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# PRINCIPLES AND CONCEPTS **FOR DEVELOPMENT** IN NOWADAYS SOCIETY

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# CHAPTER 44

# MIG PV Process: effect of negative electrode proportion on aluminum weld bead geometry

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**ABSTRACT**
The MIG (Metal Inert Gas) process with variable polarity is a relatively new process that can be applied in the welding process industry with high rates of productivity and competitive cost. The process uses compound curves of pulses in positive and negative polarities, and presents as main benefits in relation to the conventional process, high melting rate, allied to low heat input, smallerdeformations and better control of penetration and dilution. The objective of this work is to analyzethe effects of the proportions of the negative polarity (%EN), of the typical current curve of the process, seeking to relate with the penetration and dilution of the resulting weld bead. Three levelsof %EN percentages of 0%, 30% and 50% were used for the study. Weld beads were made in the flat position (1G), depositing ER5356 aluminum onto the free surface of Al5052-F sheet. The negative polarity parameters used were compared with different forms of calculations proposed inthe literature for determining the value of the negative electrode ratio. It is suggested that for the calculation of the negative electrode ratio (% EN), all parameters of the curve (currents and times)should be considered in order to obtain an effective comparison of the % EN levels. It was concluded that increasing the proportion of negative electrode causes decreased penetration and dilution in the weld bead.

**Keywords**: MIG Variable Polarity, Negative Electrode Ratio, Aluminum Welding.

## 1 INTRODUCTION

With the advent of manufacturing processes, especially after the consolidation of the large- scale production process, the need to join similar or dissimilar materials has become increasingly necessary. In this context, welding 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 metals.

There is today, in the industrial sector, a predominance, when we talk about welding process, in the use of the electric arc method, being MIG/MAG 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) [1], and nowadays, it is widely used worldwide, being the main welding method used [2]. The MIG/MAG process presents a range of advantages, such as a high rate of productivity, a considerable and unquestionable quality of the weld bead allied to a moderate cost of production of the process.

With the constant increase in demand for productivity, the need arose for the welding process to become more flexible and the optimization and constant improvement of the MIG/MAG process caused its variant called Variable Polarity to become widespread in the production process. This process has as its main characteristic the high rate of material fusion.

There is, however, a porem in the MIG/MAG PV process that is precisely the adjustment of the six parameters of the current curve, which generate welding welds in satisfactory conditions, this is basically by the method of trial and error to the point where it reaches a gap of parameter

values that meet expectations [3]. Basically the variables changed in each of the parameters of the work were: Negative pulse time (Tn) in (ms), Negative pulse current (In) in (A), and base current time (Tb) in (ms).

In particular, in this work they sought to understand how the process parameters affect the characteristics of the weld bead, which are penetration and dilution, important parameters when it comes to surface coating by welding, also in root pass.

For this, the welding process MIG/MAG Variable Polarity was chosen to perform the weld beads since it allows the accurate control of the characteristics of the weld bead. This process provides the best control of penetration, less dilution and as an advantage, less distortion [3].

The present work aims to evaluate the effect of negative polarity parameters (time and intensity) through negative polarity ratios (%EN) on weld bead geometry (penetration, height and width) and dilution.

## 2 THEORETICAL BACKGROUND

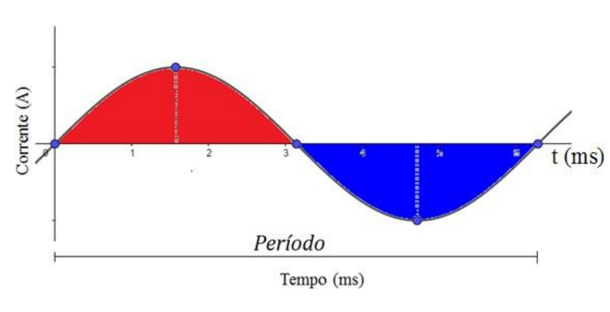
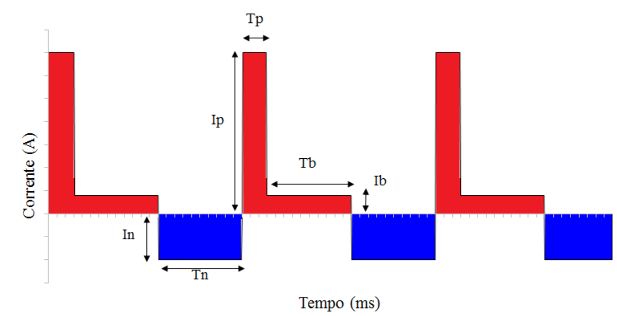
### 2.1 MIG/MAG WELDING PROCESS VARIABLE POLARITY

The MIG/MAG process is one of the most used welding processes today for the production of weld beads in large extensions, as in the coating of surfaces, resistant to wear, corrosion, heat, among others. However, normally some problems are encountered, especially in the coating done by welding, such as high fusion of the base metal that produces high dilution and distortions. The MIG/MAG welding process using an alternating current would be ideal to solve some of the difficulties listed above [4].

