Exploring the use of switchback for mitigating homoepitaxial unidirectional grain growth and porosity in WAAM of aluminium alloys

Yurii Yehorov¹ · Leandro João da Silva¹ · Américo Scotti^{1,2}

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Abstract

In this work, an alternative approach to prevent unidirectional grain growth in wire + arc additive manufacturing (WAAM) is proposed and assessed, by moving cyclically the torch forward and backward, likewise the welding technique known as switchback. A series of tests were planned with CMT (cold metal transfer) process to compare three wall-like build-ups, which uses different deposition patterns, namely, in one-way direction, reverse direction, and switchback. The same equivalent travel speed and number of deposited layers were kept among them. Longitudinal sections were taken to identify the grain growth behaviour. Finally, samples were removed from the walls for porosity evaluation. The results confirmed the characteristics of unidirectional grain growth, when one-way direction condition was employed, and the break of growth direction between layers, when reverse direction was used, yet a zig-zag pattern became present. Differently, the application of switchback showed no preferential or unidirectional grain growth, suggesting less anisotropy of mechanical properties. In addition, switchback reduced porosity.

Keywords WAAM · GMAW · Aluminium · Unidirectional grain growth · Anisotropy · Switchback

1 Introduction

Grain structure or texture of metals has had its importance recognized in engineering for a long time, because of its effect on the mechanical properties of a given alloy. For instance, in Davies and Garland's review [1], it was stated that fine-grained cast metals are far more resistant to cracking than are coarse-grained ones. Nowadays, it is widely claimed that large columnar grains can cause anisotropy of the mechanical properties. For instance, Joo et al. [2] studied microstructural anisotropy due to banding and elongated grains. They also critically assessed steels for pipeline and the orientation

dependence of their mechanical properties, especially toughness. Considerable anisotropy in the mechanical properties of quaternary Al–Li–Cu–Mg alloys was observed by Prasad and Malakondaiah [3]. These alloys showed remarkable increase in tensile ductility in an angle-oriented direction as compared to that in the rolling direction. A concomitant decrease regarding strength was also found.

Aluminium alloys are usually prone to columnar grain growth during solidification, since the primary phase transformation (liquid to solid transformation) determines the final morphology and microstructure in the solid state, considering the existence of no secondary transformations. And this phenomenon is not exclusive for casting. This is the reason for having grain structural formation as a study target also in weldable aluminium alloys. For example, Ganaha et al. [4] studied several years ago grain textures from weld of different aluminium alloys to clarify the mechanisms of grain refinement in welds. In summary, they found that axial (continuous grains along the weld centreline) or stray (intermittent new grains) structures with columnar grains closer to the fusion boundaries were favoured by low welding speeds. At high welding speeds, on the other hand, columnar grains either

✉ Américo Scotti
americo.scotti@hv.se

¹ Center for Research and Development of Welding Processes, Federal University of Uberlandia (UFU), Laprosolda, Uberlândia, MG 38408-100, Brazil

² Department of Engineering Science, Production Technology West, Division of Welding Technology, Högström Väst (University West), Västra Götaland, SE-461 86 Trollhättan, Sweden

grew all the way to the centreline or were blocked by equiaxed grains. Increased heat input would aid the formation of equiaxed grains by allowing more time for nucleus activated growth due to a decreased temperature gradient. Yunjia et al. [5] mentioned that the phenomenon of dendrite fragmentation is well known in the solidification of castings and ingots, but these mechanisms are considered to be impossible for the 6061 aluminium weld metal. Later, the studies, which were intensified on the influence of alloying elements on the grain structure of alloys based on aluminium, became more popular. Lin et al. [6] studied the microstructure after gas tungsten arc welding of the aluminium-lithium-zirconium alloy using different filler material varying in content of Li and Zr. They observed equiaxed grain zone around the fusion boundary and figured out that the zone width depends proportionally on the content of these elements.

