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Morphological and Microstructural Evaluation of Welding Beads Manufactured by SAW Process with Thermal Pulsing

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Abstract: The thermal current pulsation is a technique widely used mainly in the GTAW process. The advantages of this technique range from operational gains in the process to metallurgical weld improvements. However, despite the advantages already reported in several studies that employ the GTAW and GMAW processes, there is no reference in the literature to the use of this technique in the submerged arc process. From this perspective, an investigation was carried out regarding the use of the current pulsation technique at low frequencies. Bead-on-plate tests were performed, varying the pulsation times from 0.5 to 2.0 s for two different welding speed (18 and 36 cm/min). The results showed that, besides being viable, the application of the thermal pulsation technique in SAW welding resulted in greater process efficiency. This result was obtained without causing instabilities or problems related to the inclusion of slag. However, unlike what is reported in the literature for the GTAW process, thermal pulsation did not show significant metallurgical improvements for any of the operating conditions used.

Key-words: Submerged arc; Thermal pulsation; Low frequency.

1. Introduction

The pulsed current technique at low frequencies has been widely used in the GTAW process since the 1980s and is commonly known as thermal pulsation. This consists of using a high value peak current to promote the formation of the molten pool, and a low base current, just enough to maintain the electric arc and cool the molten pool. Current pulsation dynamically affects the molten pool resulting in a scaly bead geometry as the weld is conducted by several overlapping weld points. The overlap between these points depends on the pulse frequency and the welding speed [1]. Based on the information available in the literature, there are numerous advantages attributed to this technique, including greater control over the molten pool [2,3], reducing the heat input [4], residual stresses and distortions [4,5] and grain refinement in the molten zone [2-4,6].

Traidia et al. [7] studied the effect pulsed GTAW frequency on the welding of AISI 304 stainless steel. They found that, keeping the similar pool dimensions, a 22% reduction in welding energy was possible by introducing the technique. Furthermore, by working with 2, 4 and 6 Hz, they realized that the largest weld bead was obtained with a pulse frequency of 2 Hz. The authors concluded that, as the peak current is maintained longer at lower frequencies, it causes an increase in the temperature of the weld pool and, therefore, in its dimensions. They also found that the higher the frequency, the more the weld pool dimensions are similar to those obtained with direct current.

Seeking to bring together the characteristics of greater control of the weld pool in the pulsed GTAW process with the greater production capacity of the pulsed GMAW process, GMAW welding with thermal pulse was conceived. In this one, the thermal pulsation, also known as double pulse, consists in alternating the mean welding current in two well defined levels. Therefore, the thermal base and pulse time are defined, which result in a low current pulsation frequency. Coexist in this low pulsation frequency, the pulsation of the current at a higher frequency. The definition of the parameters of thermal pulse and base current at this higher frequency, as well as their respective actuation times, aims both to control the metallic transfer and to produce a mean current compatible with the respective thermal period. As in the GTAW process, the best control of weld bead penetration acquired by the thermal pulse technique is also observed in the GMAW process. In this context, Wang et al. [6] demonstrated, for an aluminum alloy in GMAW welding, that the thermal pulsation frequency has a significant effect on the weld beads depth and penetration regularity. Furthermore, the authors observed the wavy effect not only on penetration but also on the surface appearance of the weld beads. The authors carried out experiments with 2, 3 and 4 Hz using 100 A mean current and observed that with lower frequencies, weld beads with greater penetration regions are obtained. Furthermore, the higher the frequency used, the greater the regularity of penetration, however, for the three frequencies analyzed, the authors

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did not observe any variation in the mean penetration. On the other hand, when using 300 A mean welding current, Sen et al. [8] obtained an increase in penetration with a lower frequency from 1.2 to 0.4 Hz and little change in the weld beads width. In addition, the authors observed an increase in reinforcement with increasing pulsation frequency. Using lower mean welding currents, however, the authors did not observe the same effect of frequency on penetration, nor was it possible to observe any trend. Probably these observations result of the approach employed by the authors, because the geometric measurements were obtained from transversal cross sections of the weld beads. This approach makes it difficult to analyze mainly the penetration variation due to thermal pulsation, as the cross section is not constant along the weld bead.

The thermal pulsation technique, applied in the GTAW and GMAW welding processes, is also reported in the literature as an excellent grain refiner. In this context, Wu et al. [3] studied the effects of double pulse in GMAW welding with two different wire diameters on the geometry and microstructure of the weld bead, in addition to the effects on hardness of the molten zone. The authors observed a predominantly columnar structure in the region close to the fusion line for both conditions, however, they observed an interruption in the growth direction in the region between pulses. In the central region of the molten zone, the authors Wu et al. [3] obtained a more refined microstructure when using the double pulse technique compared to the conventional technique. The use of the thermal pulsation technique for microstructural refinement is also reported in aluminum alloys [6,9], in stainless steels with GTAW process [10], but also in GMAW welding [4] and in low carbon steels [11,12].

As seen, there are a lot of potential effects arising from the use of thermal pulsation in welding processes such as GTAW and GMAW. Although this type of pulsation is successfully used in the GTAW and GMAW processes in order to control the weld pool in out of position welding or in small thickness joints, both unusual situations in the SAW process, there is potential for application of this technique in the SAW process aiming beneficial microstructural alterations to the weld bead, control of the heat input and especially increase of the process fusion efficiency. However, there is no reference on the effect of this technique applied to submerged arc welding in the literature. To fill this gap, this work investigates the use of thermal pulsation in the SAW process with the objective of evaluating the effect of the technique on the weld beads morphology and microstructure.

