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DEVELOPMENT OF A MICROCONTROLLED SYSTEM FOR ELECTROMAGNETIC ARC OSCILLATION IN GAS METAL ARC WELDING

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Abstract. *This research presents the development of an electronic system to control the oscillation of the welding arc by electromagnetism during the GMAW process, enabling the automation of weaving motion and possibility of improving weld quality. The oscillation system is composed of an electronic circuit containing a microcontroller and an H bridge, two electromagnetic coils and two power supplies. The circuit is attached to a tractor, which is responsible for moving the welding torch along the workpiece during the process at constant linear velocity. The coils are fixed to a support attached to the tractor and positioned parallel to the welding direction, producing transverse arc oscillation. The proposed system allows the control of amplitude and frequency of oscillation, the desired values of which are sent to the oscillation system via USB communication from interface created in MATLAB®. The arc can be oscillated at frequencies between 0 and 122 Hz and amplitudes between 0 and 5.6 mm. The system was tested during GMAW welding of austenitic stainless steel AISI 316L, with wire electrode ER308LSi and 97%Ar-3%CO_2 shielding gas. The results showed that arc oscillation occurred satisfactorily, ensuring greater control of weld bead geometry as well as improving weld visual aspect. Additionally, for frequencies of oscillation greater than 50 Hz, it is observed complete elimination of finger type penetration.*

Keywords: *Arc Oscillation, Electromagnetism, Gas Metal Arc Welding, Microcontrolled System, Finger Type Penetration*

1. INTRODUCTION

During the execution of weld bead with weaving motion by GMAW or GTAW processes, the oscillatory movement of the torch is usually performed manually or by a mechanical system. However, the electric arc is a flexible conductor, subject to the influences of external magnetic fields, allowing its deflection by electromagnetic forces. According to classic physics textbooks (Halliday *et al.*, 2012) when electric current flows through an electrical conductor with defined length, which is immersed in a magnetic field, the conductor will experience a force, known as "Lorentz Force", which is perpendicular to the magnetic field and the length of the conductor. According to Marques *et al.* (2013), the welding arc is a gaseous electrical conductor. When compared with a metallic wire, it tends to be more sensitive to the influence of magnetic fields, which enables the development of a system capable of oscillating the electric arc by electromagnetism.

The first studies in this area occurred in 1960, when William J. Greene (1960) applied a patent concerning an electromagnetic system capable of oscillating the electric arc in arc welding processes with shielding gas used to coat metal sheets. This system consisted of two coils connected in series and a variable frequency power source. The electric arc was positioned between the two coils, with poles of opposite polarity close to either side of the electric arc. Greene (1960) noticed a critical relationship between the oscillation frequency of the electric arc and the time required to transfer the molten metal from the tip of the electrode to the workpiece. According to his observations, this time should be less than a half cycle of arc oscillation, preferably less than a quarter cycle. Greene (1960) affirms that the best results of the process are ensured when the welding current is continuous and the electric current of the coils, alternated, in the form of square wave. If the welding current is alternated, the frequency of arc oscillation is the difference between the frequency of the welding current and the frequency of the electric current in the coils.

Chen *et al.* (1990) developed an electromagnetic oscillation system to control the welding arc oscillation in GTAW process. In this system, a microcomputer, an analog digital converter, power amplifiers and a single coil were used. The authors (Chen *et al.*, 1990) affirmed that the electromagnetic coil should be positioned behind the electrode at a distance of 5 mm and recommended a trapezoidal waveform for the electric signal in the coil in order to improve control of weld bead width and extent of fusion zone. It was observed that the intensity of the magnetic field, the deflection of electric arc and, consequently, the arc voltage grow linearly with the increase of current in the coil and that the greater the intensity of the magnetic field, wider the weld bead and shallower the penetration. The welding arc oscillation also promoted a significant improvement in the weld bead appearance.