Constitutional supercooling mode usually does not happen in welding, due to the non-fast enough cooling rates. However, Yunjia et al. [5], in their review, showed that there is no consensus about microstructural development in welding. It is argued whether microstructure is influenced by nucleation or controlled by the solidification rate. They mentioned the possibility of grain refinement as a result of competitive nucleation and growth processes. In a recent comprehensive study, Rios and Zöllner [7] confirmed that, although grain growth in metals has been a topic of intense experimental, analytical theories and computer simulations research, for more than 60 years, several unresolved issues remain. They pointed these out as cause of the difficulties in investigating experimentally the grain growth of polycrystalline grain structures.

Regardless, what has been the consensus is that the weld metal grain structures near the fusion boundary are dominated by homoepitaxial nucleation and growth process (the crystal grows on a partially melted substrate, yet with enlarged grains due to a high temperature that the substrate is exposed), as illustrated in Fig. 1. This epitaxial grain growth phenomenon is named homoepitaxy when taking place over the same or compatible material. As deduced from Yan et al. [8], the subsequent growth is influenced by both the preferred

crystallographic direction and the dominant local heat flow direction at the growth interface. Consequently, in the bulk weld metal, grains with their easy growth direction parallel to the direction of the maximum temperature gradient will grow easier and crowd out their less favourably oriented neighbouring grains. This phenomenon has been referred as directional solidification.

As epitaxial growth requires a minimal undercooling to proceed, cellular and columnar grains grow epitaxially from the substrate grain. According to Wei et al. [9], using simulations, this columnar grain growth happens in a curved pattern rather than along straight lines from the fusion boundary towards the centre of the molten pool. At low heat source moving speed, only curved columnar grains are formed, while a transition to equiaxed morphologies will take place at faster heat source movements. Yunjia et al. [5] showed that without adding grain refiners in the weld pool (heterogeneous nucleation), epitaxial growth happens with a coarse columnar texture directed most of the way across the weld deposit.

Solidification in wire + arc additive manufacturing (WAAM) is a particular case, in which multiple melting-solidification cycles occur. However, the similarities between the physical processes governing fusion welding and additive manufacturing make possible a model, as developed by Wei et al. [9], capable of predicting grain orientation in both processes. In this line, the authors of the present work presented, as in Fig. 2, an extension of Kou's scheme (Fig. 1) to illustrate the directional solidification pattern that takes place in WAAM of an aluminium alloy homoepitaxially nucleated. As the deposited layers are relatively short in the height direction and the heat flows practically in just one direction (downwards), and if a thin wall is considered, the nucleation takes place on the solid surface of a previous columnar grain, in such a way that a continuous columnar grain is formed and elongates with the subsequent deposited layers. As cited by Wei et al. [11], the maximum heat flow direction in AM is perpendicular to the trailing edge of the molten pool towards the substrate. Figure 3, produced by Wang et al. [12], shows these long grains formed in WAAM. According to Yan et al. [8], the re-melting of the previous layer during AM generally

Fig. 1 Schematic illustration of competitive epitaxial grain growth in the melt pool during solidification as the heat source moves away, in which the arrows indicate the easiest growth direction; for instance, $\langle 100 \rangle$ in fcc and bcc metals (after Kou [10])

Fig. 2 Schematic extension of Kou's illustration (Fig. 1) to demonstrate the directional solidification pattern of competitive epitaxially columnar grain growth through the layers during WAAM

induces nucleation and epitaxial grain growth at the solid-liquid interface with cellular or dendritic solidification front. Therefore, the grain size of the substrate governs the transverse columnar grain size. Nevertheless, Yan et al. [8] also say that, if the epitaxial growth of columnar grains is restrained by the formation of equiaxed grains near the surface of the melt pool in additive manufacturing, and if the equiaxed grain

depth within the melt pool is greater than the penetration depth during re-melting, then equiaxed grain size dominates the average transverse grain size (equiaxed grain size is greatly determined by the number density of heterogeneous nucleation sites).

