligned with the help of a level so that the system was horizontal.

IMC Welding's equipment, SAP4.01, was used for data acquisition, to collect instantaneous current and voltage values at a rate of 5000 samples per second. In SAP4.01 you can obtain graphs of the instantaneous values during the execution of the weld seam. Figure 4 shows the equipment used in the experiment.

The weld seams were deposited on AA5052-F aluminum sheets of dimensions 150x100x8 mm, the filler metal used was AWS A5.10: ER5356 of 1.2 mm diameter. The shielding gas was air with a flow rate of 18 l/min. The weld seams were deposited on the free surface (*bead-on-plate*) in the flat position (1G). The chemical composition of the base metal and that of the filler metal are described in Tables 1 and 2, respectively.

The variable polarity current curve used in this study (Figure 2) is composed of six (6) independent parameters (factors), of which two (2) were varied, In and Tn. From the variation of Tn it was possible to obtain the proportion of negative electrode (%NE). The other parameters Ip, Tp, Ib and Tb were kept constant for all weld beads.

In order to analyze the behavior of the negative polarity, the negative current (In) was varied in three levels: -70, -50 and -30 A, the proportion of negative electrode (%EN) in four levels: 20; 30; 40 and 50 % by varying the negative current (Tn) time between 1.5; 2,5; 3.9 and 5.8 ms, respectively.

The parameters kept constant in the experiment were: peak current intensity (Ip) of 280 A, positive peak time (Tp) of 1.8 ms, and for non-extinguishing of the electric arc, the base current (Ib) was kept constant at 65 A with a time of 4.0 ms, as shown in Table 3. With these values for each combination, electric arc stability was obtained by adjusting the wire feeding speed. The other parameters of the welding process were kept constant as shown in Table 4.

Table 1 – Chemical composition of the base metal (%) according to supplier.

Alloy	Oneself	Fe	Ass	Mn	Mg	Cr	Zn	To the
AA 5052F	0 - 0,25	0 - 0,40	0 - 0,10	0 - 0,10	2,20 - 2,80	0,15 - 0,35	0 - 0,10	Remainder

Source: Author (2024).

Table 2 – Chemical composition of the filler metal (%) according to AWS A5.10 – ER5356.

Material	Yes	Faith	With	Minutes	Mg	Cr	Zn	In	To the
ER5356	0,25	0,4	0,1	0,2	5,0	0,2	0,1	0,2	Rest.

Source: Author (2024).

Figure 4 – Welding equipment on the left, Motoman robot and data acquisition equipment, the IMC welding source and the wire feeder.

Source: Author (2024).

Table 3 – Variable Polarity MIG Process Current Curve Parameters

Parameters			Level		
Description	Symbol				
Negative Current (A)	In	-70	-50	-30	
Negative Electrode Ratio	%EN	20	30	40	50
Negative current time (ms)	Tn	1,5	2,5	2,9	5,8
Negative Electrode Ratio Eq. (2)	%EN'	18,6	13,3	8,9	5,6
Peak Running (A)	Ip		Constant = 280		
Positive peak time (ms)	Tp		Constant = 1.8		
Base Current (A)	One		Constant = 65		
Base time (ms)	Tb		Constant = 4.0		

Source: Author (2024).

Table 4 – Welding Process Parameters

Process Parameters	Symbol	Constant Values
Welding Speed (mm/s)	Vs	3,0
Torch Travel Angle (Pulling) (°)		+10
Distance of contact nozzle piece (mm)	DBCP	18
Shielding gas flow rate (l/min)		18

Source: Author (2024).

To study the effect of the negative electrode proportion, a fully crossover factorial design (multiple levels) was applied, with the following parameters and levels, the execution of the weld beads was according to the matrix of experiments in Table 5.