Juliani *et al.* (2013) presented a system capable of oscillating the welding arc by electromagnetism. In their equipment, the electrical signal is issued to the coil with different waveform characteristics. From a wide combination of amplitude, frequency and type of electrical signal wave, the system can impose welding arc movements similar to the ones performed by a welder. According to the authors (Juliani *et al.*, 2013), a drop of molten metal tends to follow the welding arc, which, once positioned in the correct location, with adequate energy intensity and moving harmonically at defined trajectories, can produce a weld pool with controlled features, ensuring better control of weld bead geometry and, consequently, overall weld quality. Thus, they affirm that the system is capable of achieving better conditions for execution of the root pass, since the electromagnetic oscillation system is able to position the electric arc at a strategic location in order to overcome obstacles in the execution of the first pass of weld.

Corradi *et al.* (2013) presented a methodology to develop an electromagnetic oscillation system able to control the arc oscillation in GTAW processes. In their experiments, they observed the welding arc behavior in the presence of magnetic field. The authors (Corradi *et al.*, 2013) observe that the magnetic field necessary to deflect the electric arc is of order of mT and its response is instantaneous. Another observation was that the increase in welding current increases electric arc stability in the presence of magnetic field, although promoting a reduction in the oscillation amplitude.

Several studies have shown the effects of electric arc oscillation in welding of various alloys. In general, it is observed that for optimal values of frequency and amplitude of arc oscillation, the weld presents an improvement in their mechanical properties, due to the grain refining and increasing of the proportion of equiaxed grains in relation to the columnar grains in the fusion zone (Reddy *et al.*, 1997; Janaki Ram *et al.*, 1999; Sundaresan *et al.*, 1999; Koteswara Rao *et al.*, 2005; Kumar *et al.*, 2008; Lim *et al.*, 2010a; Lim *et al.*, 2010b; Biradar and Raman, 2012; Mahajan *et al.*, 2012). The welding arc oscillation is also able to minimize the occurrence of hot cracking in alloys prone to this phenomenon, as shown in studies made by Biradar and Raman (2012) and by Yu *et al.* (2014).

With the benefits of the welding arc oscillation and the possibility to deflect the arc by electromagnetism, this article presents the development of an electromagnetic oscillation system for GMAW process able to control the frequency and the amplitude of arc oscillation.

2. METHODOLOGY

2.1 Development of the electromagnetic oscillation system

The electromagnetic oscillation system is basically composed of an electronic circuit containing a microcontroller (PIC18F4550) and an H bridge (L298), two electromagnetic coils and two power supplies. The electronic circuit is attached to a tractor, which is responsible for moving the welding torch along the workpiece during the process at a constant linear velocity. The coils are fixed on a mechanical support attached to the tractor and positioned parallel to the welding direction, producing a transverse arc oscillation, perpendicular to the welding direction and with an inclination of 45° toward to the workpiece. Figure 1 presents the tractor with the electronic circuit and the coils.

