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Chapter 4

Gas Tungsten Arc Welding with Synchronized Magnetic Oscillation

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Additional information is available at the end of the chapter

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Abstract

The search for improvements in mechanized/automated welding techniques has been intense due to skilled labour shortage. In this line, the combination of operational modes (polarity and/or metal transfer mode) within a process has gained attention, since it expands the adjustability of the arc energy. By combining this feature with arc motion, the arc energy delivered to the workpiece can be optimally distributed. Therefore, this work exploits the synchronization between arc magnetic oscillation and gas tungsten arc welding (GTAW) process to control weld bead formation. A system was devised to control the magnetic oscillation and a welding power source synchronously. Characterization of the synchronized magnetic oscillation was carried out based on high-speed filming and electrical data. The welding process was then synchronized with the magnetic oscillation varying the level of welding current according to the arc time-position, being the effect on weld bead width considered for analysis. Welding without oscillation and with unsynchronized magnetic oscillation were taken as references. The synchronized magnetic oscillation made possible to achieve larger weld bead width on the side with higher current level and longer lateral stop time and vice versa. This technique might be beneficial to applications where extreme weld bead control is required.

Keywords: magnetic oscillation, arc welding, GTAW

1. Introduction

The search for improvements in mechanized/automated welding processes has been in evidence for quite a long time, with remarkable recurrence and intensity nowadays due to shortage of qualified workforce. One way to exploit the mechanical/automated welding processes with

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more efficiency (productivity) has been through the combination of operating modes (polarity and/or metal transfer mode) within a single process, in addition to the possibility of combining welding current levels. With the combination of operating modes (possible with modern power sources) and current levels in the same welding operation, it is possible to vary the energy of the process, both thermal (heat delivered to the base metal) and mechanical (arc pressure and impact of droplets on the base metal, the latter in the case of consumable electrodes). In this line, an interesting approach, not much exploited yet, but promising, is to use this feature to distribute the energy of welding optimally into the workpiece to control the weld bead formation (molten material from both electrode and workpiece). This could be done by synchronizing the welding operating modes and/or current levels with the position of the arc/torch. The arc position can be changed mechanically (by moving the torch) or magnetically. The magnetic deflection of arcs (deviation of arc coupling with the workpiece by external magnetic fields) is a relatively versatile and inexpensive technique. The arc magnetic oscillation is composed of a series of magnetic deflections (pendulum-like movement of the arc when subjected to a variable and/or alternating magnetic field). Once the electromagnet is positioned/mounted relative to the arc/torch and thereby the direction of the magnetic flux lines is defined (longitudinal for lateral/transversal oscillation and transversal for longitudinal oscillation), the extension of the arc movement in each position depends on the magnetic field level applied and the time spent in each position depends on the application time of the magnetic field. As shown in **Figure 1**, the direction of deflection (left and right or forward and backward in relation to the welding travel speed direction) depends on the direction of magnetic flux lines produced by the electromagnet; the inversion of arc positions/direction of deflection is given by the inversion of the electromagnet control signal (voltage/current).

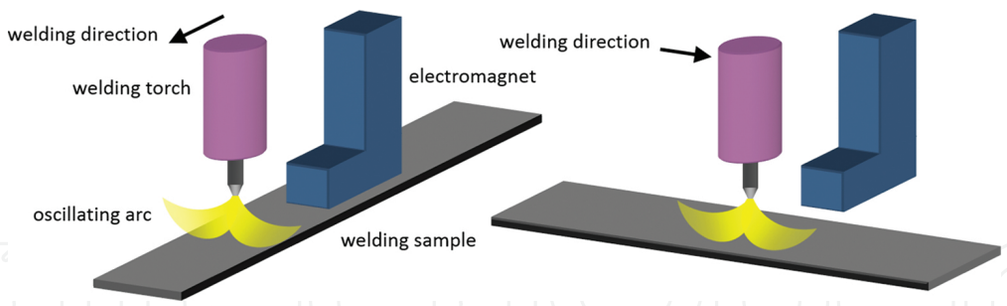


Figure 1. Direction of magnetic deflection: on the left hand side—magnetic field parallel/aligned with the welding direction generates transversal/lateral arc deflection; on the right hand side—magnetic field transversal to the welding direction generates longitudinal arc deflection.

This work aims to better exploit the potential of magnetic oscillation. The overall goal is to synchronize the magnetic oscillation of the arc with the welding process (current levels), gas tungsten arc welding (GTAW) in this case, and evaluate the potential of this technique to control/modify the welding results, specifically in terms of the weld beads' external geometry. With the synchronization proposed, it would be possible to choose the thermal and mechanical energy of the arc (current levels) for each of its positions. The setting of arc position and time at each position with prechosen energies (welding current levels) is controlled by the wave-

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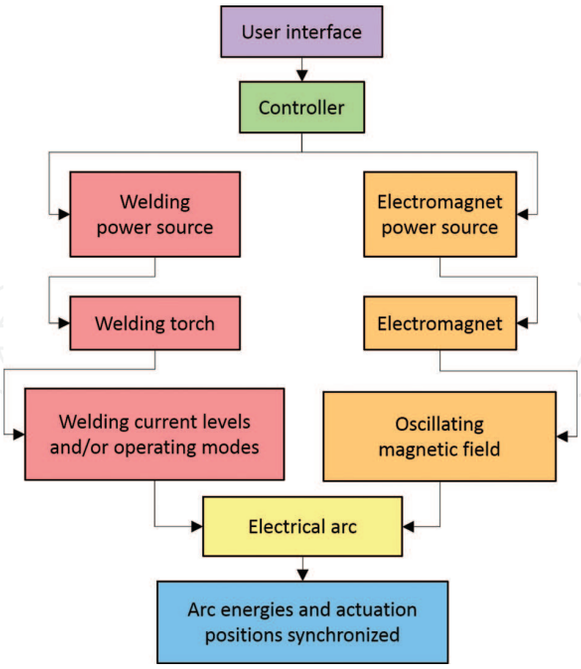


Figure 2. Schematic description of the idea of synchronizing the arc positions with its energy levels using magnetic oscillation.

form (amplitude and time) of the voltage/current signal applied to the electromagnet. A short schematic description of the idea of synchronizing the arc positions with its energy levels by the use of magnetic oscillation is shown in **Figures 2** and **3**. Examples of motivating applications for the development of magnetic oscillation synchronized with welding processes are

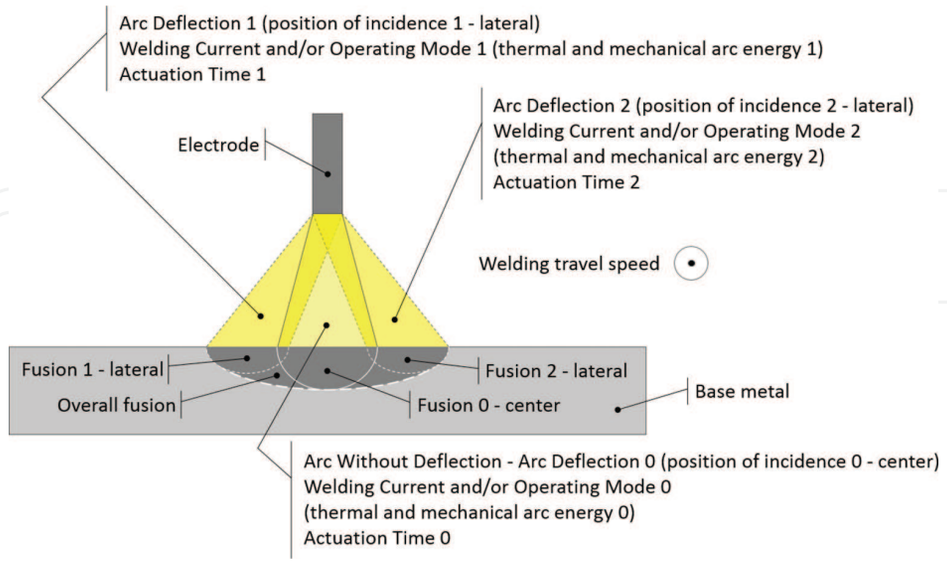


Figure 3. Schematic welding transverse cross section with the arc at the centre, left, and right positions with different levels of thermal and mechanical energy in each position as result of synchronizing the arc positions with its energy levels using magnetic oscillation in the case of transverse arc deflection.

the ability to act differently on the geometry of the weld beads (molten and heat-affected zones), affect grain size for improvement of weld properties, allow weld pool control for out-of-position welding operations, and facilitate narrow gap welding, root passes, among others.