Design of Experiments Parameters (Fixed and Independent Factors)

- Three levels of Negative Current (A) – In: -70 -50 -30
- Four levels of the Negative Polarity Ratio (%) - %EN: 20 30 40 50

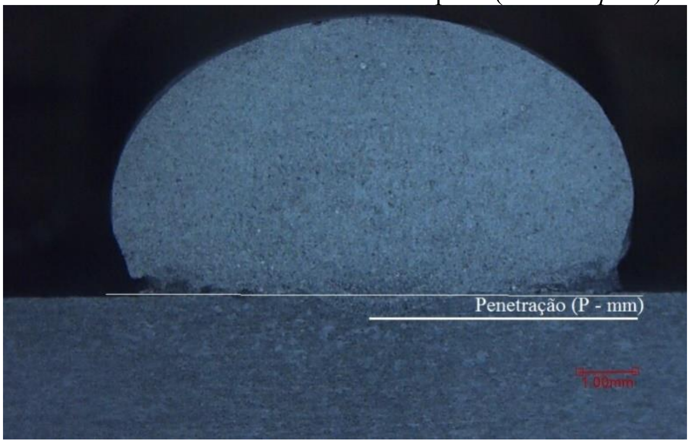
MATERIALS FOR CHARACTERIZATION OF WELD BEADS

Once the weld seams were finished, the process of generating and treating the samples began. The first step was to perform the cross-section of the beads with the use of the *cut-off* cutting machine, in order to obtain specimens of approximately 1.5 cm bead length. Next, the specimens were sanded at 120, 220, 320, 400, 500, 600 and 1000 grain sizes, making sure to start all samples in the same direction and rotate the specimen 90° at each sanding grain size change.

The cross-sections for the macrographs were attacked with the 10% HF (48%) + 90% H_2O reagent, according to ASTM E340-15, in order to obtain contrast between the weld metal and the base metal. All of the attacks were carried out in a chapel and with appropriate security equipment. The macrographs were obtained using a microscope with an 8x magnifying lens and analyzed using the free software ImageJ, with which the response variable: penetration (P – mm) was measured, as shown in Figure 5.

Table 5 shows the randomized welding sequence of the specimens according to the combination of the levels of the controllable factors and the response considered in this study: penetration (P – mm).

Figure 5 – Schematic of the weld bead on the free surface of the plate (*bead-on-plate*) and the response variable.



Source: Author (2024).

RESULTS AND DISCUSSION

Table 5 shows the randomized welding sequence of the specimens according to the combination of the levels of the controllable factors and the penetration response (P – mm).

Figure 6 shows the images corresponding to trials #3, #4 and #19 of the 24 strands generated by the fully crossed factorial design. The visual aspect of essays #13 and #23 can be seen in Figure 7.

Table 5 – Sequence (randomized) and combination of parameters according to the design of experiments for the welding of the specimens, and penetration

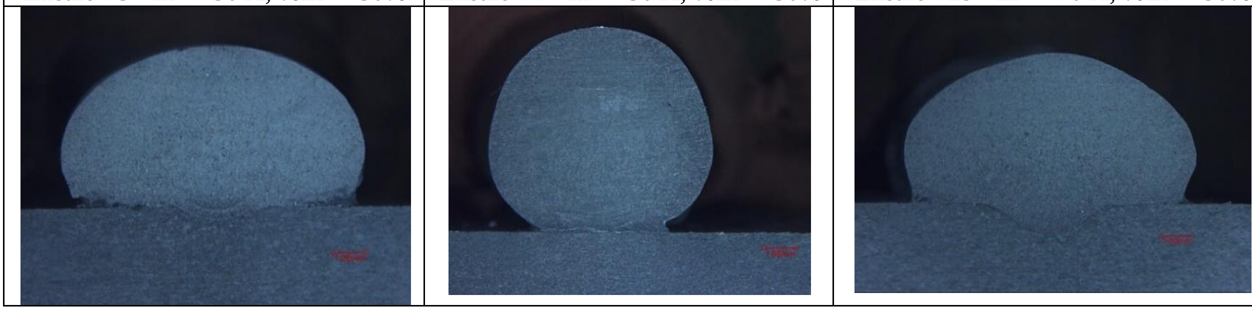
Order Pattern	Seq. Essay	In (A)	%EN (%)	P(mm)
12	#1	-30	50	0,000
15	#2	-70	40	0,292
6	#3	-50	30	0,436
8	#4	-50	50	0,000
23	#5	-30	40	0,000
5	#6	-50	20	1,027
1	#7	-70	20	0,681
3	#8	-70	40	0,250
21	#9	-30	20	0,791
18	#10	-50	30	0,325
20	#11	-50	50	0,171
13	#12	-70	20	0,925

