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A NOVEL ACTIVE COOLING TECHNIQUE FOR WIRE + ARC ADDITIVE MANUFACTURING

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Abstract. *Heat accumulation is likely the main limiting operational characteristic of directed energy deposition additive manufacturing. In this scenario, this work aims to present and explore the potential of a novel thermal management technique, named Near-Immersion Active Cooling (NIAC), to mitigate heat accumulation in Wire + Arc Additive Manufacturing (WAAM), in contrast to conventional cooling approaches. According to the NIAC concept, the preform is deposited inside a work tank that is filled with a cooling liquid, which level rises closely to the arc level while the metal layers are deposited. For validation of the NIAC technique, aluminum single-pass multi-layer linear walls were deposited as preforms by using the CMT® process. During depositions, temperature information of each preform was surveyed. The potential negative effect of water as cooling liquid in the NIAC technique was assessed by means of porosity ratios. The geometric quality of the preforms was also evaluated. The results revealed that the NIAC technique imposed the lowest and more steady temperature profiles to the preforms. Moreover, there was no measurable increase in porosity and the wall width remained virtually constant, which characterizes geometric quality improvement. To sum up, the NIAC technique is demonstrated as a feasible thermal management approach to mitigate preform heat accumulation in WAAM and, consequently, its related drawbacks.*

Keywords: *WAAM, Heat accumulation, Thermal management, Active cooling.*

1. INTRODUCTION

Additive Manufacturing (AM) of functional metallic components is already a reality in aerospace, medical, energy, automotive and many other fields. According to Herzog et al. (2016), the most popular processes for AM of metals are Laser Beam Melting (LBM), Electron Beam Melting (EBM) and Laser Metal Deposition (LMD), which all use powder as feedstock. These processes have great resolution, allowing in some cases to produce the component without any additional finishing operation. However, Debroy et al. (2018) explain that these powder-based AM processes are prohibitively expensive and their production time is too long for large components (> 10 Kg). Williams et al. (2016) and Ding et al. (2015) agree with these limitations as reasons for a continuous increase of the academic and industrial interest in Wire + Arc Additive Manufacturing (WAAM). According to an ASTM guide (ASTM, 2015), WAAM, together with LMD and EBM, composes the AM category named Directed Energy Deposition (DED), which uses focused thermal energy to fuse materials by melting as they are being deposited.

As also described in an ASTM guide (ASTM, 2015) dedicated to DED AM processes, the arc-based processes suitable for AM are ostensibly based on the gas shielded welding processes, namely Gas Tungsten Arc (GTA), Plasma Arc (PA), Plasma Transferred Arc (PTA) and Gas Metal Arc (GMA), and variants thereof. Not specifically to one of the referred methods, the high deposition rate (1 to 4 kg/h) is referenced by Williams et al. (2016) as one of the many advantages of WAAM. However, this characteristic is accompanied by high heat input. As a result, it may lead to heat accumulation and related deleterious consequences on the integrity of the preform and/or performance of the component (preform geometry, microstructural aspects, distortion, residual stresses, etc.).

Wu et al. (2018) explain that, despite an increasing amount of heat is dissipated to the surrounding atmosphere via convection and radiation as a preform is built up, these temperature-reducing means are less effective than direct conduction to a cool substrate, and thus lead to slower heat dissipation and more heat accumulation. Therefore, heat accumulation is hereafter defined in this work as a not homogeneous and inconstant concentration of heat in the preform as a consequence of heat flow restriction, which happens mainly downwards through narrow walls. As per Yang et al. (2017), the heat accumulation becomes more significant with the increase in the number of deposited layers, *i.e.*, with increased height of the preforms. According to Wu et al. (2018), the heat accumulation translates into interpass temperature rise throughout the deposition time.

Heat accumulation is not exclusive to WAAM, happening also with other DED AM processes. The effect of heat accumulation on the metallurgical aspects of austenitic stainless steel walls made by LMD was investigated by Manvatkar et al. (2014). These authors verified molten pool enlargement, higher temperature experienced by the previous layer, lower cooling rate, lower G/R solidification parameter and lower hardness as the wall is built up. Subsequent results reported by Wang et al. (2016), using GTA AM and Inconel® 625 wire, and by Foster et al. (2017), using LMD and Inconel 625® and Ti6Al4V powder, have corroborated and extended these behaviors to other materials and energy sources, including wire and arc.

