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# DEVELOPMENT OF A FORCED AIR-COOLING SYSTEM APPLIED TO ADDITIVE MANUFACTURING BY ARC DEPOSITION

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**Abstract.** *Smart manufacturing, a key aspect of Industry 4.0, focuses on Additive Manufacturing (AM) as a revolutionary approach. Unlike traditional manufacturing methods, AM involves layer-by-layer material addition to create parts. AM offers advantages such as improved finish, reduced manufacturing steps, and minimized material waste. Wire Arc Additive Manufacturing (WAAM) is a notable AM process for manufacturing metallic parts using cost-effective equipment, which saves materials and reduces environmental impacts. However, the accumulation of excessive heat in previously deposited layers during interpass deposition leads to macro and microstructural defects. To ensure high-quality and structurally sound products, controlling interpass temperature in the WAAM process is crucial. This work aims to develop a forced air-cooling system for WAAM, employing a microcontroller for integral control, a temperature sensor for interpass temperature measurement, a compressor for supplying gaseous fluid, and an actuator to control airflow. The system operates after each layer deposition to decrease the interpass temperature until reaching the desired level. The results demonstrate the system's functionality, enhancing manufacturing speed while reducing the time required to achieve the desired interpass temperature. This research contributes to understanding the influence of interpass temperature on WAAM-produced parts and paves the way for further studies in this area.*

**Keywords:** *WAAM, Interpass temperature, Forced air-cooling.*

## 1. INTRODUCTION

With the increasing demand for the production of complex parts with high levels of precision and quality, Additive Manufacturing (AM) has emerged as a promising technology (Santos; Silva, 2021). This technique involves the layer-by-layer manufacturing of a three-dimensional object based on a digital model (Silva; Souza, 2020). AM possesses fundamental characteristics, including a reduction in manufacturing steps and processes, material savings, and the ability to combine geometries and materials in innovative ways. In comparison to conventional methods that typically require multiple machines, specific tools, in addition to machining and finishing processes to produce a single part of complex geometry, AM can manufacture it in a single step or significantly fewer steps. This is achieved by depositing material layer by layer, thereby eliminating material waste generated by machining. This approach enables designers and engineers to create prototypes of their designs quickly and efficiently for testing or presentation to collaborators or clients. Additionally, AM is extensively applied in the production of complex goods, such as customized medical prosthetics. Consequently, AM is increasingly becoming an integral part of the industrial production chain (Hopkinson; Hague; Dickens, 2006; Strano et al., 2013; Guo; Leu, 2013).

Among the various additive manufacturing processes, Wire Arc Additive Manufacturing (WAAM) stands out as capable of producing high-density and mechanically robust metal parts (Santos et al., 2019). WAAM is an advanced additive manufacturing method that utilizes electric arcs to melt and deposit materials layer by layer, with the objective of building three-dimensional objects (Gong et al., 2015). In this process, an electric arc is established between a consumable electrode and the substrate, resulting in controlled fusion and deposition of the material (Seifi et al., 2016).

During WAAM processing, the electric arc generates high-focused temperatures at the point of contact between the consumable electrode and the substrate. This causes the consumable electrode material to melt and be deposited on the substrate, forming a solid layer. The process is repeated layer by layer until the desired three-dimensional object is fully

constructed (Gonçalves; Santos, 2021). However, one of the main challenges in WAAM is the thermal control during the manufacturing process. Inadequate cooling can lead to deformations and high levels of residual tensile stresses, which compromise the structural integrity of the part (Cunha et al., 2018). To address this issue, Santos et al. (2019) proposed the utilization of forced air cooling, which involves the application of compressed air jets onto the part to reduce its temperature.

Interpass temperature is a fundamental parameter in arc-based additive manufacturing, directly influencing the quality and properties of the manufactured parts. During the process, the interpass temperature refers to the temperature reached in the region adjacent to the current deposition, between two subsequent layers. Proper control of the interpass temperature is crucial to avoid issues such as residual stresses, distortions, and undesired porosities. Studies have emphasized the importance of this control to ensure the structural integrity and desired mechanical characteristics of the manufactured parts (Gonçalves; Santos, 2021).

