26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0229

ANALYSIS OF THE CO2 INFLUENCE IN THE GAS MIXTURE FOR WAAM USING CMT VERSION OF THE GMAW PROCESS

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***Abstract**: A researching hype upon the Wire and Arc Additive Manufacturing (WAAM) seen in the last decade, has led to a notable increase of the knowledge in how parts built by WAAM are affected by the electrical and thermal parameters, and deposition strategies. In this innovative manufacturing route, the selection of the welding conditions seems to be even more critical than in usual joining and facing applications. The deposition planning in WAAM is highly influenced by these conditions, for example, the feedstock characteristics (composition, form, size), the electric arc (power and density) and metal transfer conditions. A factor that highly influences these parameters is the shielding gas mixture choice. The Gas Metal Arc Welding (GMAW) shielding gas mixtures are mostly based in Argon with parts of Carbon dioxide due to its relatively lower cost. However, the increase of the Carbon dioxide content can negatively influence the stability of the metal transfer and increase the presence of undesirable oxides between the layers. Although, the influence of Carbon dioxide in the formation of these defects during the manufacture of parts via WAAM using the Cold Metal Transfer (CMT), an advanced variant of the GMAW process, is not yet fully described and explained in the literature.*

To fulfill this gap, this work focuses on the analyses of two types of industrial gas mixtures: 92% Argon + 8% CO2, and 75% Argon + 25% CO2. As feedstock, 1.2 mm ER70S6 filler wire was deposited over 12.7 mm thickness ASTM A36 carbon steel plates. The welding process used in this study was the Fronius CMT, due to its highly usage among WAAM manufacturing and research groups. The influence of CO2 content on the electrical, thermal, and geometrical characteristics of single welding beads, single bead walls and pads was qualitatively and quantitatively analyzed. The results showed a correlation with the increase of CO2 content and the increase in the silicon oxide formation and incidence of pores and lack of fusion between layers. The thermal analysis showed that the thermal profile did not change within the range of 8% to 25% of CO2, even the processes showing a slight difference in electrical power. Furthermore, the geometric profile showed no significant difference between specimens. Therefore, to attenuate inclusions of silicon oxide and to diminish the lack of fusion incidence the mixture with 25 % of carbon dioxide is the most adequate, however this does not discredit the usage of 8% of carbon dioxide in the gas mixture, but it shows the need for the implementation of a more accurate overlapping parametrization.

***Keywords**: WAAM, gas mixture, CMT, GMAW, additive manufacturing.*

1. INTRODUCTION

The term Additive Manufacturing (AM) has been used to describe a group of technologies which utilize a free form layer-by-layer approach to create objects, beginning from bottom to the top (Alberti *et* al., 2014). AM was first used as a method to build small series and prototypes, especially by the aerospace industry, that used this kind of technology to design lighter and customized components, which led to the usage of AM in different kinds of market. This is due to the fact that AM processes can produce complex free form objects, while classic subtractive manufacturing cannot (Hoefer *et al.*, 2018).

An AM process is composed of a motion system, a source of heat and a feedstock. A dedicated system to generate the deposition path to speed up the planning phase, thus converting the CAD object into points in the space which will make the trajectory of deposition (Venturini *et al.*, 2018). Among the variant AM techniques, the Directed Energy Deposition (DED) focuses its thermal source on the fusion of a feed material simultaneously with its deposition of a previously defined path, thus making a layer. Wire Arc Additive Manufacturing (WAAM) is a DED variant that can improve productivity and material deposition efficiency, which can produce products of large dimensions and volume, and with low dimensional complexity, this process uses technology that it is already available in the welding market and that is very familiar to the user, thus necessitating a low investment to it (Silva *et al.*, 2019). There are a few challenges that come due to the usage of wire as additive material that is: (i) residual stresses and distortion originated from the welding heat input, (ii) relatively poor part accuracy, and (iii) poor surface finish of the produced part. It is also emphasized that the geometry-related process parameters like the process itself (arc, beam), energy input, travel speed, deposition width, layer thickness, wire diameter and wire feed rate should be carefully controlled to avoid tolerance deviation (Horgar *et al.*, 2018).