2. Methodology

To evaluate the effects of the thermal pulsation technique in the SAW process, a test bench was designed consisting of a wire feeder module, flux feeder and torch displacement system developed in Laboratório de Tecnologia da Soldagem (LTS), a multi-process welding power source model DigiPLUS A7, welding torch and a data acquisition system, model SAP V4, with the objective of recording instantaneous data of arc voltage and welding current. With these data, the mean current measurements for each test, as well as the calculated value of the welding energy were calculated. The Equation 1 was used to calculate the mean welding energy as a function of the sum of the product of the instantaneous welding current (Ii) and instantaneous arc voltage (Ui) in "n" points and as a function of the welding speed (Ws).

$$E = \frac{1}{n.Ws} \sum_{i=0}^{n} U_i . I_i$$

Bead-on plate tests were performed on ASTM A36 steel with dimensions of 250 mm x 120 mm x 13 mm. Regarding consumables, the flux-wire set was chosen based on the AWS 5.17 standard (AWS, 1997). The filler metal used was AWS EM12K wire with a 2.4 mm diameter and the flux F7A6, also classified by the AWS A5.17 standard, resulting in the flux-wire set F7A6-EM12K. Table 1 presents the constant parameters for all tests.

Table 1. Welding process parameters common to all tests.

Parameter	Value
Wire diameter	2.4 mm
Flux-wire set	AWS F7A6-EM12K
Contact tip-to-workpiece distance (CTWD)	25 mm
Adjusted welding voltage	30 V

Considering that the welding source was used in constant voltage mode, the value of the welding current is self-adjusted according to the wire feeding speed to maintain the welding set voltage in the welding power source. Figure 1 shows, as an example, the acquisition of data from a test performed with pulse/base time set to 1.0 seconds. To obtain a pulsed current, the wire feed was adjusted to achieve two values of wire feeding speeds periodically alternating with well-defined and equal times (50% duty cycle), which resulted in the values of the thermal pulse and base current. Since the alternation of thermal base and pulse currents actually depend on the alternation between the set wire feeding speeds, the pulse and base times have been defined according to the dynamic capability of the wire feeder. The defined pulse times were 0.5, 1.0, 1.5 and 2.0 seconds. Table 2 lists the set of parameters adjusted for each test.

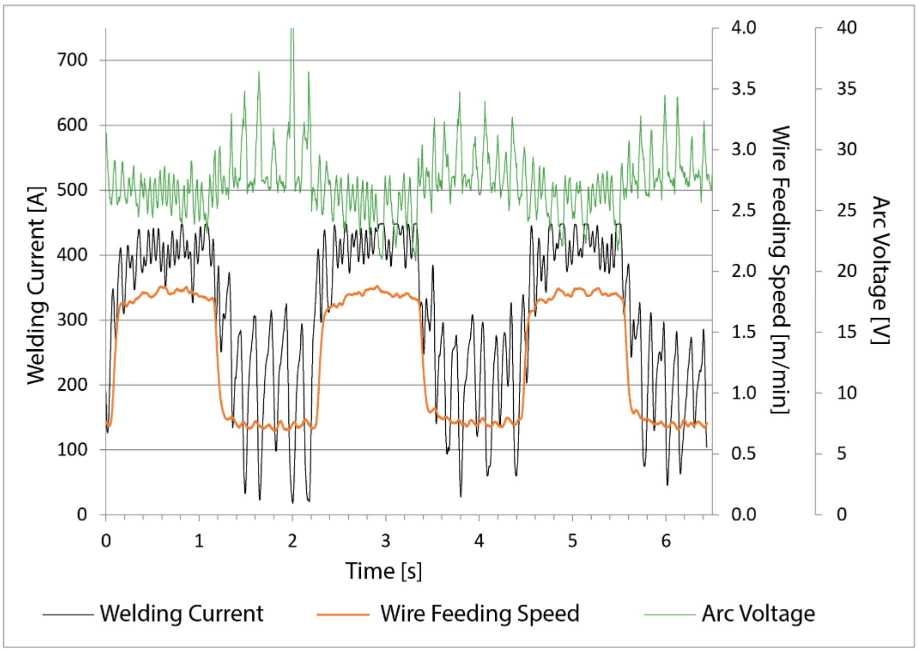

Figure 1. Welding current, arc voltage and wire feeding speed acquisitions.

Table 2. Variation of parameters and sample nomenclature.

Sample	Welding Speed	Arc Voltage	Base Wire Feeding Speed	Pulse Wire Feeding Speed	Thermal Base Time	Thermal Pulse Time	Frequency
S18-0.0	18 cm/min	30 V	1.3 m/min	1.3 m/min	-	-	-
S18-0.5			0.7 m/min	1.8 m/min	0.5 s	0.5 s	1.00 Hz
S18-1.0					1.0 s	1.0 s	0.50 Hz
S18-1.5					1.5 s	1.5 s	0.33 Hz
S18-2.0					2.0 s	2.0 s	0.25 Hz
S36-0.0	36 cm/min	30 V	1.3 m/min	1.3 m/min	-	-	-
S36-0.5			0.7 m/min	1.8 m/min	0.5 s	0.5 s	1.00 Hz
S36-1.0					1.0 s	1.0 s	0.50 Hz
S36-1.5					1.5 s	1.5 s	0.33 Hz
S36-2.0					2.0 s	2.0 s	0.25 Hz

In Table 2, ten weld beads were made with different parameters. The values of pulse and base time, and welding speed were varied, aiming to carry out tests with four different pulse frequencies: 1, 0.5, 0.33 and 0.25 Hz, and two welding energy levels. To enable the analysis and discussion of the results, two of the tests took place without the application of the studied technique, where the wire speed value for these tests was adjusted to provide a mean constant current value equal to the mean current value of the tests with the pulsation technique.