2. Bibliographic review

Magnetic fields are intrinsic to the welding arc. As it is widely known, self-induced magnetic field is the basis for the formation of plasma jet, which has beneficial effects on the penetration of the weld bead, for example [1, 2]. On the other hand, external magnetic fields can be used to oscillate arcs, replacing mechanical devices for coating operations, for example. The idea of using magnetic fields to oscillate welding arcs is not new. It was designed and patented in 1960 by Greene [3]. Currently there are commercial systems to magnetically oscillate welding arcs, and alternating current sources are used to control the oscillation. General recommendations for construction of electromagnets for welding arc deflection are found in the literature [4].

The magnetic deflection of welding arcs can occur in various ways. The most commonly known is certainly the magnetic arc blow [1, 5, 6]. Another is the deflection of arcs in double wire gas metal arc welding (GMAW) [7]. Additionally, there is the case of deflection caused by external magnetic fields, such as those used in equipment to deflect welding arcs [8].

It is important to review the basic electromagnetic effect that governs the magnetic deflection phenomenon. If an electric charge travels within a magnetic field, it is subjected to a magnetic force of magnitude proportional to its velocity and magnetic field strength (**Figure 4**). The direction and orientation of the force are determined by the left-hand rule; place the index finger of the left hand in the direction of the magnetic field lines and the middle finger in the direction of conventional electrical current. In this case, the thumb when oriented perpendicular to the index finger points in the direction of the force to which the electric charge is subjected. A charged particle, stationary or moving parallel to the magnetic field lines, will not suffer any magnetic-induced force due to this field. However, a charged particle travelling, not parallel, through a magnetic field will have its direction of movement changed, that is, its trajectory will undergo magnetic deflection.

With the illustration of **Figure 4** in mind, **Figure 5** sequentially shows an arc deflection can be obtained by applying an external magnetic field on it. In accordance with the principles of electromagnetism, a linear conductor in the presence of a magnetic field is subjected to a force

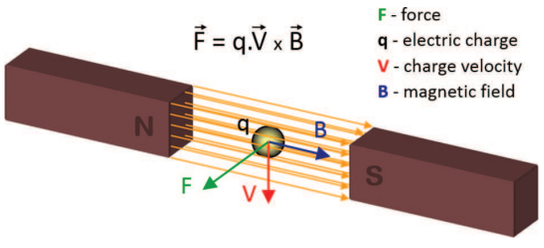


Figure 4. Force produced on a positive electrical charge moving through a magnetic field (the force direction points the opposite way if the electrical charge is negative).

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proportional to the conductor length within the magnetic field, the electrical current flowing through this conductor and the magnetic flux density. Therefore, in welding, in a simplified manner, if a current *I* is flowing from the electrode to the workpiece through an arc of length *La* and this arc is in the presence of a magnetic field *Be* (externally produced by an electromagnet, for example), a force *F* acting in the arc (perpendicular to the magnetic field and current flow) is generated.

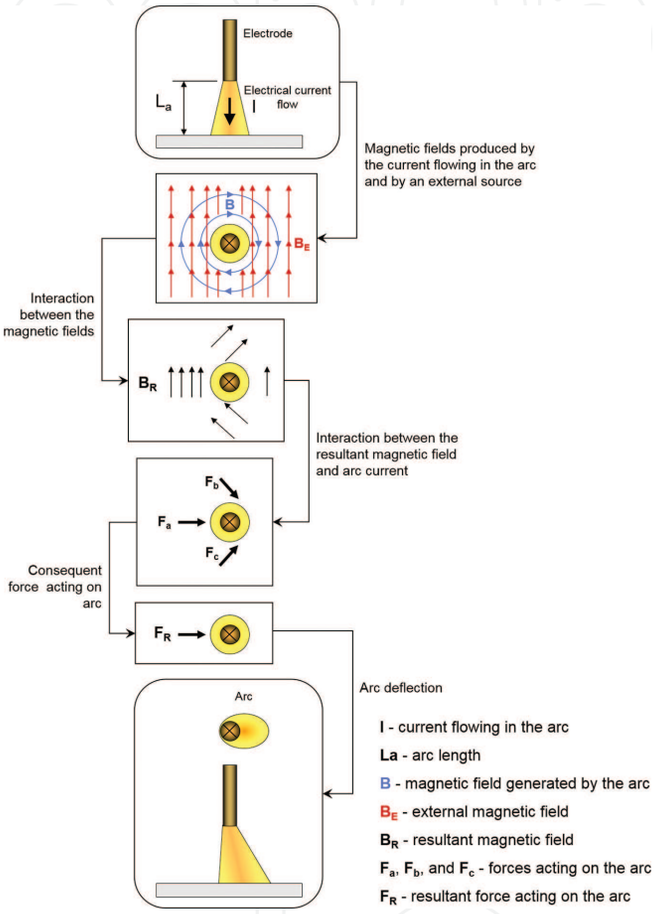


Figure 5. Diagrammatic explanation on how the deflection of an arc in the presence of an external magnetic field takes place.

2.1. Advantages and limitations of arc magnetic oscillation

Perhaps the main advantage of using magnetic oscillation is the virtually unlimited capability to create arc deflection patterns, either sideways or forward and backward relative to the direction of welding. Manufacturers of magnetic oscillation systems commonly point arc stabilization, arc positioning, heat distribution control, undercut minimization, porosity reduction, improved penetration, and uniform side melting in joints as advantages of this technique. In practical terms, the magnetic deflection is more adequate for high-frequency movements and with greater precision (no mechanism inertia, etc., typical of mechanical devices). Despite the fact that magnetic oscillation can be used in favour of welding, some

issues may arise related to the use of magnetic fields along electric arcs. Perhaps the destabilization of the arc in the presence of strong magnetic fields is the main disadvantage of using magnetic fields to oscillate welding arcs. These instabilities in the arc may even lead to its extinction, even temporally. Problems with arc instability and interruption in double wire GMAW are mentioned in the literature [7, 9–11]. The main reason for this phenomenon is linked to magnetic fields generated by the arcs operating adjacent to each other and the "stiffness" presented by these arcs. Magnetic fields up to 50 Gauss have been used to oscillate welding arcs without problems [8], although manufacturers build systems to operate up to 600 Gauss. Of course, what really matters is the value of the magnetic field acting effectively on the arc. In practical terms of magnetic oscillation, there may be limitations on the range (extension) of the arc deflection, since the arc is attached on one end (electrode) and moves on the other (workpiece) such as a pendulum.

2.2. Applications of magnetic oscillation

Several studies have been conducted to explore the application of magnetic oscillation to control the weld bead geometry and hence mitigate defects, as well as to improve mechanical properties of the weld as a result of grain refinement, for instance. A study analyzed the effect of frequency and amplitude of GTAW arc oscillation on the mechanical properties of the welded material [12]. The results demonstrated a grain refinement as compared with welds realized with constant and pulsed currents, both without arc oscillation. The obtained hardness was higher due to the grain refinement and low segregation of phases. Another study investigated the grain refinement in aluminium alloys [13]. The results concluded that by magnetically oscillating the arc it is possible to disturb the profile of solidification of the weld pool, causing the grain refining of the molten zone. Magnetic oscillation has been successfully used in GTAW for grain refinement of titanium alloys [14]. Another work used the transverse magnetic oscillation in GTAW with filler metal, and by extending the amplitude of the magnetic field, the authors obtained an increase of the weld bead width and were able to reduce penetration [15]. Another study used transverse magnetic oscillation in GMAW for narrow gaps and the authors obtained good penetration and melting uniformity on both sides of the groove [16]. A more recent work used a system to synchronize the electrode polarity with the torch position in GMAW for hardfacing, that is, the synchronized oscillation (weaving) was with a mechanical device [17]. In this case, negative polarity was used in the centre of the weld bead (high melting rate and welding speed, low dilution and penetration) and positive polarity was used on the sides of the weld bead to facilitate overlapping of the next bead, avoiding lack of fusion defects. According to the authors, the process was satisfactory for carrying out hardfacing with little penetration, surface smoothness, and good aspect ratio (width/height). In addition, the weld beads showed no discontinuities and had an excellent visual appearance with few spatters. Therefore, the synchronization between magnetic oscillation (arc position) and the welding process (level of current and/or operating mode) may have potential in similar situations.