Two distinct nomenclatures are defined in the literature: pulsed alternating current (AC) or variable polarity (PV). Both forms of nomenclature are related to the use of negative polarity in the welding process [1]. However, alternating current is linked to the sine waveform, where the positive and negative parts are very close, of equal magnitude. Therefore, the expression variable polarity is more related to waveforms with variation between the polarities, positive and negative in the welding current curve, and may contain more time and intensity in its positive part, or similarly in the negative.

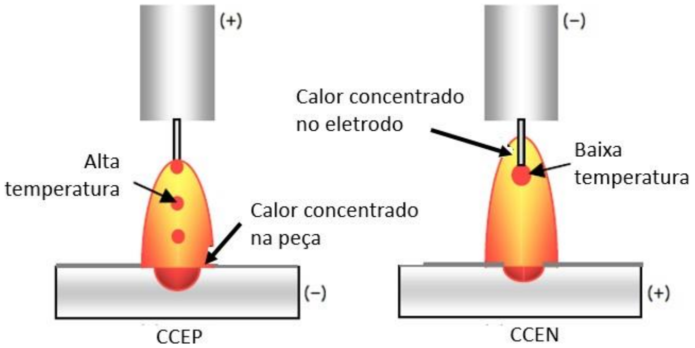
Currently two different nomenclatures are recognized: the alternating current (AC) waveform can be seen in Figure 1 and the variable polarity definition (Figure 2). Both nomenclatures bring with them the concept of using negative polarity during part of the welding, which allows the welding of thin sheets [1].

In Figure 1 you can see the waveform for the MIG/MAG welding process Alternating Current (AC) is used to describe a sine wave. Also to describe a current that alternates between positive and negative polarity. The term alternating polarity relates to waveforms with varying positive and negative polarity in the welding current curve, whereby the time and intensity can be adjusted in its positive part, or likewise in its negative part. The MIG/MAG welding process Variable Polarity (Figure 2) is used to describe pulsed waveforms (alternating in polarity) in which the ratio between the two polarities can be varied and the "negative electrode ratio - %EN" is used as the process parameter.

| Figure 1 - Waveform of the Alternating Current MIG/MAG welding process. Author Source. | Figure 2 - Waveform of the Variable Polarity MIG/MAG welding process. Source Author |
| --- | --- |
|  |  |

The negative polarity, direct current and negative electrode (CCEN), drastically changes the behavior of the MIG/MAG process, changing the distribution of energies between the electrode and the workpiece. In Figure 3, in the process positive polarity, constant continuous current and positive electrode (CCEP), the highest concentration of heat happens in the workpiece, greater penetration, one can work with various modes of transfer [5]. However, in negative electrode (CCEN), this situation is inverted and most of the heat is concentrated in the electrode, and with this occurs an increase in the fusion rate, increased arc voltage, decreased temperature in the workpiece and reduced penetration, also affecting the transfer mode that in most cases is globular.

Figure 3 - Arc behavior in CCEP and CCEN. Adapted from [5]



The use of direct current and negative electrode (CCEN) compared to conventional MIG/MAG presents lower temperature values on the part [4]. As a result, they verified a reduction in the deformation of the final part, as well as less penetration and dilution. This benefit was also proven by [6], who verified a reduction in the temperature of the welded part with the increase in the use of the negative electrode.

In the PV MIG/MAG process, it is possible to obtain higher fusion rate, coupled with low temperature in the base metal generating great instabilities in the electric arc and in the metal transfer from the tip of the electrode to the fusion puddle, in the vast majority of situations making it impossible to use CCEN in the MIG/MAG process. The instability is explained by [7] mainly by the metal transfer mode, which is limited to globular mode for CCEN. But to minimize the arc instability and thus utilize the benefits of the negative electrode, such as reduced penetration, reduced temperature in the base metal, the positive electrode is applied to the process, which brings with it the arc stability. According to [8], each polarity presents a heat balance, but combined they allow control of the heat of the workpiece and electrode, as well as control of penetration, and according to [9], this combination generates low temperatures allied to increases in the productivity rate in the welding process.

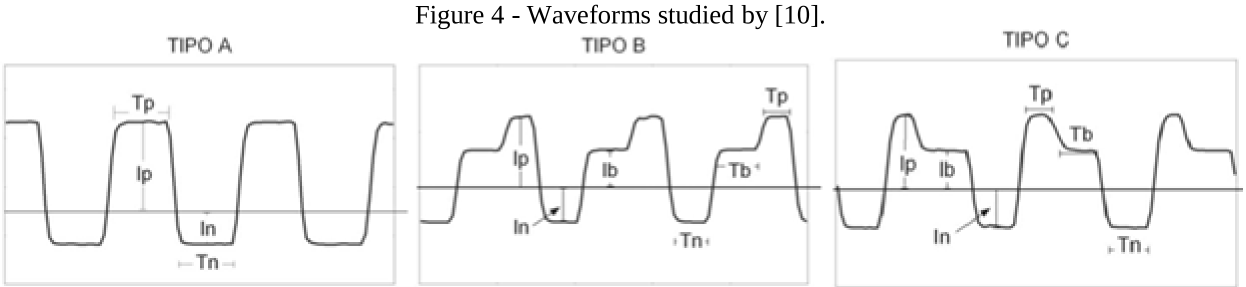
### 2.1.1 MIG/MAG PV process waveforms

In the Variable Polarity MIG/MAG welding process the current waveform is currently a widely explored topic, [10] studied three waveform variations, seeking to understand the relationship between the shape of the curve and the weld bead geometry. The studied waves are listed in Figure 4.

