The significance of supplementary shielding in WAAM of aluminium thin walls

Vinicius Lemes Jorge a, Felipe Ribeiro Teixeira a, Americo Scotti a,b,*, Fernando Matos Scotti c, Erwan Siewert c

a Federal University of Uberlandia, Center for Research and Development of Welding Processes, Uberlandia, MG 38400-901, Brazil
b University West, Department of Engineering Science, SE-461 86 Trollhattan, Sweden
c Linde GmbH, Linde Technologies, Department of Arc Technologies, Unterschleissheim, Germany

ARTICLE INFO
Keywords:
WAAM
Aluminium alloy
Thin wall
Supplementary shielding gas
Soot
Metal transfer
Dimension control

ABSTRACT
WAAM (wire arc additive manufacturing) of aluminium requires special operational care to avoid problems such as instabilities, contamination or porosities. This work aims at verifying whether supplementary shielding gas can affect the WAAM performance when building Al alloy thin walls, in terms of metal transfer, porosity, superficial finishing, and geometrical and metallurgical features. Thin walls were manufactured with and without supplementary shielding (ultra-pure Ar). A dedicated nozzle was designed in-house to provide additional protection against the reaction with surrounding atmospheric gases. Pure Ar and two Ar-based commercial shielding gases with different additives were employed to make the conclusions more sustainable. It was possible to conclude that supplementary shielding leads to better metal transfer regularity, cleaner lateral and surface, a shinier top layer appearance, and a slight trend to higher microhardness. On the other hand, it does not affect porosity after layer depositions, wall geometry (the total and effective layer width, layer height, and surface waviness of the walls), and microstructures. Finally, regarding the performance of shielding gases, there is no evidence of any effect from the supplementary shielding, since this approach improved the process operationality with the three different shielding gases but did not change their individual tendencies.

1. Introduction

Among the deposition processes used in WAAM (wire arc additive manufacturing), GMA (Gas Metal Arc) is widely used. The main reason is its high deposition rate, arc-feeder rotational symmetry, and ease of use. Due to its wide application in the aerospace and automotive industries, studies focused on building light structure thin walls have been carried out using WAAM. Aboulkair et al. [1], among others, state that aluminium alloys offer a satisfactory balance between strength and density for applications where performance and light-weighting are simultaneously required. However, the propensity to porosity related to arc welding is a setback for the deposition of these materials; the impact of porosity on the aluminium alloy mechanical properties is known. For instance, when evaluating the effect of porosity in welded joints with 5xxx series alloys (AlMg), Ashton et al. [2] verified that the weld tensile strength and ductility were reduced by the increase in porosity, while yield strength was only slightly affected. In terms of WAAM, when comparing three different variants of the CMT (Cold Metal Transfer) technique, Gierth et al. [3] found that the tensile strength and elongation to fracture of walls made with an AlMg5Mn wire were significantly lower when higher porosity levels were observed.

As widely reported in the literature, porosity in aluminium and its alloys is related to the high solubility of hydrogen. The formation of porosity in aluminium alloys depends on absorption and escape of hydrogen by or from the molten pool. According to Gu et al. [4], air moisture, grease, and other hydrocarbons on the workpiece or wire surfaces are the main sources of hydrogen. Concerning moisture, Kou [5] points out that oxide films can absorb hydrogen on the surface of the workpiece or wire-electrode. Derekar [6] reinforces that contamination and moisture in the shielding gas can also increase the hydrogen content in the molten pool. The more abundant the source, the higher the chances of absorption. Concerning the escape aspect, considering that the solubility of hydrogen (in the atomic form) in aluminium is higher in the liquid phase than in the solid phase (approximately 7 mL/kg in liquid and 0.4 mL/kg in solid just below the melting temperature [7], reducing progressively towards the room temperature), atomic

* Corresponding author at: University West, Department of Engineering Science, SE-461 86 Trollhattan, Sweden.
E-mail address: americoscotti@hv.se (A. Scotti).

https://doi.org/10.1016/j.jmapro.2023.09.063
Received 29 July 2023; Received in revised form 22 September 2023; Accepted 27 September 2023
Available online 16 October 2023
1526-6125/© 2023 The Authors. Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
hydrogen is rejected by the advancing solid-liquid interface. Non-solubilised hydrogen atoms gather together in a molecular state ($H_2$), as “bubbles”. The hydrogen molecules can move inside the remaining liquid during the solidification and eventually leave the metal through its surfaces, due to the higher pressure of the gathered $H_2$. The release of $H_2$ depends basically on its amount and concentration distribution and on the surface tension and viscosity of the liquid. However, suppose the solidification rate is faster than the “bubbles” movement. In that case, hydrogen escape is prevented and can be entrapped inside the WAAM layers under deposition, resulting in porosities. Therefore, as Mathers [8] points out, a hotter molten pool (slower cooling rate) allows hydrogen to diffuse, which may reduce the amount of porosity. Kou [5] still mentions that the magnetic stirring of the molten pool can also help the “bubbles” escape and minimise this problem.

From sources and absorption point of view, Mathers [8] and Anderson [9] listed that welding area, wires and shielding gases free of any contamination (moisture and hydrocarbons) are the valid recommendations to prevent porosity formation. Besides that, operating conditions that ensure adequate protection are essential (gas turbulence and/or external air currents can also introduce contamination). Still, according to the literature focused on welding, another possibility concerns the shielding gas composition itself, not only contaminations (the subject of this work). Collins [10] found lower porosity when pure helium or a 65%He + 35%Ar blend was used as shielding gas, compared to pure argon. The Ar-He blend also provided wider operational ranges of current and voltage (larger working envelope). As Olabode et al. [11] mentioned, adding He provides a hotter arc, allowing a longer time for hydrogen to diffuse and escape. In due course, hotter arcs are related to a greater heat exchange capacity of helium and its higher enthalpy to ionise. For the same reason, the amount of porosity can be reduced with high heat input [12].