Besides metallurgical changes, the heat accumulation also impacts on operational, geometric and superficial aspects of WAAM. Xiong et al. (2017) reported molten pool collapse and geometric deviation of the preforms due to heat accumulation in WAAM of low carbon steel when using the GMA process. Wu et al. (2017), in addition to a width enlargement effect on the walls, described excessive oxidation due to heat accumulation in WAAM of Ti6Al4V with the GTA process. Xu et al. (2018), in a more detailed study on this feature, found that excessive oxidation impairs the wettability and, consequently, the geometric regularity of layers produced with Maraging steels in WAAM with the GMA process.

To deal with all sort of heat accumulation drawbacks, different approaches for thermal management in WAAM have been proposed and are found in the current literature. The control of the inter layer dwell times is the simplest and most referenced approach, for instance, as by Yang et al. (2017) and Lei et al. (2018). Denlinger et al. (2015) performed *in-situ* measurements of the accumulation of distortion during LMD of titanium and nickel-based alloys as a function of changes in the dwell time. They reported that both distortion and residual stress levels decrease over the course of the nickel-based builds with increasing of the dwell times (lower interpass temperatures). However, according to their results, the opposite is true for the titanium builds, in which shorter dwell times minimize distortion accumulation and residual stresses, particularly when no dwell time is applied (higher interpass temperatures). Denlinger et al. (2015) accredit the lower distortion and residual stresses to phase transformations and relaxation at high temperature that happens for the Ti6Al4V alloy around 600 ºC. From their results, it can be concluded that heat accumulation has a significant effect on the level of distortion and residual stresses, yet in a not predicted bias. But despite fulfilling the goal of mitigating heat accumulation, the dwell-time-based cooling strategy compromises productivity, since there is a dead time between each layer, which significantly extend production time.

Another possibility is to build up the preform over a cooled platform, as described by Lu et al. (2017), although this approach seems more efficient only for the first layers and/or when applied to small preforms. Wu et al. (2018) used forced interpass cooling with compressed CO_2, while Henckell et al. (2017) used forced cooling with a punctual jet of N_2+5%H_2 behind the arc. Wu et al.'s approach has the advantage of not disturbing the arc, in contrast to the use of a gas jet behind the arc. On the other hand, the Henckell et al.'s (2017) forced cooling during the deposition does not delay the production time. Wang et al. (2004) and Xiong and Zhang (2014) reported good results through decreasing of the heat input as preforms are built up, although this approach does not eliminate deleterious effects of thermal degradation.

All that been said, it is established that heat accumulation is a limiting characteristic of WAAM and LMD towards their practical application. Although there are approaches to mitigate heat accumulation, each one with its own advantages and limitations, the challenge that remains is to control the heat accumulation, regardless of the perform geometry, without disturbing the arc and compromising productivity and with low environmental impact. In this sense, the present work aimed to introduce a novel concept of active cooling of preforms, named here as Near-Immersion Active Cooling (NIAC), and firstly explore its potential to reduce heat accumulation in WAAM and, consequently, to mitigate correlated problems.

2. NIAC CONCEPT AND PROOF OF CONCEPT

2.1 NIAC concept

As detailed in Reis et al. (2018), the concept of NIAC has its foundations based on an active cooling of the preform by means of its relative continuous and controlled near-immersion in a cooling liquid within a work tank throughout the building time. Figure 1 schematically illustrates the application of the concept, in contrast to more common thermal management approaches, such as without any forced cooling means (hereinafter called Natural approach) or conducted by means of substrate and/or building platform cooling (hereinafter called Passive approach). Thus, the cooling rate of the non-immersed part of the preform and the interpass temperatures would be controlled by the level of the cooling liquid and by the heat exchange with its part just immersed.

By this cooling approach, direct contact of the cooling liquid with all the layers of the preform inside the work tank is assured, except for a few ones just below the ongoing level of material deposition. The cooling liquid could, thus, act constantly to withdraw heat directly from the preform, significantly lowering the interpass temperature, i.e., the minimum temperature of the previous layer before the new deposition of material, thus potentially reducing in an expressive manner the accumulation of heat in the preform as its building goes on.