The base current is critical for severe polarity changes, and prevents spatter in the welding process [11].

The three types of waves contemplate, not using the base time (type A), using the base time before the positive peak current (type B) and the base current after the positive peak (type C). The results obtained showed that the waveform has no significant influence on the weld bead geometry, but there is a significant effect of the interaction of the weld bead geometry with the negative polarity parameters.

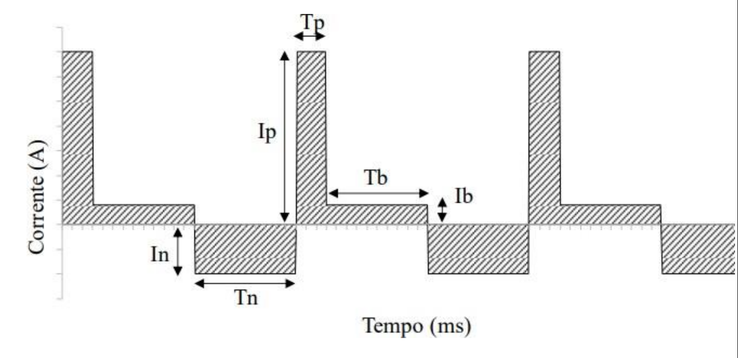
Figure 4 - Waveforms studied by [10].



The current curve of the Variable Polarity MIG/MAG process has three parts: positive pulse, positive base and negative pulse. As shown in Figure 5, the waveform of the PV MIG/MAG welding process, 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 5 - MIG/MAG-PV waveform and its parameters. Source Author

**Ip = Positive current -** energy to melt and detach the drop
**Tp = Time of positive current -** time required to ensure full fusion
**Ib = Base current -** current that ensures the non-extinction of the arc
**Tb = Base current time -** assists in cooling the part
**In = Negative current -** increases melt rate of the electrode
**Tn = Negative current time -** determines penetration and helps cooling




According to [4], a positive base current with a duration of approximately 1.5 ms before or after the detachment pulse (Positive Peak Current), recommended for aluminum welding, is a mechanism that allows the bead to reach the fusion puddle free of repulsive forces, thus minimizing or avoiding spatter. The stepping of the base current, before and/or after the detachment pulse, assists in mitigating the rapid polarity reversal and in stabilizing the arc [12].

### 2.1.2 Proportion of negative polarity (%EN)

Along with the use of the equation for the proportion of negative polarity, the following authors [4, 10, 12-14] use penetration as an object of study, seeking improvements in the processes, so for example, to improve root passes, closing of gaps between plates or welding for coating, where there is 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 make the variable polarity applicable on an industrial level.

The current curve in Figure 5 consists of pulses formed by six different parameters. The choice and understanding of these six different parameters make the process of parameterization, i.e., the proper combination of parameter values for the desired response, quite complex. For this reason, many authors use a factor that represents the percentage of negative polarity in relation to the total current curve, called electrode negative percentage (%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, among others. The %EN ratio is found from the literature in two different ways of calculation according to Equations (1) and (2).

The ratio calculated according to Equation (1), considers the composition of the time and intensity of the negative current relative to the total current waveform in the period. In summary, the %EN term compares the area of the current curve as a function of time (I x T) of the current in the negative part relative to the total area of a pulse cycle. This type of calculation has been used by [5, 6, 10,13, 15, 16].

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

However, a second way to calculate the percentage of negative electrode can be found in the literature. This considers only the times between polarities, with the response being the proportion of the negative current time (Tn) in relation to the total pulse period (T), this being the sum of the base current time (Tb) and positive peak (Tp) and the negative current time (Tn). This calculation method has been used by [9, 11, 12 14, 17-19].

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

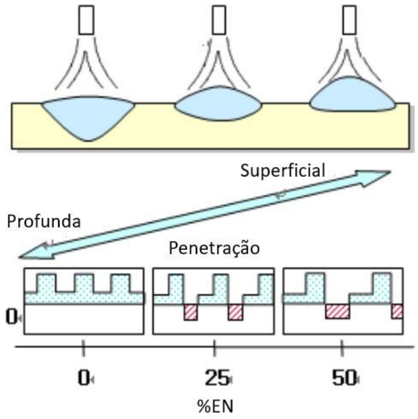
Essentially, the difference between the two ways of calculation, shows that in Equation (1) the %EN is calculated considering all six parameters of the current curve, while in Equation (2) only the current action times and not their respective intensities are considered. Considering an arbitrary set of values of these six parameters, depending on whether Equation (1) or Equation (2) is used, one can arrive at different %EN values.