Although the above-described aspects of porosity and the shielding gas effect seem to be a maxim when evaluating works and books focused on welding, the same trends and causes are not always evidenced when evaluating the WAAM literature (in particular, considering thin walls manufactured with aluminum alloys). Considering thin walls deposited by WAAM, Gierth et al. [3] observed an opposite behaviour concerning that mentioned by Collins [10] and Olabode et al. [11], that is, porosity decreased with lower heat input, either by increasing deposition speed or by using CMT variants with lower heat input. This tendency was also verified by Dererak et al. [6] using the CMT process, but the opposite occurred when the current was pulsed with the conventional GMA process. Evaluating single-layer deposits, Cong et al. [13] also identified fewer porosities with higher heat input using conventional CMT, but the trend was reversed with other process variants of lower heat input. On the other hand, using the CMT Advanced process, Scotti et al. [14] did not identify changes in porosity levels considering different positive and negative polarity ratios (EP/EN). However, changing this parameter led to different energy levels per unit length (125 to 175 J/mm).

In terms of this variation of behaviours identified in the literature, Scotti et al. [14] offer an important reflection: if, on the one hand, the lower arc energy increases the solidification rate and favours the entrapment of dissolved hydrogen within the molten pool, on the other hand, it also results in a smaller and cooler molten pool, which can reduce the susceptibility to hydrogen absorption. Furthermore, although there are similarities between additive manufacturing and welding operationally speaking, one must say that the cooling rates experienced in these two processes are totally different. Considering thin walls, for example, heat transfer occurs predominantly by conduction along the height of the wall towards the substrate, while the conduction in welding sets in along all directions into the plate. As a result, welding tends to have faster cooling rates for the same arc energy. WAAM of thin walls tends to heat accumulation underneath the layer under deposition. Therefore, for the same combination of deposition parameters, the molten pool with WAAM of thin parts can be larger and present a more elongated profile, being able to stay outside the region covered by the...
shielding gas using conventional torch gas nozzles. Consequently, the pool can pick up hydrogen from the atmosphere where the pool is not entirely shielded. In relation to the shielding deficiencies of standard torch nozzles, Da Silva et al. [15], building a working envelope for thin parts with an AlMg alloy, observed that the surface of the walls was always rough and matte finish due to excessive oxidation. To face that, the authors developed a supplementary shielding gas system (also referred to in welding as trailing or secondary gas) to cope with excessive oxidation. The walls deposited with this device turned smoother and brighter (free of excessive oxidation).

Soot (sometimes called smut) was also observed on the top surface of the last deposited layer in Da Silva et al.’s work [15]. Anderson [9] mentions that soot is a black deposit on the aluminium surface which appears during welding and is more prevalent when gas metal arc welding with the 5xxx series filler alloys. Anderson [9] also describes soot as a deposit of finely divided metal oxides and is not harmful, although unattractive. Torsten and MacKenzie [16], in turn, state that this material is composed primarily of magnesium oxide (MgO). It can be easily wiped off if done immediately, but brushing may be required if left on for a few hours. Obviously, surface cleaning is applicable in welding operations. But, for productivity reasons, surface cleaning is not desirable in WAAM, where multiple layers are deposited without any prior cleaning between them. Furthermore, in contrast to what is mentioned by Anderson [9], Mathers [8] states that soot left in place between passes can affect arc stability and is unsightly in welding operations. So, it is critical to evaluate whether the performance of thin walls deposited by WAAM can be affected by the presence of soot.

Given the above, two questions were raised. The most general one is how significant supplementary shielding is for the WAAM performance when building Al alloy thin walls. More specifically, would the supplementary shielding affect the performance of the conventional shielding gas? Therefore, this work aims at confirming whether supplementary shielding gas can affect the WAAM performance when building Al alloy thin walls, in terms of the electrical parameter-related metrics, metal transfer regularity, porosity formation, wall surface appearance, and geometrical and metallurgical features. A specific objective of this work is to verify the influence of the supplementary shielding gas on the shielding gas performance.

2. Methodology and experimental procedure

To compare GMA wire arc additively manufactured thin walls with and without using supplementary shielding gas (SSG), a dedicated nozzle was designed in-house to provide additional protection to the shielding from the conventional torch nozzle (see Fig. 1), at the front and rear of the arc. This dedicated 92-mm-long and 57-mm-high nozzle is gas-fed independently from the torch nozzle, and each additional nozzle played the role of reference to the result analysis. The 50 % He in Blend 1 intended to contrast the performance of pure Ar with a commercial gas used for Al welding that would deliver higher heat to the walls during the depositions. The addition of helium to argon is usually applied to improve molten pool wettability and avoid problems such as lack of fusion, since the provided higher heat transfer compensates for the fast cooling rates of aluminium alloy (a concept usually applied in welding of thick section components). The slower cooling rate is still commonly associated with reduced porosity, allowing hydrogen to escape before solidification. Finally, the designers of Blend 2 (Ar + 200 ppm O2 + 200 ppm N2O) claim that with this composition, a surprising combination of good bead weld appearance, improved wetting, enhanced weld penetration, and reduced arc etch zone are met (Miller et al. [18]). So, using the called doped gases, where small amounts of active components are added to the gas, is based on the concept that the active components provide better arc stability by avoiding the effect of arc wandering when searching for oxides in the plate. Based on the previous welding knowledge, the current paper investigates whether such advantages are transferrable to WAAM.