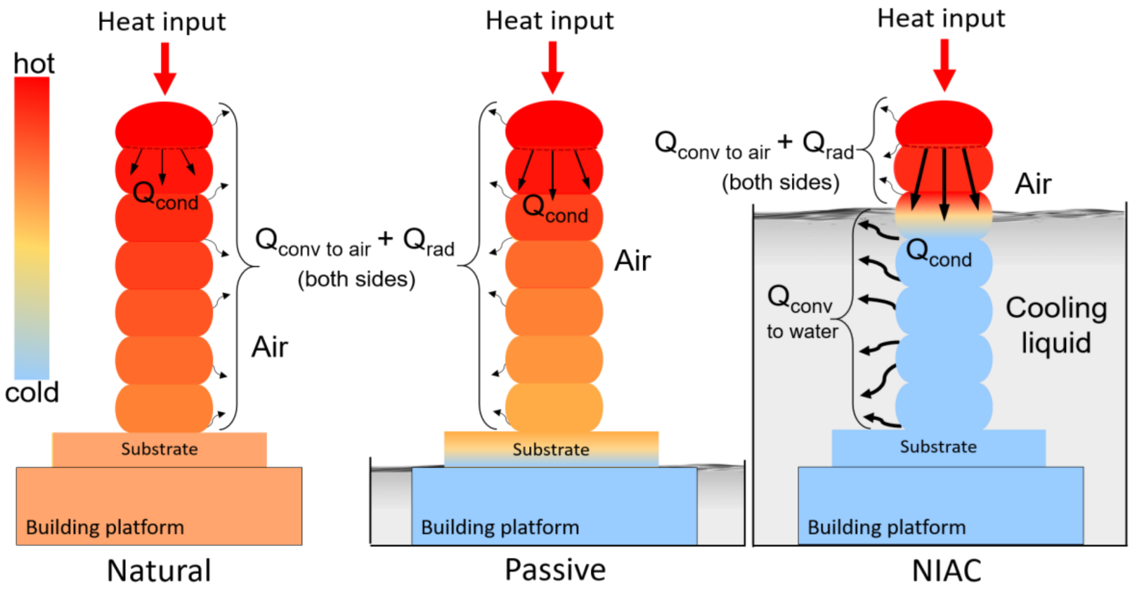

Figure 1. Schematic illustration of the NIAC concept versus the Natural and Passive thermal management approaches (the arrows are proportional to the heat sink intensity), where: Q_{cond} = conduction heat sink; Q_{conv} = convection heat sink; Q_{rad} = radiation heat sink.

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Thus, the NIAC technique is expected to allow the mitigation of several problems linked to heat accumulation in WAAM. In addition to being able to favorably regulate characteristics more related to the preforms, the NIAC implementation would allow to preserve or even increase the productivity by increasing the building rate. This could even occur without any or with shorter and/or less frequent dwell times, due to the NIAC intense and continuous cooling, and/or by performing at higher melting-deposition rates, since the corresponding increase in energy (heat) input would be counterbalanced by a larger heat dissipation capacity provided by its efficient cooling strategy. By promoting better thermal management of preforms through the NIAC technique, it would be possible to couple higher manufacturing productivity with improved mechanical and geometric qualities. In achieving success, the NIAC concept could be extended to other DED AM processes, such as to LMD. Finally, as devised, the NIAC concept relies preferably on the use of water as the cooling liquid, which in itself adds to the green-manufacturing appeal of additive manufacturing.

In view of the diversity of foreseen potentials, some aspects of the NIAC concept are evaluated as following to validate it as a proof of concept as introduced for thermal management in WAAM.

2.2 NIAC proof of concept (experimental validation)

The experimental validation of the concept was based on the comparison of three cooling approaches applied to the preforms; Natural, Passive and NIAC. Figure 2 shows the experimental rig employed for the NIAC concept. The same arrangement was used for the Passive and Natural approaches by fixing the cooling liquid level at the substrate-building platform and by draining it from the work tank, respectively, as illustrated in Figure 3.

Single-pass multi-layer linear preforms (single walls) were deposited under the three different cooling approaches. Considering that one potential setback of the NIAC concept would be hydrogen contamination of the deposition pool from vaporized water, an aluminum alloy was chosen as preform material, yet due to the high level of hydrogen solubility in liquid aluminum. The deposition settings are summarized in Table 1 and were kept constant throughout the experiments. Three walls were produced for each cooling approach. For the NIAC one, the distance separating the deposition level (arc root) from the cooling liquid was kept constant throughout the deposition height by means of a pressurized water tank. It is also important to mention that the NIAC concept was applied just after the 9th layer (approximately from 15 mm of wall height) to prevent water turbulence and evaporation and consequent process instability and/or preform contamination.