Order Pattern	Seq. Essay	In (A)	%EN (%)	P(mm)
22	#13	-30	30	0,459
7	#14	-50	40	0,266
4	#15	-70	50	0,472
11	#16	-30	40	0,000
9	#17	-30	20	0,671
16	#18	-70	50	0,278
2	#19	-70	30	1,080
17	#20	-50	20	0,899
14	#21	-70	30	0,966
10	#22	-30	30	0,571
19	#23	-50	40	0,000
24	#24	-30	50	0,000

Source: Author (2024).

Figure 6 – Weld seams generated with treatments, assays #3, #4 and #19

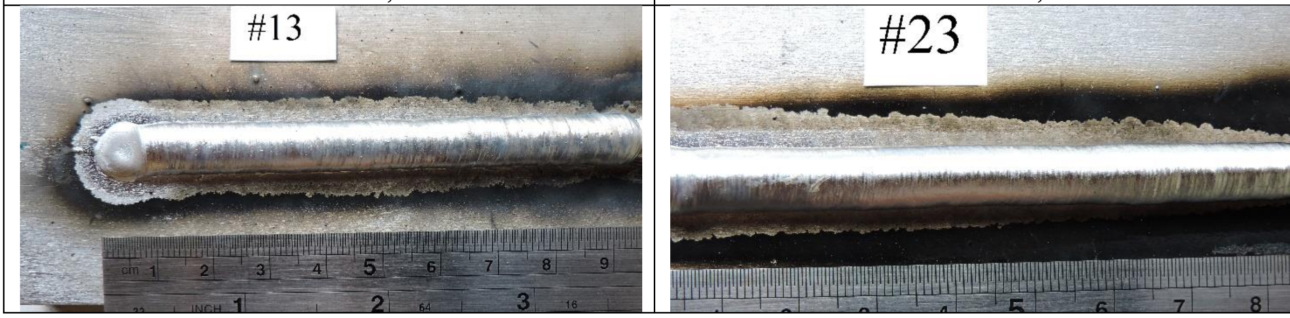
Ensaio #3 - In = -50 A; %EN= 30%	Ensaio #4 - In = -50 A; %EN= 50%	Ensaio #19 - In = -70 A; %EN= 30%



Source: Author (2024).

Figure 7 – Visual appearance of the weld seam from tests #13 and #23

Ensaio #13 - In = -30 A; %EN= 30%	Ensaio #23 - In = -50 A; %EN= 40%



Source: Author (2024).

In order to evaluate more consistently the effects (linear and quadratic) of the main factors employed and the interactions of two factors on the observed response, analysis of variance was submitted.

Using *Minitab*®'s software, the data in Table 5 were processed for the analysis of which parameter and/or interaction has an effect on penetration (P). For this analysis, a 95% confidence interval was used, i.e., for alpha (α) values lower than 5%, it was assumed that the control variable in question is significant in the response. It is noteworthy that the lower the *p-value value*, the greater the influence of the parameter on the analyzed response.

The following sections will introduce the ANOVA Table, the Pareto chart, graphs of the main parameters and interaction, which will show the influences of the main parameters and their combinations on the response, and which of them are significant.