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3. Methodology and results

The synchronization between the magnetic oscillation of the arc and the welding process, GTAW in this case, was assessed in two parts; characterization of arc deflection and magnetic oscillation synchronized with GTAW. Concerning the arc deflection characterization, high-speed filming and electrical signal data were used to evaluate the GTAW arc behaviour during magnetic oscillation and to verify if the synchronization system was working properly. In addition, some general consideration on the effect of the synchronization on the weld bead formation was carried out. In the assessment of the magnetic oscillation synchronized with GTAW, transverse/lateral oscillation to the direction of welding was employed with three arc stop positions synchronized with three welding current levels and three actuation times (one for each position), as illustrated in **Figure 3**. To support the analysis of this combination, electrical signals from the electromagnet and the welding process, including electrical transients, were assessed along with weld surface appearance as well as measurements related to the width of the resulting weld beads. All welds were produced as bead-on-plate tests in 250 X 60 X 3 mm mild carbon steel and argon was used at 14 l/min as shielding gas. The arc length (electrode to workpiece distance) was always kept at 6.5 mm (this setting is a little above the value conventionally used for welding, but was adopted to increase the arc deflection and therefore boost any related effect). A Th2 tungsten electrode with 4 mm diameter and 60 degrees sharp was used. The welding travel speed used was always 200 mm/min, unless stated differently. The magnetic flux density acting on the arc was estimated with a Gaussmeter by conducting measurements for different electromagnet voltages for an electromagnet-to-GTAW-electrode (arc centre) distance of 15 mm and with the electromagnet placed 3 mm above the test sample (as the actual welding tests) (the measurements are shown in **Figure 6**), but with no arc (no welding). **Figure 7** illustrates the general equipment used during the tests. As shown, the test samples were replaced by a stationary water-cooled copper block to facilitate high-speed filming (no weld pool formation). It is worth saying that the welding power source employed (IMC DIGIPlus A7) allows to switch between up to six pre-set welding programs (welding modes and/or current levels) by an external control input, the same used to control the electromagnet and then synchronize the magnetic oscillation with the welding process.

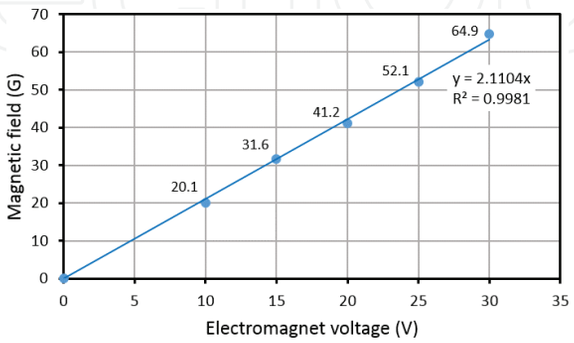


Figure 6. Magnetic field "acting on the arc" versus electromagnet voltage for an electromagnet-to-GTAW-electrode (arc centre) distance of 15 mm and with the electromagnet placed 3 mm above the test sample.

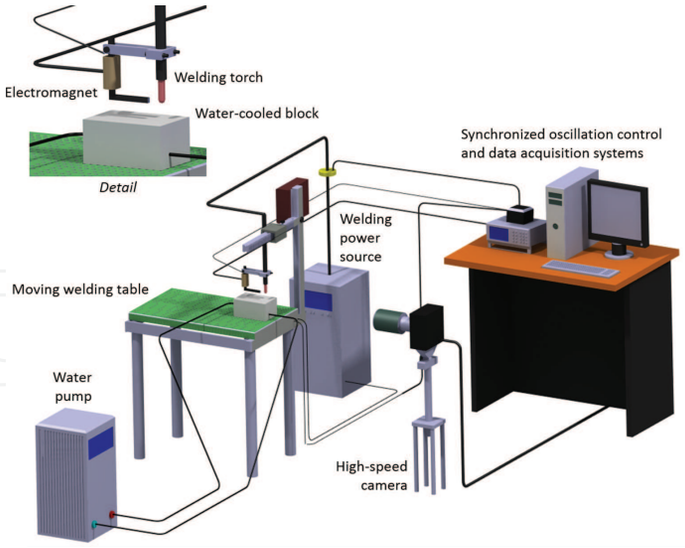


Figure 7. Illustration of general equipment used for testing GTAW with synchronized magnetic oscillation.

3.1. Characterization of arc deflection

3.1.1. Magnetic deflection response time

In order to verify the responsiveness of the synchronized magnetic oscillation system, three tests were carried out as shown in **Table 1**, and high-speed images of the GTAW arc analyzed. By the images of the deflected arc (**Figure 8**), it is possible to see that with the lateral (left and right) stop times set in 50 ms the arc reached virtually the same deflection levels obtained with 200 ms of lateral (left and right) stop times. Thus, 50 ms was considered sufficient for the electromagnet coil current (controlled by the electromagnet voltage) to reach the level required to take the arc to the expected deflection range (around 12 mm). On the other hand, the reduction of the lateral (left and right) stop times to only 5 ms made the arc reach levels significantly reduced (to about 8 mm), indicating that in this case the electromagnet coil current had not reached the level required to lead the arc to the expected deflection range. As the manufacturer of the welding power source recommends a dwell time in each welding mode or current level of at least 100 ms and considering that 50 ms allowed the expected level of arc deflection, 100 ms will be the minimum allowed for the actuation time of the combinations of arc position and welding current level.

Test	Welding current (A)	Left stop time (ms)	Right stop time (ms)
1	200	50	50
2	200	5	5
3	200	200	200

Table 1. Tests to assess the responsiveness time of the synchronized magnetic oscillation system (electromagnet voltage = ±20 V—tests without central stop time).

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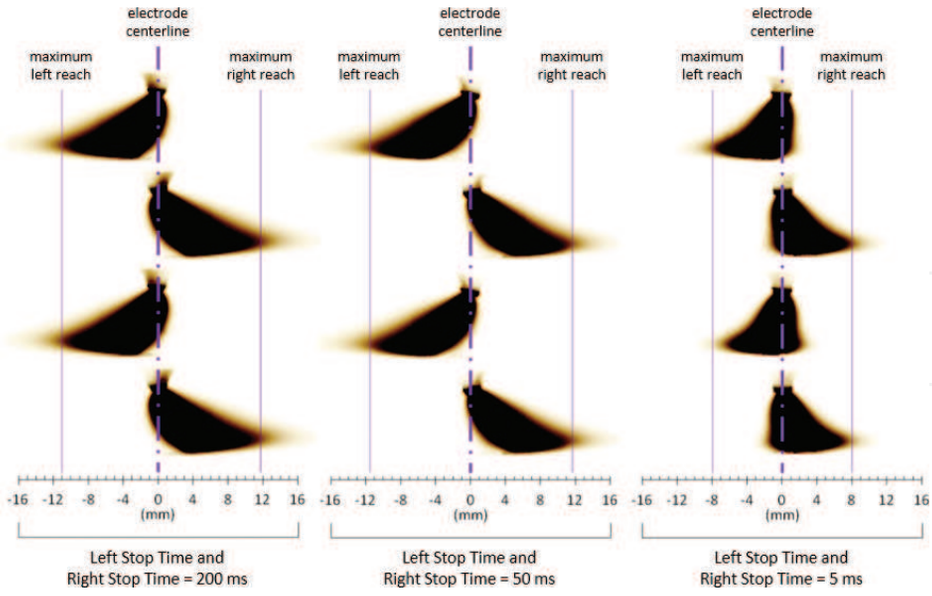


Figure 8. Maximum arc deflection reach for different lateral stop times (the arc image colours are inverted for better visualization).

3.1.2. Synchronism between magnetic oscillation of the arc and welding current level

A test was carried out to demonstrate visually the synchronism between the arc melting capacity (represented by the welding current level) and the position-time of application of this melting capacity (determined by the magnetic oscillation). **Table 2** lists the parameters used in this test.

Test	Left stop time (ms)	Central stop time (ms)	Right stop time (ms)	Left welding current (A)	Central welding current (A)	Right welding current (A)
4	250	500	750	100	200	300

Table 2. Test to demonstrate the synchronism between magnetic oscillation (arc time-position) and welding current level (electromagnet voltage = ±20 V).