However, only one commercial wire composition (AWS ER5356 wire, a Mg-based Al alloy) was used for the comparisons. The choice of this feeder alloy was based on its oxidation potential, increasing the test sensitivity to compare the shielding gas effect on the wall features. The Cold Metal Transfer (CMT) variant of the GMAW process was the deposition process (synergetic line code 1678·AlMg5, φ = 1.2 mm, 100% Ar). The contact tube-to-work distance (CTWD) was maintained at 12 mm during all depositions.

The layers to be deposited with each shielding gas under study were planned to keep the same average current and volume (deposition rate per unit of length). As the arc pressure directly correlates with the current (since it is due mainly to the electromagnetic field of the arc), it is important to keep the same In to maintain pressure as close as possible between the different gases. The arc pressure can modify the shape of the melt pool and, consequently, the geometry of the wall. Moreover, keeping the same volume to reach the closest geometry between the samples was a target. Because the comparable wall widths for all cases mean similar heat conduction through the walls; uneven cooling rates would imply different aspects on the surface, hindering the evaluation of the significance of SSG. For that, potential variations in the melting rate (MR), as a function of the shielding gas, were compensated by changing the set deposition speed (DS), being DS in WAAM the equivalent to travel speed in welding. Clarifying this statement, to keep the same welding average current when the shielding gas imposes a change in the melting rate, wire feed speed (WFS) must be adjusted (for instance, to increase the WFS if the MR turns higher). Deposition rate (DR), in turn, when using controlled metal transfer modes (see reference 17 for metal transfers in GMAW), as done by CMT, can be assumed to be equal to WFS. That said, the average current and the WFS and DS ratio (WFS/DS) were not considered a variable (kept as identical as possible) for each shielding gas under study, but not necessarily the same WFS or DS. The same interlayer temperature was used in the experiments (≤50 °C, considering the whole extension of the walls).

Two walls with 30 layers and 200 mm of length were deposited with each shielding gas. The supplementary shielding gas (SSG) was enabled only in the replicated wall, for comparison purposes. Aluminium plates (240 mm × 50 mm × 6.4 mm) were used as substrate. The substrates were positioned in a fixture with their narrow side facing up, as also illustrated in Fig. 1, mimicking a pre-wall (keeping the heat flux as constant as possible since the first layers). An A/D (analogic to digital conversion) board, operating for 8 s at an acquisition rate of 5 kHz and 14 bits (signal resolution), was employed to monitor the electrical signals (current and voltage) and wire feed speed. The mean and root mean square (RMS) of current and voltage and the average values of wire feed...
speed and instantaneous power were determined for each layer. Considering to be bi-directional depositions, each layer started from the wall edges (right and left), when a target interlayer temperature (IT) of 50 °C was reached (natural cooling). IT was monitored over the deposited layer top surface at 30 mm ahead of the arc centreline (wire position) by an infrared pyrometer (Mikron MI-PE140), measurement range between 30 and 1000 °C, resolution of 0.1 °C and acquisition rate of 10 Hz. The same procedure performed in this current work is detailed in Teixeira et al. [19]. The comparison criteria to assess the impact of the supplementary shielding was applied over operational, geometrical, and metallurgical features, as will be shown later.

Before starting the analysis of the 3 pairs of walls towards the influence of the supplementary shielding gas, the porosity soundness of each wall was certified by radiography and Archimedes’ principle method. For that, each thin wall was cut off into three sections (as illustrated in Fig. 2). Initially, sections A and B went through digital radiography (X-Ray ERESCO, model 65 MF4: picture plate size = 10” × 12”; Voltage = 100 kV; Current = 1.6 mA; Exposition Time = 30 s; Expected resolution based on the settings, material and IQI of 0.08 mm). To make the conclusions more consistent, the Archimedes method was performed over volumetric samples A and B to estimate the volume of voids. This latter approach is based on the differential weighing of the samples, first in the air, and then in water, to calculate the specific density of the samples. The masses of sections A and B were measured on an analytical balance with a maximum load of 6.2 kg and a resolution of 0.01 g. From each sample, three mass measurements were taken in dry conditions (in the air) and three with the sample immersed in a beaker of distilled water. By knowing the theoretical density of the same material with no voids (assuming the drawn wire to be free of voids), any reduction in density is attributed to the void presence (mainly internal pores, but including cracks, lack of fusion, etc.). To estimate the density of the material with no pores (used as reference density), a 400-mm-long and coiled wire sample (AWS ER5253), which has basically the wall composition, was subjected to the same procedure. It is not in the scope of this work to study the Archimedes’ principle method. The interested ones are suggested to go to the literature for more details, being a starting point for it the publications either from Saperstein et al. [20], dealing with porosity in aluminium welding, or from De Terris et al. [21], dealing with porosity rate measurement methods inside selective laser melted (SLM) parts. It is important to state that both methods for porosity assessments are subject to uncertainties.