However, as presented by [10,15], who used Equation (1), or as demonstrated by [12], using Equation (2), the higher the value of the proportion of negative electrode (%EN) the lower the penetration values obtained.

In general, the increase in the percentage of negative polarity in the current curve generates a reduction of penetration in the weld bead geometry. This condition is represented by [15] in

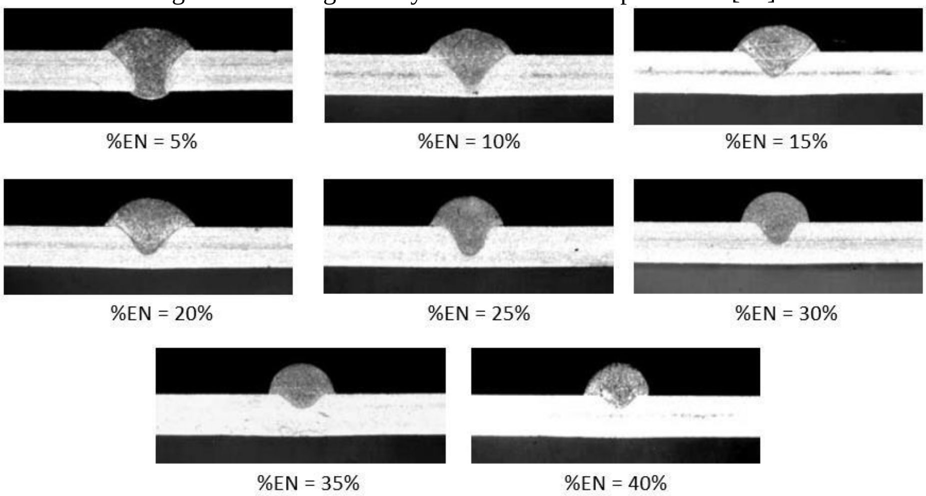
Figure 6, where the increase in the percentage of negative polarity is illustrated, considered by the value of %EN between zero and 50%, and in turn the effects on penetration and characteristic of the weld bead.

Figure 6 - %EN versus Penetration. Adapted from [15]




Experiments were performed by [15] with aluminum wires and pure argon shielding gas, thin aluminum plates from 1 to 2 mm thick, varying the %EN between 5% and 40%, with the objective of controlling penetration in the welding process. Figure 7 illustrates the results of the cross sections of the weld bead, which clearly show a reduction in penetration and width with increasing %EN, as well as an increase in the height of the weld bead.

Figure 7 - Bead geometry versus %EN. Adapted from [15]




## 3 MATERIALS AND METHODS

The experimental part was developed in the Welding and Allied Techniques Laboratory of the Technology Center of the UFRGS. The welding source used was the DIGIPlus A7 450. For the torch conduction, a CNC orbital welding robot, Tartilope V4, was used to ensure the advancement and speed control, as well as the maintenance of the contact tip-workpiece distance (DBCP), everything was properly aligned with the aid of a level so that the system was horizontal.

The data acquisition was done by the equipment of IMC Welding, the SAP4.01 that collected the values of current and voltage at a rate of 5000 samples per second. The values of current and voltage were acquired by the SAP 4.01, equipment from IMC Welding (same manufacturer of the power source), which collected and stored the data, besides showing instantaneous graphs during the execution of the weld bead. Figure 8 shows the equipment used in the experiment.

The weld seams were deposited on AA5052-F aluminum plates of dimensions 150x100x7.9 mm, the filler metal used was ER5356 of 1.2 mm diameter. The weld beads were deposited on the bead-on-plate in the flat position (1G). The chemical composition of the base metal and filler metal are described in Tables 1 and 2, respectively.

Figure 8 - Welding equipment on the left, Tartilope in the background, and acquisition equipment on the white table on the right.

Table 1 - Chemical composition of the base metal (%).

| League | Zn | Mg | Ass | Al |
|---|---|---|---|---|
| Al5052-F | - | 2,5 | - | Rest |

Table 2 - Chemical composition of the filler metal (%).

| Material | Si | Fe | Ass | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| ER5356 | 0,25 | 0,4 | 0,1 | 0,2 | 5,0 | 0,2 | 0,1 | 0,2 | Rest. |

Some parameters were previously set and kept constant during the experiment, such as torch offset angle of -5° (pushing, the melt puddle in front), feed speed of 4 mm/s, wire feed speed of 6.0 m/min, commercially pure argon shielding gas, shielding gas flow rate of 15 l/min and DBCP of 18 mm.

Table 3 lists the parameters used for the three conditions of negative electrode ratios (% EN), obtained from equation (2), which considers the actuation times of each polarity, used during the depositions.