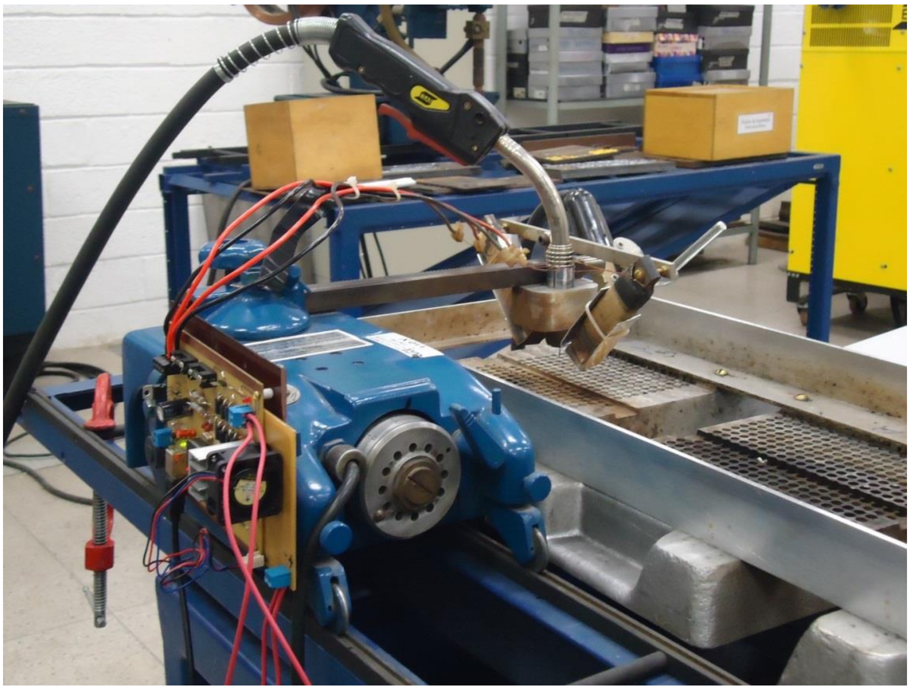

Figure 1. The tractor with the electronic circuit and the coils

The proposed system allows the control of two process variables, which are the amplitude and the frequency of arc oscillation. The desired values of these two parameters are sent to the oscillation system via USB communication from an interface created in MATLAB®. The welding arc can be oscillated at frequencies from 0 to 122 Hz and amplitudes from 0 to 5.6 mm. The maximum values of amplitude and frequency of welding arc oscillation are limited by the electrical characteristics of the electromagnetic coils. These were determined empirically based on previous studies of Corradi *et al*. (2013), which present the methodology to calculate and measure the electrical constants of the coils, and Reis *et al.* (2012), which show that the magnetic field strength required to deflect the arc is in mT order.

The electromagnetic coils of the developed system are connected in parallel and are capable to generate a magnetic field of 30 mT when they are conducting 1.0 A each one, which is enough to oscillate the welding arc (Corradi *et al.*, 2013; Reis *et al.* 2012). In the imposed conditions during the experiments, the magnetic field produced was able to deflect the welding arc to maximum amplitude of 5.6 mm.

The electric circuit composed by an electromagnet and a continuous voltage source can be modeled as a resistor-inductor circuit, whose characteristic equation is given by Eq. (1) (Halliday *et al.*, 2012).

$$\mathrm{R}i(t) + \mathrm{L}\frac{di(t)}{dt} = \mathrm{E} \tag{1}$$

Where R is the resistance (Ω), L is the inductance (H), E is the continuous voltage (V), i(t) is the electric current in function of time (A) and t is the time (s).

The electric current in this kind of circuit presents a characteristic behavior due to the presence of the inductor. Inductive loads behave according to the Law of Lenz (Halliday *et al.*, 2012), which affirms that, initially, an inductor opposes to any change in electrical current flowing through it. After a certain time, the inductor behaves like a common wire. This time is known as settling time and separates the transient regime, where the current increases exponentially from the permanent or stationary regime, where the current remains constant and with its maximum value, which is the desired value (Ogata, 2003). Figure 2 illustrates the behavior of the current in the coils of this work that are in parallel, whose equivalent resistance (R) is 2.22 Ω and the inductance (L) is 4.53 mL for a continuous voltage (E) 8.0 V.