To measure the geometric characteristics of the weld beads, two cross-sectional samples were taken from the specimens, aiming to improve the reliability of the results, and a longitudinal sample with an approximate 25 mm length, to visualize the penetration profile of each weld bead. After metallographic preparation, the samples were chemically etched with 4% Nital reagent. The images were analyzed using ImageJ image processing software. Thus, from the transversal samples, measurements of width (W) and reinforcement (R) of the weld beads were carried out. All values presented are the simple arithmetic mean of measurements performed for each sample. As for the longitudinal sample, it was used to perform the measurements of maximum penetration (Pmax) and minimum (Pmin) to obtain mean weld bead penetration, considering that the penetration profile is not constant. The reinforcement measure from the transverse sample served as a reference to identify the plate surface line, thus allowing to measure penetration as shown in Figure 2.

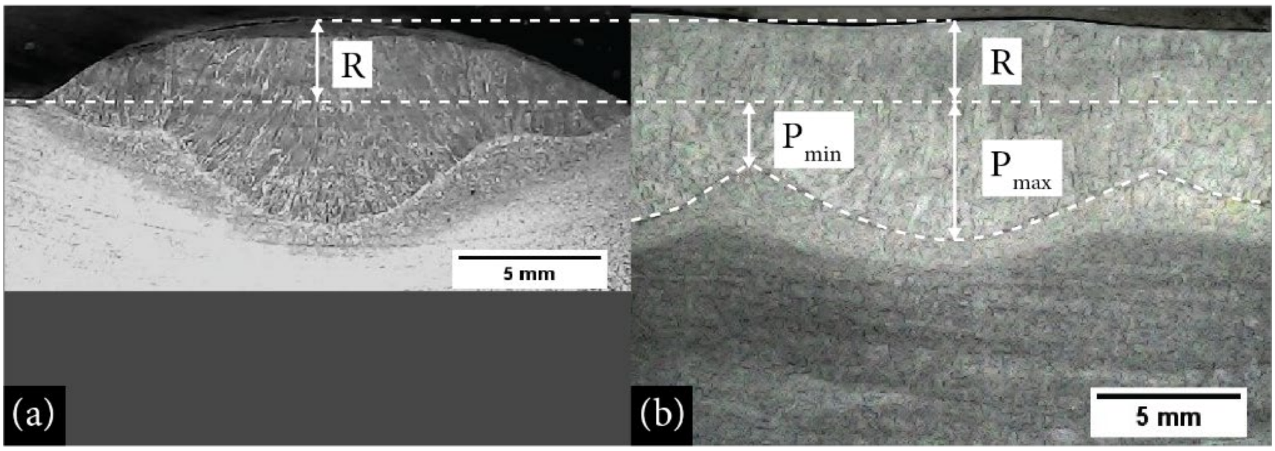

Figure 2. Measurement methodology: (a) reinforcement, (b) minimum and maximum penetration measurement.

Since the analysis of the molten area based on the cross-section can result in a wrong conclusion, due to the variation in the penetration profile and the uncertainty regarding the cutting location of the sample, an alternative approach was adopted for melting efficiency evaluating. Through longitudinal samples, it was decided to measure the area comprised by unit of weld bead length. For samples that do not have penetration variation, a measurement of 10 mm of weld bead length was performed. In the case of weld beads with pulsation that presented a wavy penetration profile, the measurement was performed between two consecutive minimum penetration points and the distance “L” between them, resulting in a measurement of the molten area per unit of length. Figure 3 illustrates the approach used.

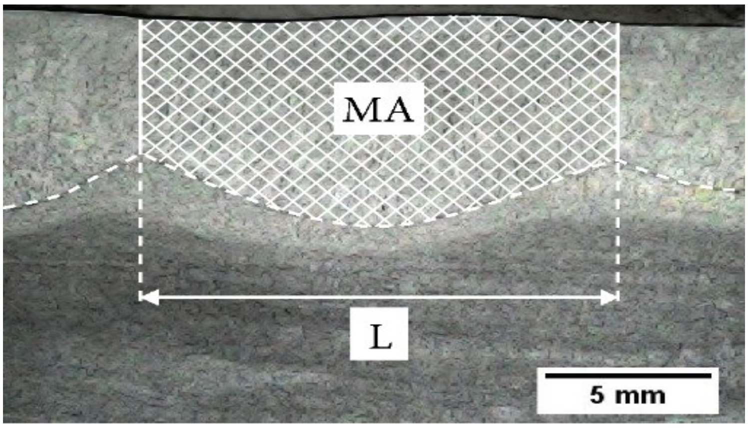

Figure 3. Measurement of the molten area (MA) per unit of weld bead length (L).

For the microstructural analysis, five regions of each cross-sectional sample were recorded, as shown in Figure 4a. As for the longitudinal sample, the analysis was performed in the overlapping region, as can be seen in Figure 4b.