Table 3 - Current parameters and times of the waveform from Figure 5, Negative Electrode Percentage determined with Eq. (2).

| | Negative Electrode Percentage | | |
|---|---|---|---|
| Parameter | 0% EN | 30% EN | 50% EN |
| Ip (A) | 300 | 300 | 300 |
| Tp (ms) | 1,5 | 1,5 | 1,5 |
| Ib (A) | 60 | 60 | 25 |
| Tb (ms) | 7,3 | 4,6 | 2,9 |
| In (A) | 0 | 47 | 47 |
| Tn (ms) | 0 | 2,6 | 4,4 |

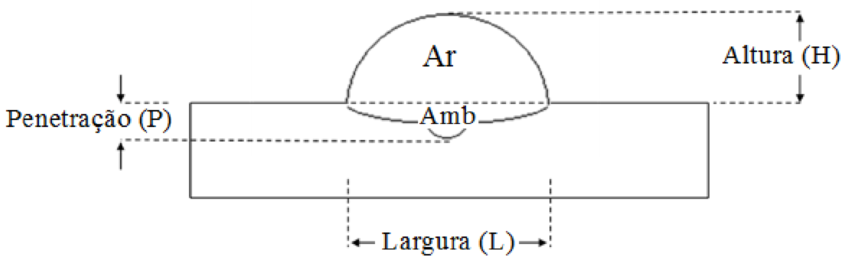
## 3.1 MATERIALS FOR CHARACTERIZATION OF WELD SEAMS

From each of the three slabs used, four samples of the cross-section were taken, one for each pass increment, using the Cut-off machine. These samples were embedded with self-curing acrylic, to avoid problems during grinding and to increase the efficiency of the step. Following preparation of the samples they were sanded in grits 120, 220, 320, 400, 500, 600 and 1000, making sure to start all samples in the same direction and to rotate the sample 90° at each change of sanding grit size.

The cross sections for the macrographs were attacked with Keller Reagent, which, according to ASTM E340, is a mixture of hydrofluoric acid, concentrated hydrochloric acid, concentrated nitric acid, and distilled water. All the attacks were done in a chapel and with appropriate safety equipment. The macrographs were obtained using a microscope with an 8x magnification lens and analyzed using the free software ImageJ, with which the response variables were measured: addition metal area (Ar), base metal fused area (Amb), penetration (P), weld bead width (L) and reinforcement height (H), as shown in Figure 9.

In addition to the geometrical characteristics mentioned above, the beads were also evaluated qualitatively for other aspects such as spatter level, visible pores in the cross section of the weld bead, and overlap defects.

Figure 9 - Schematic of the bead-on-plate free weld bead and the response variables.




## 4 RESULTS AND DISCUSSIONS

This section presents and discusses the results of the work, obtained through the analyses performed on the geometry and other pertinent aspects of the strands in relation to the percentage of negative polarity (% EN).

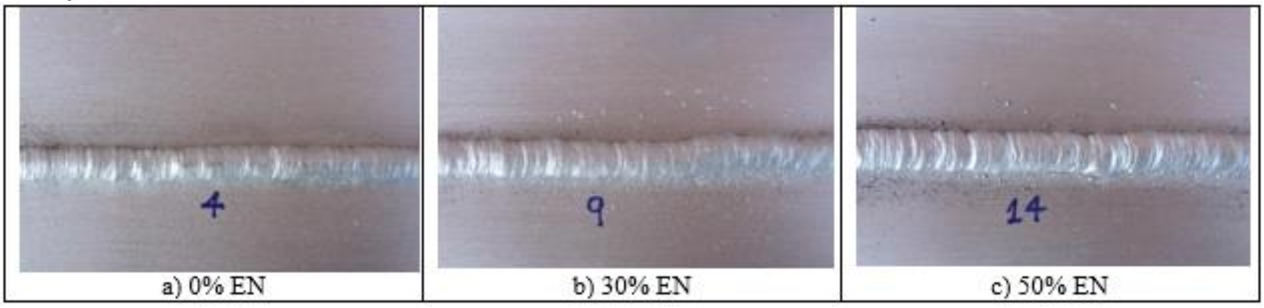
## 4.1 VISUAL ASPECT OF THE WELD BEAD

The level of spatter was visually evaluated through images (photos) taken after the weld bead was made. Spatter represents less material being deposited on the weld beads, it also affects the visual quality, and if cleanup is required it adds cost to the welding process.

Higher process expenses as less material is deposited on the weld bead and more time is required in fabrication. A significant increase in the amount of spatter was easily noticed with increasing %EN, as can be seen in Figure 10.

Several authors have stated and proven that the negative electrode generates instability in the arc. This usually happens due to the suspension of the droplet formed at the tip of the electrode, creating an asymmetric magnetic field that acts on the droplet in an unpredictable manner [20].

Figure 10 - Visual appearance of the spatter level for the Variable MIG-Polarity process with 0% EN, 30% EN and 50% EN, respectively.