GMAW CMT version is a widely applied method in the fields of AM, the detection of the short-circuit with the subsequent wire pullback, produces a more spatter-free and stable process when compared to other dip transfer arc welding processes (Hoefer *et al.*, 2018) . The electrical signal cycle of a CMT process can be defined as the period required to deposit a droplet of molten electrode into the welding pool. This cycle can be divided in three phases, (I) The peak current phase, where the voltage remains constant while there is a peak of current, thus igniting the electric arc, that heats the electrode which form the molten droplet, (II) The background current phase, current is decreased to prevent occurring globular transfer of the molten droplet in the tip of the wire, and (III) The short-circuiting phase, which the voltage is brought to zero, while the wire pullback occurs, assisting in the metallic bridge break and it's transferring to the welding pool (Selvi *et al.*, 2018). One thing that is noted, as it was stated by Ali *et al.* (2019), is that there is a difference between the real (measured) and the adjusted wire feed speed, this occurring because of the necessity that the power source has to maintaining the arc length constant and independent of surface and stick-out changes, which led to the researchers in their article that the real wire feed speed in the CMT-process is 20-32% less than the adjusted wire feed speed (Ali *et al.*, 2019).

In the GMAW, one of principal features is the shielding gas, which has as main function, in addition to the ionization and electron transport, relies on protecting the wire feedstock, metal droplets and welding pool from atmospheric gas. As cited, it's also responsible for being an ionizing environment, thus conferring the stability properties of the electrical arc, and control of the metallic transferring modes (Scotti and Ponomarev, 2008). The different composition of gases utilized to shield the arc affect directly in what is going to be the bead geometry. Gas mixtures which contain percentages of carbon dioxide (CO_2) have a higher dissociation and ionization potential than argon in the shielding gas, this leads to a major demand for power and consequently increased temperature of the arc that causes alteration in the weld bead penetration profiles (Ebrahimnia *et al., 2009)*. It was also shown in the article proposed by Liskevych and Scotti (2014), that the increase of carbon dioxide leads also to an increase of the penetration and fusion area of the welding bead, which led the authors to propose that 10 to 30% of CO_2 in the mixture of Ar leads to the most appropriate geometric parameters and appearance of weld bead, with an acceptable spatter rate generation (Liskevych and Scotti, 2014) .

In this innovative manufacturing route, the selection of the welding conditions seems to be even more critical than in usual joining and facing applications. The deposition planning in WAAM is highly influenced by these conditions, for example, the feedstock characteristics (composition, form, size), the electric arc (power and density) and metal transfer conditions. A factor that highly influences these parameters is the shielding gas mixture choice. The GMAW shielding gas mixtures are mostly based in Argon with parts of Carbon dioxide due to its relatively lower cost. However, the increase of the Carbon dioxide content can negatively influence the stability of the metal transfer and increase the presence of undesirable oxides between the layers. Although, the influence of Carbon dioxide in the formation of these defects during the manufacture of parts via WAAM using the Cold Metal Transfer (CMT), an advanced variant of the GMAW process, is not yet fully described and explained in the literature. To fulfill this gap, this work focuses on the electrical, thermal and geometrical analyses of the pads manufactured from two types of industrial gas mixtures: 92% Argon + 8% CO2, and 75% Argon + 25% CO2.

2. EXPERIMENTAL PROCEDURE

ASTM A36 carbon steel plates of 9,53 x 37,50 x 250 mm were used as substrate in the experiment. For the WAAM technique it used an anthropomorphic robot with 6 axes of motion from Motoman Yaskawa model HP20D as a motion system, and a CMT Advanced 4000R with an interface configuration module RCU5000i from Fronius as a power source. For all depositions was used a synergetic G3Si1 – CMT 1220 (V2.3.8.4) program, the wire feed speed was 5.0 m/min, welding speed 30 cm/min, contact tip-to-work distance 15 mm and gas flow 13 L/min. The wire feedstock used was a ER70S6 of 1.2 mm diameter and two types of industrial gas mixtures: 92% Ar + 8% CO_2 (C8), and 75% Ar + 25% CO_2 (C25). Figure 1 shows the working base used to do the experiment.