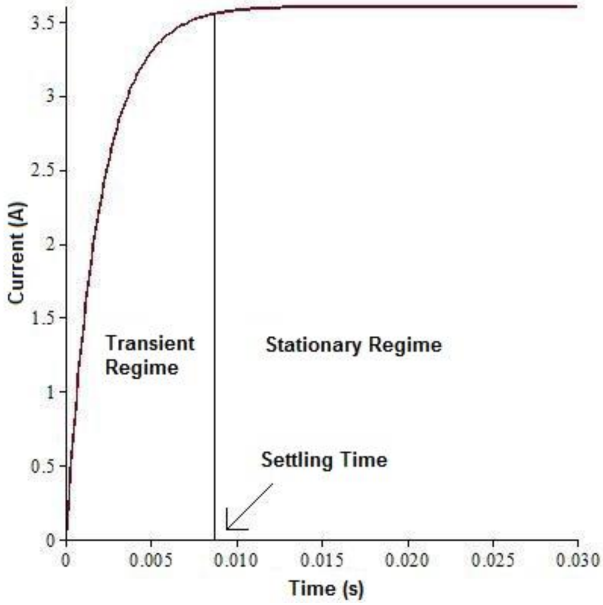

Figure 2. Current versus time in coils

The settling time is a determinant factor, since it limits the maximum frequency of the oscillation. It occurs because before this time has been reached, the current imposed in the electromagnet to produce a desired magnetic field will not have been reached yet. So, for frequencies above this maximum value, the reversal of the current in the electromagnet, in order to reverse the direction of the magnetic field and, consequently, the direction of the welding arc deflection, occurs before it reaches its maximum value, affecting the amplitude of the arc oscillation, which will not reach its desired value, since it depends of the magnetic field, which depends of electrical current. From Eq. (2), it is possible to calculate the value of this time for an accommodation of 98.2% (selected arbitrarily) of the maximum value (Ogata, 2003). According to this equation, the settling time (t_{st}) depends on the inductance (L) and resistance (R) of the electromagnet.

$$t_{st} = 4\frac{L}{R} \tag{2}$$

For the electromagnetic oscillation system developed, the settling time is 8.16 ms, and since the maximum frequency of oscillation is given by the inverse of the settling time, its value is 122.55 Hz.

The microcontroller used was the PIC18F4550 and this choice was based on its operational characteristics, commercial availability and price. The function of the microcontroller is to receive the values of frequency and amplitude of oscillation sent from the MATLAB® via USB communication and converts them to electrical signals that are sent to an H bridge. The desired amplitude value is converted to a PWM signal, allowing the control of the average voltage in the electromagnetic coils, the intensity of the generated magnetic field and, thus, the amplitude of deflection of the welding arc. The value of the frequency is converted to digital electric signals that alternate in high level and low level at this frequency, to control the frequency of reversing electric and magnetic polarity of the coils. The H bridge used was the L298 and his choice was based on their operational characteristics, availability commerce and affordable.

The other components on the electronic circuit of the electromagnetic oscillation system are filters, protection system, cooling etc.

2.2 GMAW welding of austenitic stainless steel AISI 316L

The electromagnetic oscillation system developed was tested during GMAW welding of austenitic stainless steel AISI 316L, with wire electrode ER308LSi and 97%Ar-3%CO_2 shielding gas (Corradi *et al.*, 2015). In this investigation, plates of austenitic stainless steel AISI 316L in hot rolled condition and with dimensions of 12.7 mm x 300 mm x 100 mm were used.

Two kinds of welding experiments were performed: bead on plate and V-groove butt welds. In both tests, only the oscillation frequency was varied, the other parameters remained constant. Eight weld beads and five butt welds were produced in the tests. The V-groove used in butt welding had a null grove face, a null root opening and a 60º groove angle. The welding parameters used are presented in Tab. 1 and Tab. 2.

Macrographic analysis were performed in order to prove the deflection of the electric arc and to evaluate the visual aspects of the weld bead produced.