2.1. Evaluation of the operational features

The metal transfer regularity is an operational feature of a WAAM deposition process, because it is highly related to arc stability and spattering. And it is well-known that metal transfer is governed by the shielding gas. What is not well evaluated yet is whether the supplementary gas affects metal transfer resulting from different shielding gases. Regarding the metal transfer regularity, analyses were made qualitatively (through oscillograms and cyclograms of voltage and current) and quantitatively (by using a metal transfer regularity index – IVsc). The chosen IVsc index, also employed in Jorge et al. [22], is strongly related to a constancy of arcing and short-circuiting times. IVsc is calculated by Eq. (1), where: σarc = the standard deviation of the average short-circuiting times; σsc = the standard deviation of the average arcing times; tarc = the average of the short-circuiting times; tsc = the average of the arcing times. That is, the lower IVsc, the more regular the metal transfer. It is important to state that a longer tsc also represents more time during arcing times (more energy transferred to the metal at the anodic region), while a longer tarc indicates lengthier heating by the Joule effect transferred to the metal. Subsequently, the duration ratio (tarc/tsc) can roughly predict the heating efficiency of the arc into the base metal. Therefore, the increase in this ratio for the same arc energy suggests higher heat input.

\[
IV_{sc} = \frac{\sigma_{sc}}{t_{sc}} + \frac{\sigma_{arc}}{t_{arc}} \tag{1}
\]

Another operational feature of the deposition process is its capacity to protect the molten metal from the oxidising atmosphere. One can consider that the supplementary shielding is directly linked to this operational feature. However, how much additional shielding will affect the performance of the shielding gas in Al thin wall wire arc additively manufactured is not spread. Therefore, the quantity of entrapped black soot over the lateral surface of the walls and the black spots over the surface layers were used as an assessment parameter. The black soot on the plate surface surrounding Al-Mg beads is expected in welding. Usually, the Mg-based (MgO, according to Totten and MacKenzie [16]) fumes are easily removed by using solvent and/or metal wire brushing (yet one-direction brushing is recommended to avoid entrapping oxides even more). Nonetheless, removing black soot between each layer in
WAAM is laborious and would increase the total production time. The entrapped black spot formation (also Mg-based) on the top layer surface and trapped in the valleys of the wall surface waviness could be related to insufficient gas protection. This phenomenon is less observed in welding, likely due to the smaller number of multi-passes in aluminium GMA welding (material thickness to be welded) when contrasted to the number of layers in WAAM of thin walls.

2.2. Determination of the geometrical features

One can expect that the shielding gases will also affect the geometrical features of the Al thin wall manufactured using WAAM. Four metrics were arbitrarily chosen to define the geometric features of the wall, named layer height (LH), external wall width (WW\text{ext}), effective wall width (WW\text{eff}) and surface waviness (SW). However, how much supplementary shielding impacts the shielding gas performance is unknown. Accordingly, all built walls were scanned using a 3D scanner (HandySCAN 3D). Only the central region (180 mm × 50 mm) of the walls was sampled, accounting to avoid the influence of non-conformities arising from the starting and ending deposition positions. Fig. 3(a) illustrates this sampling. The same methodology presented in Teixeira et al. [19] was used to quantify the geometrical features of the samples (the 4 metrics), using a computer code developed in-house in Python. The two lateral sides of each wall were separated, using a dedicated commercial computer program (VXModel scanner software), associated with the 3D scanner. Then, the generated point clouds (a set of data points in a 3D coordinate system) of each side were exported to text files (.txt). To turn the information into 2D, it is necessary to set a segment in the axis Y of the sample (Fig. 3(a)). After systematically searching, a value of 0.5 mm was chosen as the smallest segment capable of generating profiles without “holes” for the sample under measurement. This segment length will lead to the number of cross-sections to be analysed. Considering the defined 180-mm long central region sample in the Y direction, 360 cross-sections (180/0.5) were generated and evaluated at each wall side. Fig. 3(b) presents the corresponding typical graph of one wall side, considering twenty profiles obtained by the code for each side of the wall. As can be seen, the graph axes contain the reference axis, perpendicular to the side of the wall (X) and representing the wall width, an axis along the length of the wall (Y), and an axis that coincides with the building direction (Z).

Quantities taken from geometric parameters from Fig. 3 are calculated using the following Eqs. (2) to (12), where $\text{max}_{\text{ave}}$ (Eq. (3)) and $\text{min}_{\text{ave}}$ (Eq. (4)) are the averages of them for each side profile, $\Delta x$ (Eq. (5)) is the difference between $x_{\text{max}}$ and $x_{\text{min}}$ per $\lambda_c$, $\Delta x_{\text{ave}}$ (Eq. (6)) is the average of $\Delta x$ per side profile, $\text{WW}_{\text{ext/p}}$, $\text{WW}_{\text{eff/p}}$ and $\text{SW}_{p}$ (Eqs. (7), (8) and (9), respectively) are the partial (referent to just one of the 360 cross-sections) of External/Effective Wall widths and Surface WAViness index, taken from both side profiles of each of the 360 cross-sections. In
Δ (whole profile of each wall sample side. The

\[ \text{WW}_{\text{target}} = \sum_{k} (x_{\text{min}}(\text{left side}) + x_{\text{max}}(\text{right side})) / n \text{ per side profile} \] (3)

Δx = x_{\text{max}} - x_{\text{min}} per \lambda

\[ \Delta x_{\text{ave}} = \sum_{i} x_{\text{ave}} \] (4)

The external wall width per cross-section (WW_{ext}) is compiled. Following, the code provides the average of \( x_{\text{ave}} \). The creation of the central slice of each wall (Fig. 2), two Vickers microhardness 8-mm-long profiles were raised in the mid-height of the cross-sections of each thin wall (L1 and L2, showed in Fig. 4(a)). The dimension of 8 mm was selected to make it possible to analyse two completed layers and interlayer regions (given a maximum layer height obtained of 2.6 mm). It is important to note that in parts manufactured by WAAM, as long as an interlayer temperature is adopted and maintained throughout the deposition for the same parameter conditions, the same microstructural and hardness behaviour is expected throughout the entire central region of the wall. The regions corresponding to the first and last layers deposited were not evaluated as they are generally regions subjected to post-processing and consequently removed, a subject that is also not the aim of the study of the present work. The indentor employed a load of 50
gf (490.3 mN), for 15 s, with a distance between indentations of 0.25 mm. After the microhardness test, the samples were etched in a solution of 20%HF + 80% H₂O₂ for an immersion time of 35 s. Then, four macrographic images were obtained at the wall mid-height, using a polarised light microscope. As depicted in Fig. 4(b), the microstructures were purposely taken from positions at the centres of layers (CL1 and CL2) and interlayer regions (IL1 and IL2).