Wang et al. [13] demonstrated that directional columnar grains in WAAM cause anisotropy of the mechanical properties. According to them, the samples tested from the vertical build direction exhibited lower yield (YS) and ultimate tensile strengths (UTS) than did the samples tested in the horizontal direction. However, the most significant property anisotropy was noticed in the ductility data, which was much worse when measured in the horizontal direction. Zhu et al. [14] in their review about laser metal deposition (LMD) of Ti alloy point out that for some authors, the as-deposited samples exhibited higher strength and lower ductility at the longitudinal direction compared to the transverse direction, although they found themselves and from other publications diverging results. As

Fig. 3 Through layer columnar grains formed during WAAM production of the Ti-6Al-4V wall (after Wang et al. [12])

Fig. 4 Solidification patterns of **a** unidirectional printed IN718 wall and **b** bidirectional printed IN718 wall (after Dinda et al. [26])

Fig. 5 Switchback schematic (after KANEKO et al. [29])

property anisotropy is undesirable, layer building strategies on the mechanical properties of printed part have been the main focus of several works. The effect of anisotropy was also confirmed by Lu et al. [15], whose results exhibited better mechanical property with specimens perpendicular to the building direction. A literature review about the effects of test orientation/build direction on properties was provided by Lewandowski and Seifi [16], along with discussion of the potential sources, e.g., texture, microstructure changes, and defects. It is important to note the observation of Kok et al. [17], in which metal AM parts exhibited anisotropy and heterogeneity (anisotropy would depict a variety of orientation-dependent features of a material, while heterogeneity is defined as uniformity in its features).

According to what has been presented, in order to avoid homoepitaxial and directional grain growth in WAAM of aluminium alloy, it is important to enlarge the field of application of this manufacturing process. Quested [18] cited that grain refinement of aluminium alloys has been achieved by chemical inoculation (current

grain-refinement practice involves the addition of master alloys, e.g., Al–Ti–B, Al–Ti–C, before casting, introducing inoculant particles to the melt). However, inoculation is a difficult practice to be applied in welding. Fortunately, there are other different approaches to avoid or mitigate epitaxial growth of big columnar grains.

One of the divulged methods is to apply high-pressure interpass rolling. It would be equivalent to apply large deformation to the materials and then heat treat the materials to trigger recrystallization, so that large deformed grains can be replaced by fine equiaxed grains. In additive manufacturing, this heat treatment would be simulated by the successive layer depositions. This approach was supposedly used for the first time in 1984 by Kurkin and Anufriev [19], to prevent distortion of thin welded wall. In 2009, Altenkirch et al. [20] described high-pressure interpass rolling as a means of decreasing residual stresses. In 2013, Colegrove et al. claimed to improve the microstructure of WAAM printed walls. The principle of this method is to roll under high pressure each layer after its deposition. More details can be found in Colegrove

Fig. 6 Cross sections at different positions of switchback welding with 140 mm of forward stroke and 140 mm of backward stroke: section AA is approximately 10 mm from the reversal point, while section B-B is at 120 mm (after Almeida et al. [30])

et al. [21], Donoghue et al. [22], and Williams et al. [23]. According to Martina et al. [24], when applied to WAAM structures, rolling resulted in a reduction of the grain due to the enhanced recrystallization, which occurs with the deposition of the subsequent layer on the plastically deformed layer.

Fig. 7 Schematic of the wall printing procedures. **a** Unidirectional deposition (without changing of the deposition direction). **b** Bidirectional deposition (deposition with changes of the welding direction). **c** Switchback deposition

The other advantage of this approach would be, as claimed by McAndrew et al. [25], a simultaneous reduction of residual stress. However, it has some limitations too. It would be very difficult to print a part with complicated geometrical shape due to the constructional features of the equipment (low operational flexibility). To provide ability for the roller to repeat complicated trajectory of the torch, a design of a very complicated and expensive motion system would be required. In addition, there is shortening and widening of the walls after rolling.