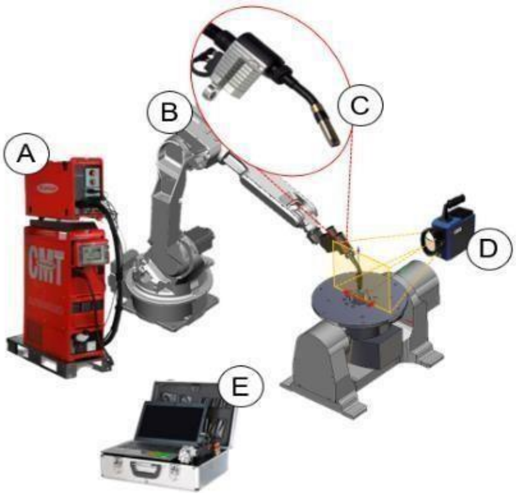

Figure 1. Schematic representation of the experimental base, where: A – Power source Fronius CMT Advanced 4000R; B – Anthropomorphic robot Motoman HP20D; C – Welding torch Robacta Fronius; D – Thermografic camera FLIR SC7000; E – Oscilloscope IMC SAP V4.

The voltage and current signals were simultaneously measured during welding by means of a portable oscilloscope acquisition system (SAP). The voltage signal was measured between the workpiece and welding torch and the current signal through a coaxial Hall effect sensor around the ground cable. These signals were used to analyze the effect of the waveform on stability, molten pool dynamics and temperature (heat input and heat transfer).

The acquisition of the thermal profile generated by each gas mixture was made with a FLIR SC7000 thermographic camera. The temperature range of 300 to 1500 °C with an emissivity of 0.8 was used. The thermographic images allowed the influence of the variation of the dioxide carbon increase on the thermal profile of each weld bead deposited to be determined. The method applied consisted of monitoring the temperature variation over time of a region of interest (ROI) (Figure 2). In this case, the temperature of the ROI is given by the average maximum temperature for five pixels.

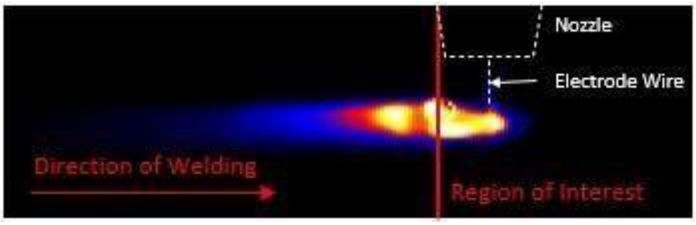

Figure 2 – Temperature measurement method used in thermography.

Initially, it was realized single bead welds in order to preliminary characterization of the weld bead geometrical profile as height, width, penetration and surface appearance by means macrographic analyze. By means this preliminary study, pads with five horizontal bead and five vertical beads were produce in order to evaluate the process stability, thermal profile and welding defects incidence. The method used consists of depositing five overlapping weld beads side by side with 33% overlap in the same direction for each layer. For the next layer of weld the direction is reversed. This path strategy decreases geometric deviation along of layer length.

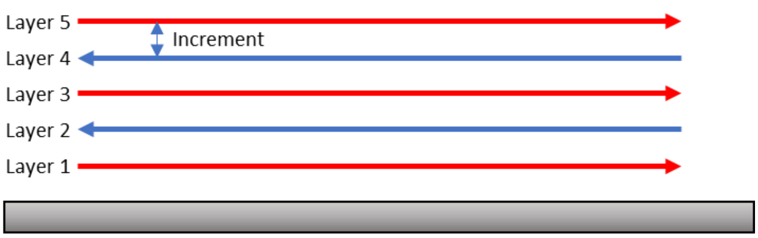

Figure 3 – Schematic of the welding torch path used in the pads deposition.

In addition, a measurement process was performed to verify the influence of each gas mixture in the geometrical weld bead profile. The method used to measure the pads consists in measure three points along the horizontal and vertical section as described in Figure 4.