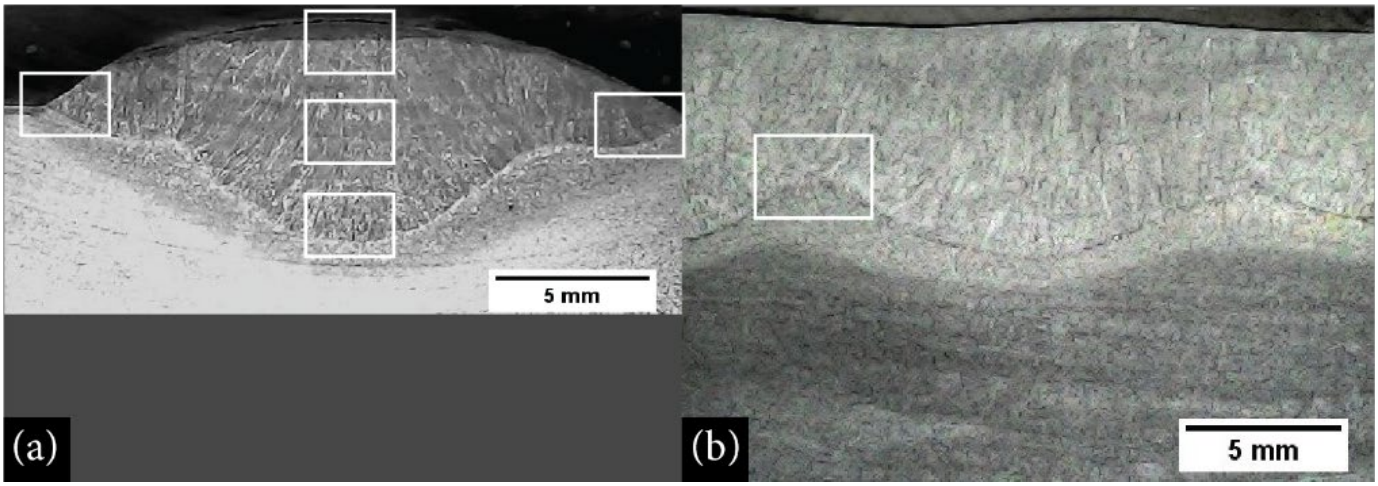

Figure 4. (a) Transversal and (b) longitudinal microstructural analysis regions.

3. Results and Discussion

The mean values of welding current and arc voltage obtained during tests with constant current and with the thermal current pulse technique are presented in Table 3. As expected, as a behavior of a constant voltage process, the mean arc voltages measurements were presented in a small range of values, with a maximum variation of 0.4 volts between records. The mean current values varied by about 3% between the highest and the lowest value recorded for each level of current used. Thus, the welding energies were also similar, within the same welding speed group, as can be seen in Table 3. For the tests carried out with a welding speed of 18 cm/min, the calculated energy values were close to 28 kJ/cm and for the set of weld beads with a speed of 36 cm/min, 14 kJ/cm.

Table 3. Measured values for each test.

Test	Thermal Base Time [s]	Thermal Pulse Time [s]	Frequency [Hz]	Mean thermal base current [A]	Mean thermal pulse current [A]	Mean welding current [A]	Arc voltage [V]	Welding energy [kJ/cm]
S18-0.0	-	-	-	-	-	308	27.2	27.9
S18-0.5	0.55	0.55	0.90	229	403	316	27.2	28.6
S18-1.0	1.10	1.10	0.45	210	413	312	27.1	28.2
S18-1.5	1.65	1.65	0.30	203	410	307	27.2	27.8
S18-2.0	2.20	2.20	0.23	205	405	308	27.1	27.8
S36-0.0	-	-	-	-	-	306	27.5	14.0
S36-0.5	0.55	0.55	0.90	205	406	306	27.2	13.9
S36-1.0	1.10	1.10	0.45	207	408	307	27.2	13.9
S36-1.5	1.65	1.65	0.30	199	409	304	27.3	13.8
S36-2.0	2.20	2.20	0.23	200	410	305	27.1	13.8

Figure 5 shows the surface images of the produced weld beads. It is possible to observe that the weld beads did not show inclusion of slag or apparent porosity and the absence of any surface discontinuity that, perhaps, would be caused by the effect of the thermal pulsation of the current. In the weld bead carried out with a welding speed of 18 cm/min, it presents smut spots on its surface and not pores, proof of this is that in samples of the cross-section and longitudinal it is not possible to visualize such discontinuities.

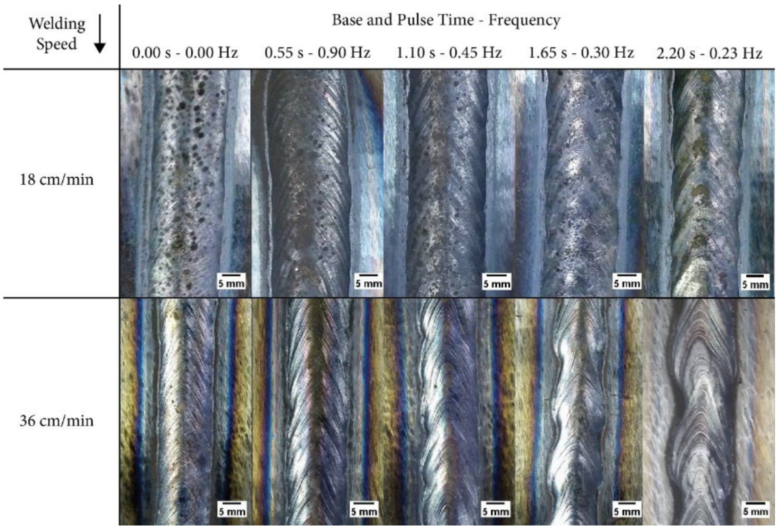

Figure 5. Surface appearance of the weld beads.

The characteristic scaly appearance on the weld beads is observed due to the current pulsation. This aspect was intensified with the current pulse time increase, that is, the pulse frequency decrease. It is also possible to verify that, in the weld beads made with the highest welding speed (36 cm/min), the scaly appearance was more evident, to the point that, when the current was pulsed with longer time, the pulse frequency was so low as to became incompatible with the employed welding speed. This was the case of the weld beads resulting from tests S36-1.5 and S36-2.0 which, as can be seen in Figure 5, showed a large variation in width. Therefore, it can be concluded that the welding speed used, of 36 cm/min, and the pulsation times, of 1.65 and 2.2 seconds, were not adequate parameters, so very irregular weld beads were obtained with relation to the width and, possibly, penetration of the weld, which is not considered satisfactory for the process. For this welding speed condition, therefore, a maximum pulse/base time limit of 1.1 second can be set.