Figure 9 demonstrates how the GTAW arc resultant from test 4 changes its position due to the magnetic field controlled by the electromagnet voltage as well as how it changes its "volume" due to the welding current applied in each position. The arc starts deflected to the left (left stop position) showing small "volume" level due to the small welding current used (low ionization degree). Past the short application time of low current, when the electromagnet voltage goes to zero, the welding current changes to an intermediate level, which is evident by the increase in arc "volume". The arc then quickly reaches the position without deflection (central stop position) with the welding current kept at the intermediate level. Next, after being centralized for relatively long time, the electromagnet voltage goes to the same level previously used in the left stop position deflection, but this time with reverse sign (negative). At this moment, the welding current rises to a high level (the arc clearly further increases in "volume"). The arc is

then quickly deflected to the right side (right stop position) maintaining this high welding current level. Next, after the arc spends an even longer time at this high current level and in this position, the electromagnet voltage is set back to zero and the welding current switches back to the intermediate level (the arc decreases in "volume"). The arc then quickly returns to the state of no deflection (central stop position) keeping the level of intermediate welding current. Once again, elapsing the time without arc deflection and at the intermediate welding current, the electromagnet voltage returns to the level programmed with a positive sign, which makes the welding current return to the low level. The arc is then quickly deflected to the left again (left stop position), beginning a new cycle of magnetic oscillation synchronized with the welding current. The short time required for the arc to stabilize at each oscillation position

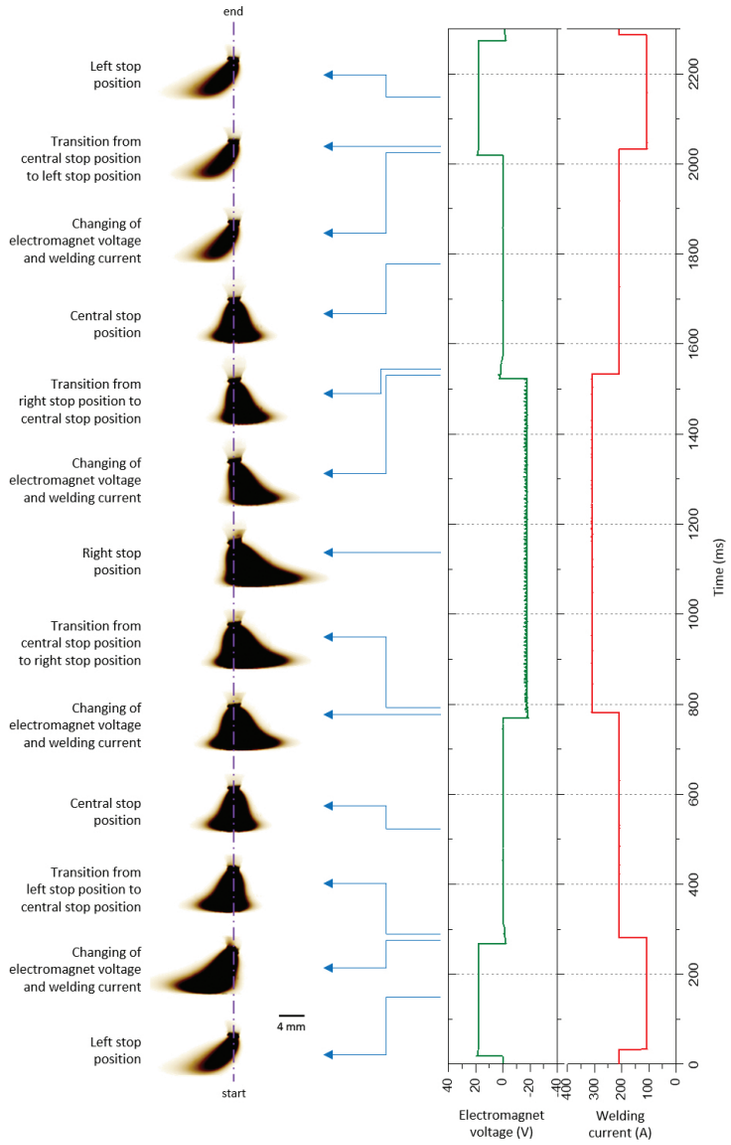


Figure 9. Sequence of high-speed images of a GTAW arc with synchronized magnetic oscillation (the arc image colours are inverted for better visualization).

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(transition between deflections) reflects the behaviour of the electromagnet coil current, which induces the magnetic field for deflection changes and slightly lags the electromagnet voltage, here used as control signal. It is believed that this arc stabilization time could be reduced by using a current source for the electromagnet control. Finally, it is also observed in **Figure 9** that the electromagnet voltage and welding current levels as well as the dwell times at these levels were according to plan (**Table 2**).

3.1.3. General effect of the synchronization on weld bead formation

In order to demonstrate in a simple way the effect of the synchronization between magnetic oscillation of the arc and welding current on weld bead formation, three tests were performed (**Table 3**), with the object of evaluation being the surface appearance of the resulting weld beads. The arc stop times and current levels were set in such a way their product resulted always in 37.5 A.s in each arc position.

Test	Welding speed (mm/min)	Left stop time (ms)	Central stop time (ms)	Right stop time (ms)	Left welding current (A)	Central welding current (A)	Right welding current (A)	Average welding current (A)
5*	180	250	250	250	150	150	150	154.4
6	180	150	350	150	250	107	250	154.1
7	200	150	350	150	250	107	250	152.3

* Test with constant current and magnetic oscillation—without synchronization.

Table 3. Tests to assess the general effect of the synchronism between magnetic oscillation of the arc (arc time-position) and welding current level on weld bead formation (electromagnet voltage = ±30 V; oscillation frequency = 1 Hz).

By comparing the weld beads resulted from tests 5 (constant current magnetic oscillation) and 6 (synchronized magnetic oscillation), shown in **Figure 10**, it can be noted that, for the same oscillation frequency and amplitude (voltage applied to the electromagnet) and the same average welding current and welding speed, the condition with constant current magnetic oscillation (conventional oscillation— test 5) did not result in a weld bead with continuous lateral melting. On the other hand, by using the synchronized magnetic oscillation (test 6), there was lateral melting continuity as the molten marks of the arc merged on both sides of the weld bead. Thus, it is demonstrated, by the visual appearance of the weld surface, that the magnetic oscillation enhances the ability to adjust the shape of the weld bead. In conventional arc oscillation, more lateral melting could be attained by increasing the arc stop time on each side and reducing it at the centre, but this would certainly result in increased "melting waves", leaving the weld beads "zigzag" shaped as the arc would stay too long on one side before returning to the centre and then to the other side. The formation of lateral "melting waves" could be overcome by decreasing the welding travel speed, but with sacrifice in productivity. With the synchronized oscillation approach, the arc stop times and the welding current levels can be combined to keep the overall melting capacity of the arc (average welding current).

Thus, it is possible to avoid the formation of lateral "melting waves" on the welds without reducing the welding speed (productivity loss).

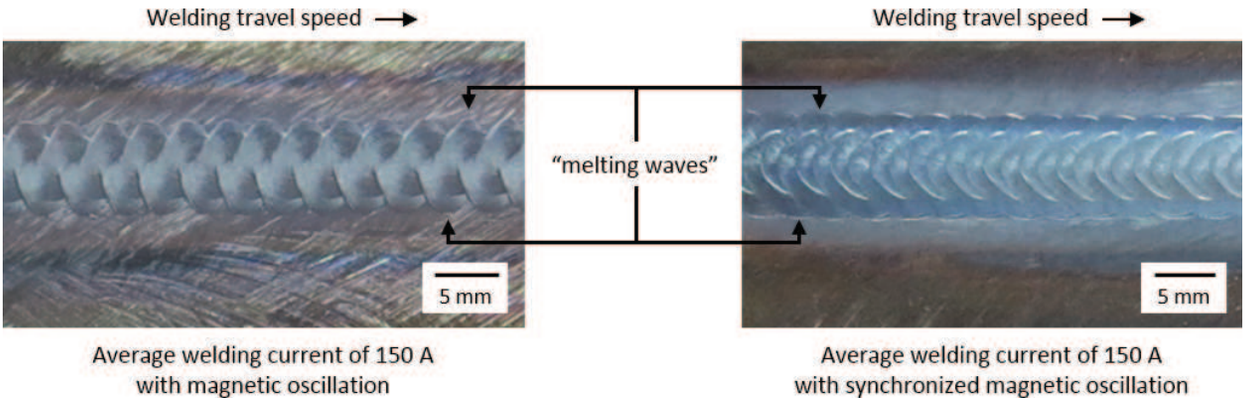


Figure 10. Superficial appearance of weld beads resulted from tests 5 (left hand side) and 6 (right hand side).