## 4.2 WELD BEAD GEOMETRY

Table 4 shows the geometrical parameters obtained after the analysis of the samples (cross section of the weld bead), which are respectively the welded area of the base metal, area of the reinforcement, dilution, penetration, width and height of the weld bead. The weld seams were made with the materials and parameters of the MIG PV process from Tables 1, 2, and 3. The results in Table 4 were obtained by measuring the samples using ImageJ software.

The value of %EN' calculated with Equation (1) considers all six parameters of the current curve, while in Equation (2) only the current action times and without their respective current intensities are considered. Table 5 shows the ratio of the negative proportions calculated by Equation (1) and Equation (2).

Table 4 - Geometric parameters obtained for the negative electrode percentage (%EN) values.

| Parameters | Symbol | 0% EN | 30% EN | 50% EN |
|---|---|---|---|---|
| Penetration | P (mm) | 0,92 | 0,71 | 0,57 |
| Reinforcement Height | H (mm) | 3,96 | 4,04 | 3,98 |
| Width | L (mm) | 7,32 | 7,79 | 7,39 |
| Dilution | D (%) | 7,66 | 4,12 | 4,05 |
| Reinforcement Cast Area | Air ($mm^2$ ) | 26,72 | 28,40 | 24,97 |
| Base Metal Area | Amb ($mm^2$ ) | 2,05 | 1,17 | 1,01 |

Table 5 - Negative electrode percentage values obtained from equations (1) and (2).

| Equation (2) | Equation (1) |
|---|---|
| %EN | %EN' |
| 0% EN | 0% EN' |
| 30% EN | 14.4% EN' |
| 50% EN | 28.4% EN' |

Figures 11A, 12A and 13A show the macrographs of the weld beads obtained for 0% EN, 30% EN and 50% EN, respectively. Meanwhile, Figures 11B, 12B and 13B show the oscillograms of the welding current as a function of time obtained for the 0% EN, 30% EN and 50% EN negative electrode percentages, respectively.

The three macrographs show the presence of overlap, that is, there is no fusion of the base metal, there are also some pores (not quantified) in the weld bead. The argon as shielding gas is a gas with low thermal conductivity, which provides higher energy in the central region of the weld bead and less energy as the distance in the radial direction of the arc increases.

Figure 11A - Macrograph of the cross section of the weld bead obtained with PV 0% EN MIG.

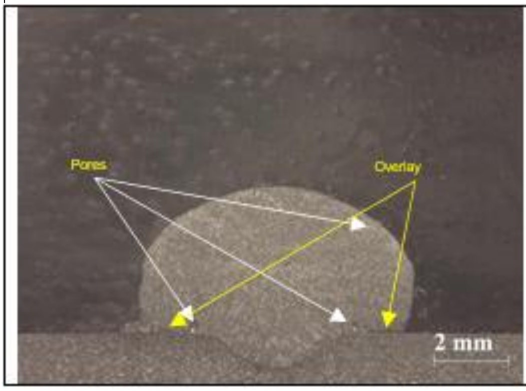



Figure 11B - Welding current waveform as a function of time, MIG PV 0% EN.

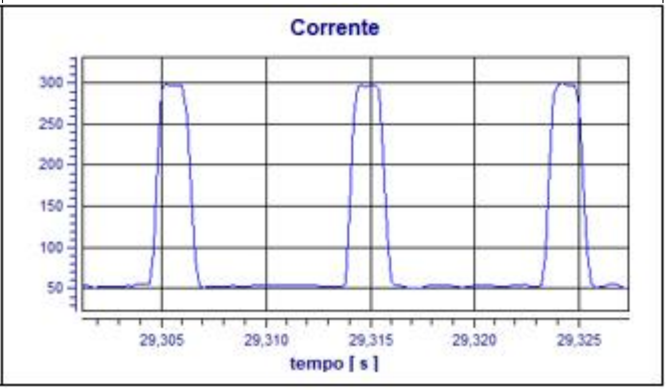



Figure 12A - Macrograph of the cross section of the weld bead obtained with MIG PV 30% EN.