Forced air cooling is a widely adopted technique in Wire Arc Additive Manufacturing (WAAM) to enhance the mechanical properties and reduce deformations of 3D-printed parts. According to Wu et al. (2019), the utilization of interpass forced air cooling during WAAM of Ti6Al4V titanium alloy resulted in a significant increase in the hardness and tensile strength of the 3D-printed part. This is because rapid interpass cooling prevents the formation of coarse grains, which can adversely affect the mechanical properties of the part. Additionally, Kozamernik et al. (2018) reported that the application of interpass forced air cooling combined with temperature control allowed for the 3D printing of small-sized metal components with high precision and improved surface finish. Forced air cooling is employed to control the cooling rate during WAAM and prevent the formation of residual stresses, which can lead to deformations and cracking in the 3D-printed part.

Therefore, forced air cooling is an effective technique for improving the mechanical properties and reducing deformations of 3D-printed parts during WAAM. Precise control of the interpass temperature and the utilization of interpass forced air cooling are critical factors in achieving high-quality and precise 3D-printed parts (Santos; Oliveira, 2022). Therefore, systems utilizing forced air cooling have emerged as an alternative for thermal control and reduction of manufacturing time for metal parts in WAAM. In this regard, prospective studies and applicability evaluations on the use of forced air-cooling systems applied to WAAM are of paramount importance in understanding the influence of thermal control on the quality and integrity of the produced metal preforms.

## 2. MATERIALS E METHODS

The apparatus for layer depositions consists of a Digiplus A7 power source in conjunction with the wire feeder, both from IMC Welding, an XYZ CNC table to ensure better precision in each layer deposition. Carbon steel wire was used for the depositions with the parameters shown in Table 1.

Table 1. Process parameters used for WAAM of the preforms.

Process	GMAW
Wire	Carbon steel
Average current	50 A
Peak current	250 A
Wire feed speed	4 m/min
Deposition speed	300 mm/s
Shielding gas	Argon 75% / Helium 25%
Angle of the torch with the workpiece/substrate	90°
Interpass temperature	80 °C

The CNC controller was programmed for a 2.5 mm increment in the Z-axis after each deposition, both in the preform with cooling and in the preform without the use of the forced air-cooling system applied to WAAM. Therefore, the interpass temperature was set at 80°C in both preforms as a fixed parameter during the experiments.

### 2.1 Forced air cooling applied in WAAM

The system developed at LABSOL (Welding Laboratory), at the Federal University of Campina Grande (UFCG), operates after each layer deposition, cooling it until it reaches the desired interpass temperature. The system is microcontrolled by ATmega328 using data obtained from the MLX90614 infrared temperature sensor, which is located beside the torch at the same level. The cooling is activated using an Air Compressor connected to the air diffuser on top of the torch, as Illustrated in Figure 1.