WELD BEAD PENETRATION

Table 6 shows the Analysis of Variance (ANOVA) for weld seam penetration. The p-value can be used to determine the significance of major factors or interactions on penetration. This value is an indicator that quantifies the significance of the response. The term "p-value" is known for its probability of significance, if it presents values lower than 0.05 (5%), the null hypothesis (factor is significant) can be rejected with 95% confidence. By means of ANOVA, it was determined that the main parameters In and %EN have a strong significant effect on penetration for a significance level α

= 0.05 (p-value < 0.05). Also, the interaction (In*%EN) has a significant effect on penetration for a significance level α = 0.05.

Table 6: Analysis of Variance for Penetration versus In (A) and %EN (%)

Source	GDL	SQ	SQM	F-value	p-value	Contribution
Model	11	2,9579	0,26890	24,12	0,000	95,67% (R2)
In (A)	2	0,4052	0,20259	18,17	0,000	13,11%
%EN (%)	3	2,2142	0,73807	66,20	0,000	71,62%
In (A)*%EN (%)	6	0,3385	0,05641	5,06	0,008	10,95%
Error	**12**	0,1338	**0,01115**			4,33%
Total	23	3,0917				100,00%

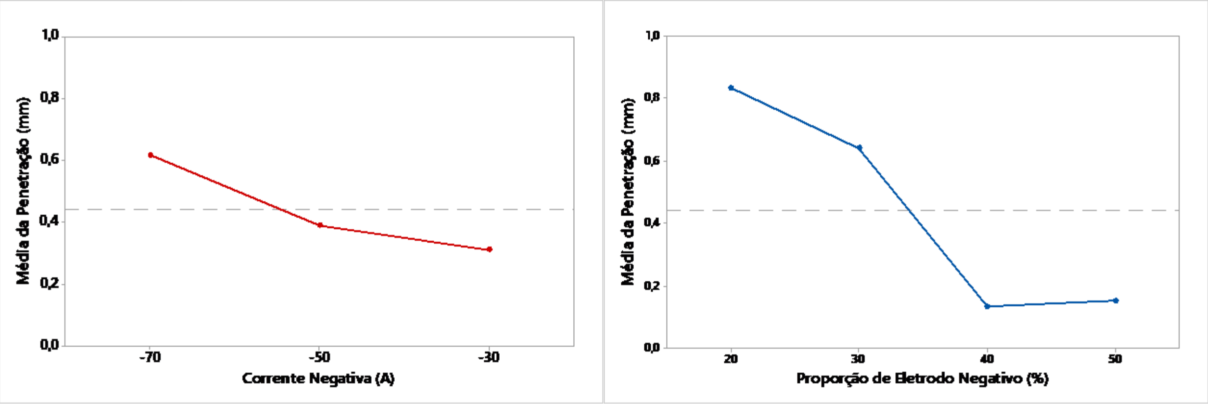
Note: GDL: Degrees of Freedom; SQ: Sum of Squares; MQ: Mean of Squares
Source: Author (2024).

Figure 8 shows the effects of the main parameters In and %EN, and it is observed that the penetration suffers a small decrease when the negative current (In) reduces in modulus from -70 to -30 A, which is in agreement with what was found by (BAUMGAERTNER, 2017). The contribution of negative current variation in penetration is 13.1%.

Increasing the ratio of negative electrode (%EN) reduces penetration as its value increases, see Figure 8. For %EN = 20%, the penetration (P) has an approximate value of 0.83 mm, when this value increases to 30%, the mean P decreases to a value of approximately 0.64 mm, increasing %EN to 40% at P = 0.13 mm and from %EN = 40% to %EN = 50% P = 0.15 mm. Results are similar to those found by (KIM ET AL., 2002; KIM ET AL., 2007; VILARINHO ET AL., 2009). The contribution of the variation in the proportion of the negative electrode to the penetration is 71.6%.