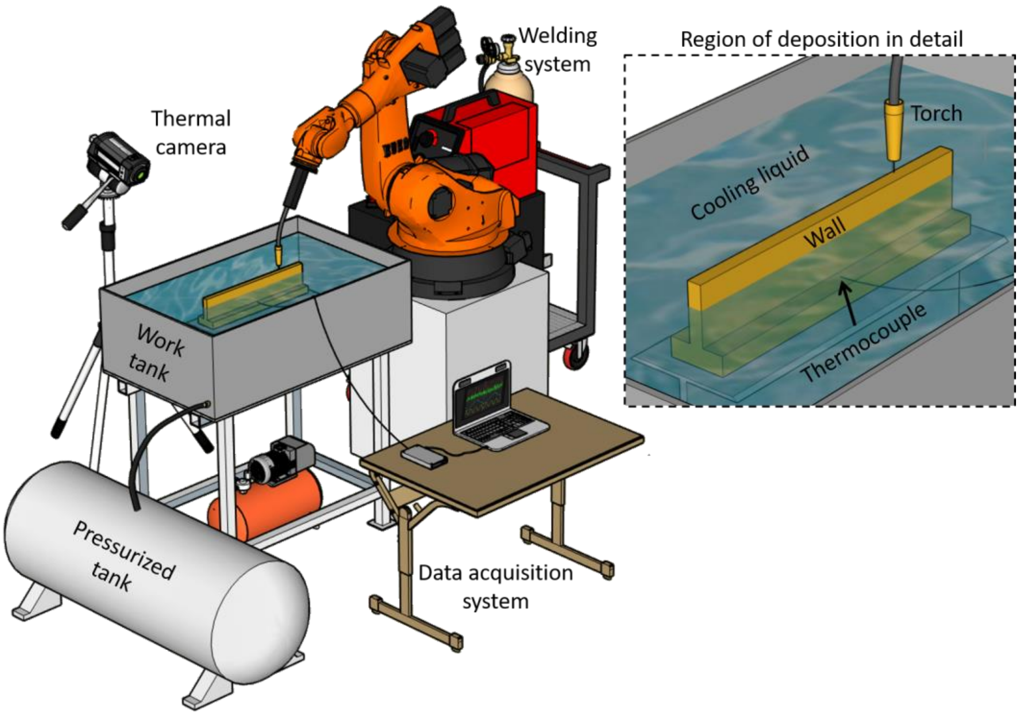

Figure 2. Experimental rig representation for the NIAC concept.

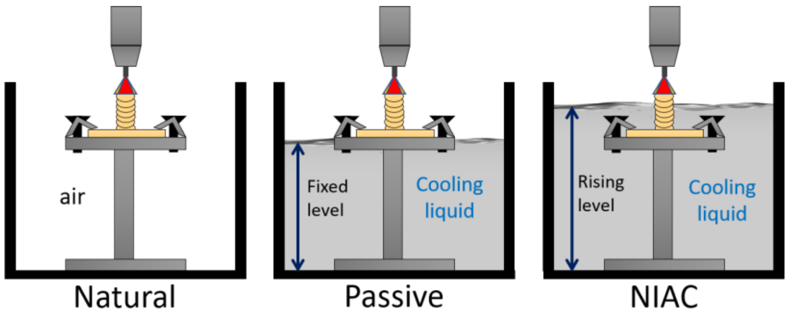

Figure 3. Schematic representation of the cooling approaches.

Table 1. Deposition settings for each cooling approach.

Item	Natural	Passive	NIAC
	Specification		
WAAM deposition equipment	Fronius CMT® TransPuls Synergic 500		
Wire (deposition material)	AWS ER 5356 with Ø 1.0 mm		
Substrate	Al5052 (300 x 40 x 3 mm)		
Wire feed speed	8.2 m/min		
Deposition speed	45 cm/min		
CTWD(1)	12 mm		
LEWD(2)	-	-	15-20 mm
Shielding gas	Commercial argon at 15 L/min		
Cooling liquid	-	Tap water at around 20 ºC	
Work tank volume	50 L		
Preform geometry	Single wall with 28 layers and length of 380 mm		
Building strategy	Single-pass multi-layers bidirectional depositions		
Dwell time	0 s		

(1)CTWD = contact tip to work distance; (2)LEWD = layer edge to water distance; The measured resultant average deposition current and arc voltage levels were 90 A and 8.5 V, respectively.