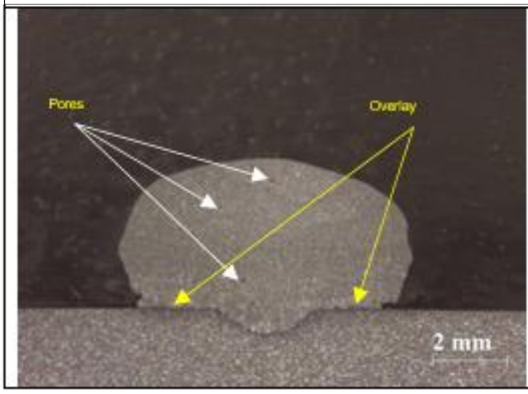
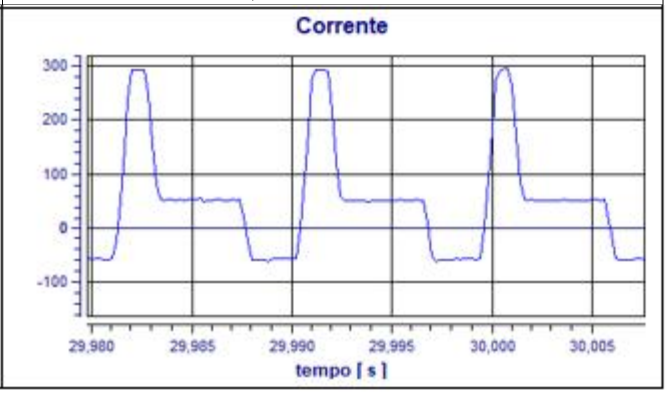
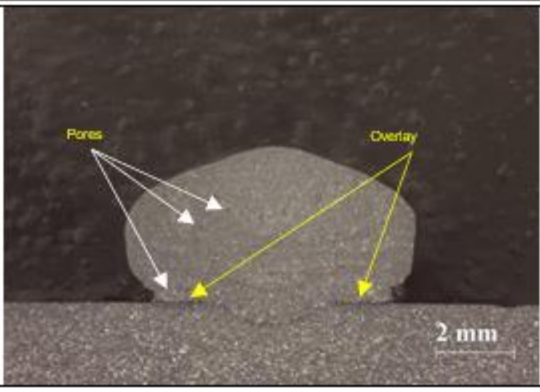
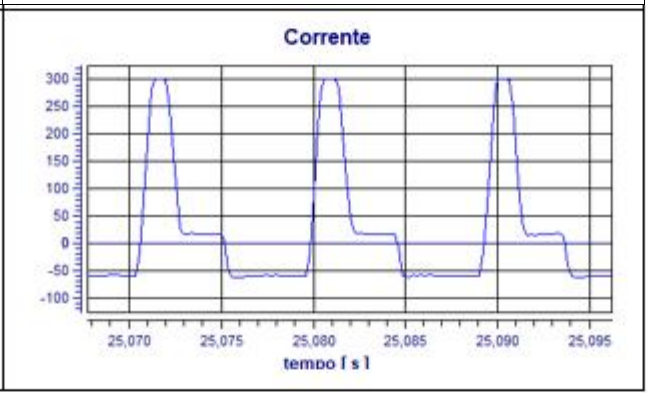



Figure 12B - Welding current waveform as a function of time, MIG PV 30% EN.



| Figure 13A - Macrograph of the cross section of the weld bead obtained with PV 50% EN MIG. | Figure 13B - Welding current waveform as a function of time, MIG PV 50% EN. |
|---|---|
|  |  |

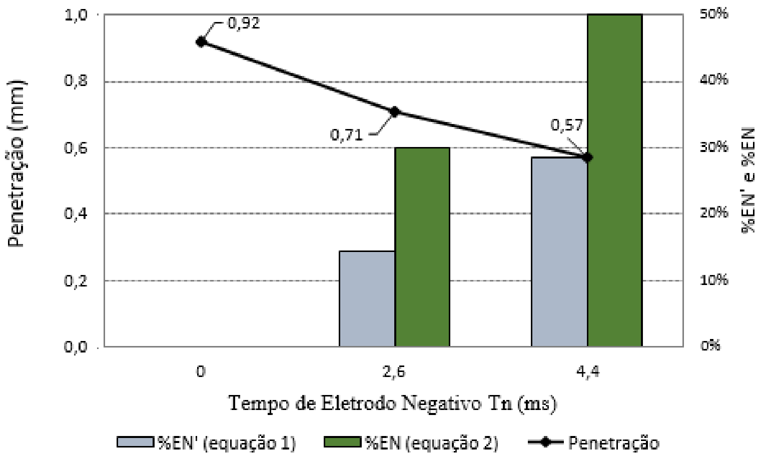




The penetration (P - mm) was measured considering the maximum distance to the center line of the base metal. It was added to the graph the proportions of negative polarity, %EN, considering the two forms of calculation [Equation (1) and Equation (2)], where it can be verified the relationship presented in the literature, regardless of the equation used, there is a reduction of penetration with the increase of %EN.

Figure 14 shows the relationship between the percentage of negative electrode (%EN) and the weld bead penetration. The analysis of this response variable is of utmost importance for the MIG PV process, because according to the literature the greater presence of negative polarity in the process results in lower penetration in the weld bead, as presented by [15], that is, the negative polarity can be used to control the penetration and the fusion rate of the welding process.

Figure 14 - Penetration versus negative electrode time addition (Tn) and the percentage of negative electrode (%EN' and %EN) calculated by the two equations (1) and (2) proposed in the literature.