3.1. Macrographic analysis

The macrographs of the cross-section of the weld beads are shown in Figure 6. It was decided to exclude from this analysis the specimens resulting from tests S36-1.5 and S36-2.0, which, as already discussed, presented too much irregularity.

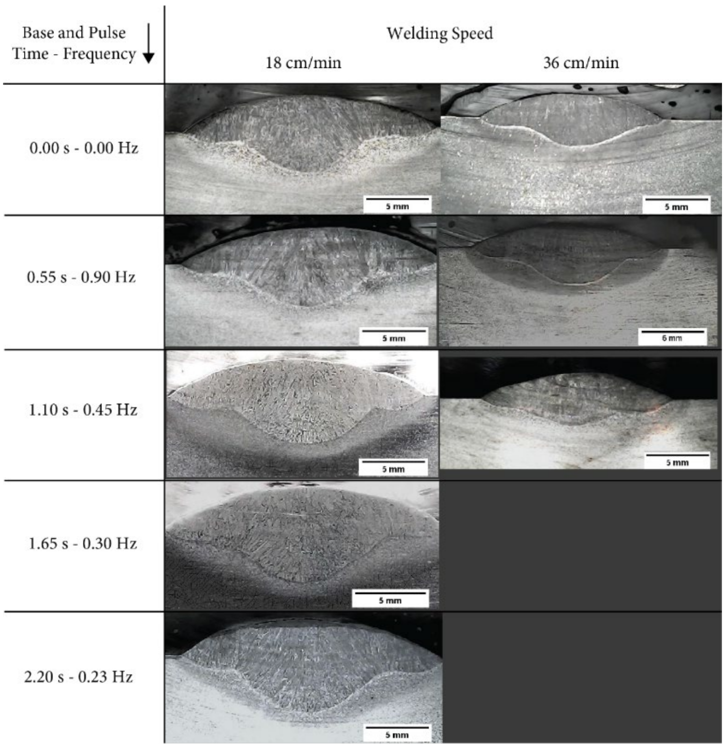

Figure 6. Macrographs of the cross section of the weld beads performed.

When cutting the cross section of the weld beads, there was no internal discontinuity such as inclusion of slag or porosity, just superficially. Also, in relation to the visual aspect of the weld beads, it is clear that the resulting geometry is similar in terms of shape for the samples welded with the same value of welding energy, that is, the pulsation of the current was not able to promote significant changes in the weld bead morphology. As for the linear dimensions of the samples, there was no variation in the measurements of the width of the weld beads, when compared to samples with the same welding energy. This result agrees with the results obtained by Sen et al. [8] for the GMAW process employing similar mean welding current. A behavior analogous to width occurs with the reinforcement values, which are approximately constant and equal to the value for the weld beads without pulsation. The width and reinforcement for the welding speed of 18 cm/min was 20±0.7 and 3±0.3 mm, respectively, and for the condition of welding speed of 36 cm/min, the measured values were approximately 15±0.8 and 2±0.1 mm for width and reinforcement, respectively, with a confidence level of 95%.

To obtain greater reliability in terms of penetration values and considering the typical undulating aspect of welding with thermal pulses, a penetration analysis was carried out based on the longitudinal sections of the weld beads. Figure 7 shows the weld beads macrographs of the longitudinal sections.

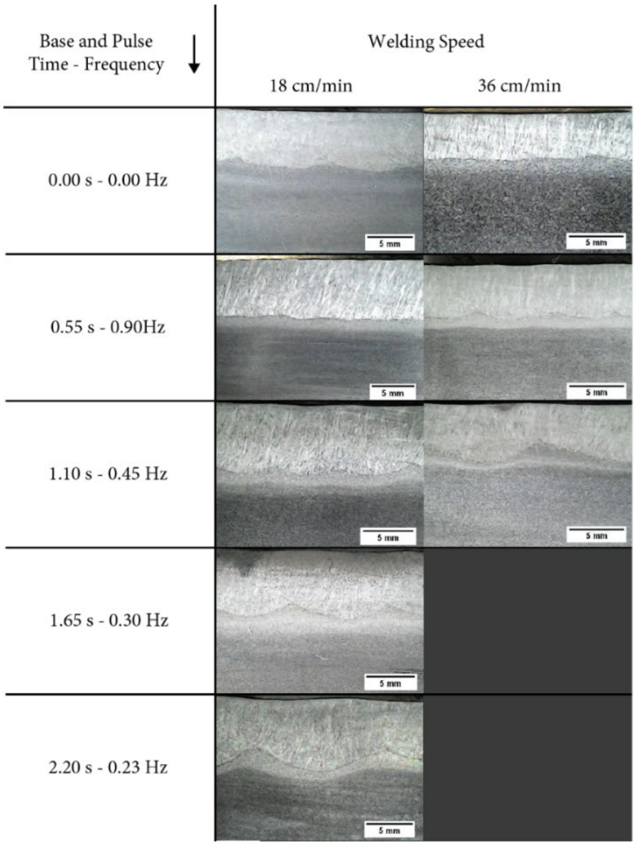

Figure 7. Macrographs of the longitudinal section of the weld beads performed.