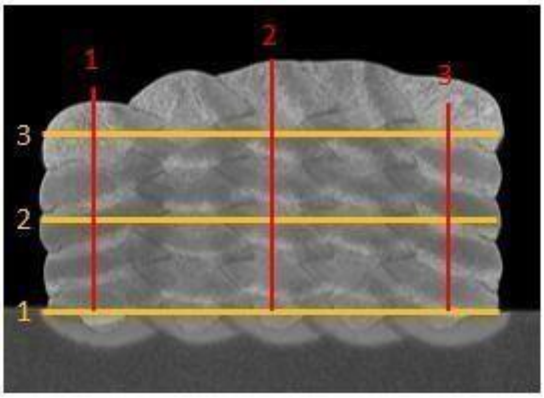

Figure 4 - Method used to the pads measurement.

3. RESULTS AND DISCUSSIONS

Based on the current and voltage oscillogram of the C8 gas mixture shown in Figure 5 it's possible that average current was 165A and average voltage was 12.2V which results in a power at 2.4kW. The detachment frequency was 93Hz. It's possible to verify the same voltage peaks in a period of 2.04 to 2.06 seconds. These peaks represent small instability points in the metal transfer.

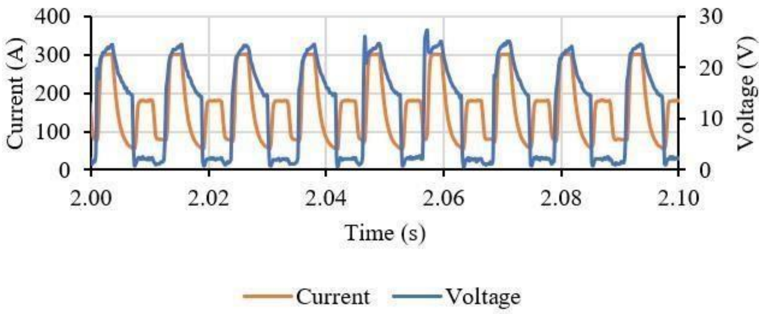

Figure 5 – Instantaneous current and voltage oscillogram for C8 gas mixture.

For the other case where C25 was used as gas mixture, observing the current and voltage oscillogram shown in Figure 6 it's possible to verify that the average current was 163A and average voltage was 13.9V which results in a power at 2.7kW. The detachment frequency was 94Hz. All the electrical values were very similar to the values seen for C8, but in this case the oscillogram regularity was higher in relation to the C25 case. In addition, it was observed that the WFS for both cases were lower than the regulated on the power source, about 4.5m/min, 0.5m/min lower that programmed.

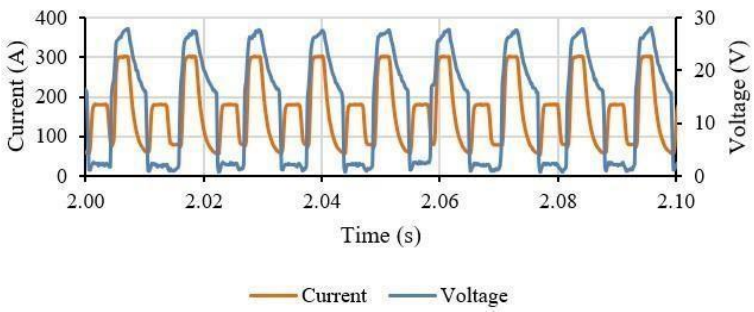

Figure 6 – Instantaneous current and voltage oscillogram for C25 gas mixture.

The thermal profile for both cases is depicted in Figure 7. Analyzing the maximum temperature over time it was noted that there was no difference between the gas mixtures. This is contrary to what is conventionally presented when it comes to carbon dioxide welding procedures, where an increase in heating of the weld pool is suggested.