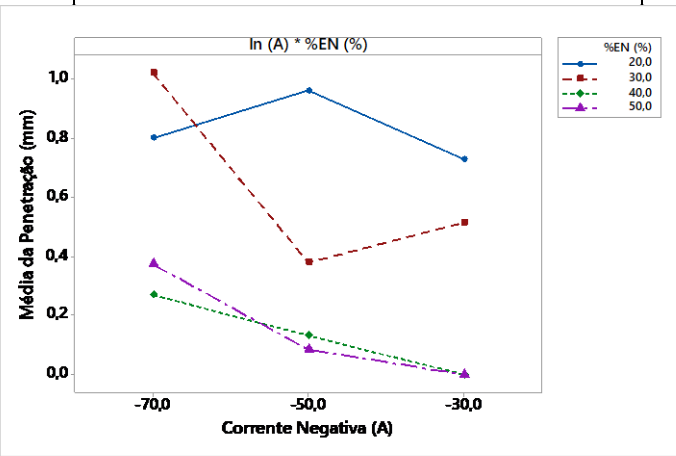
Table 6 of the ANOVA and Figure 9 show that the In*%EN interaction is significant, and the contribution to penetration is 11%.

Figure 8 – Graph of the effects of the main parameters (In and %EN) on penetration.



Source: Author (2024).

Figure 9 – Graph of the effects of the interaction of In and %EN on penetration.



Source: Author (2024).

MULTIPLE COMPARISON OF MEANS - TUKEY TEST

When conducting an analysis of variance (ANOVA) for the fixed-effects model, the null hypothesis is rejected, because there are differences between the treatment means. Sometimes, in this situation, additional comparisons and analyses between treatment mean groups can be helpful, to determine which treatment averages differ by testing for differences between all treatment mean pairs.

The Tukey test can be applied to test for any and all differences between two treatment means, the method is specifically designed for matched comparisons between all means in a population, and applies when the "p-value" for ANOVA treatments is significant.

Tukey's test will be applied to the data of the average penetration (P – mm) of the weld bead. Note that in this experiment, the interaction is significant. When the interaction is statistically significant, comparisons between the means of a parameter (e.g., **In**) can be confounded by the In*%EN interaction. One approach to this situation is to fix the %EN factor at a specific level and apply Tukey's test to the means of the In parameter at that level. It is desired to evaluate the negative current (In), for this purpose, the interest is to detect differences between the means of its three levels. Since the interaction is significant, the comparison takes place at only one %EN level, e.g. level 2 (%EN = 30%). It is necessary to estimate the variance of the error and the best estimate is to use the *MQE* of the penetration ANOVA table for the In and %EN factors, using the assumption that the variance of the experimental error is the same in all treatment combinations.

NEGATIVE CURRENT RATING AND CONSTANT %EN

Keeping constant %EN = 30%, for each negative current level (-70 A, -50 A, -30 A), the mean penetration data is calculated from the penetration data, respectively, 1.023 mm, 0.381 mm and 0.515 mm, see Table 7.

The mean of the squares of the error term (MQE) = 0.01115 can be obtained from the ANOVA, see Table 6, the degrees of freedom for the error term is *f* = 12 and the number of treatment for the negative current is *a* = 3, the number of repetitions is *n* = 2, the significance level is α = 0.05. The value of , = 3.77 can be obtained. Substituting the values in Eq. (5) $q_{\alpha}(a,f) q_{0,05}(3,12)$ *T0.05 can be calculated.*

$$T_{0,05} = q_{\alpha}(a,f)\sqrt{\frac{MQE}{n}} = 3{,}77\sqrt{\frac{0{,}01115}{2}} = 0{,}281491 \qquad (6)$$

Thus, any pairs of treatment means that differ in absolute value by more than would imply that the corresponding pair of population means is significantly different. $T_{0,05} = 0{,}281491$

Table 7: Mean Penetration Values (mm) of the Experiment Design

	%EN (%)			
In (A)	20	30	40	50
-70	0,803	1,023	0,271	0,375
-50	0,963	0,381	0,133	0,086
-30	0,731	0,515	0,000	0,000

Comparisons of penetration averages for In: -70 A, -50 A and -30 A, keeping constant %EN = 30%.