The wavy aspect of penetration as a function of the pulsation of the welding current reduced with increasing pulsation frequency. This phenomenon related to dimensional variations that occur in the weld bead due to the pulsation of the current had already been observed in Figure 5 when considering the surface aspect of the weld beads. This is mainly due to the fact that a higher intensity welding current (thermal pulse current) acting for greater period (lower pulsation frequency) results in greater penetration, since in this period there is significantly greater welding energy. The weld beads made with a welding speed of 18 cm/min resulted in higher penetration values, due to the higher welding energy in these tests. On the other hand, the higher the pulse frequency, the greater the similarity of the penetration profile with that obtained with constant current, a result that agrees with what was observed by Wang et al. [6] in the GMAW process, despite the mode of operation used by the authors be different from the one used in the present work. While in the GMAW process with thermal pulsation a welding source operating in constant current mode is used, in the present work the constant voltage mode was used in which the current variation is the result of the internal control of the process in face of the variations in speed of wire feed imposed, as shown in Figure 1. The behavior of the penetration profile as a function of the pulsation frequency, regardless of the way of obtaining the current pulsation, is due to the fact that, as the pulsation frequency increases, the fusion and solidification kinetics of the material are no longer able to keep up with the temperature variations imposed by the pulsed current. Thus, the thermal effect in the molten pool tends to approach that obtained with constant direct current.

To quantitatively evaluate the effects of current pulsation on the penetration of the weld beads, measurements of maximum, minimum and mean penetration values were performed, as shown in Figure 8.

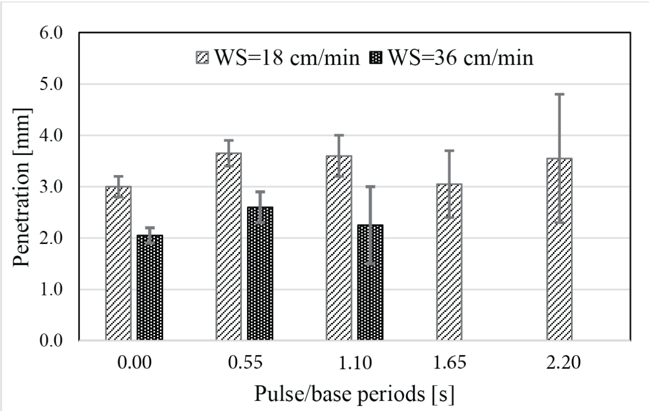

Figure 8. Mean penetration and variation of welded samples (representing the minimum and maximum penetration measurements).

Despite the results obtained with a 36 cm/min welding speed have a more restricted number of samples, it shows a similar behavior of penetration in relation to that obtained with a welding speed of 18 cm/min. In both cases, the highest mean penetration values were obtained for the pulsed current for shorter pulse times/base and, consequently, higher frequency. There is also a tendency to increase the variation in penetration with the increase in pulse time. This is due to the fact that a longer pulse time allows the action, for a longer time, of a relatively high value of welding current, which naturally increases the penetration values. Similarly, the same occurs during base periods, thus resulting in lower penetration values. Furthermore, with the longer base time, the longer the time between pulses and, consequently, the increase between the distances of the regions with the highest heat input. This results in regions of lower penetration between pulses, reducing the minimum penetration value and, consequently, greater penetration variation.

For the condition of pulse time of 0.55 s and welding speed of 18 cm/min, a variation similar to the weld bead produced with constant current is observed, however, the mean penetration is about 20% higher. When using a welding speed of 36 cm/min, using the same pulse time of 0.55 s, an increase in mean penetration of 25% was obtained. With relatively higher welding speeds, the weld pool is smaller, so during the period of the thermal pulse current there probably is a smaller barrier of molten metal interposed between the arc and the unfused base metal. With this, the effect of the thermal pulse current becomes more effective, showing the effect of the thermal pulsation of the current. On the contrary, a relatively lower welding speed results in higher welding energy, which results in a greater volume of weld pool, acting as an obstacle between the arc and the pool root, acting to reduce the effect of the pulsation of the current at the root of the weld pool.

In general, all mean penetration values were higher than those obtained without current pulsation, thus indicating a higher melting efficiency of the process under these conditions. This increase in the fusion efficiency with the thermal pulsation of the current was also obtained by Cunha [1], with pulsation times of 0.5 s, however, in the welding of thin AISI 304 stainless steel sheets with the GTAW process. Traidia et al. [7] also obtain an increase in efficiency since they obtained weld beads with dimensions compatible with the conventional GTAW process, but with a reduction of about 20% in welding energy. To evaluate the melting efficiency from another perspective, measurements of the molten area per unit length were performed in the samples taken longitudinally (Figure 9).

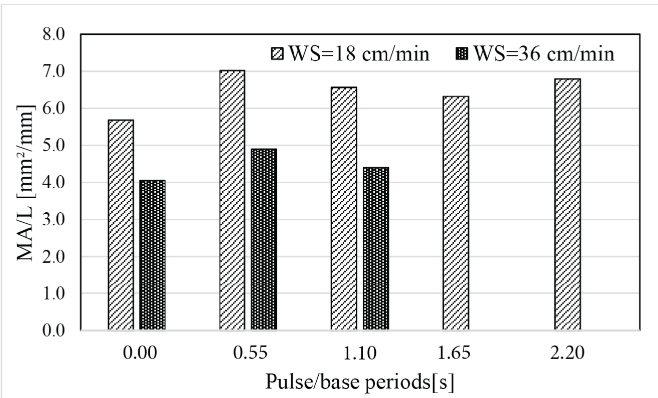

Figure 9. Molten area per unit of length measured from the longitudinal section samples.

The behavior of the graph of molten area per unit of length, for both welding speeds, is similar to penetration. For a welding speed of 36 cm/min, an increase in the molten area per unit of length is observed with the application of the technique, and with a pulse time of 0.55 s, an 20% increase compared to the conventional process. For a welding speed of 18 cm/min, the highest measured value also corresponds to a pulsation time of 0.55 s, with an increase of 20% compared to the conventional process, this increase being equal in percentage to penetration. In fact, this result is coherent since the reinforcement of the weld beads is approximately equal. Hence, increases in mean penetration are reflected in the molten area.