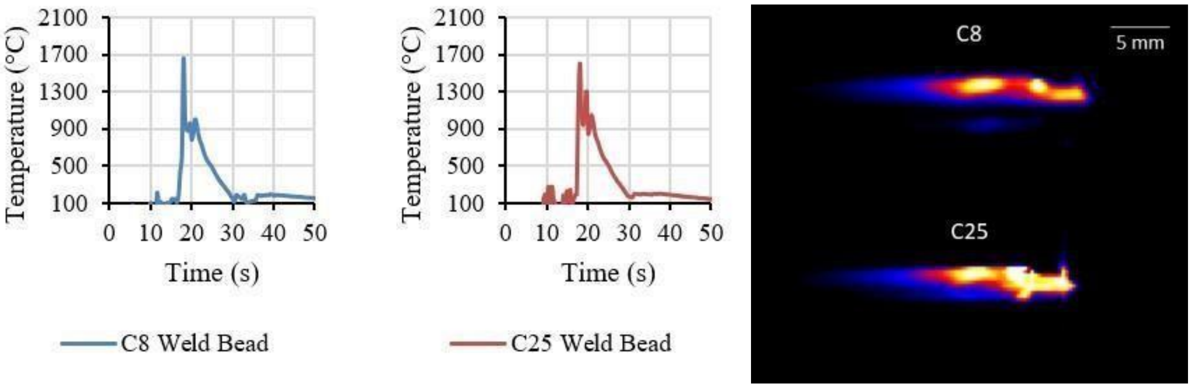

Figure 7 – Thermal profile for both gas mixture.

The geometric profile of the different mixture gas weld beads can be seen in Figure 8. It was possible to verify a difference between samples, in the C8 weld bead sample is observed a lower dilution, penetration and wetting angle in relation to C25 sample.

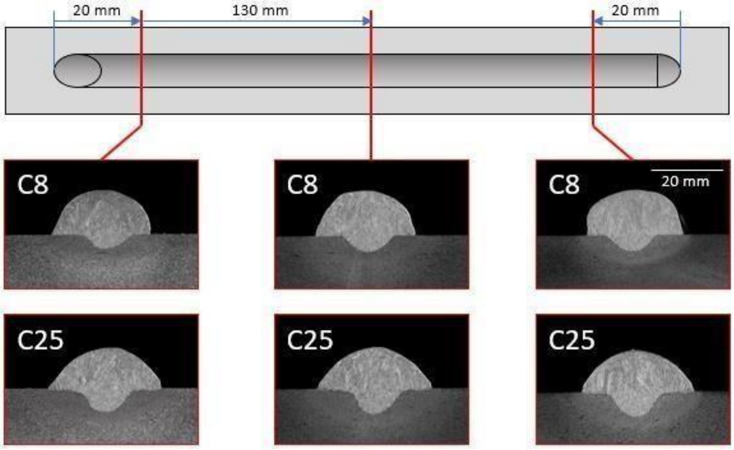

Figure 8 – Macrographs of the weld beads cross section.

From measurement of the macrographs samples was elaborate Table 1 which showed an average of three samples for each weld bead deposition. The difference in cross-section profile between the gas mixtures is visible even though the depositions show similarity between electrical and thermal parameters. This fact, in theory, is linked to the gas mixture properties, where increasing carbon dioxide concentration it was possible modify the geometric weld bead profile.

Table 1 - Geometric characteristics of the samples cross section

Description	Width (mm)	Height (mm)	Penetration (mm)	Wetting Angle	Dilution (%)
C8	27.1	12.6	4.4	101	13
C25	28.0	10.2	5.9	126	24

In order to verify the influence of carbon dioxide on the welding defects formation in additive manufacturing parts, pads were constructed by the described methodology. From single weld bead parameters, the pads were deposited. For all pads deposition processes the current and voltage, as well as the power and WFS, were similar. The thermal profile obtained by mean infrared filming for both pads were described in Figure 9. Looking at the average temperatures for deposited weld beads that make up each pad noted no difference between C8 e C25 depositions.