Table 1. Bead on plate welding parameters

Welding Speed (mm/s)	**Gas Flow (L/minute)**	**Feed Speed of The Electrode Wire (m/minute)**	**Contact Tip to Work Distance (mm)**	**Welding Voltage (V)**
7.5	18	7.1	18	31.5
Welding Current (A)	**Type of Current and Polarity of The Electrode**	**Metal Transfer**	**Frequency of oscillation (Hz)**	**Amplitude of Oscillation (mm)**
270	CC+	Spray	0, 5, 10, 25, 50, 70, 90, 100	5.6

Table 2. Butt welding parameters

Welding Speed (mm/s)	**Gas Flow (L/minute)**	**Feed Speed of The Electrode Wire (m/minute)**	**Contact Tip to Work Distance (mm)**	**Welding Voltage (V)**	**Welding Current (A)**
4.5	25	6.9	23	31.0	240
Type of Current and Polarity of The Electrode	**Metal Transfer**	**Number of Passes**	**Frequency of oscillation (Hz)**	**Amplitude of Oscillation (mm)**	
CC+	Spray	4	0, 25, 50, 75, 100	5.6	

3. RESULTS AND DISCUSSION

From the obtained macrographs for bead on plate welding (Figure 3), it is noted that during the oscillation of the welding arc at frequencies below 50 Hz the heat source moves perpendicularly to the welding direction and is distributed along the weld bead rather than remaining concentrated at its center. Thus, it is shown welding arc deflection can be used to obtain satisfactory results concerning visual aspect. Besides, the oscillation of the electric arc influences significantly in the weld bead geometry, since the penetration, width and reinforcement of the weld beads were changed. For frequencies of oscillation greater than 50 Hz, it is observed the complete elimination of the finger type penetration, which is a characteristic of the weld bead produced without oscillation.

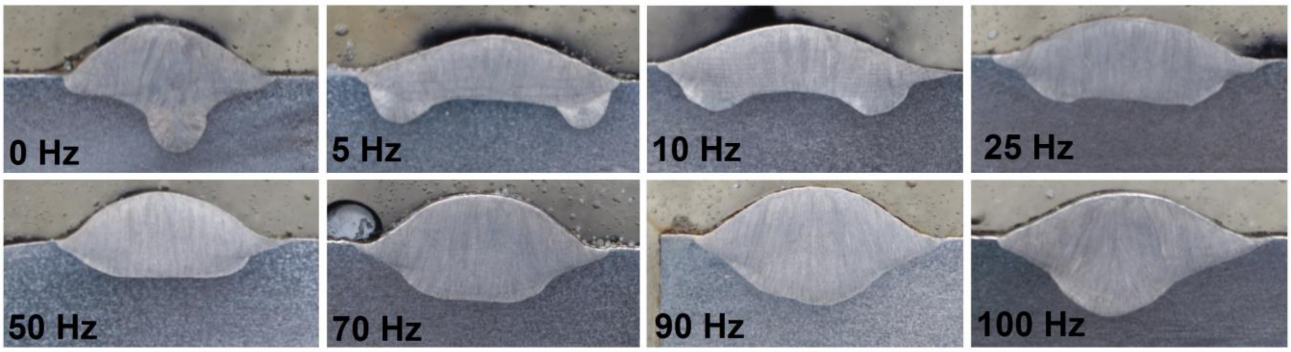

Figure 3. Macrographs for bead on plate welding

The macrographs for butt welding are presented in Fig. 4. It is noted that the visual aspect of the welds improved with arc oscillation.