3. Results and discussions

3.1. Layer characterisation

### a) Setting and monitored parameters

Table 1 presents the averaged electrical parameters obtained for each thin wall (with and without using supplementary shielding) from the last 25 layers. There were no statistically significant changes in the electrical parameters when using or not supplementary shielding, except for a slight increase in current with Blend 2 (Ar + 200 ppm O₂+ 200 ppm N₂O), yet within the uncertainty range, considering the higher standard deviations when applied with no supplementary shielding. The mean resultant WFS/DS is the same or very close to each other when comparing monitored or calculated data from the walls, which satisfies the condition imposed in the methodology to ensure the comparison between different shielding gases with and without the supplementary shielding.

#### Table 1

Average of mean wire feed speed (WFS\textsubscript{m}), mean current (I\textsubscript{m}), RMS current (I\textsubscript{rms}), mean voltage (U\textsubscript{m}), RMS voltage (U\textsubscript{rms}), mean instantaneous power (P\textsubscript{inst}) and the resultant wire feed speed and deposition speed ratio (WFS/DS), corresponding to the last 25 layers of each thin wall.

<table>
<thead>
<tr>
<th>Gas</th>
<th>WFS\textsubscript{m} (m/min)</th>
<th>DS\textsubscript{m} (cm/min)</th>
<th>WFS/DS</th>
<th>I\textsubscript{m} (A)</th>
<th>I\textsubscript{rms} (A)</th>
<th>U\textsubscript{m} (V)</th>
<th>U\textsubscript{rms} (V)</th>
<th>WFS\textsubscript{m} (m/min)</th>
<th>P\textsubscript{inst} (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 5.0\textsuperscript{a}</td>
<td>4.5</td>
<td>35.0</td>
<td>13.4 ± 0.1</td>
<td>88.6 ± 0.1</td>
<td>90.8 ± 0.1</td>
<td>10.2 ± 0.0</td>
<td>12.8 ± 0.1</td>
<td>4.5 ± 0.1</td>
<td>47 ± 0.0</td>
</tr>
<tr>
<td>Ar 5.0</td>
<td>4.5</td>
<td>35.0</td>
<td>13.4 ± 0.3</td>
<td>88.7 ± 0.9</td>
<td>90.7 ± 1.0</td>
<td>10.2 ± 0.1</td>
<td>12.7 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>982.6 ± 22.0</td>
</tr>
<tr>
<td>Blend 1\textsuperscript{b}</td>
<td>4.4</td>
<td>38.7</td>
<td>13.6 ± 0.1</td>
<td>88.5 ± 0.3</td>
<td>90.5 ± 0.3</td>
<td>11.5 ± 0.1</td>
<td>14.2 ± 0.1</td>
<td>5.3 ± 0.1</td>
<td>1098.4 ± 8.4</td>
</tr>
<tr>
<td>Blend 1</td>
<td>4.4</td>
<td>38.7</td>
<td>13.2 ± 0.3</td>
<td>88.8 ± 0.1</td>
<td>90.9 ± 0.1</td>
<td>11.8 ± 0.3</td>
<td>14.7 ± 0.3</td>
<td>5.3 ± 0.1</td>
<td>1135.9 ± 24.8</td>
</tr>
<tr>
<td>Blend 2\textsuperscript{b}</td>
<td>4.4</td>
<td>34.6</td>
<td>13.1 ± 0.5</td>
<td>86.9 ± 1.4</td>
<td>88.9 ± 1.5</td>
<td>9.9 ± 0.2</td>
<td>12.5 ± 0.2</td>
<td>4.5 ± 0.2</td>
<td>929.8 ± 36.4</td>
</tr>
<tr>
<td>Blend 2</td>
<td>4.4</td>
<td>34.6</td>
<td>13.6 ± 0.3</td>
<td>88.4 ± 0.5</td>
<td>90.4 ± 0.5</td>
<td>10.2 ± 0.1</td>
<td>12.8 ± 0.2</td>
<td>4.7 ± 0.1</td>
<td>980.4 ± 20.5</td>
</tr>
</tbody>
</table>

\textsuperscript{a} No supplementary shielding.

#### b) Porosity soundness of the walls

Fig. 5 presents the cross-sections of the thin walls, built without and with the supplementary shielding. In general, no discontinuities (lack of fusion, cracks, porosity clusters) were observed in these images (remember, they represent only one cross-section per wall), except for the evidence of a single pore (white spot in Fig. 5(f)) in the wall built with Blend 2 as shielding gas and with supplementary shielding gas.

Figs. 6 and 7 show radiograph images from sections A and B of each thin wall (Fig. 2), without and with the supplementary shielding gas, respectively. It can be seen that the presence of the wall waviness impairs the visualisation of pores, making it challenging to identify the porosity. In addition, considering the low density of aluminium and the surface appearance of the walls (repeatable pattern between layers, i.e., one layer protruding and the other depressed from a wall side view alternatively), to determine whether there are lines due to lack of fusion or just a significant thickness difference is difficult. Regardless of these limitations, all samples showed pores, although few in quantity and very small in size. The maximum pore size for all samples was estimated to be 0.6 mm (micropores), using the dimension of an identification letter of the images as a scale. According to ASME IX [23], the maximum permissible dimension for rounded indications shall be the lesser of 20% of the thickness (from 6 to 13 mm) or 3 mm, whichever is smaller. Another criterion is based on the typical quantity (clustered, assorted, and randomly dispersed configurations) in 150 mm length. Thus, based on this standard acceptance criteria, the walls built with the three blends are in conformity. On the other hand, the use of supplementary shielding gas did not decrease the number of microporosities.