Test 7 (**Table 3**) was carried out to show more clearly the arc action at each position using the synchronized magnetic oscillation. The current levels and times at each arc stop position were the same as in test 6, but there was a small increase in welding speed to cause a larger spacing between the arc action marks. As shown in **Figure 11**, the so-called arc action marks are represented by melting edges left by the arc at each stop position. The marks denote something like typical pulsing current marks in Pulsed GTAW, but displaced both longitudinally (as would be in Pulsed GTAW) and transversely/laterally to the weld bead axis. It is possible to note the formation of large marks on the sides (high current) and small marks in the centre (low current). These arc action marks tend to become more evident (spaced) for low frequencies and high amplitudes of arc oscillation and for high welding speeds.

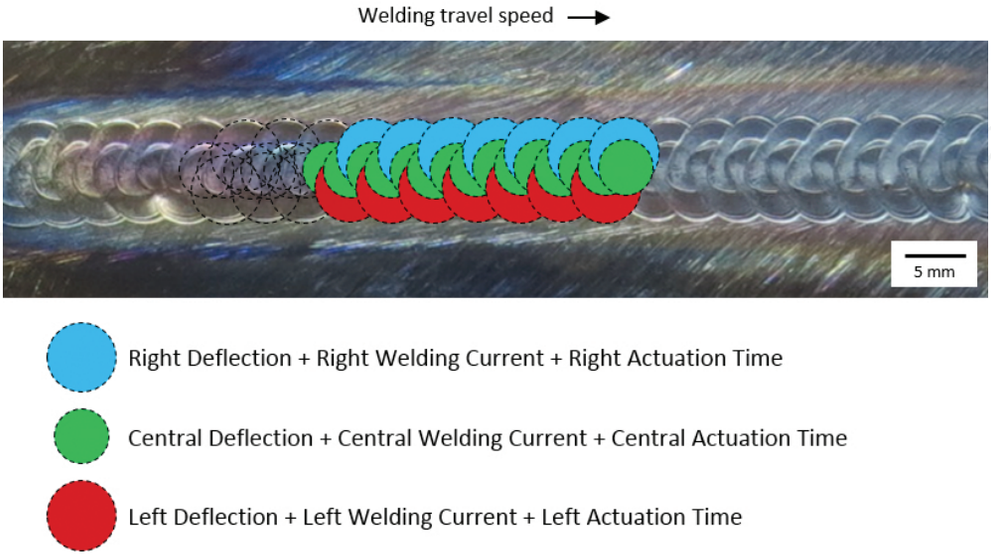


Figure 11. Demonstration of arc action marks in synchronized magnetic oscillation.

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3.2. Magnetic oscillation of the arc synchronized with GTAW

The effect of the synchronization between the magnetic oscillation of the arc and the GTAW process was assessed based on the combination of tests showed in **Figure 12**. Two average welding current levels, two oscillation frequencies, and two oscillation amplitudes (electromagnet voltages) were tested for the synchronized approach and compared to similar situations without synchronization and even without arc oscillation. In the synchronized case, lateral/transversal arc oscillation was employed as illustrated in **Figure 3**. For the tests with magnetic oscillation (with and without synchronization), the arc stop times (left, central and right) were as shown in **Table 4**. In order to assess the effect of welding current change in each arc stop position, different current levels were used for each position according to **Table 5**, but always keeping the average welding currents to 150 and 200 A as shown in **Figure 12**. For the tests in pulsed mode, a different approach was used compared to conventional pulsed GTAW. The same three different current levels were applied in sequence and with the same actuation times as in the cases with synchronized oscillation for comparison. All results were assessed in terms of weld bead formation, specifically the effect on the weld width.

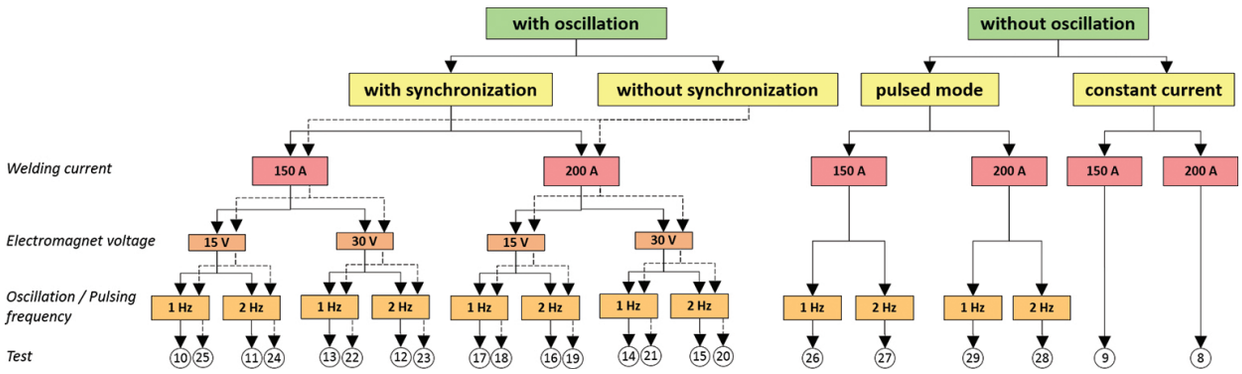


Figure 12. Flowchart of tests with magnetic oscillation of the arc synchronized with GTAW.

Left stop time (ms)	Central stop time (ms)	Right stop time (ms)	Oscillation frequency (Hz)
300	250	200	1
150	125	100	2

Table 4. Arc stop times for the tests with magnetic oscillation and oscillation frequencies.

Left welding current (A)	Central welding current (A)	Right welding current (A)	Average welding current (A)
210	111	158	150
280	148	210	200

Table 5. Welding current levels for each position of the arc and average currents.

Test	Electromagnet voltage				Welding current and Arc Voltage		
	Left Voltage (V)	Central Voltage (V)	Right Voltage (V)	Frequency [Hz]	Current [A]	Voltage [V]	Frequency [V]
			Without oscillation and with constant current				
8	–	0.07	–	–	205.1	14.53	–
9	–	0.07	–	–	154.5	12.86	–
			With oscillation and without synchronization (with constant current)				
10	−12.98	0.30	13.16	1.01	154.4	13.14	–
11	−13.03	0.53	13.23	1.97	154.4	13.03	–
12	−27.47	0.78	27.72	1.98	154.4	12.89	–
13	−27.51	−0.24	27.72	1.00	154.4	12.86	–
14	−27.49	−0.24	27.70	1.00	204.9	13.87	–
15	−27.54	−0.61	27.78	2.00	204.9	13.76	–
16	−13.03	0.51	13.23	1.98	204.8	14.22	–
17	−13.01	0.15	13.19	1.01	204.8	14.20	–
			With oscillation and with synchronization				
18	−13.02	-0.18	13.21	0.99	203.7	14.62	1.00
19	−13.04	0.41	13.22	1.99	206.4	14.15	2.04
20	−27.52	−0.60	27.74	2.01	202.9	14.18	2.03
21	−27.48	−0.28	27.68	1.00	204.7	14.35	1.00
22	−27.50	0.25	27.69	0.99	153.9	13.33	1.01
23	−27.57	−0.56	27.81	1.99	154.8	13.55	1.98
24	−13.06	−0.38	13.24	2.00	154.2	13.56	2.00
25	−13.02	−0.17	13.20	1.00	155.6	13.39	1.00
			Without oscillation and with pulsed mode				
26	–	0.07	–	–	153.9	13.43	1.01
27	–	0.07	–	–	156.3	13.27	1.98
28	–	0.07	–	–	204.5	14.05	1.98
29	–	0.07	–	–	205.1	14.19	1.01

Table 6. Resultant average electrical parameters from the GTAW tests.

3.2.1. Resultant electrical parameters and oscillograms

Table 6 shows the electrical parameters resulted from the GTAW tests and collected by the data acquisition system. All the electrical parameters, including those resulting from the synchronized magnetic oscillation tests were reasonable according to plan, showing the proper operation of the electromagnet control system and the welding power source. **Figures 13** and **14** present examples of electrical oscillograms resulted from tests with synchronization between magnetic oscillation and welding current level. It is possible to note that the welding current and the arc voltage followed the electromagnet voltage changes, evidencing the synchronism.