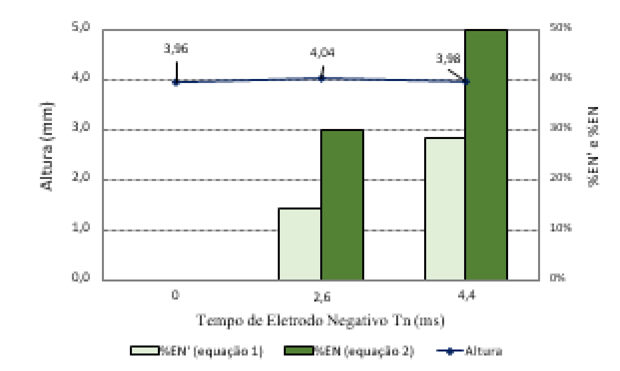
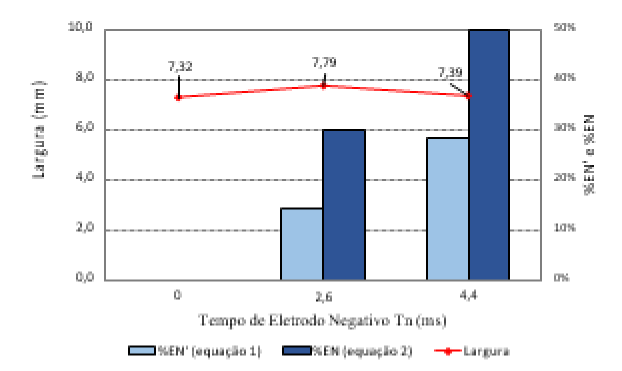




The reinforcement height (H - mm) was measured considering the maximum distance to the center line of the base metal. The variation of the electrode negative percentage (%EN) has no significant effect on the height. By keeping the wire feed speed constant at 6.0 m/min and the welding speed constant at 4.0 mm/s, it means that the amount of filler metal deposited per unit length should be constant. Figure 15 shows that the height of the weld beads does not differ significantly among the %EN values used in welding, less than 2%.

In Figure 16 it can be seen that the weld bead width does not differ significantly among the %EN values used in welding, approximately 6.0 %.

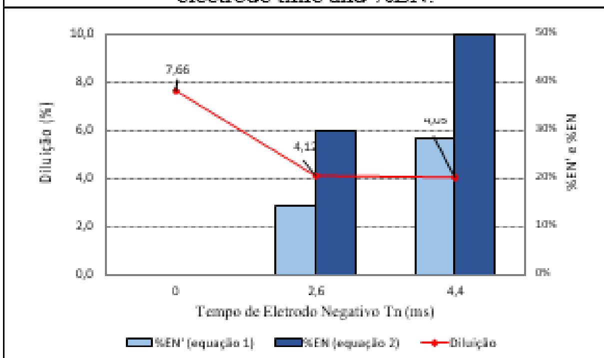
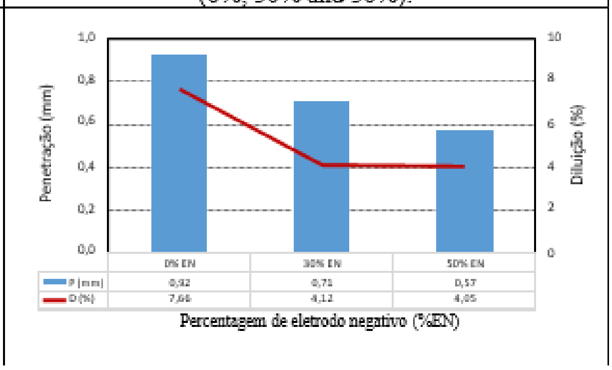
Figure 15 - Height with respect to negative electrode

| Figure 15 - Height with respect to negative electrode time addition and %EN. | Figure 16 - Width versus increasing negative electrode time and %EN. |
|---|---|
|  |  |

The low values of dilution (D - %), as well as the overlap observed in the weld bead, may be related to low values of welding energy and high thermal conductivity of the base metal. By the characteristics of the MIG PV process (see Table 4 and Figure 17) the values of dilution of the weld beads found were very low, less than 10%, for 0% EN presented the highest values, about 185% compared to the second highest dilution, 30% EN. According to [21], for surface coating obtained by the arc welding process, very similar to the bead-on-plate welding employed here, dilution values between 10 and 15% are ideal.

This can be explained by the effect of the negative current in the process, due to its higher melt rate and lower heat input, as presented by [14], generates a larger area of filler metal.

In Figure 18 it can be seen that penetration and dilution vary inversely with the percentage of negative electrode, that is, as %EN increases there is a decrease in penetration and dilution.

| Figure 17 - Dilution versus increasing negative electrode time and %EN. | Figure 18 - Penetration and dilution in relation to %EN (0%, 30% and 50%). |
|---|---|
|  |  |

## 5 CONCLUSION

- When analyzing the data obtained during depositions with different negative electrode ratios, regardless of the %EN calculation employed, an increase in %EN causes a decrease in penetration and dilution.
- The number of defects found was large, the porosities need to be investigated, as well as the overlap of the filler metal on the base metal. The deposited weld beads showed spatter and qualitatively there was an increase in spatter with increasing %EN.
- The results obtained were satisfactory, showing potential for new research to be done on the subject, which is vast and with many questions still to be answered.

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