Table 2 presents the density measurements according to the Archimedes method, from both the AWS ER5356 wire (used as reference), and the samples of the thin walls without and with the supplementary shielding gas. Table 2 also presents the calculated relative amount of voids using the Archimedes method. It is essential to remember that in the Archimedes method, the result should not be referred to as pores (full of gas), because it is quantified as any internal volume not filled with the base material. Therefore, the percentual volume can be pores, voids, cracks, etc. To such an extent, the negative porosity values in relation to the reference suggest the method uncertainties and the low resolution of the method to detect such low differences in specific density (between the reference and the WAA Manufactured samples, mainly when light alloys are used).

It is important to emphasise that, although the radiographic method suggested the presence of some micropores, the gravimetry-based method (Archimedes) did not show evidence of density drop (presence of pores, for instance). Radiography is able to detect pores only larger than a given size (in the current case, >0.08 mm). In addition to the image resolution setback, one pore can be hidden by another if they are located on the same through-thickness line, or one pore overestimates the total amount of pores, by presenting them as on a surface instead of on the whole thickness (that can be different when compared). Therefore, to support the final analysis, a simplified calculation to estimate the potential content of micropores (in % of the sections A and B areas) was proposed and performed. That is: let us conservatively and arbitrarily suppose that 100 micropores with a diameter of 0.3 mm would be...
visualised in these combined radiograph areas (summation of the surface areas of sections A and B). It means that 100 micropores would correspond only to 0.05 % of the area $A + B$. If this number of pores were less conservative (given 15 pores, for instance), the corresponding area would downsize to 0.01 %. Or, as a third possibility, even being more conservative and increasing to 1000 micropores, the corresponding area would enlarge the size to 0.52 %.

As wanted to be demonstrated, a minimal number of pores/voids (for sure <0.5 % in the worst case of assuming to exist 1000 micropores in the assessed $A + B$ area) was generated in thin wall, deposited with the AWS ER5356 wire, with and without using supplementary shielding. A rate that is not sensitive to the Archimedes method with aluminium (low density). This uncertain amount (from a metrology point of view) is acceptable in welding. Even normal in WAAM (Gierth et al. [3] found the area percentage of porosity varying from 0.07 to 0.45 %). This porosity level would exist in most conventional manufacturing techniques that work with aluminium (and are coherent with the values close to zero in the gravimetry test).

Regardless of the method (radiographic or Archimedes’ principle), this current study was not able to present evidence that the additives in the shielding gas affected porosity in the WAAM deposit. And, this is not due to the supplementary shielding, since the same results were detected either with or without using SSG, with the three shielding gases. It is important to remember that, concerning protection, shielding gases act on the molten pool surface, which is hot and prone to reactions between air or other containing $H_2$ source and metal. However, droplets have a greater surface area per volume ratio than that of the pool. Thus, the droplet surfaces are likely at a higher temperature (pools exchange heat with the base metal). Consequently, $H_2$ dissolution occurs more effectively in droplets, but molten metal reactions cannot be neglected. Anyway, entrapped $H_2$ in the droplets would be carried out to the pool, since the droplet travels under positive pressure. Therefore, the difference in parameters and consumables might be the reason for discrepancies between these findings and the trends presented in the introduction section. Gierth et al. [3] observed a significant variation in porosity in WAAM of thin walls when comparing different variants of CMT GMAW, even at the same deposition speed (DS). They credited these differences to variations in arc energies. They observed that for most cases, but not all, there is a decrease in porosity as the DS increases (for a given WFS). Some authors [11,12] claim that He based arc
welding shielding leads to a longer time for hydrogen to diffuse and escape from the pool, consequently reducing porosities. This trend is supported by Collis’s paper [10].

3.2. Operational features

a) Metal transfer regularity

Metal transfer regularity might be qualitatively evaluated through the current and voltage oscillograms. From a sample of 100 ms during
the 15th layer deposition, Fig. 8 shows high regularity of the arcing ($t_{arc}$) and short-circuiting ($t_{sc}$) times, among different typical cycles. When supplementary shielding is not used (left side of Fig. 8), few current and voltage pattern deformations can be seen.

Cyclograms (Fig. 9) also supported this analysis. The cyclogram method was also used by Jorge et al. [22], among others, to evaluate metal transfer behaviour. It is noteworthy to say that a controlled metal transfer process, such as the Fronius trade name CMT, influences the cyclogram pattern, but the natural effect from the wire and shielding gas on the arc also plays an important role in the phenomenon. As seen, the supplementary shielding provided a greater superimposition of the voltage x current traces, suggesting higher metal transfer regularity.

However, the use of either oscillograms or cyclograms to determine the short-circuiting metal transfer regularity is questionable. The authors of this paper prefer to trust more quantitative parameters. Table 3