In order to verify the effectiveness of each cooling approach, thermal analyses were carried out based on thermocouple and thermography data. During depositions, a commercial infrared camera was used to register lateral infrared portraits (thermograms) from the whole walls. From the thermograms generated, the thermal cycles of the 23rd layers at a fixed position (mid length) were monitored during the next 5 subsequent layers. In addition, at the same time, a thermal history of the substrate was measured by a 0.6-mm-diameter (each wire) K-type thermocouple fixed at the substrate mid length and positioned at approximately 5 mm of the deposition centerline. Data from the thermocouple was used to adjust the infrared emissivity.

The possibility of deposition pool hydrogen contamination was assessed by a porosity measure. Considering the proof-of-concept purpose of the present work, the Archimedes method was chosen to assess porosity level in the walls for being reliable and the simplest non-destructive method for measuring the percentage of voids of an entire specimen. However, the details of the shape, size and distribution of pores cannot be determined using this method. Neither other internal voids, such as solidification shrinkages, lack of fusion and cracks, can been distinguished from pores. The results are only presented in terms of percentual volume of voids. Two samples weighing around 100 g were cut from one of the preforms produced for each cooling approach. A digital balance with resolution of 0.01 g and distilled water were used. Three measurements were performed over each sample. The aluminum alloy theoretical density was considered as 2.64 g/cm^3 to calculate the volume of voids.

At last, the remaining walls were mechanically sectioned in their central regions and standardly prepared by grinding and polishing. Then, the preforms produced with each cooling approach were assessed in terms of geometric quality (form regularity) by cross-sectional-view macroscopic examination.

3. RESULTS AND DISCUSSIONS

3.1 Thermal analysis

Thermograms of the lateral surface of the walls deposited under the three different thermal management approaches, immediately after the arc has been switched off, are shown in Figure 4. In qualitative terms, the thermal field of the preform deposited with the NIAC technique is remarkedly different and evidences how it has been actively cooled. For the Natural and Passive cooling approaches, the respective entire preforms exhibit high temperatures after deposition, as the heat from the deposition source (electrical arc) has been accumulated, which it is in accordance with Yang et al. (2017). With the NIAC technique, on the other hand, only a preform small area surrounding the arc last position appears expressively heated as the water level following immediately below quickly cools the rest of the preform down.

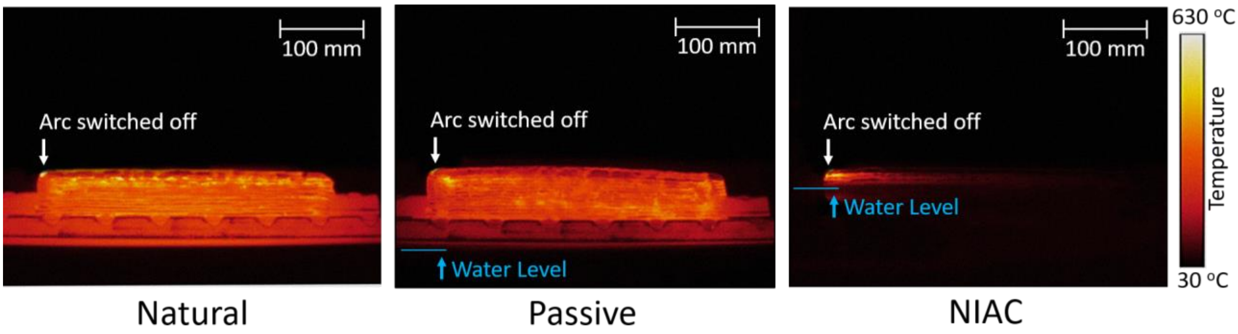

Figure 4. Thermograms of the lateral surface of the walls deposited under the different thermal management approaches at the end of the 28th deposited layer.