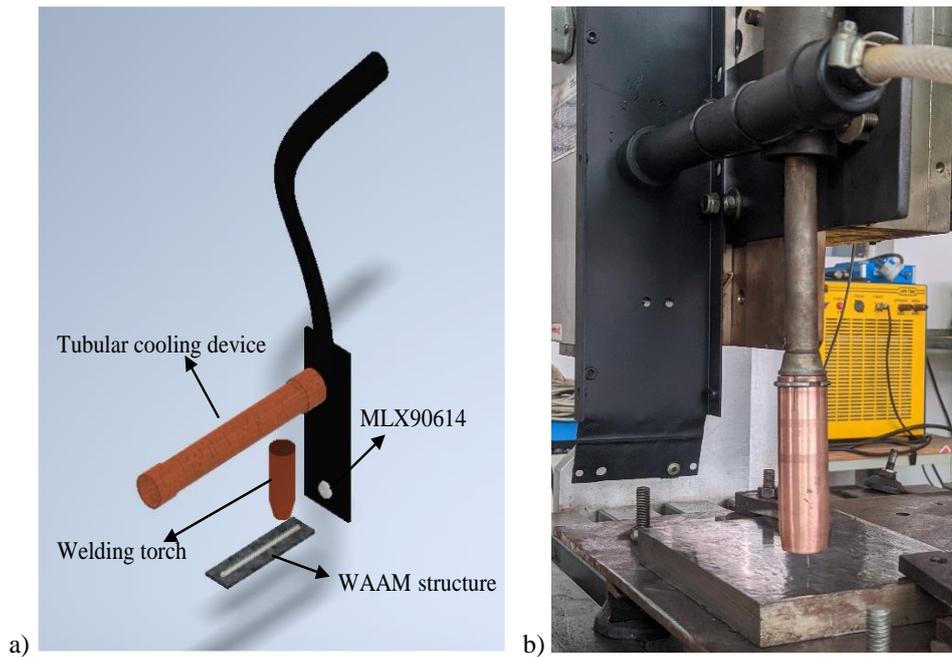


Figure 1. Setup for a) Forced air cooling system and b) Implemented system.

In addition, the activation of the air compressor is controlled by a stepper motor, as illustrated in Figure 2, allowing for control of the desired airflow in the diffuser. After proper cooling, the deposition process of the next layer is resumed. This precise control of the air compressor and airflow in the diffuser is essential to ensure an appropriate temperature during the metal deposition and to prevent the formation of structural defects. The integration of the stepper motor into the cooling system contributes to efficient and reliable control, allowing for precise adjustment of the cooling speed as needed. With this approach, it is possible to further optimize the manufacturing process, increasing the efficiency and quality of the parts produced through WAAM.

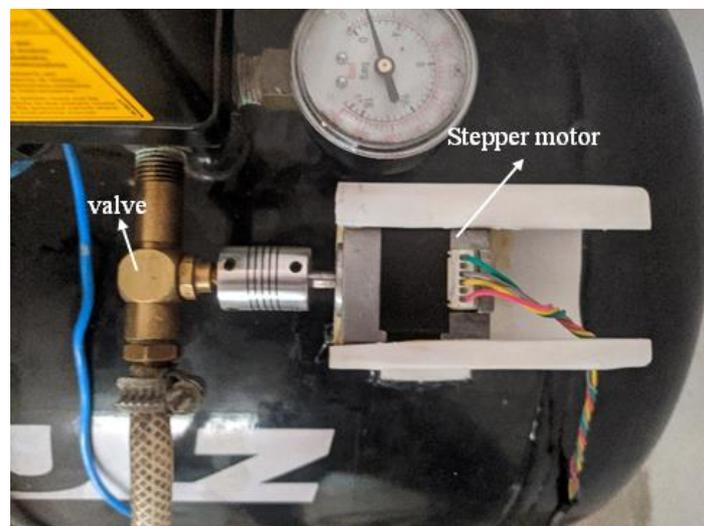


Figure 2. The drive system of the compressor.

### 3. RESULTS AND DISCUSSION

#### 3.1. Interpass time

Figure 3 illustrates the comparison of cooling times between each deposition when a forced air-cooling system or natural cooling is applied. The count of time was obtained by starting it when the deposition ceased until reaching the predetermined interpass temperature (80 °C), at which point a new deposition would begin. As observed in the graph shown in Figure 3a, the natural cooling process requires a significant production time compared to when the air-forced

cooling system is applied. This issue can be improved through the adoption of strategies such as simultaneous manufacturing of multiple parts and the implementation of highly effective cooling methods, such as partial immersion in liquid or forced-air cooling. This improvement has been demonstrated and confirmed in this case. The production time with forced-air circulation cooling shows a decrease of over 278% compared to the process with natural cooling, as evidenced in the graph.