Another published method for mitigation of the mechanical property anisotropy is to change the layer deposition direction at each deposition start (bidirectional depositions). As columnar growths follow the heat flow direction and as each layer when deposited in a bidirectional mode changes accordingly the direction of heat flow, a “zig-zag” solidification pattern is formed in the longitudinal direction (layer by layer) of the printed wall. The effect of using of bidirectional deposition on the texture of an IN718 LMD wall was shown by, for instance, Dinda et al. [26], as illustrated in Fig. 4. Another source of information on this subject is Parimi et al. [27], who demonstrated that this “zig-zag” solidification pattern is supposed to reduce the mechanical property anisotropy. Nevertheless, some setbacks also exist to this approach. One of the limitations would be the fabrication with uninterrupted deposition, such as a circular component. Another one would be an overheating at the ends, if the direction reversion is carried out with a dwell time.

Zhang et al. [28] proposed that the use of GMAW (gas metal arc welding) with variable polarity was also able to change continuous columnar growth into equiaxial texture. However, this method has not been widely used with this purpose in WAAM. Yunjia et al. [5] cite that magnetic stirring has been shown to extend the range of welding conditions by producing a partially equiaxed structure and by increasing the

Fig. 8 Experimental rig

fraction of equiaxed grains in the weld metal. These methods, though, have not been widely used with this purpose in WAAM.

Therefore, this work aimed to seek and assess another method to mitigate homoepitaxial and continuous columnar grain growth as well as perform grain refinement in WAAM of aluminium. The target was a method that would also mitigate the limitations of the approaches of high-pressure interpass rolling, bidirectional depositions and VP GMAW (variable polarity gas metal arc welding).

2 Methodology

A special welding technique called switchback has been reported in current literature, yet scarcely, with some very interesting features, such as control of the weld pool and grain refinement, both highly desirable in additive manufacturing (AM). Therefore, this technique was chosen as potential means of mitigating homoepitaxial and continuous columnar grain growth and performing grain refinement also in wire + arc additive manufacturing (WAAM) of aluminium alloys. Switchback is a welding technique that uses short-amplitude longitudinal oscillation of the welding torch, in contrast to the stringer mode, in which the torch moves continuously forward. This welding technique was firstly described likely by Kaneko et al. [29]. According to them and as illustrated in Fig. 5, the welding torch is linearly moved forward at a travel speed (TSf). After having moved a given forward stroke distance (F), the travelling direction is reversed, and the torch is moved backward at a travel speed

(TSb). Usually TSb is the same as TSf, yet not compulsory. After the torch is moved in the given backward stroke distance (B), the travelling direction is again reversed and the torch is moved forwards. Usually, the distance B is shorter than the forward stroke distance (F). In this way, a welding torch is periodically moved forwards and backward.

This technique was developed as a means of increasing travel speed, avoiding dragon back like bead formation. It has not been widely studied, though there are already promising results, even regarding metallurgical improvement. For example, Almeida et al. [30] noticed that the usage of switchback technique with selected parameters leads to the recrystallization of the bottom part of the weld bead (Fig. 6). Thus, in spite of the fact that switchback technique has not found wide application in welding, in the case of confirmation of the expected effects from using of this technique in WAAM, it can be a good solution for preventing epitaxial columnar growths in additive manufacturing industry.

To assess the application of the switchback technique in this work, the proposed methodology was to compare this approach with known benchmarks, such as unidirectional and bidirectional layer depositions, as illustrated in Fig. 7. Therefore, three walls using WAAM were planned. Each wall, over a same substrate size, consisted of a same number of layers and was built with the same welding process and set of parameters, such as wire (composition and size), shielding gas, arc current, arc length, travel speed (equivalent travel speed for switchback), wire feed rate, etc. One wall was produced using the same welding direction for each layer (unidirectional deposition). The second wall was printed using opposite welding direction for each layer (bidirectional deposition). The last wall was made using switchback technique.

Geng et al. [31] demonstrated that a bead shape stability is easily reached with WAAM when small interlayer temperature is applied (dragon back-like layers appeared in the research conditions when interlayer temperatures changed from room temperature to 80 °C and turned progressively more remarkable when the interlayer temperature reached 120 °C). Therefore, controlling the interlayer temperature at each layer/wall is essential to be able to make comparisons amongst AM walls. Consequently, to prevent the big changes of heat flow amongst the layers, the first layer was deposited over the longitudinal edge of test plates of similar aluminium and the start/interlayer temperature before each layer was kept as much the same as possible.

