

Comparative Study of Basic and Interleaved Pixel Toolpaths in Wire Arc Additive Manufacturing

Carlos Eduardo Ferreira Bezerra

eduardobezerra@acad.ifma.edu.br

IFMA: Instituto Federal de Educacao Ciencia e Tecnologia do Maranhao

Lucas Gabriel Silva Lobato

Waldemir dos Passos Martins

Mauro Araújo Medeiros

Keyll Carlos Ribeiro Martins

Ferdinando Marco Rodrigues Borges

Samuel Filgueiras Rodrigues

Rafael Pereira Ferreira

Research Article

Keywords: Wire Arc Additive Manufacturing (WAAM), Toolpath planning, Pixel strategy, Efficiency, Effectiveness

Posted Date: June 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9829838/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on August 18th, 2026. See the published version at

<https://doi.org/10.1007/s00170-026-18956-z>.

Comparative Study of Basic and Interleaved Pixel Toolpaths in Wire Arc Additive Manufacturing

Carlos Eduardo Ferreira Bezerra, eduardobezerra@acad.ifma.edu.br¹ - (corresponding author)

Lucas Gabriel Silva Lobato, lucas_gabri_e@live.com²

Waldemir dos Passos Martins, waldemir@ifma.edu.br¹

Mauro Araújo Medeiros, mauro@ifma.edu.br¹

Keyll Carlos Ribeiro Martins, kmartins@ifma.edu.br¹

Ferdinando Marco Rodrigues Borges, ferdinando@ifma.edu.br²

Samuel Filgueiras Rodrigues, samuel.filgueiras@ifma.edu.br²

Rafael Pereira Ferreira, rafael.ferreira@ifma.edu.br¹

¹ Postgraduate Program in Mechanical Engineering (PPGMEC) – Federal Institute of Education, Science and Technology of Maranhão (IFMA), São Luís 65030-005, MA, Brazil

² Postgraduate Program in Materials Science and Technology (PPGCTM) – Federal Institute of Education, Science and Technology of Maranhão (IFMA), São Luís 65030-005, MA, Brazil

ABSTRACT

Additive Manufacturing (AM) has become increasingly prominent in the transition from rapid prototyping to the production of end-use components, particularly in metal manufacturing, due to its ability to fabricate geometrically complex parts with high dimensional precision. Among the most widely adopted AM technologies are Powder Bed Fusion (PBF) and Directed Energy Deposition (DED), with Wire Arc Additive Manufacturing (WAAM) emerging as a promising approach because of its high deposition rate and suitability for large-scale component fabrication. Nevertheless, defects such as porosity and lack of fusion still compromise part quality, making toolpath planning a critical aspect of process optimization. In this study, the operational efficiency and metallurgical performance of the WAAM process were evaluated using two toolpath strategies, namely Basic Pixel and Interleaved Pixel. Operational efficiency was assessed in terms of printing time, travel distance, and number of stops, whereas metallurgical and geometric performance were analyzed based on microhardness, microstructure, surface quality, and dimensional conformity. The results showed that both strategies exhibited similar operational efficiency, with differences of less than 0.2%. However, the Basic Pixel strategy demonstrated superior overall performance, providing higher dimensional accuracy, improved surface quality, and lower defect incidence. In contrast, the Interleaved Pixel strategy promoted greater microstructural homogeneity and lower microhardness variation, although it exhibited higher sensitivity to thermal fluctuations. Overall, despite the microstructural advantages associated with the Interleaved Pixel strategy,

the Basic Pixel strategy proved to be the most robust approach, combining improved mechanical performance, structural integrity, and geometric accuracy.

Keywords: Wire Arc Additive Manufacturing (WAAM), Toolpath planning, Pixel strategy, Efficiency, Effectiveness.

1. Introduction

Additive Manufacturing (AM), also referred to as 3D printing, has become a key enabling technology for the fabrication of complex components, evolving from applications primarily focused on prototyping to the production of functional and end-use parts. Based on the layer-by-layer deposition of material, AM offers significant advantages over conventional manufacturing processes, including greater design freedom, reduced material waste, and lower production costs [1].

Among metal AM technologies, Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) have attracted considerable attention due to their ability to manufacture components with high geometric complexity, dimensional precision, and structural performance. In particular, DED has gained prominence because of its suitability for repairing damaged components and fabricating large-scale metallic structures.

Within the DED category, Wire Arc Additive Manufacturing (WAAM) has emerged as a promising technology owing to its high deposition rate, relatively low operational cost, and broad material compatibility. In WAAM, an electric arc is used to melt a metallic wire, which is deposited layer by layer to form the desired geometry. The process is compatible with a wide range of materials, including stainless steels, titanium alloys, and aluminum alloys, making it suitable for several industrial applications. However, the quality and reliability of WAAM-produced components are strongly influenced by the adopted toolpath planning strategy, which defines the trajectory followed by the welding torch during deposition [2].