	Average 1	Average 2	Module	T-value0.05	Decision
In -70 A vs In -50 A =	1,023	- 0,381	= 0.643	> 0,281491	Dif. Signif.
In -70 A vs In -30 A =	1,023	- 0,515	= 0.508	> 0,281491	Dif. Signif.
In -50 A vs In -30 A =	0,381	- 0,515	= 0.135	< 0,281491	There is no Diff. Signif.

The analysis indicates that at level 2 of the proportion of negative electrode (%EN = 30%), in Figure 10 it can be observed that the average penetration of the weld bead is the same when applied to the negative current, In = - 50 A and In = - 30 A and that the average penetration for the negative current In = - 70 A is significantly higher when applied to In = - 50 A and In = - 30 A. the difference in mean penetration between the negative current of -70 A and -50 A is statistically significant, as is the difference in penetration between -70 A and -30 A. However, the difference in penetration between -50 A and -30 A is not statistically significant.

By keeping the proportion of negative electrodes constant, and varying only the negative current, in the three levels evaluated, the difference should not be significant in the comparison of the means, so that the mean penetration is not affected by the In value. Thus, it is demonstrated that it is necessary to consider the value of the negative current and the proportion of the negative electrode to obtain the desired condition of penetration of the weld bead. The authors (KIM ET AL., 2002; KIM

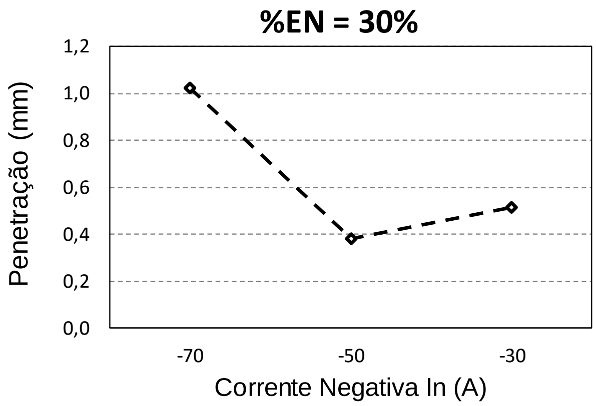
AT EL., 2007; VILARINHO AND NASCIMENTO, 2009) in their studies of the proportion of negative electrode (%EN) on the geometry of the weld bead, did not report whether or not the negative current varied.

In this study, the effect of %EN' was not evaluated, which considers the composition of time and the intensity of the negative current in relation to the total current wave in the period. %EN' compares the area of the current curve as a function of the time (I x T) of the current in the negative part with respect to the total area of a pulse cycle.

Table 6 of the ANOVA shows that the interaction is significant, so it is necessary to compare all the means of *the ab* = 12 cells to determine which ones differ significantly. In this analysis, the differences between the cell averages include the interaction effects as well as the two main effects.

To perform the penetration mean comparisons, the result would be 30 comparisons between all possible pairs of the twelve (12) cell averages.

Figure 10: Average penetration for %EN = 30% and negative current: -70 A, -50 A and -30 A



Source: Author (2024).

EVALUATION OF THE RATIO OF NEGATIVE POLARITY AND CONSTANT IN

It is intended to evaluate whether the proportion of negative electrode (%NE), for this purpose, the interest is to detect differences between the means of the four levels of %NE. Since the interaction is significant, the comparison takes place at only one negative current level, e.g. level 1 (In = -70 A). It is necessary to estimate the variance of the error and the best estimate is to use the MQE in Table 6 of the penetration ANOVA for the In and %EN factors, using the assumption that the variance of the experimental error is constant in all treatment combinations.

Keeping constant In = -70 A, for each level of negative electrode proportion (20%, 30%, 40%, 50%), the mean penetration is calculated from the penetration data, respectively, 0.803 mm, 1.023 mm, 0.271 mm and 0.375, see Table 7 and Figure 11.