The produced walls were compared to each other in terms of quality parameters. Quality parameters are defined in this work as the ones with direct relation to the subject of the work, i.e., they can affect mechanical properties of the printed part. The chosen quality parameters in this work were microstructure (grain growth pattern and grain sizes) and porosity.

Fig. 9 Test plate and plate holder.
a Perspective view. **b** Top view

3 Experimental procedure

In the scope of this work, a GMAW Fronius CMT (Cold Metal Transfer) was chosen as deposition process, due to its low heat input that provides lower layer distortion. In addition, CMT is qualified by the author as the most efficient arc welding process to accomplish the three commandments, as follows:

First Commandment: The arc pressure should be minimized to avoid pool lateral sag (downward lateral running). This can be reached, for a given material and wall thickness, by using short arc, lower current-travel speed ratio, lower interlayer temperature and gas composition that favours cathodic emission concentrated in the arc centre line

Second Commandment: The pool should present a proper volume for a given deposition rate and current (a too small pool volume means low heat transferred to the prior layer, and a too large pool is prone to run downward). There is always an adequate range of pool volumes (for a given material, wall thickness and arc energy).

Third Commandment: The material underneath each layer under deposition should be as cool as possible, so that the heat transfer through the erect wall becomes easier. The faster is the heat transfer from the pool of the layers under deposition, the smaller and less fluid becomes the pool, preventing pool collapse to the sides.

A computer numerically controlled (CNC) customized 3-axis worktable was chosen instead of a robotic system, because it can be easily programmed by G-Code to weld any geometrical configuration if needed. Bandari et al. [32], although working with a CNC system for machining rather than one dedicated to AM, showed, through a comparative analysis with robot, other advantages of CNC system to be used for this purpose. The welding torch moved only in the z axis, while the support with fixed test plate moved on the horizontal plane. To protect the welding zone, a home designed trailing gas device was used. The experimental rig with mounted support and trailing gas is shown on Fig. 8.

The printed walls consisted of 15 layers. The first layer was deposited over the longitudinal edge of test plates

of a commercially pure aluminium ($190 \times 50 \times 6$ mm), fixed in a plate holder as illustrated in Fig. 9. An advantage of this approach is to reduce thermal buckling of the substrate, considering the higher moment of inertia of this plate positioning. Substrate buckling during the deposition would interfere in the layer formation, impairing the comparisons. The criterion to keep the same interlayer temperature was to cool down the walls after each layer deposition with the aid of compressed air until the different parts of the walls could be grasped with bare hands.

The common set parameters for the all three experiments were:

- ✓ Welding wire = AWS /SFA 5.10 ER5356 (Al-Mg5), 1.2-mm-diameter
- ✓ Wire feed speed (WFS) = 4.9 m/min
- ✓ Contact tip-work distance (CTWD) = 15 mm
- ✓ Shielding gas: Ar (purity 99,995—% by volume)
- ✓ Shielding gas flow (GFR) = 15 l/min
- ✓ Travel speed (TS) = 420 mm/min.

Fig. 10 Walls built up using different techniques. **a** Unidirectional welding. **b** Bidirectional welding. **c** Switchback mode (for **a** and **c** modes, the welding direction was from right to left)

Fig. 11 Longitudinal macrostructures of the walls, emphasizing the pattern of columnar grain growth. **a** Unidirectional mode. **b** Bidirectional mode. **c** Switchback mode (amplification of cross sections from the 4th to the 8th layers of each wall)

Note: resultant mean welding current (I) = 81 A from all three experiments.