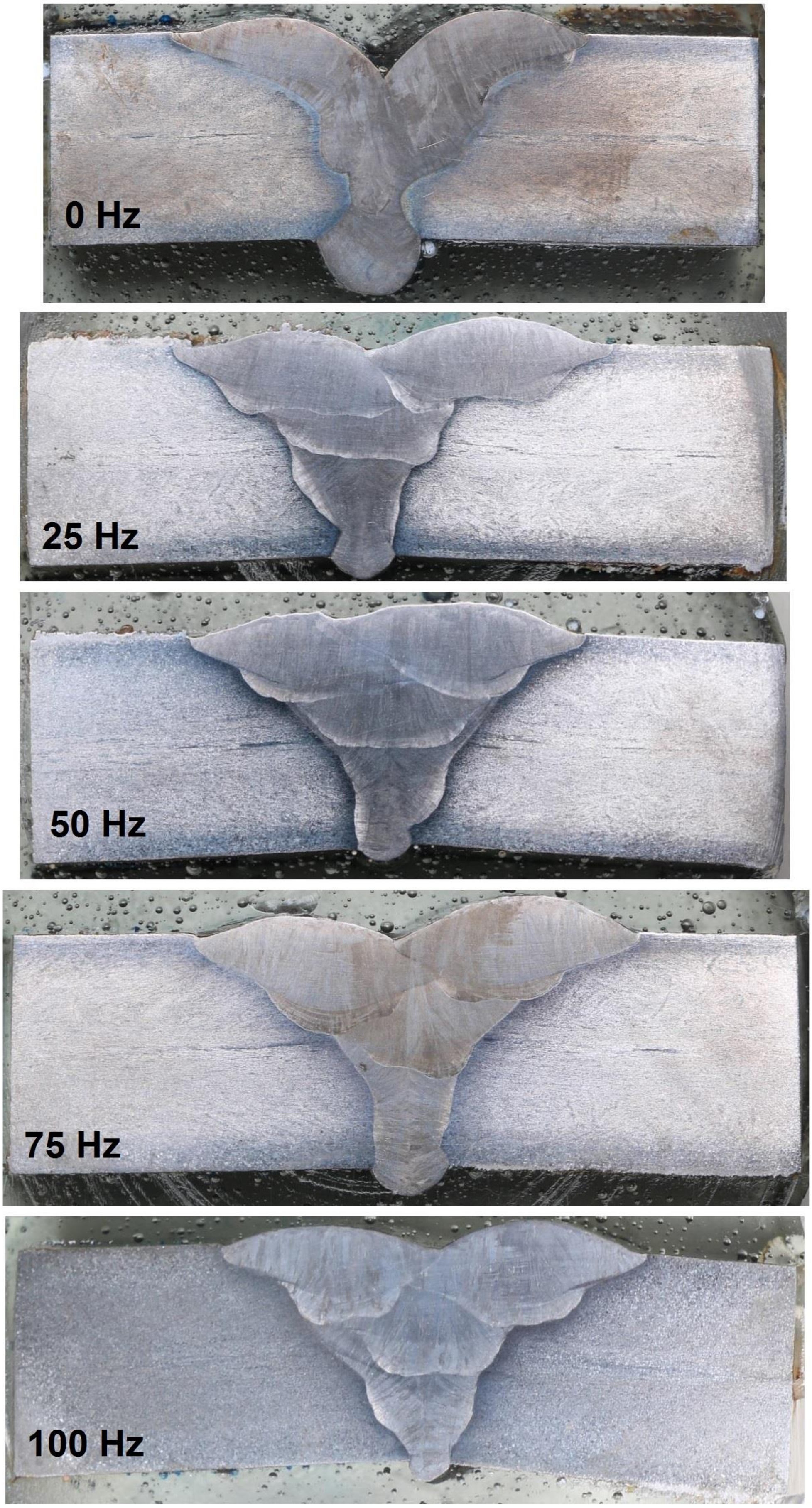

Figure 4. Macrographs for butt welding

The bottom surface of the sheets welded without arc oscillation presents the occurrence of excessive weld penetration, leakage of the weld pool and holes whereas the bottom surface of the sheets welded with arc oscillation presents better quality (Figure 5).