The data are as follows: *QE* = 0.01115; number of treatments, *a* = 4; degrees of freedom, *f* = 12; number of repetitions, *n* = 2. The value of , = 4.2 can be obtained. Substituting the values in Eq. (5) $q_{\alpha}(a, f) q_{0,05}(4{,}12)$ *T0.05 can be calculated.*

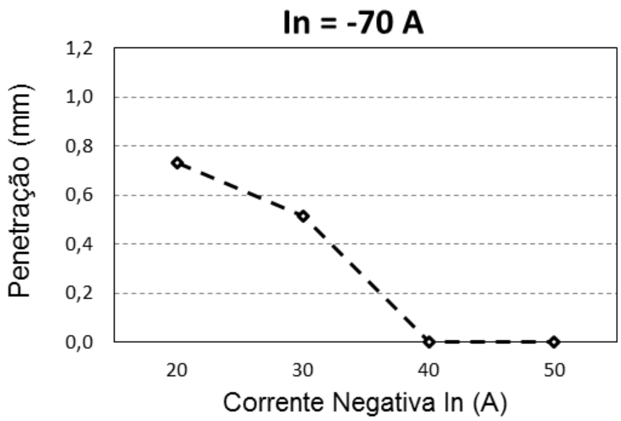
$$T_{0,05} = q_{\alpha}(a, f)\sqrt{\frac{MQE}{n}} = 4{,}2\sqrt{\frac{0{,}01115}{2}} = 0{,}31359687 \quad (7)$$

Comparisons of the means of the ratio of negative electrode to %NE: 20%; 30%; 40% and 50%, keeping constant In = -70 A.

	Average 1	Average 2	Module	T-value0.05	Decision
%EN 20% vs %EN 30%	= 0.803	- 1,023	= 0.220	< 0,3136	There is no Diff. Signif.
%EN 20% vs %EN 40%	= 0.803	- 0,271	= 0.532	> 0.3136	Dif. Signif.
%EN 20% vs %EN 50%	= 0.803	- 0,375	= 0.428	> 0.3136	Dif. Signif.
%EN 30% vs %EN 40%	= 1.023	- 0,271	= 0.752	> 0,3136	Dif. Signif.
%EN 30% vs %EN 50%	= 1.023	- 0,375	= 0.648	> 0,3136	Dif. Signif.
%EN 40% vs %EN 50%	= 0.271	- 0,375	= 0.104	< 0,3136	There is no Diff. Signif

From the comparison of the penetration means for %EN 20% vs %EN 30% and %EN 40% vs %EN 50% it was determined that there is no significant difference. However, the penetration averages for %EN 20% vs %EN 40%, %EN 20% vs %EN 50%, %EN 30% vs %EN 40% and %EN 30% vs %EN 50% are statistically significant.

Figure 11: Mean penetration for In = -70 The constant and the proportion of negative electrode (%EN): 20%; 30%; 40%



Source: Author (2024).

CONCLUSIONS

Based on the evaluation of the penetration of the weld seams with variation of the negative current and negative electrode ratio parameters, it can be concluded that:

- There is a reduction in penetration with an increase in %EN due to the reduction in thermal contribution, which allows the welding of thin sheets and the application of coatings.
- From the statistical evaluation it was determined that the effect of EN on penetration is 13.1%, however the effect of %EN is 71.6%, also the interaction is statistically significant contributing with 11.0%.
- It is possible to select the combination of negative current and negative electrode ratio appropriately to achieve the desired penetration depending on the application (coating, root pass, additive manufacturing).

REFERENCES

1. Baumgaertner, A. J. (2017). Análise dos Parâmetros da Polaridade Negativa na Curva de Corrente de Soldagem MIG/MAG Polaridade Variável Aplicados à Soldagem para Revestimento (Dissertação de Mestrado). Universidade Federal do Rio Grande do Sul.

2. Cirino, L. M. (2009). Estudo dos efeitos da polaridade na soldagem com corrente contínua e alternada pelos processos TIG e MIG/MAG (Dissertação de Mestrado). Universidade Federal de Santa Catarina.