<table>
<thead>
<tr>
<th>Gas</th>
<th>SSG</th>
<th>$p_1$ (g/cm³)</th>
<th>$p_2$ (g/cm³)</th>
<th>$p_3$ (g/cm³)</th>
<th>$p_m$ (g/cm³)</th>
<th>Standard deviation</th>
<th>Voids (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference –</td>
<td>2.64</td>
<td>2.63</td>
<td>2.63</td>
<td>2.63</td>
<td>0.01</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Ar5.0</td>
<td>Disabled</td>
<td>2.64</td>
<td>2.64</td>
<td>2.67</td>
<td>2.65</td>
<td>0.01</td>
<td>−0.62</td>
</tr>
<tr>
<td>Blend 1</td>
<td>Disabled</td>
<td>2.64</td>
<td>2.64</td>
<td>2.64</td>
<td>2.64</td>
<td>0.00</td>
<td>−0.21</td>
</tr>
<tr>
<td>Blend 2</td>
<td>Disabled</td>
<td>2.64</td>
<td>2.64</td>
<td>2.65</td>
<td>2.64</td>
<td>0.00</td>
<td>−0.39</td>
</tr>
<tr>
<td>Ar5.0</td>
<td>Enabled</td>
<td>2.65</td>
<td>2.64</td>
<td>2.65</td>
<td>2.65</td>
<td>0.00</td>
<td>−0.51</td>
</tr>
<tr>
<td>Blend 1</td>
<td>Enabled</td>
<td>2.64</td>
<td>2.64</td>
<td>2.63</td>
<td>2.64</td>
<td>0.01</td>
<td>−0.13</td>
</tr>
<tr>
<td>Blend 2</td>
<td>Enabled</td>
<td>2.64</td>
<td>2.66</td>
<td>2.65</td>
<td>2.65</td>
<td>0.01</td>
<td>−0.65</td>
</tr>
</tbody>
</table>

Fig. 8. Current, voltage and power oscillograms from the 15th layer using, without (left side) and with (right side) supplementary shielding gas (SSG): a) Ar5.0 (pure argon); b) Blend 1 (Ar + 50 % He); c) Blend 2 (Ar + 200 ppm O₂+ 200 ppm N₂O).
presents the short-circuiting metal-transfer parameters, obtained for each thin wall. Similar short-circuiting frequencies ($F_{sc}$) and arcing and short-circuiting times ratios ($t_{arc}/t_{sc}$) can be accounted between the conditions with and without supplementary shielding, regardless of the shielding gas (those metrics are very synergic line related). Power is always higher during arcing than during short-circuiting times, in phase with current typically high in arcing times and low at short-circuiting times, typical behaviour of CMT. Last but not least, the short-circuiting times are relatively long (approximately 40%) compared to conventional short-circuit metal transfer (usually 15%–20%). These quantitative parameter trends may justify the low heat input, yet the good performance of the bead formation.

Fig. 9. Voltage versus current cyclograms from the 15th layer using, without (left side) and with (right side) supplementary shielding gas (SSG), respectively: (a) Ar5.0 (pure argon); (b) Blend 1 (Ar + 50 % He); (c) Blend 2 (Ar + 200 ppm O$_2$ + 200 ppm N$_2$O).
However, the most important quantitative parameter for the metal transfer regularity analysis is the metal transfer regularity index ($IV_{sc}$), described in Section 2.1. This index is believed to be more shielding gas-related than only synergic line connected. As seen in Table 3, the supplementary shielding gas provided, at the statistical level, regardless of the shielding gas composition, a greater metal transfer regularity (smaller $IV_{sc}$), in line with the qualitative analysis from Figs. 8 and 9.

The reason supplementary shielding gas impacts the metal transfer regularity is a thermophysical-related phenomenon involving several forces acting in the droplet formation and detachment. The hindrance for oxidation to grow over the weld pool outside the main torch nozzle would contribute to this complex phenomenon. Therefore, identifying the SSG mechanism that improves the metal transfer regularity is challenging. It is important to state that a potential reduction of black spots on the wall would be evidence of higher metal transfer regularity by using SSG. This subject will be analysed in the next section.

**b) Surface aspect and Black soot**

A representative aspect of the lateral surface after the deposition of thin walls is shown in Fig. 10. It is possible to visualise the surface covered by black soot, as expected for GMAW Al-Mg wires. As mentioned, soot in arc welding is attributed to MgO formation in the arc atmosphere (metal-gas reaction) [16]. However, even after cleaning the surface with a rotative wire brushing, entrapped black spots became present on both lateral and top surfaces of the walls, which can be seen in Figs. 11 and 12. Comparison of these figures shows a remarkable reduction in black spots and shinier top surfaces when supplementary shielding was used.

**3.3. Geometrical features**

Fig. 13 presents the total and effective widths, the layer height, and the surface waviness obtained for each thin wall, with and without supplementary shielding. Considering the effect of the shielding gas composition, Blend 1 (Ar + 50 % He) resulted in greater total and effective widths and, consequently, a lower layer height (since the actual deposition rate per unit of length was the same), suggesting more heat transferred to the pool. This finding was expected due to the high content of He in the blend. However, considering the same gas, there are no statistically significant changes in total width, effective width, layer height, and surface waviness values between the walls with and without supplementary shielding.

**Table 3**

<table>
<thead>
<tr>
<th>Gas</th>
<th>$F_{sc}$ (Hz)</th>
<th>$IV_{sc}$</th>
<th>$t_{arc}$ (ms)</th>
<th>$t_{sc}$ (ms)</th>
<th>$t_{arc}/t_{sc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 5.0</td>
<td>116.7 ± 4.5</td>
<td>0.19 ± 0.09</td>
<td>5.2 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>1.5 ± 0.0</td>
</tr>
<tr>
<td>Ar 5.0</td>
<td>109.9 ± 1.4</td>
<td>0.31 ± 0.02</td>
<td>5.5 ± 0.1</td>
<td>3.6 ± 0.0</td>
<td>1.5 ± 0.0</td>
</tr>
<tr>
<td>Blend 1</td>
<td>121.8 ± 1.2</td>
<td>0.11 ± 0.04</td>
<td>5.1 ± 0.1</td>
<td>3.1 ± 0.1</td>
<td>1.6 ± 0.1</td>
</tr>
<tr>
<td>Blend 1</td>
<td>120.1 ± 2.3</td>
<td>0.25 ± 0.03</td>
<td>5.2 ± 0.1</td>
<td>3.2 ± 0.1</td>
<td>1.6 ± 0.0</td>
</tr>
<tr>
<td>Blend 2</td>
<td>117.7 ± 3.5</td>
<td>0.18 ± 0.07</td>
<td>5.2 ± 0.2</td>
<td>3.3 ± 0.1</td>
<td>1.5 ± 0.0</td>
</tr>
<tr>
<td>Blend 2</td>
<td>103.5 ± 11.3</td>
<td>0.37 ± 0.14</td>
<td>5.8 ± 0.6</td>
<td>3.9 ± 0.5</td>
<td>1.5 ± 0.0</td>
</tr>
</tbody>
</table>