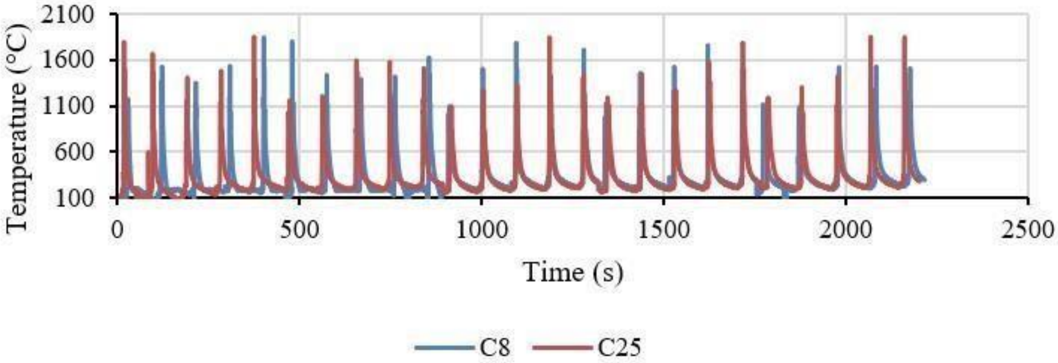

Figure 9 – Pads thermal profile comparison for both gas mixture.

The surface appearance for both cases showed higher quality with no defects and a low geometric deviation as can be seen in Figure 10. However, in the case of C25, there was an excessive presence of silicon islands. The silicon islands can be induced in function of the carbon dioxide content. Carbon dioxide molecules break down into carbon, carbon monoxide and oxygen in the welding arc. This oxygen that results from the carbon dioxide breaking down will combine with deoxidizers in the weld metal (silicon, manganese and aluminum are the most common) to form oxides which float to the surface of weld producing these silicon islands (Kou, 2002).

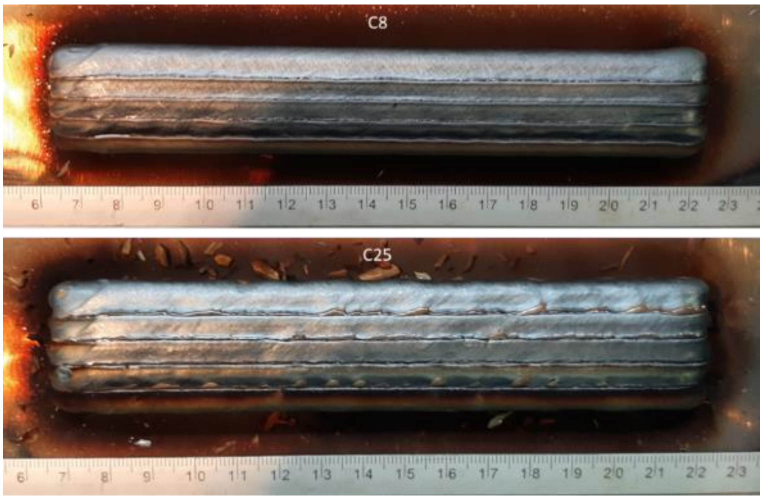

Figure 10 – Pads Surface appearance

The geometric profile of the different mixture gas weld pads can be seen in Figure 11. A slight reduction in height is noticed in the first column that makes up the pad, especially for the C8. In addition, for both samples it can be observed to lack of fusion in the first layer. However, the C8 pad can be noted lack of fusion in first weld bead of each layer.