3. Dutra, J. C., Gonçalves e Silva, R. H., Savi, B. M., Marques, C., & Alarcon, O. E. (2015). New methodology for AC-pulsed GMAW parametrization applied to aluminum shipbuilding. The Brazilian Society of Mechanical Sciences and Engineering.

4. Farias, J. P. (2005). Efeito da Soldagem MIG/MAG em Corrente Alternada sobre a Geometria da Solda. *Soldagem Inspeção*, 10(4), 173-181.

5. Joseph, A., Webb, C., Haramia, M., & Yapp, D. (2003, July). Variable Polarity (AC) Arc Weld Brazing of Galvanized Sheet. In *56th IIW International Conference*, Bucharest.

6. Kah, P., Suoranta, R., & Martikainen, J. (2013). Advanced gas metal arc welding process. *International Journal of Advanced Manufacturing Technology*, 67, 655-674.

7. Kim, T. J., Joe, G. J., Kong, H. S., Cho, S. M., & Kim, C. U. (2002). The study of variable polarity AC pulse GMA welding system. In *International Conference on Electrical Engineering* (pp. 688-691).

8. Kim, T. J., Lee, J. P., Min, B. D., Yoo, D. W., & Kim, C. U. (2007). Characteristics of Pulse MIG Arc Welding with a Wire Melting Rate Change by Current Polarity Effect. *Journal of Electrical Engineering and Technology*, 2(3), 366-372.

9. Miranda, H. C., & Ferraresi, V. A. (2003, May). Identificação da transferência metálica na soldagem MIG/MAG pulsada de aço inoxidável a partir de um sensor óptico. In *2º Congresso Brasileiro de Engenharia de Fabricação*, Uberlândia.

10. Monteiro, L. S., & Scotti, A. (2013, November). A methodology for parametrization of the MIG/MAG CA and its application in service repair of pipelines of oil and gas. In *22nd International Congress of Mechanical Engineering*, Ribeirão Preto.

11. Montgomery, D. C. (2009). *Design and Analysis of Experiments* (7th ed.). John Wiley & Sons, Inc.

12. Nascimento, A. S. (2011). Fenomenologia da soldagem MIG/MAG-PV e sua aplicabilidade para juntas sobreposta e em V (Passe de raiz) (Tese de Doutorado). Universidade Federal de Uberlândia.

13. Nascimento, A. S., Fernandes, D. B., Mota, C. A. M., & Vilarinho, L. O. (2008). Metodologia para Determinação de Parâmetros para Soldagem MIG com Polaridade Variável. *Soldagem e Inspeção*, 13(2), 97-104.

14. Nascimento, A. S., & Vilarinho, L. O. (2006). Uma contribuição ao estudo da soldagem MIG-CA. In *16º Simpósio de Pós-Graduação em Engenharia Mecânica*, Uberlândia.

15. Park, H. J., Rhee, S., Kang, M. J., & Kim, D. C. (2009). Joining of Steel to Aluminum Alloy by AC Pulse MIG Welding. *Materials Transactions*, 50(9), 2314-2317.

16. Santos, T. F. (2008). Soldagem MIG com corrente alternada MIG CA (Tese de Doutorado). Universidade Federal de Santa Catarina.

17. So, W. J., Kang, M. J., & Kim, D. C. (2010). Weldability of pulse GMAW joints of 780 MPa dual-phase steel. *International Scientific Journal*, 41(1), 53-60.

18. Talkington, J. (1998). Variable Polarity Gas Metal Arc Welding (MSc Dissertation). The Ohio State University.

19. Tong, H., Ueyama, T., Harada, S., & Ushio, M. (2001). Quality and productivity improvement in aluminium alloy thin sheet welding using alternating current pulsed metal inert gas welding system. *Science and Technology of Welding and Joining*, 6(4), 203-208.

20. Vilarinho, L. O., Nascimento, A. S., Fernandes, D. B., & Mota, C. A. M. (2009). Methodology for Parameter Calculation of VP-GMAW. *Welding Journal*, 88, 92-98.