Switchback has distinguishable set parameters, such as oscillation frequency (f), oscillation amplitude (Amp), forward stroke length (F), backward stroke length (B), forward stroke speed (SF), and backward stroke speed (SB). To keep the same TS, each deposit should be kept at the same deposition time (t) to accomplish the same layer length (LL). Hence, equivalent travel speed is the speed needed to deposit one given layer length. Equivalent travel speed is the same as travel speed for unidirectional and bidirectional experiments ($TSeq = TS = 420$ mm/min). In the present work, it was defined $LL = 190$ mm, $F = 6$ mm, $B = 3$ mm. Both SF and SB were set as the same, i.e. $SF = SB = 1230$ mm/min. Oscillation frequency (f) resulted in 2.2 Hz.

During the metal deposition, data acquisition of arc voltage (U), welding current (I) and wire feed speed (WFS) was carried with the aid of a commercial data acquisition board. WFS was monitored through an encoder-based sensor. Data computation was carried out with a home-designed software using a NI LabVIEW 2016 platform.

For texture visualization of the columnar growth patterns of each wall (a quality parameter), longitudinal sections of the walls were taken at the centre of the wall. The samples were

milled to remove half of the thickness, and then ground with sandpapers from 400 to 1200 mesh, polished with aluminium oxide of 5 μ m and etched with a 20% HF acid solution in water for 15 s. Optical microscopy with polarized light was used to expose the microstructures. Macrographic photos were taken from longitudinal and cross sections of the walls.

Average grain size was measured according to the ASTM E112-12 standard. For porosity measurements, another set of walls was built up (unidirectional mode, bidirectional mode and switchback mode). Samples of the same height and length were cut from the middle part of the walls. A sample of the substrate material with same dimension was taken. A gravimetry method was used to evaluate the presence of pores in samples removed from the walls, method successfully applied to measure pores by Silva and Scotti [33]. Gravimetry is based on the Archimedes principle, i.e. on the analysis of the forces acting on the samples outside and inside water. The final result does not show the number of pores and their dimensions, but the percentage of voids in relation to a reference (a sample considered pores free). According to the procedure, the sample is weighed in a precision scale in air and “floating” inside a container with water. When in water, there is the presence of

Fig. 12 Longitudinal microstructures of the walls, emphasizing the grains sizes: **a** Unidirectional mode. **b** bidirectional mode. **c** Switchback mode (amplification of cross sections from the 5th to the 7th layers of each wall)

Table 1 Grain sizes of the wall microstructures (according to ASTM E112–12 standard, average of 6 different sections)

Sample	Average number of grains (units/mm ²)	ASTM number	Average grain diameter (mm)	Standard deviation
Unidirectional mode	84.3	7.4	0.064	0.002
Bidirectional mode	92.8	7.5	0.058	0.001
Switchback mode	101.0	7.7	0.054	0.001

the upthrusting force and the weight force. Upthrusting force, also called buoyant force, is the force that the liquid exerts on an object on its surface.

4 Results and discussions

The average monitored current was 85 A, the average wire feed speed was 5 m/min and the average voltage was 12.5 V, regardless the operational mode (uni, bidirectional and switchback). Notwithstanding, the parameter of most interest in the scope of this work is welding current, because it governs the heat input, consequently grain growth and bead formation.

Figure 10 presents the general aspects of the three walls. As one can see, there is significant difference amongst the walls. The wall built-up by unidirectional welding has a hump at the layer deposition start point and a descendent ramp at the end. Concerning WAAM of aluminium, this humping is due to the high cooling rate when each layer deposition starts (cold wall material). As long as the heat distribution along the wall

reaches the steady state, the humping disappears. Due to analogue effect, yet inverse, at the end of the layers, one can see the opposite situation (descendent ramp rather than humping). To avoid these effects, operational parameter corrections can be applied in manufacturing of actual parts.

The wall printed using switchback technique (Fig. 10c) presented the same behaviour as the unidirectional deposition in relation to the presence of humping. Despite this, much better regularity and smoothness of the surface is visually perceived. In the wall made using bidirectional depositions (Fig. 10b), humping was not observed, once the humps are remelted at the end of each layer (however, as this wall was the last one to be built, pyramidal wall shape was used to assure ever more regular layer starts and ends, keeping the same wall height, but not entirely the wall length).