Complementing, now in quantitative aspects, Figure 5 shows the thermal cycles measured at fixed spots (at the mid length) on the substrates (left-hand side), along the whole deposition, and of the 23rd layers (right-hand side), during the execution of the last 5 layers. The peaks of temperature are consequence of the moments that the arc passes by aligned with the points of measurement and the valleys correspond to the moments between each deposition (representative of the interpass temperatures).

Under the Natural cooling approach, the substrate and the 23rd layer temperatures are seen to continuously rise as the layers are deposited and reach the highest levels observed, as evidence of the largest heat accumulation. Specifically for the case of the temperatures measured at the substrate, each time the deposition source (electrical arc) gets far away, the values tend to reach a maximum level and then would gradually reduce to the room temperature, as reported by Denlinger et al. (2015). In this case, the heat input would be balanced by the heat sink via conduction through the preform and to the substrate and to the building platform, convection to the air and radiation to the surroundings. However, as seen, after the end of deposition, the temperature starts to fall down as air cooling continuous.

For the Passive cooling approach, the same general trend is noticed. However, the substrate temperature seems to reach a constant mean level much sooner (around 400 s) and of significantly lower value (around 150 ºC), indicating lesser heat accumulation. In this case the conduction through the preform and to the substrate and to the building platform is boosted by the water convection around it, and so it is the heat sink. The 23rd layer temperature, in turn, continues to ascend until the end of the deposition time, yet with the valleys at lower levels than with the Natural approach, but with similar ascending rate. This fact suggests that the Passive cooling approach at this layer level is no longer effective to promote as much as of heat sink as for the first layers. This behavior corroborates observations made by Wu et al. (2017), who argue that there is a large discrepancy between the temperature measured at the substrate and the actual layer temperature, particularly if the dwell time between layers is short or nil, as it is the case of the present work.

Under the depositions with the NIAC technique, the first 9 layers were in fact deposited with the Passive approach and, as noticed, the thermal cycles were very similar. As soon as the substrate was immersed by the rising water level (around 260 s), its temperature sharply dropped to the that of the water. The elapsed time till the water temperature is simply explained by the substrate heat sink by the water convection. The thermal cycles of the layers above the water level and then, as the preform is built up, also of the layers that have been immersed, cannot be detected by the thermocouple, since the heat flow by conduction through the preform is dissipated by the water convection before it reaches the substrate. It is also worth mentioning that there is a small water evaporation at the immersion level (water-preform contact). As the cooling power due to water phase transformation is much higher than that equivalent to water heating (convection), it is believed that evaporation also significantly contributes to preform heat sink.

Still regarding the NIAC technique, the 23rd layer valley temperatures (representative of the interpass temperatures) were the lowest, compared with the Natural and Passive approaches, and remained almost unchanged during all the deposition time, clearly showing no heat accumulation. This behavior took place as expected, since the water level rises as the layers are deposited, keeping similar deposition conditions independently of the preform height.