3.2. Micrographic analysis

In Figure 10 the micrographs from the central region of the molten zone of the welded samples are presented.

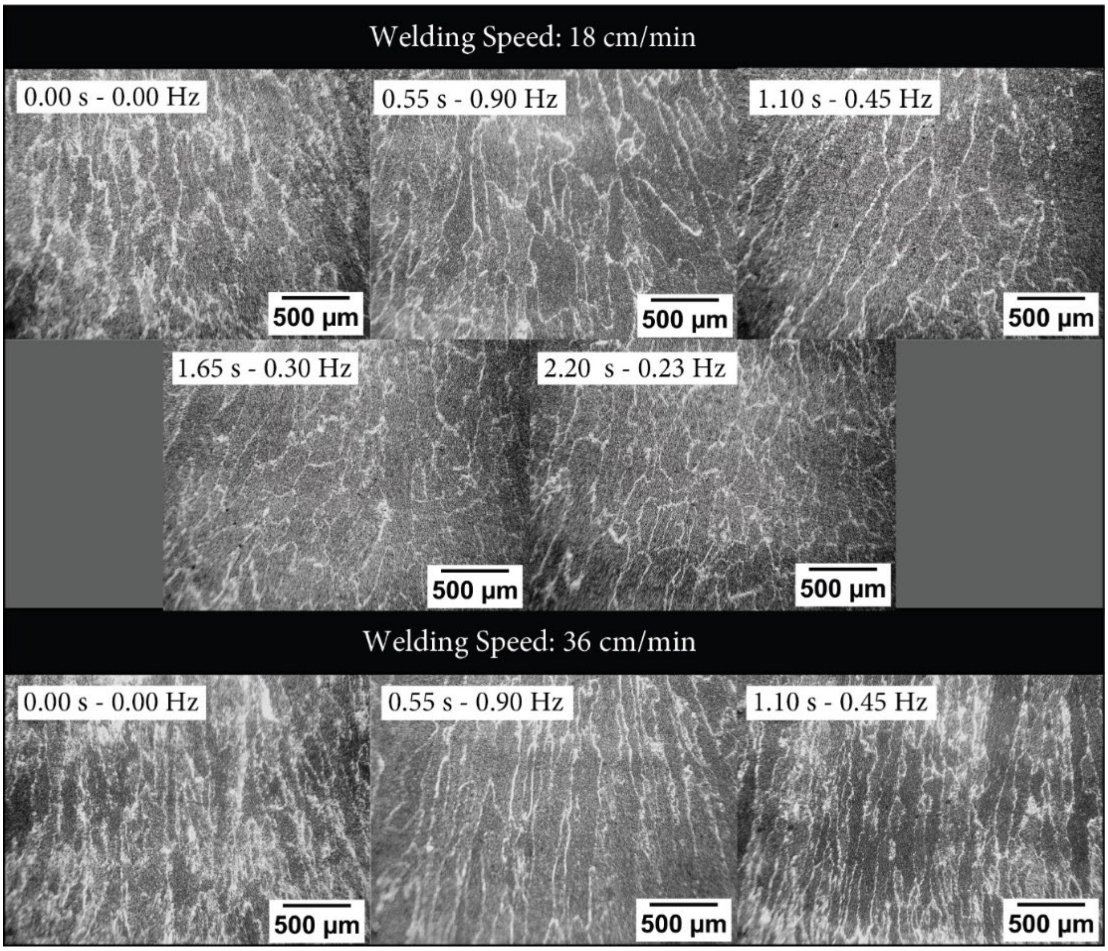

Figure 10. Micrographs of the central region of the molten zone.

Analyzing the images in Figure 10, it is verified that the microstructural behavior of the samples produced with thermal pulsation is similar. At both welding energy levels used, it was not possible to observe significant changes in relation to the microstructure for any of the analyzed regions. Differently from what is reported in the literature, for the welding conditions used, thermal pulsation did not cause a more refined microstructure for any of the studied welding energies. It is known that one of the consequences of the thermal fluctuations of the current pulsation is the periodic interruption of the solidification process of the molten pool, allowing its cooling. According to Reddy, Gokhale and Rao [9], this process comes from the overlapping of the weld beads, causing the imposed heat input to break the crystals of the growing grains of the preceding weld bead and, therefore, bringing about the refinement of the microstructure. However, the reports found in studies of this phenomenon concern the GTAW and GMAW welding processes. In the present study, using the SAW welding process, the same was not observed, possibly due to the inherent higher welding energy of this process, and consequently, a higher heat input than the previously mentioned processes. Thus, the hypothesis is that with a higher energy input, the base time used in the tests was not enough to allow the adequate cooling of the molten pool to the point that it solidifies properly before the next energy pulse, and so allow the reflow mechanism responsible for refining the material grains. Thus, the thermal effect in the molten pool tended to approach that obtained with constant direct current. To analyze the effect between pulses, Figure 11 shows the micrographs of this region taken from the longitudinal samples.