Considering that the main scope of this work is related to columnar epitaxial grain growth and microstructural refinement, Fig. 11a and b initially makes clear that the unidirectional and bidirectional dispositions, as expected, presented typical solidification patterns, respectively with continuous

Fig. 13 Microstructure of the walls, using bright field. **a** Unidirectional mode. **b** Bidirectional mode. **c** Switchback mode

Fig. 14 Microstructure of the walls, under polarized light. **a** Unidirectional mode. **b** Bidirectional mode. **c** Switchback mode

columnar growth and zig-zag-like columnar growth. These phenomena have already been reported by several researchers, amongst them Parimi et al. [27]. Figure 11c, deposited with switchback mode, suggests no trends concerning direction of the epitaxial columnar grain growth. From this characteristic of the switchback mode of deposition, it is expected much more isotropic properties of the wall.

Figure 12 presents an amplification of the microstructures presented in Fig. 11. Visually, one cannot see remarkable differences in grain sizes, whose quantification is summarized in Table 1. It is worth noting smaller grains when bidirectional and switchback modes were applied. The reason for grain refinement also with bidirectional deposition mode may be based on the breakage of the growth direction at each deposited layer surface, which happens following the direction of the maximum temperature gradient. Switchback, on the other

hand, plays the same role, in a much shorter decomposition length though. This latter fact may justify the same level of grain refinement of both bidirectional and switchback modes.

Despite all the potential advantages so far achieved by using the switchback technique in this work, an interesting microstructure-related phenomenon was observed when this deposition mode is applied. As seen in Fig. 13, black dots are present and spread on the microstructures. Tanski et al. [34], when studying the microstructure and mechanical properties of similar alloys (AlMg_3 and AlMg_5), reported also the presence of these black dots after heat treating the alloys (solubilization and artificial ageing), even using optical microscopy. They confirmed by means of transmission electron microscopy that $\beta\text{-Al}_3\text{Mg}_2$ phase precipitates during artificial ageing from supersaturated solid solution. This precipitation would be responsible for the hardening effect

Table 2 Porosity of the walls as a function of the deposition mode

Samples	Mass in air [g]	Mass in water [g]	Δmass [g]	Body density [g/cm ³]	Relative volume of voids [%]
Measured reference	74.48	47.18	27.30	2.73	—
Unidirectional mode	62.73	39.01	23.72	2.64	3.06
Bidirectional mode	62.95	39.00	23.95	2.63	3.66
Switchback mode	66.72	41.25	25.20	2.65	2.95

and increased workability of the alloys. Even turning away from the focus of the work, it is important to note that the dots on the samples taken from the wall printed using the switchback deposition are bigger than on the other two samples. Based on Fig. 14, one can suggest that the dots tended to gather in clusters on the grain borders with the switchback mode, likely due to more frequent heating cycles.

Table 2 presents the results of pore measurements by gravimetry. It can be seen less porosity in the wall using switchback mode of deposition (from 3 to 19% less). The switchback movement may have stirred the pool in such a way to facilitate escaping trapped gases. On the other hand, to find out the principles that led the wall built with bidirectional mode to higher porosity is a subject for future studies. It is important to mention that, according to the results obtained by Silva and Scotti [33] with double pulse gas metal arc welding of the aluminium, porosity can reach 6% depending on the welding parameters used. Consequently, one can consider that pore generated in WAAM of aluminium alloys is low and the use of switchback mode lessens porosity.

5 Conclusions

In this study, the potential of using switchback technique in Al alloy WAAM was assessed as a means of mitigating porosity and epitaxial columnar grain growth and reach grain refinement. It was showed that the switchback deposition mode can prevent continuous homoepitaxial grain growth, by breaking the solidification pattern, and, in addition, refine the grain. This finding suggests that with this performance, switchback deposition mode can be an operational method to solve the problem of anisotropy of the mechanical properties that is usually observed in parts produced by WAAM. The results also showed that switchback mode decreases porosity in printed parts and improves surface quality of the walls.

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