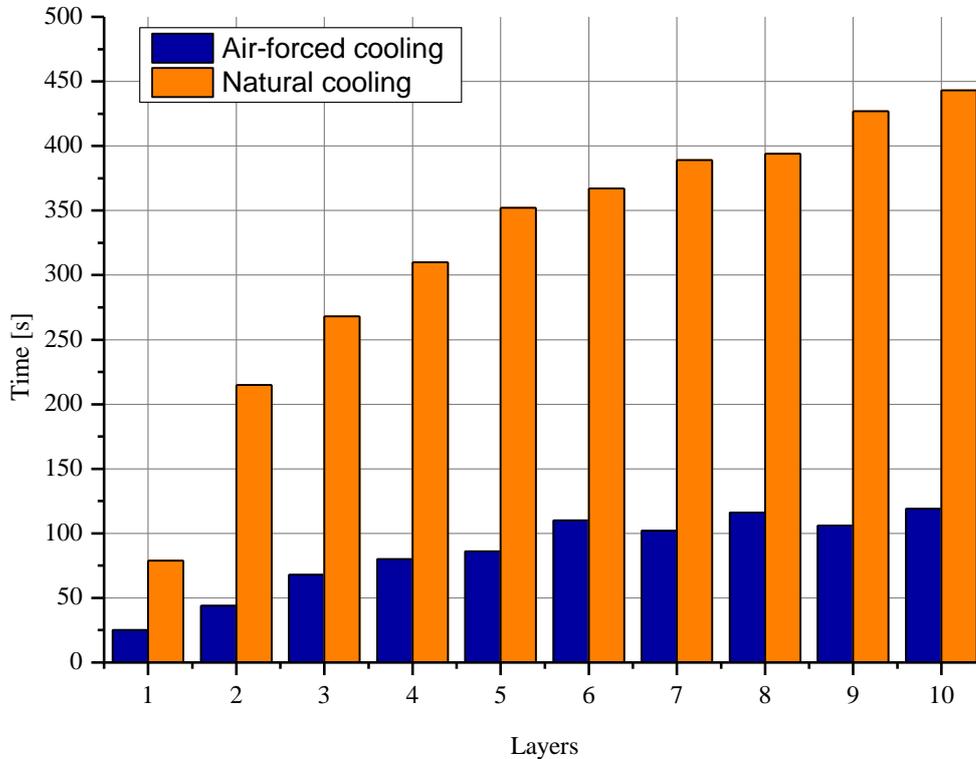


Figure 3. Interpass times between different types of cooling methods.

As the deposition of layers is advanced vertically towards the upper layers, a significant increase in the interpass time is observed. This is explained by the slower natural heat transfer to the base material in these regions. As evidenced by Kozamernik et al. (2018), the low thermal conductivity of the upper layer results in a lower heat dissipation rate to the surrounding environment, which prolongs the time required for the preform to reach an adequate temperature.

Furthermore, convective heat transfer to the air also contributes to the increased cooling time. As the upper layers of the wall cool down, the temperature gradient between the wall and the air decreases, thus reducing the rate of heat exchange between them. Therefore, an additional time period is necessary for the air to effectively cool the part, extending the total cooling time.

According to Kozamernik et al. (2018), the gradual increase in the interpass time when reaching the upper layers of the preform could be explained by the combination of these factors. It is important to consider these variations in interpass time during planning production processes in order to optimize system efficiency and overall performance. By employing additional cooling through forced-air circulation in addition with temperature control, there is a greater heat transfer to the air, resulting in a reduction of the amount of heat transferred to the base plate.

### 3.2. Geometric quality of the preforms

Figure 4 illustrates the usable area of the preforms front section under study. In this context, two cooling conditions were compared: forced-air cooling and natural cooling.