Toolpath planning plays a fundamental role in determining both process efficiency and component quality in WAAM. The selection of an appropriate deposition strategy depends on the geometry of the component as well as the desired mechanical and geometric characteristics, since each strategy presents distinct advantages and limitations. Furthermore, advances in process simulation and control are expected to improve the accuracy and robustness of toolpath generation, thereby expanding the industrial applicability of WAAM.

One of the major challenges associated with WAAM is the formation of valleys between adjacent deposited beads. This phenomenon, highlighted by the yellow circles in Fig. 1, can be observed particularly between beads 1 to 4 in the first layer and beads 5 to 8 in the second layer.

Such geometric discontinuities may lead to the formation of interlayer voids, compromising surface flatness, structural integrity, and ultimately the reliability of the manufactured component.

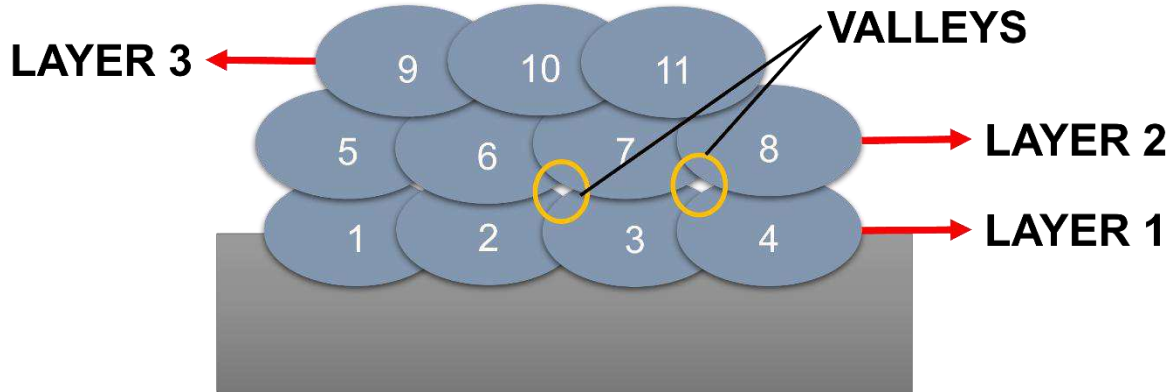


Fig. 1 Demonstration of adjacent deposited beads (Layer 1 and Layer 2) and interleaved deposited beads (Layer 2 and Layer 3)

The most comprehensive approach to mitigating the valley formation problem consists of determining the optimal distance between consecutive beads, so that the layer surface becomes as flat as possible. In this context, the literature presents several techniques and models aimed at estimating the geometry of weld beads applied in additive manufacturing. The models proposed by Suryakumar et al. [3], Cao et al. [4], and Ding et al. [5] consider only the bead width to determine the optimal center-to-center distance between adjacent beads. In addition to bead width, the model proposed by Xiong et al. [6] also takes into account the welding speed and wire feed speed. The model developed by Hu et al. [7] further considers bead height in addition to bead width. If the appropriate model is not selected, the surface quality of the printed component may be poor. Zhou et al. [8] proposed overlapping models based on isosceles trapezoids for the finite element modeling of overlapping weld bead elements. The model proposed by Foorginejad et al. [9] mainly considers the distance between weld beads and the surface tension that pulls the molten material toward the vertex of the previous weld bead, thereby helping to produce a flatter surface.

In addition to these approaches, hybrid manufacturing strategies combining additive and subtractive processes have also been investigated. In such approaches, each deposited layer is subsequently machined to improve flatness and dimensional accuracy, as reported by Li et al. [10]. Rodrigues et al. [11] proposed an alternative strategy based on the application of a forming roller after the deposition of each layer or group of layers. The induced compression improves flatness, reduces porosity and residual stresses, and promotes plastic deformation, thereby

altering the microstructure of the deposited material. Nevertheless, this approach is mainly limited to thin-wall structures produced through unidirectional deposition, restricting its broader applicability. Moreover, although these strategies can improve surface quality and dimensional conformity, they significantly increase manufacturing time due to the repeated transitions between additive and subtractive operations.

An alternative approach was proposed by Liu et al. [12], who introduced the use of interleaved deposition passes in toolpath planning, as illustrated in Fig. 1 by beads 9, 10, and 11 deposited over the second layer. In this strategy, the deposition paths of a given layer are positioned between two adjacent beads from the previous layer. For example, bead 9 is deposited between beads 5 and 6. According to the authors, this approach improves interlayer filling and reduces the occurrence of voids generated by lateral bead overlapping.