* With no supplementary shielding.
3.4. Metallurgical features

a) Microhardness Profile

Fig. 14 shows the two 8-mm-long microhardness profiles (approximately 3.5 layers) on the cross-sections of each thin wall. No visible trends between the profiles from the same wall. A compilation of the microhardness results is shown in Fig. 15. There is a slight trend towards higher hardness when supplementary shielding is applied, being the highest difference achieved with Blend 2 (Ar + 200 ppm O₂ + 200 ppm N₂O), which was approximately 3.6 HV higher. Statistically speaking (considering two-way ANOVA statistics), the difference, despite the low difference, is confirmed by a p-value equal to 0.0. Evaluating the effect of the shielding gas composition, Blend 1 (Ar + 50 % He) tends to have slightly harder walls (p-value = 1.7 × 10⁻⁷).

b) Microstructural assessment

Fig. 16 presents typical light microscopy microstructures from the centre of one of the layers at a mid-height wall. The micrographs in
Fig. 17, in turn, are from sampling the interlayer region (above and below the fusion line). Some fine white particles are observed in all micrographs, corresponding potentially to the $\beta$-phase ($\text{Al}_3\text{Mg}_2$). Zielinska-Lipiec et al. [24], Ren et al. [25], and Su et al. [26] discussed that alloys with this chemical composition are structured by an $\alpha$-phase matrix (solid solution of Mg in Al) and a second $\beta$-phase ($\text{Al}_3\text{Mg}_2$). In fact, particles of distinct phases might also be formed, but in a much smaller amount. Fined Mg oxides, entrapped between layers, could also be a possibility, considering the amount of smut produced during the WAAM depositions.

Although supplementary shielding led to slightly higher microhardness when considering the same shielding gas, no visible light microscopy microstructural changes were evidenced. For instance, there is a hypothesis that using supplementary shielding can lead to a faster cooling rate (from an extra gas flow out of the nozzle). It means that less $\beta$-phase precipitation might occur during multiple-cycle layer reheating, or a reduction in grain size may also occur. These hypotheses could explain the slightly increased microhardness in the supplementary shielding samples. Whether for one reason or another, if these changes occurred, they must have been minimal or balanced (solid solution x
second phase hardening mechanisms), as they culminated in a maximum variation of 3.6 HV on average. It is important to state that hardness variation demands a more in-depth microstructural characterisation.

4. Conclusions

The global objective of this work was to comprehensively evaluate the impact of supplementary shielding in thin walls built with an AWS ER5356 wire under three different shielding gases, in terms of operational (assessed by metal transfer regularity and surface contamination...
by black soot), geometrical (wall width, layer height, and waviness), and metallurgical features (microhardness and microstructure). From the results linked to the objective, it was possible to conclude that the use of supplementary shielding leads to:

- Better metal transfer regularity;
- Cleaner lateral surface and shinier top layer appearance;
- A slight trend of higher microhardness.

On the other hand, the supplementary shielding showed not to impact:

**Fig. 17.** Typical micrographs (obtained with 100× magnification) corresponding to the interlayer region (see positions IL in Fig. 4(b)) without (left side) and with the supplementary shielding (right side): (a) Ar5.0 (pure argon); (b) Blend 1 (Ar + 50 % He); (c) Blend 2 (Ar + 200 ppm O₂+ 200 ppm N₂O) (note: brightness and contrast correction used to highlight the grains and particles).
• Porosity after layer deposits;
• Wall geometry (the total and effective layer width, layer height and surface waviness of the walls);
• Microstructures.

The specific objective was to assess if supplementary shielding would affect the performance of different shielding gases. From all results, there is no evidence of any influence, since the supplementary shielding gas improved the operationality with the three different shielding gases, but it did not change their tendencies.

Funding

This work was supported by Linde GmbH Gas Division (project number FEMEC.PESQU.0035), the National Council for Scientific and Technological Development – CNPq (grant numbers 306053/2022-5), and the Coordination for the Improvement of Higher Education Personnel – CAPES (Finance Code 001).

CRediT authorship contribution statement

Vinicicus Lemes Jorge: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. Felipe Teixeira Ribeiro: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. Americo Scotti: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. Fernando Scotti: Conceptualisation, Methodology, Result discussions, Writing – review & editing. Erwan Siewert: Conceptualisation, Methodology, Result discussions, Writing – review & editing.

Declaration of competing interest

There are no conflicts of interest.

Acknowledgments

The authors would like to thank the Center for Research and Development of Welding Processes of the Federal University of Uberlandia (Laprosolda-UFU) for the laboratory infrastructure and technical support. We want to acknowledge Assoc. Prof. Leandro Joao da Silva, UFPR, who designed and developed the supplementary shielding gas support. We want to acknowledge Assoc. Prof. Leandro Joa˜na da Silva, Laprosolda-UFU for the laboratory infrastructure and technical Development of Welding Processes of the Federal University of Uberlandia.

References