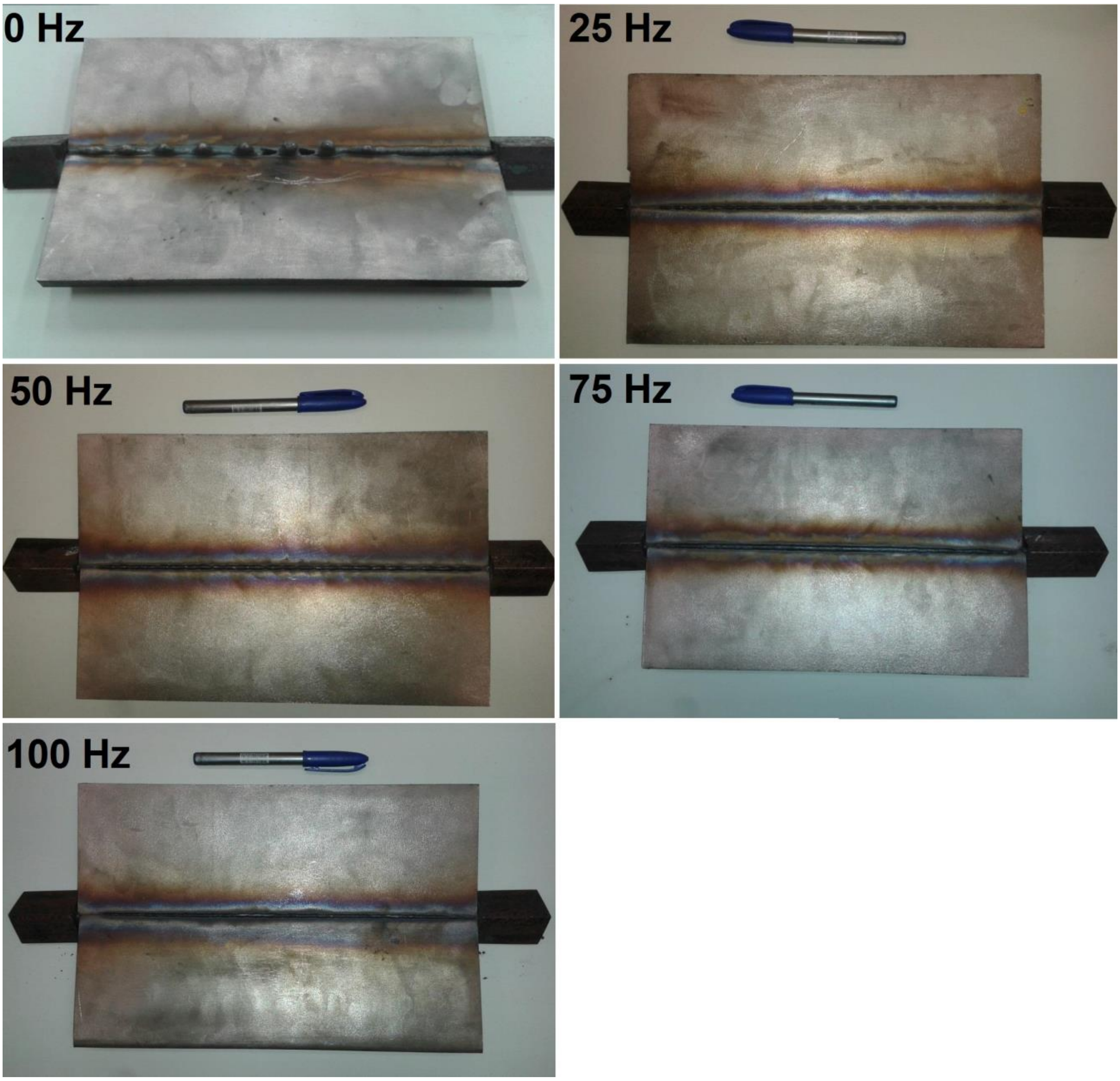

Figure 5. Bottom surface of the sheets welded

4. CONCLUSIONS

The electromagnetic oscillation system developed is able to oscillate the electric arc during GMAW process. The oscillation of the electric arc influences the geometry of the weld bead and improves the visual aspect of the weld. Additionally, for frequencies above 50 Hz, it is noted the complete elimination of the finger type penetration, which is present in the weld bead produced without arc oscillation for bead on plate welding.

5. ACKNOWLEDGEMENTS

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