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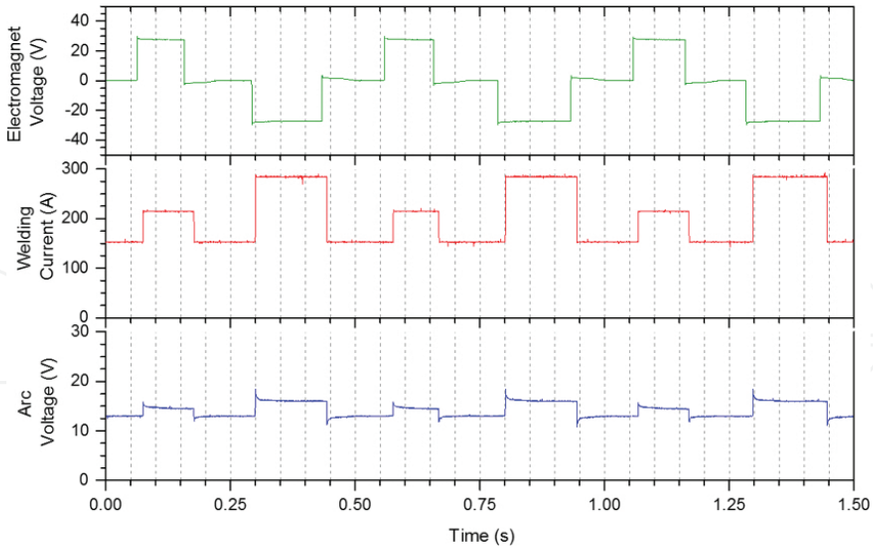


Figure 13. Electrical oscillogram from test 20—with oscillation and with synchronization.

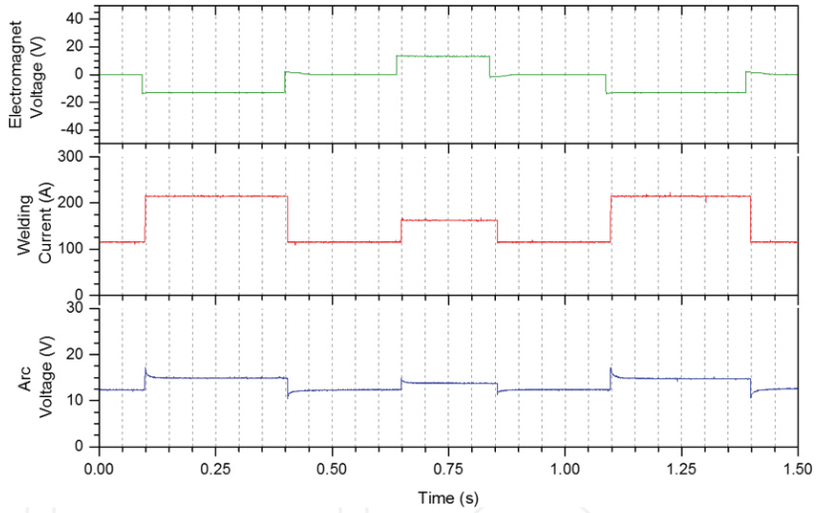


Figure 14. Electrical oscillogram from test 25—with oscillation and with synchronization.

3.2.2. Effect on weld bead width

The effect of the synchronization between magnetic oscillation of the arc and the welding current level on the change in parameters of weld bead width was evaluated. **Figure 15** shows how the width parameters of the resulting GTAW weld beads were measured. The centre of each welding movement (GTAW electrode route—baseline A) was obtained by markings previously made on the specimens. Three width measurements in different regions (beginning, middle, and end) for each specimen were carried out. The average total, right, and left widths of the weld beads then were taken for analysis. The standard deviation, not shown in the following graphs for visualization issues, was generally very low, which corroborates to the synchronized magnetic oscillation system robustness.

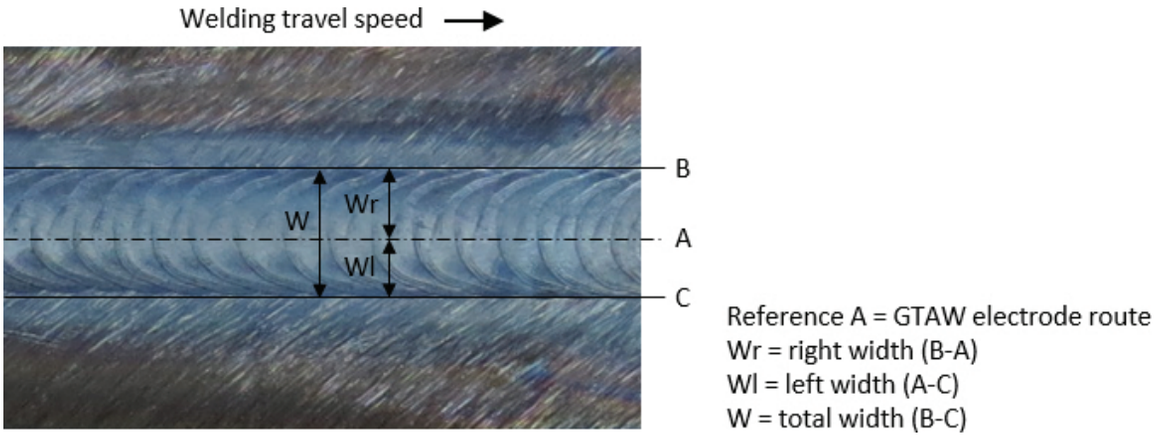


Figure 15. Weld bead width parameters analyzed.

Figure 16 shows the total width of the weld beads versus the electromagnet voltage (arc deflection) for the different GTAW configurations tested with an average welding current of 150 A. The lowest total width was reached for the case with constant current without oscillation. In the pulsed mode cases both frequencies result in weld beads of total width slightly larger and quite similar, since the arc reached higher current levels, increasing the size of the weld pool, at least in the bead surface. The two pulsing frequencies did not result in different total widths probably because the molten puddles (arc action marks) of the low levels of current were superimposed by the molten puddles (arc action marks) of the high levels of current, with the highest levels defining the total width of the bead, at least for the welding speed used. The pulsed mode resulted in intermediate levels of total width. As expected, the larger the magnetic deflection (electromagnet voltage) used, the greater the total width of the weld beads. The synchronized configuration resulted in greater total width compared to the constant current configuration with oscillation. This result can be explained as for the same average current, the lateral welding currents for the synchronized oscillation cases, especially on the left side, were superior to the central current and thus the likely tendency was the spreading of the molten metal surface (weld bead). The oscillation frequencies of 1 Hz provided larger total widths than those of 2 Hz. With 1 Hz the arc stays longer in each stop position in each deflection, giving more time for the current action in each deflection. The largest total width was achieved in the case of the synchronized oscillation at 1 Hz and with large arc defection (electromagnet voltage of 30 V).

The following graphs show the partial widths (left and right) of the weld beads to better analyze the effect of synchronizing the current level with the arc position for an average current of 150 A. The partial width values for constant current without oscillation and for the pulsed current cases are not shown here, as these conditions are transversely symmetrical to the welding direction and there is no significant difference between left and right widths.

Figure 17 shows the left width of the weld beads versus the electromagnet voltage (arc deflection) for the different GTAW configurations with an average welding current of 150 A. Generally, the left width tends to increase with the increase of arc deflection, particularly for the oscillation frequency of 1 Hz. It is clear that the synchronized configurations significantly

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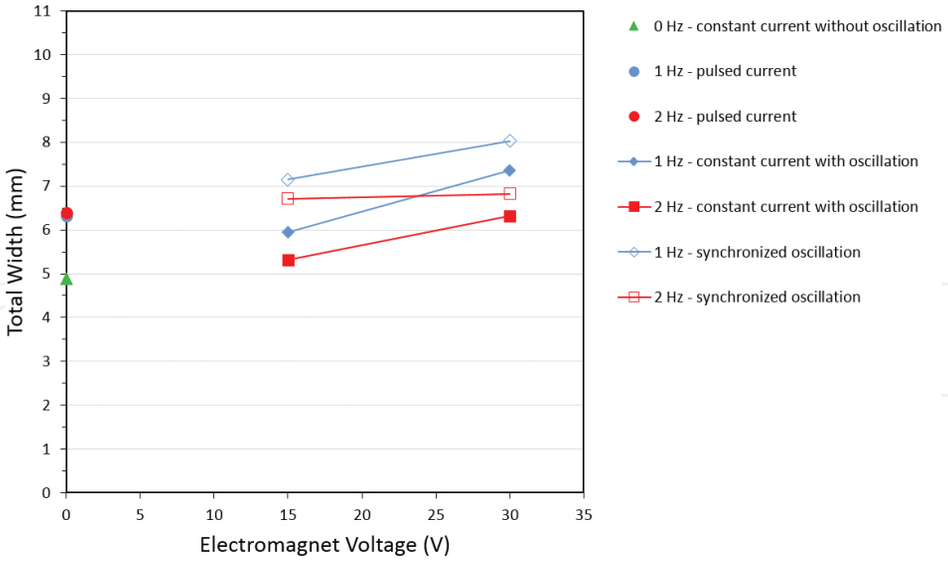


Figure 16. Total width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 150 A.

increased the left width, with greater effect for the frequency of 1 Hz. For the case of 2 Hz, with shorter times of current action in each of the arc positions, the resulting left width remained largely unchanged, and even tended to decrease in the synchronized case, with increase in electromagnet voltage. It may be that with 2 Hz the current action time to promote melting has been so short that the effect of deflection increase (expected increase in width) was attenuated. As in the total width analyses, the largest left width took place in the case of synchronized oscillation at 1 Hz and with large arc defection (electromagnet voltage of 30 V).