Although the interleaved strategy appears promising because it does not significantly increase manufacturing time, several important aspects remain insufficiently explored. The experimental setup adopted by Liu et al. [12] employed relatively large bead spacing values for both the reference and test walls, which may have influenced the reported results. In addition, the resulting geometry tends to exhibit a conical profile, representing a potential geometric limitation of the strategy. Furthermore, there is still a lack of studies investigating whether the altered interlayer interaction associated with interleaved deposition may affect the mechanical performance of the manufactured component. Similarly, the actual influence of this strategy on process efficiency, particularly in terms of production time, remains unclear.

Considering these gaps, the present study investigates the influence of basic and interleaved interlayer toolpath strategies on the efficiency and effectiveness of manufacturing complex WAAM components. Section 2 presents the analysis of operational efficiency, whereas Section 3 addresses operational effectiveness. Both sections include their respective methodologies, results, and discussions. Finally, Section 4 summarizes the main conclusions of the study.

2. Operational Efficiency

2.1. Methodology

The operational efficiency of the toolpath planning strategy was evaluated based on torch travel distance, total build time, and the number of non-deposition movements. A toolpath strategy is considered operationally efficient when it minimizes torch travel distance and idle movements while reducing overall manufacturing time.

2.1.1. Deposition Strategy

To reproduce a realistic manufacturing scenario, an innovative toolpath strategy known as Pixel was adopted. This strategy, developed by Ferreira and Scotti [13], employs optimization techniques for automated toolpath generation. Figure 2 illustrates the main stages of the approach, beginning with the two-dimensional contour of the layer obtained from the previous slicing step, a procedure inherently performed by print planning software.

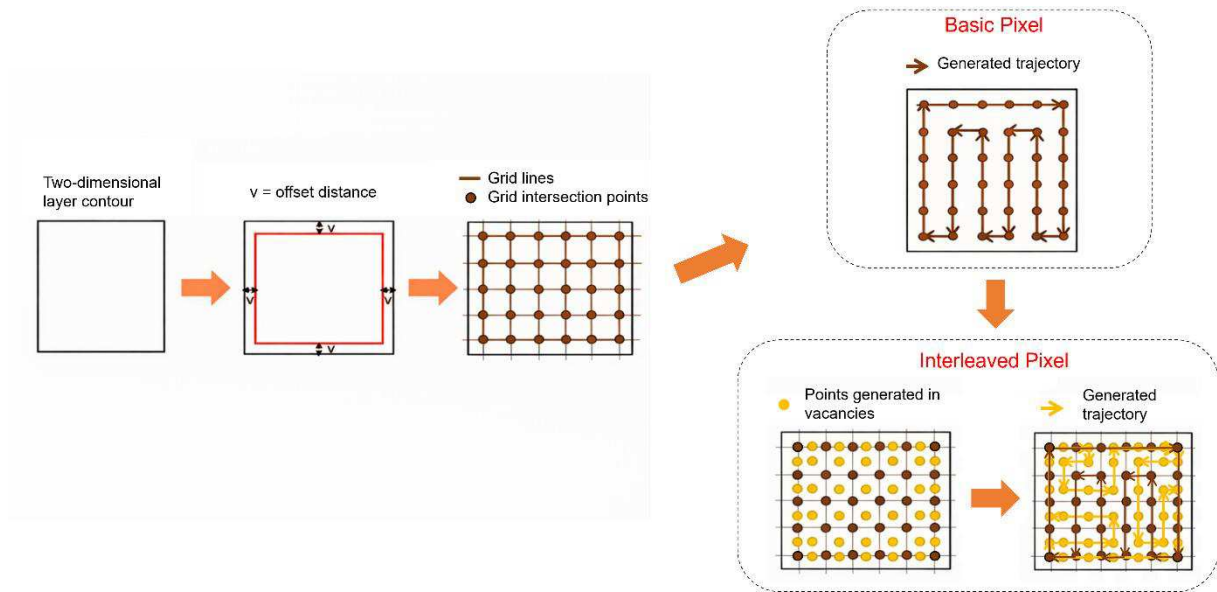


Fig. 2 Toolpath Generation Process Flow in the Pixel Strategy

Subsequently, an offset operation is applied at a distance V from the two-dimensional layer contour, with this parameter defined by the operator, as highlighted in red in Fig. 2. The resulting bounded region is then discretized into equally spaced points, referred to as brown nodes, generated from the intersections of a regular grid. The spacing between the grid lines is also defined by the operator and depends directly on the selected process parameters. After discretization, an optimization algorithm developed by the authors is employed to connect the nodes and generate the printing toolpath, represented in Fig. 2 by the brown arrows. Further details regarding this strategy can be found in Ferreira and Scotti [13].

As stated in the objective of this study, the main goal is to compare a conventional deposition strategy, represented here by the basic Pixel strategy described previously, with an interleaved deposition strategy. To generate the interleaved Pixel toolpath, additional points, or nodes, represented in yellow, are created in the gaps between the brown nodes of the previous layer, as illustrated in Fig. 2. Once these nodes are defined, the toolpath is generated following a procedure similar to that adopted for the basic Pixel strategy.