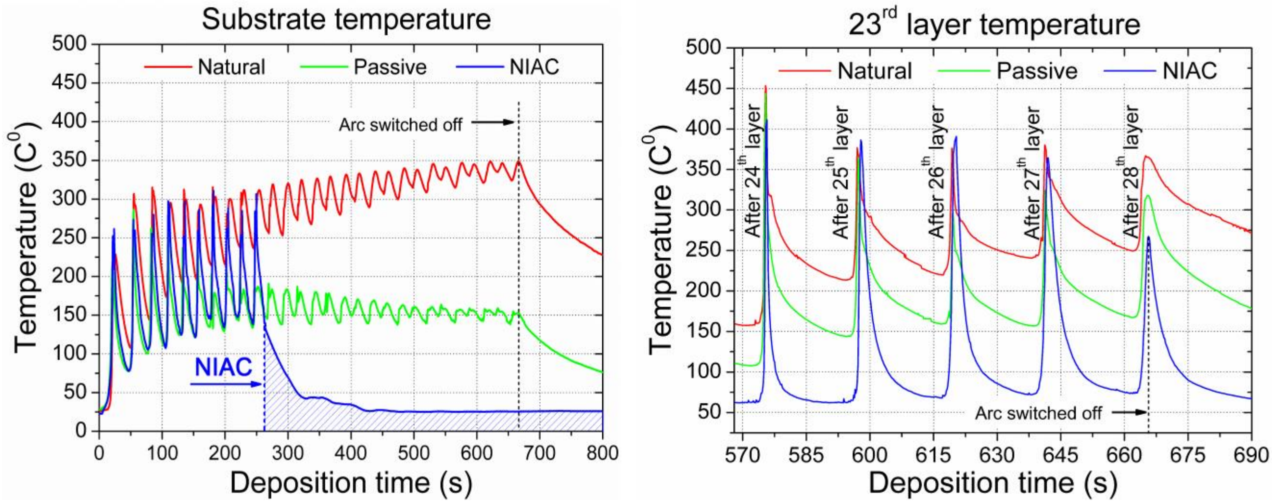

Figure 5. Thermal cycles simultaneously measured at fixed spots: registered by a thermocouple fixed to the substrates at their mid lengths 5 mm of the deposition centerlines along the whole depositions (left-hand side); taken from thermograms for the 23rd layers at their mid length during the execution of the last 5 layers (right-hand side).

3.2 Porosity assessment

It is widely recognized that hydrogen is the dominant cause of porosity in aluminum alloy weld beads. In face of the possibility of water vapor hydrates the oxide films and/or even contaminates the deposition pool and/or the electric arc, one can say that porosity is the major concern related to the application of NIAC in WAAM of aluminum. However, as shown in Figure 6, for all thermal management approaches the walls showed low porosity levels and within a range in concordance with that reported in the current literature (Haselhuhn et al., 2016; Ryan et al., 2018).

In summary, the use of water near the deposition pool and electric arc, at least for the settings adopted, is not a risk factor concerning hydrogen-induced porosity. This NIAC feature might be related to the positive pressure undergone by the deposition poll and its surroundings due to the shielding gas flow, which pushes water vapor, that is formed even with large volumes of water in the work tank, away from the deposition location.

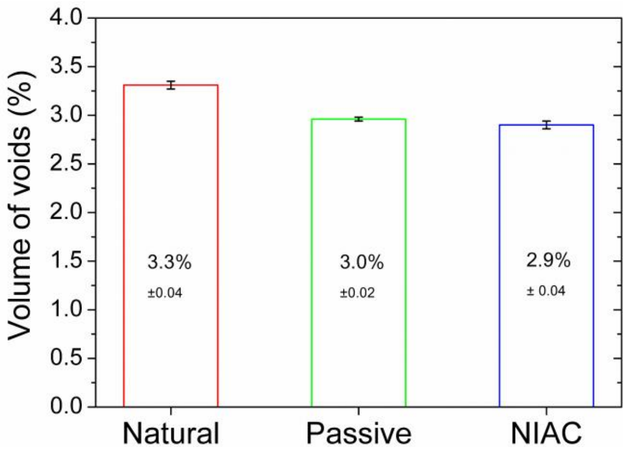

Figure 6. Effect of the thermal management approaches on average volume of voids.

3.3 Geometric quality

As typically shown in the Figure 7, the NIAC technique promotes the tallest walls and a more regular and lower surface waviness. It also leads to lower variability of the wall height along its length, even near the ends. Such regions are critical for single-pass multi-layer bidirectional continuous (no dwell times) deposition of thin walls. They tend to become lower and wider than the rest of the wall extent due to local heat accumulation. It is important to clarify that the geometric quality at the ends of the preforms could be improved with the NIAC technique by switching the arc off and adding a short dwell time before starting the next layer. In addition, the wall deposited with the NIAC showed lower levels of surface oxidation, since it remained at lower temperatures during all deposition time.