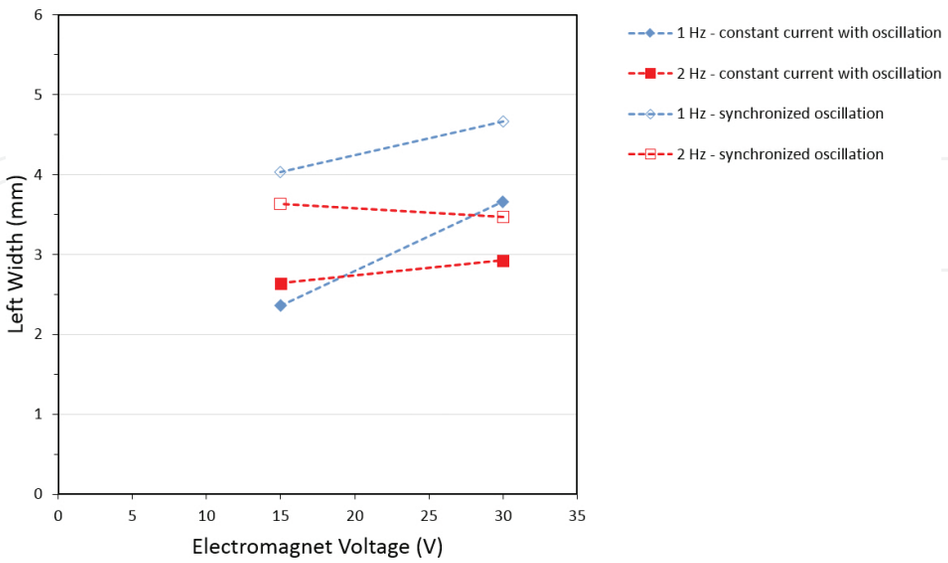


Figure 17. Left width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 150 A.

Figure 18 shows the right width of the weld beads versus the electromagnet voltage (arc deflection) for the different GTAW configurations with an average welding current of 150 A. Generally, the right width tends to increase slightly with the voltage electromagnet increase. Since the welding currents on the right side were practically the same, the right width values almost did not change comparing the cases with synchronized oscillation with those with constant current and oscillation.

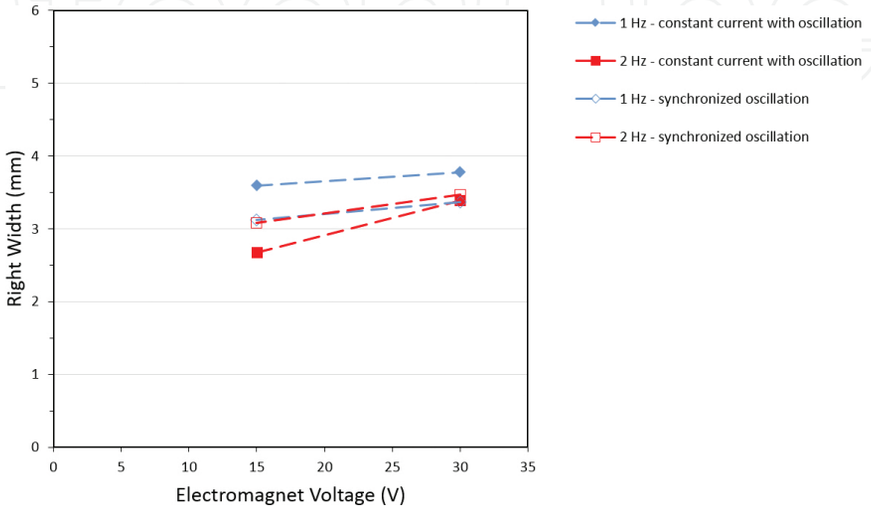


Figure 18. Right width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 150 A.

By comparing the effect on the total, left and right widths with the average welding current of 150 A, it is evident, especially for the oscillation frequency of 1 Hz, that the total width of the weld beads was mainly defined by left width. This indicates that the synchronized magnetic oscillation system was able to control the formation of the weld bead (at least in terms of surface width) as desired. That is, the highest welding current level and longest arc stop time on the left side of the oscillation led to increase of the left width, which, in turn, led to increase of the total width of the weld bead. Regarding the effect of the central welding current in terms of width, its main function is to "join" the two lateral arc deflections and melting capacities. This good control of the weld puddle could be exploited, for example, in the welding of dissimilar materials, in joining materials of different thicknesses, for root passes, narrow gaps, etc., always trying to direct more or less heat/melting capacity according to the arc position and need.

The following graphs are related to the GTAW configurations with an average welding current of 200 A. **Figure 19** shows the total width of the weld beads versus the electromagnet voltage (arc deflection) of all GTAW configurations tested with this average current level. As has occurred with the average current of 150 A, the smallest total width for 200 A took place with constant current without oscillation. In the pulsed current cases, the total width exhibited higher levels, the effect being slightly more pronounced with the frequency of 1 Hz, probably because the time the arc stays in the high current level is longer for this frequency. In the cases of synchronized oscillation and in those with constant current with oscillation, for the fre-

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quency of 1 Hz, the greater the magnetic deflection (electromagnet voltage) used, the greater the total width. The opposite took place for the frequency of 2 Hz (more pronounced for the constant current oscillation case), i.e., the overall width decreased with the electromagnet voltage increase. This unexpected result might have occurred due to the high current levels used (for the 200 A average welding current) as they make it more difficult for the arc to deflect —the higher the current flowing through the arc, the smaller its magnetic deflection [8]. In this case, to surpass this effect, even higher electromagnet voltages would be necessary, which were not attempted due to limitations in the electromagnet voltage/coil current allowed by the synchronized oscillation system. The synchronized oscillation configuration resulted in larger total widths compared with the constant current with oscillation configuration, as in the case of the average current of 150 A. This result can be explained since, for the same average welding current (in this case 200 A), the currents in the synchronized oscillation, especially on the left side, were significantly superior to the central current, which led to spreading of the weld puddle. Therefore, in general, the oscillation frequency of 1 Hz provided larger widths than those with 2 Hz, this fact being more pronounced for the high electromagnet voltage level (30 V). With the low frequency (1 Hz), the arc stays longer in each stop position for each deflection, giving more time for the current action in each deflection. Similar to the occurrence for the 150 A average current, the largest total width for the 200 A average current was achieved in the case of the synchronized oscillation at 1 Hz and with large arc defection (electromagnet voltage of 30 V).

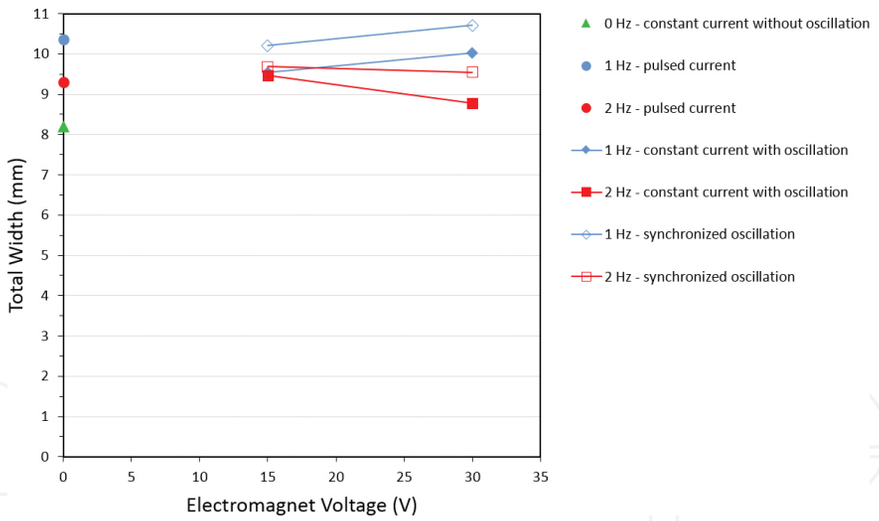


Figure 19. Total width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 200 A.