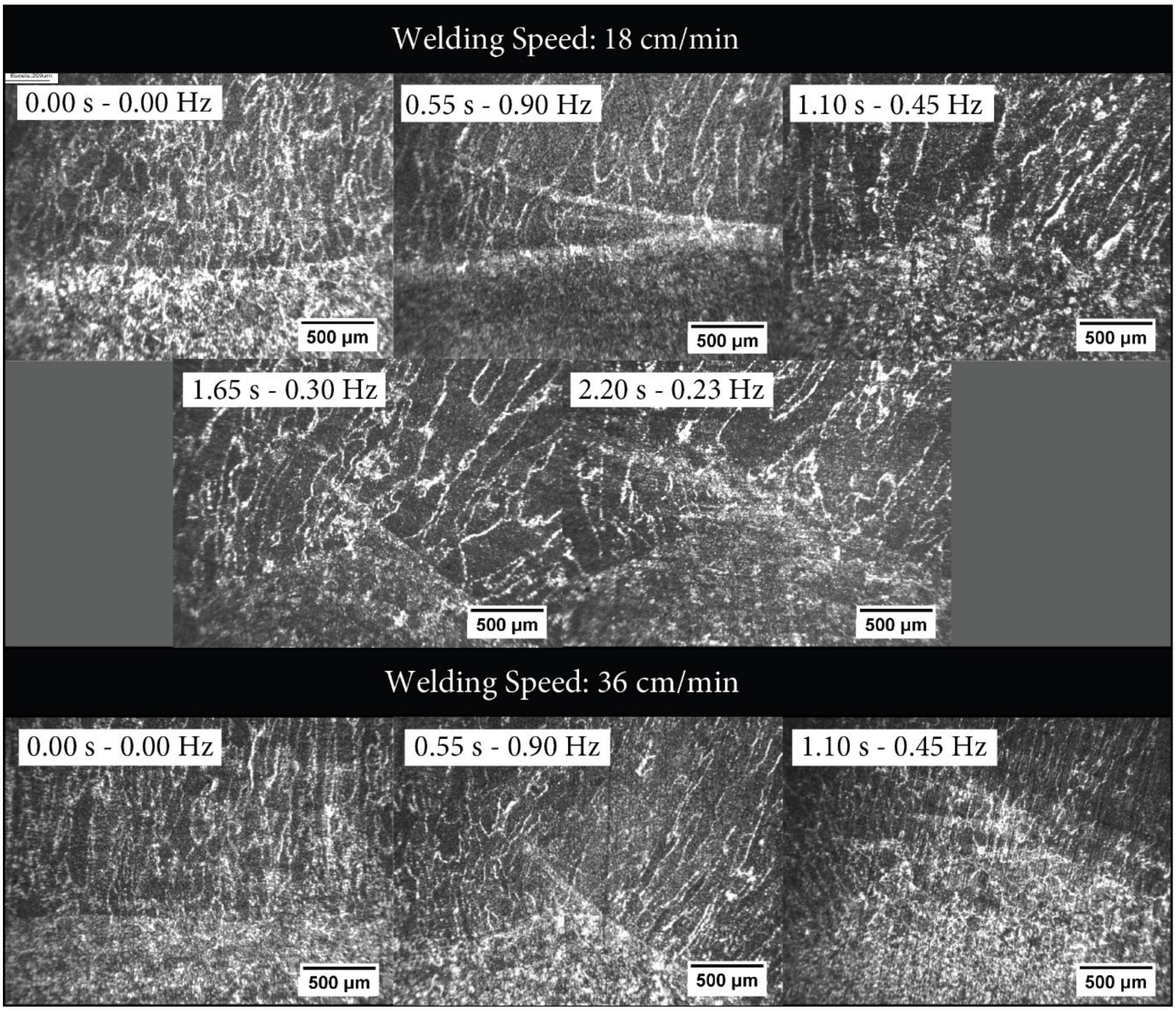

Figure 11. Micrographs of the region between pulses of the longitudinal sample.

The lower the pulsation frequency used, the sharper the refusion line promoted by the pulsation. However, this was not able to interrupt grain growth as observed by Wu et al. [3] for the GMAW process. There is little interference in the solidification mode due to thermal fluctuations caused by the periodic variation of the heat input, a fact that is caused by the high values of welding energy involved in the process. This probably is the reason for the divergences in outcome in relation to, for example, the GTAW and GMAW processes. As the heat input is considerably high, due to the operational characteristics of the SAW process, the cooling and partial solidification effect that the thermal base current would cause does not occur. Even using a thermal base current (approx. 200 A) below the minimum current recommended for this wire according to AWS 5.17, of 350 A, it does not allow the expected cooling of the molten pool for the thermal pulse technique.

As for the geometry of the grains, when using a 18 cm/min welding speed, the grains are predominantly equiaxed in the reference weld bead, while columnar grains were observed at low frequencies. This result is even the opposite of what is found in the literature. Furthermore, the pulsed current apparently caused the grain growth, which is not consistent with the results found in the literature for the other processes. This effect is intensified with the pulsation frequency reduction, in which there probably is an increase in the efficiency of the process and, therefore, an increase in the heat input to the workpiece. Thus, since the refinement of the microstructure does not occur through the mechanism of interruption of the grain's growth, they end up growing under the effect of higher temperatures for a longer period. In samples with a welding speed of 36 cm/min, no such significant changes in microstructure were observed.

4. Conclusions

In view of the materials used, the techniques applied and the results, it is possible to conclude that the use of the current pulsation technique at low frequencies in the SAW process is perfectly viable, not causing instabilities in the process, nor in problems related to inclusion and slag retention. Under the conditions studied, it was found that for a welding speed of 36 cm/min the pulse time/base limit is 1.1 second (0.45 Hz). From an operational point of view, a greater melting efficiency of the process was obtained, with an increase in the longitudinal molten area of about 20%, for the welded samples with speeds of 18 and 36 cm/min and frequency of 0.9 Hz, due to, mainly, the gain in penetration of the weld bead. On the other hand, different from what is observed in the literature for the GTAW and GMAW processes, the thermal pulsation technique applied to the SAW process did not present significant metallurgical alterations for any of the studied welding conditions.

Authors' contributions

GGS: Data curation, Formal Analysis, Writing – review & editing. TVC: Methodology, Supervision, Formal Analysis, Writing – review & editing. ALV: Formal Analysis, Writing – original draft, Writing – review & editing.

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