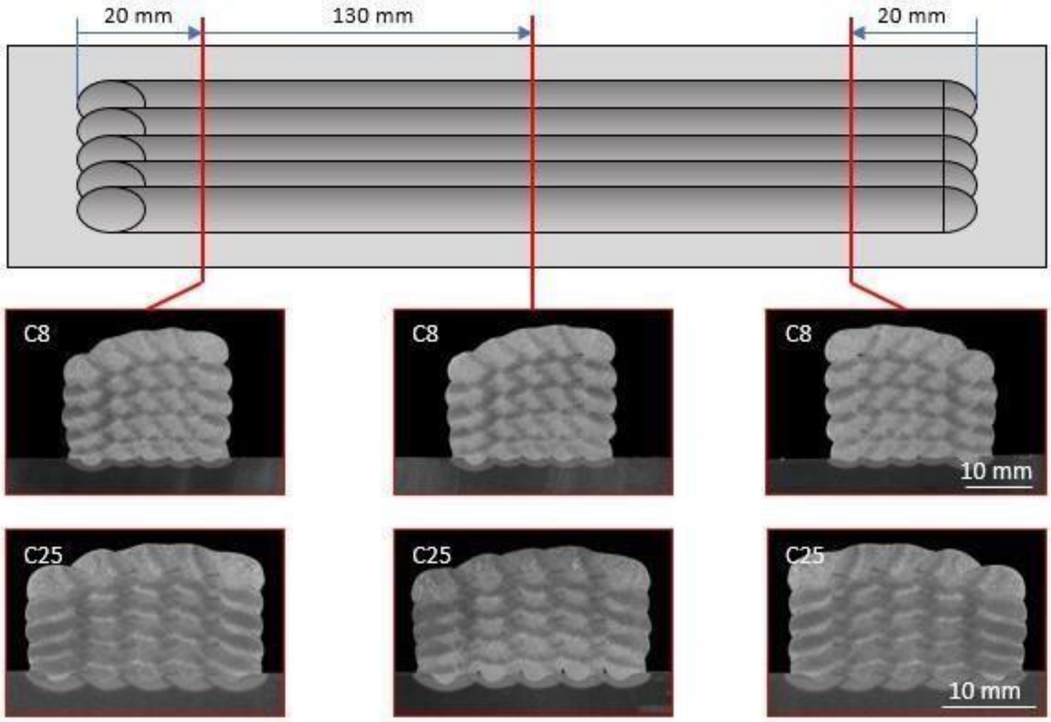

Figure 11 – Macrographs of the pads cross section.

From the method described in methodology it was realized the pads measurement and elaborate Table 2. Observing the measure noted that the C8 pads present higher deviation in relation to the C25 pad. In addition, a decrease in the height of the last weld bead of the C8 pad can be observed. This is due to the anchoring mode of the fusion puddle of this bead, which tends to be wetter. However, the biggest problem is the lack of fusion along the vertical section present in the C8 pad.

Table 2 - Geometric characteristics of the pads cross section

	C8					C25				
	Sample 1					Sample 1				
	Point 1	Point 2	Point 3	Average	Std. Deviation	Point 1	Point 2	Point 3	Average	Std. Deviation
Width	29.24	29.84	29.64	29.57	0.31	23.54	24.33	24.05	23.97	0.40
Height	13.41	16.19	15.22	14.94	1.41	15.50	18.82	18.58	17.63	1.85
	Sample 2					Sample 2				
	Point 1	Point 2	Point 3	Average	Std. Deviation	Point 1	Point 2	Point 3	Average	Std. Deviation
Width	28.64	29.67	29.38	29.23	0.53	23.42	24.87	24.49	24.26	0.75
Height	13.10	15.53	14.65	14.43	1.23	15.59	19.11	18.87	17.86	1.97
	Sample 3					Sample 3				
	Point 1	Point 2	Point 3	Average	Std. Deviation	Point 1	Point 2	Point 3	Average	Std. Deviation
Width	29.25	29.97	30.01	29.74	0.43	23.50	24.05	24.61	24.05	0.56
Height	15.15	16.20	13.41	14.92	1.41	19.93	19.16	15.66	18.25	2.28

4. CONCLUSION

Based on the results presented, it is possible to draw technological conclusions on the side of performance and comparison among C8 and C25 gas mixtures:

- There is no significant difference in the electrical parameters when using C8 or C25 as a gas mixture. There was only a slight gain in stability when testing with C25;
- It was possible to change the geometrical profile of the weld beads by increasing the carbon dioxide content in the gas mixture without changing the current waveform, as well as the feeding profile;
- There was no significant change in the thermal profile, which would be expected due to the increased carbon dioxide content in the shielding gas.
- Relating the thermal profile to the power, it can be seen that these characteristics are proportional, which corroborates Scotti and Ponomarev (Scotti and Ponomarev, 2008);
- The presence of excess silicon was verified in the C25 pad. However, this oxide did not influence negatively or in the generation of internal defects in the piece.
- Comparing the macrographs of both pads it is possible to see a higher number of defects on the C8 pad. These defects do not discredit the use of this gas mixture, but show the need for a more accurate overlapping parameterization. But considering a near net shape condition it is necessary an accurate approach to minimize these defects.

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