The following graphs show partial widths (left and right) of the weld beads for an average current of 200 A, also to better analyze the effect of synchronizing the current level with the arc position. The partial width values for constant current without oscillation and for the pulsed current cases are not shown here as they were shown earlier, as these conditions are transversely symmetrical to the welding direction and there is no significant difference between left and right widths.

Figure 20 shows the left width of the weld beads versus the electromagnet voltage (arc deflection) for the different GTAW configurations tested with an average welding current of 200 A. Here the left width also tended to increase with the arc deflection (electromagnet voltage) increase, particularly for the oscillation frequency of 1 Hz. However, for 2 Hz the left width practically remained unchanged with the increase in the electromagnet voltage, tending particularly in the synchronized oscillation case to a small decrease, probably because at 2 Hz the current action times in each of the arc stop positions were shorter. In this case also, the largest left width was obtained for the case of synchronized oscillation at 1 Hz and with large arc deflection (electromagnet voltage of 30 V).

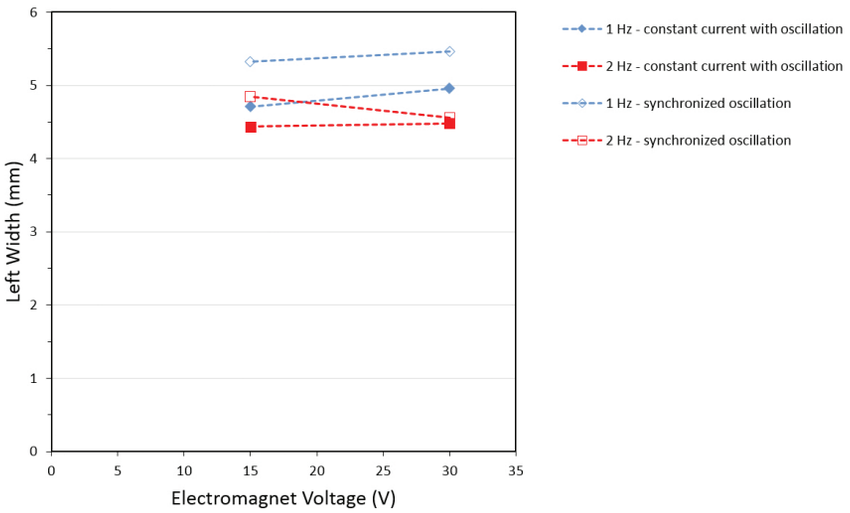


Figure 20. Left width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 200 A.

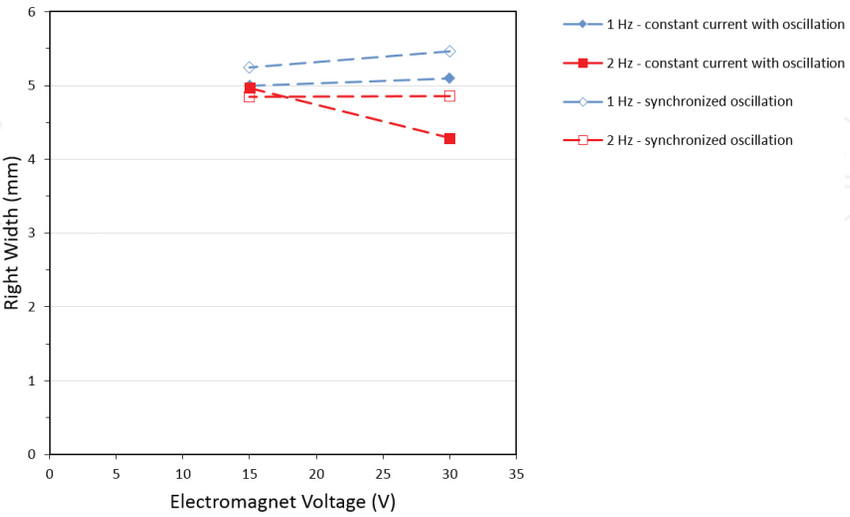


Figure 21. Right width of weld beads versus electromagnet voltage (arc deflection) for different configurations of GTAW with an average welding current of 200 A.

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Figure 21 shows the right width of the weld beads versus the electromagnet voltage (arc deflection) for the different GTAW configurations tested with an average welding current of 200 A. Since the welding currents on the right side were practically the same, the right width values almost did not change comparing the synchronized oscillation to the constant current with oscillation cases. The right width resulting from the constant current with oscillation configuration at 2 Hz was the only one that showed unexpected result—decreased with the electromagnet voltage increase, collaborating to reduce the total width—and further investigation will be needed to clarify this fact.

The analysis of the width parameters for the average welding current of 200 A indicates that the most satisfactory results (greatest control of the weld puddle and of the formation of the weld bead) were obtained with synchronized magnetic oscillation at a frequency of 1 Hz. It is worth recalling that this good control could be exploited, for example, in the welding of dissimilar materials, joining of materials of different thicknesses, root pass, in narrow gaps, etc., always seeking to drive more or less heat/melting capacity according to the arc position and need.

By comparing the results from the average welding current levels used (150 and 200 A), the total, left and right width, values were larger with 200 A as expected, since increases in the current give the arc more melting capacity. However, the increase in width values with the electromagnet voltage increase was more pronounced for 150 A—arcs with low current are easier to deflect [8]. In general, the synchronized oscillation configurations resulted in the largest widths for both average welding currents used, with 1 Hz oscillations favouring larger values compared to 2 Hz.

4. Conclusions

According to the conditions used and tests performed, the main findings were:

a. Regarding the characterization of arc deflection

- From the evaluation of the synchronism between magnetic oscillation and welding current level and by analyzing the synchronizing device response time, it was observed the efficiency of the synchronization system developed;
- From the examination of the general effect of the synchronization on weld bead formation, more flexibility to optimize the arc melting capacity was verified in each arc position during oscillation.

b. Regarding the magnetic oscillation of the arc synchronized with the GTAW process

- In general the electrical parameters, including those resulting from the synchronized magnetic oscillation tests, were according to plan, showing the proper/synchronous functioning of the electromagnet control system and of the welding power source;

- The synchronized oscillation configuration generally resulted in the largest values of weld bead width. Furthermore, the larger the magnetic deflection used, the greater the total width resulted;
- Analysis of width parameters for both average welding currents used indicated that the best results (control over the weld pool and over the weld bead formation) were obtained with the synchronized magnetic oscillation of the arc at a frequency of 1 Hz;
- For both average current levels tested, the left side width, where higher levels of current and longer times of arc action were employed, influenced more on the increase of the total width, demonstrating that the synchronized magnetic oscillation technique was able to control the formation of the weld beads. That is, the higher current and actuation time on the left side of the weld pool led to left width increase, resulting in increase of the total weld bead width.

5. Future developments

Aiming to further develop and evaluate the synchronized magnetic oscillation technique, the following ideas are proposed:

- Improve the synchronized oscillation system to have the capacity to deflect the arc with different and higher intensities at each stop position;
- Evaluate the synchronized magnetic oscillation within a broad frequency range to better exploit its capacity to control the weld bead formation;
- Evaluate the synchronized magnetic oscillation with GTAW and GMAW in applications such as the welding of dissimilar materials, joining of materials of different thicknesses, in root pass, in narrow gap, in hardfacing, for grain refinement, for out-of-position welding, etc., always seeking to drive more or less heat/melting capacity according to the position of the arc and need;
- Perform longitudinal magnetic oscillation synchronized with GTAW and GMAW to verify the effects on factors such as weld bead geometry and maximum welding speed allowed;
- Record the magnetic oscillation synchronized with GMAW using high-speed filming to verify possible effects on the transfer of metal droplets from the electrode to the workpiece.

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