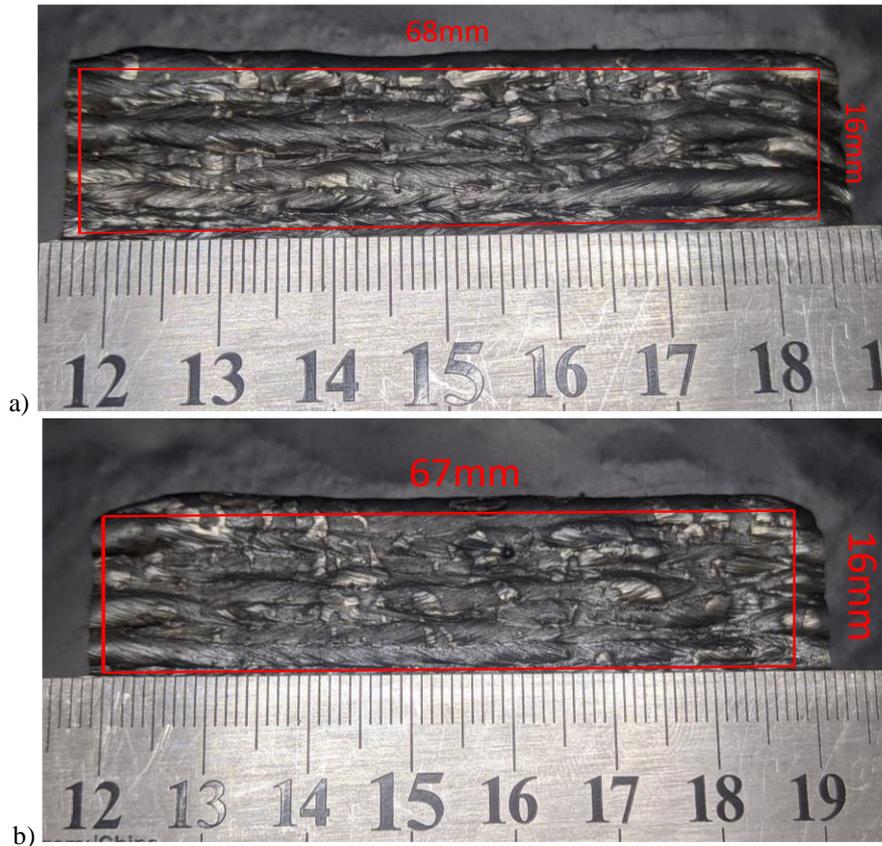


Figure 4. Frontal section area of the preform a) with natural cooling and b) with forced air cooling.

After conducting the analysis, it was observed that the preform subjected to forced-air cooling exhibited a slight decrease of 1.47% in its usable area compared to the preform subjected to natural cooling. This result indicates that forced-air cooling had a minimal impact on reducing the usable area of the front section of the object under study.

When examining the central cross-section of the preforms in Figures 5a and 5b, it can be observed that the preform with forced-air cooling maintained the same usable thickness as the preform without cooling.

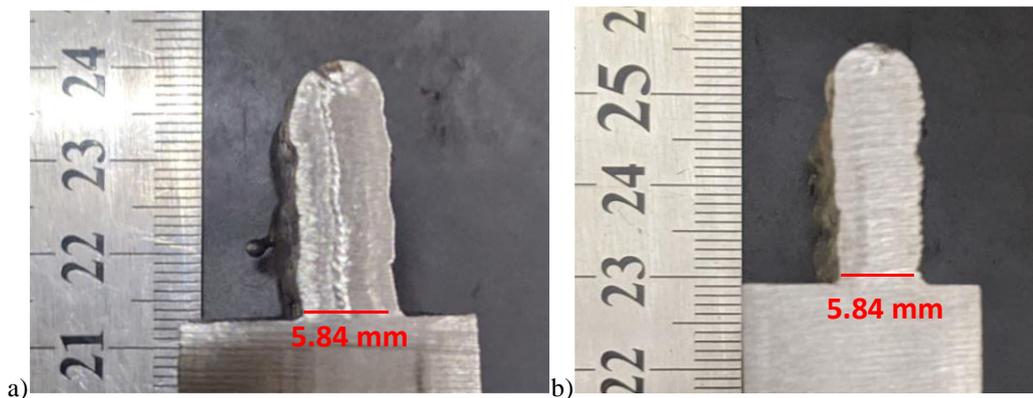


Figure 5 - Area of the cross-sectional view of the preform a) with natural cooling. Area of the cross-sectional view of the preform b) with forced-air cooling.

These findings may have significant implications for the design and optimization of cooling processes in similar applications, providing valuable insights into the differences in outcomes achieved with different cooling methods.

#### 4. CONCLUSIONS

Based on the results obtained in this study, it can be concluded that forced air cooling applied to Wire Arc Additive Manufacturing (WAAM) provides significant benefits in terms of interpass time and geometric quality of preforms. The use of interpass forced air cooling system demonstrated a reduction of approximately 278% in production time compared to natural cooling. This indicates that the utilization of this method allows for greater efficiency and productivity in the manufacturing of metallic parts through WAAM.

Furthermore, it was observed that forced air cooling did not significantly affect the useful area of the frontal section and the useful thickness of the preforms, indicating that the technique does not compromise the geometric aspect of the parts.

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