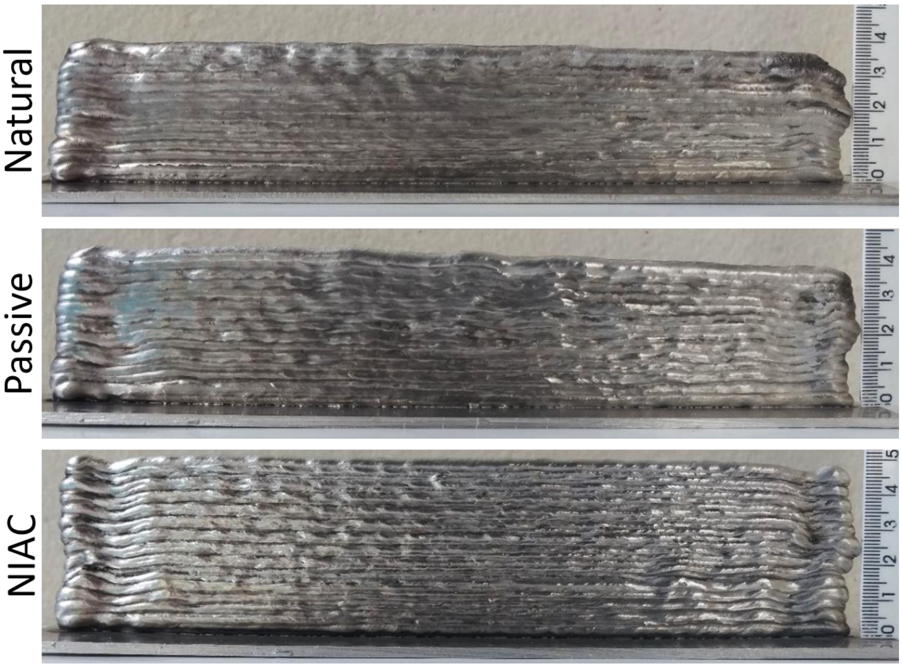

Figure 7. Typical aspects of the walls (after cleaning with a brush) deposited under the different thermal management approaches and with the same number of layers and deposition settings.

From the typical cross-sectional views displayed in Figure 8, it is visually confirmed that the tallest and slenderest walls were resulted from the NIAC application. Moreover, with this cooling technique the preform width remained virtually constant along its height, in contrast to what is verified for the Passive and yet more intensely for the Natural approach, which width significantly increased as the layers were deposited. This behavior can be explained by a molten pool enlargement due to heat accumulation. Despite the methodological nuances, Wu et al. (2018) reported a similar trend when using high interpass temperatures in WAAM of Ti6Al4V. The prominent width increasing towards the top of the wall with the Natural cooling approach is a clear evidence of the largest heat accumulation.

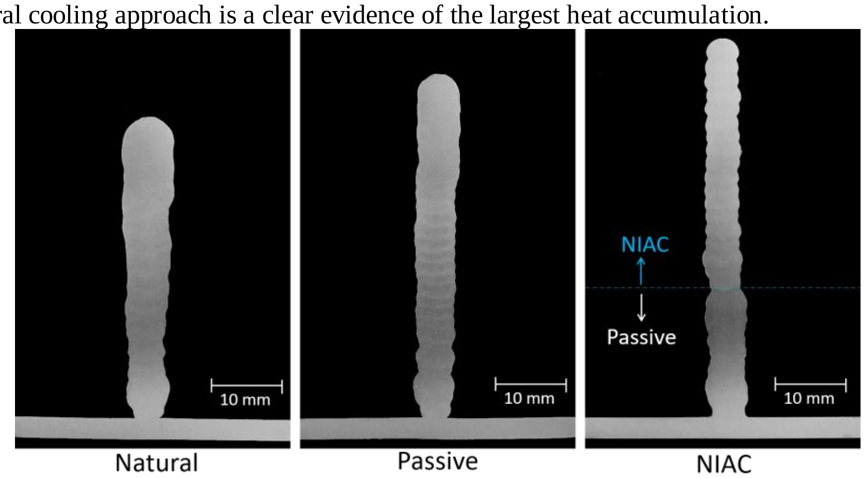

Figure 8. Typical cross-sectional views of the walls deposited under the different thermal management approaches and with the same number of layers and deposition settings.

4. CONCLUSIONS

The present work aimed to introduce and explore the potential of a concept for thermal management in WAAM, named as Near-Immersion Active Cooling (NIAC). Based on the results and compared with the conventional cooling approaches (Natural and Passive), the NIAC technique showed to be a feasible option to mitigate heat accumulation and, thus, to potentially cope with the related drawbacks of such AM emerging alternative. In addition, the following conclusions can be drawn concerning the implementation of the NIAC concept:

- ✓ The high heat sink power of this technique is capable of keeping the preforms at lower temperatures during all deposition time, independently of the preform height;
- ✓ Under this cooling technique, wall-shaped preforms become slender and taller and exhibit width virtually constant;
- ✓ The use of water in this technique does not lead to any measurable increase in porosity.

5. ACKNOWLEDGEMENTS

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