It is important to highlight that not all regions of the component will present interleaved beads, as can be observed in Fig. 2. However, in this example, a large portion of the yellow toolpath runs through the spaces between the brown toolpath segments, corresponding to the previous layer. This proportion may vary according to the geometry of the component.

2.1.2. Computational Simulations

Using the two strategies described in the previous subsection, namely Basic Pixel and Interleaved Pixel, machine instructions (G-code) were generated through the software developed by Ferreira et al. [14] for subsequent offline simulation and component fabrication, as illustrated in Fig. 3. For each printed component, specific evaluation criteria were defined to enable a comparative analysis of the operational efficiency associated with each toolpath strategy during the manufacturing process.

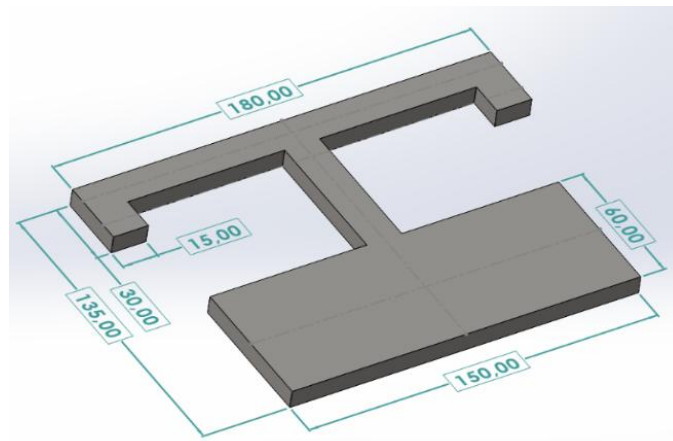


Fig. 3 Perspective view of the case study component with its respective dimensions.

In terms of operational efficiency, the toolpath distance, printing time, and number of non-deposition movements were analyzed for both components. These criteria were evaluated through offline simulations of the printing process using the parameters listed in Table 1 and the SprutCAM software. These values were obtained experimentally based on the experimental settings detailed in Table 2. The distance between the bead centers, or step-over distance, was set to 4.87 mm, according to the overlapping model described by Ding et al. [5].

Table 1 Input parameters for offline simulation of the studied components.

Input parameters	Value
Bead height	2.49 mm
Bead width	6.60 mm
Deposition speed	40 cm/min
Step-over distance	4.87 mm

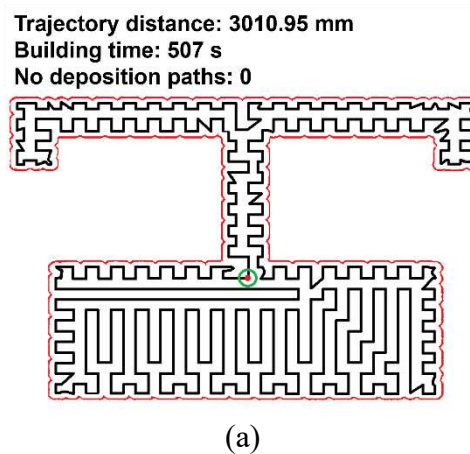
Table 2 Experimental settings for the printing processes.

Process	Pulsed GMAW
Arc deposition equipment	Fronius CMT – TransPuls Synergic 500
Rig	3-axes CNC gantry (500 x 500 x 300mm)
Substrate	SAE 1020 carbon steel (200 x 200 x 12mm)
Substrate cooling	Active cooling (NIAC)
Feedstock (wire)	AWS ER90S-B3 – $\Phi 1.2$ mm
Shielding gas	Ar e CO ₂ (4%) – 15 L/min
CTWD	17 mm
Deposition speed	40 cm/min
Wire feed speed	5.2 m/min
Interlayer	80 °C

Notes: NIAC = near-immersion active cooling; CTWD = contact tip to work distance.

2.2. Results and Discussion

Figure 4 presents the results of the printing simulations, highlighting the operational efficiency criteria associated with the two analyzed strategies, Basic Pixel and Interleaved Pixel. In the Basic Pixel strategy, the component is fabricated through the alternating deposition of the toolpaths shown in Fig. 4(a) and Fig. 4(b), corresponding to the odd and even layers, respectively. This configuration produces the characteristic bead-on-bead deposition pattern commonly observed in additive manufacturing processes. In contrast, the Interleaved Pixel strategy combines the toolpaths illustrated in Fig. 4(a) and Fig. 4(c), representing the odd and even layers, respectively, thereby promoting an interleaved deposition pattern in which each bead is positioned between two adjacent beads from the previous layer. A total of six deposited layers were considered for both strategies.



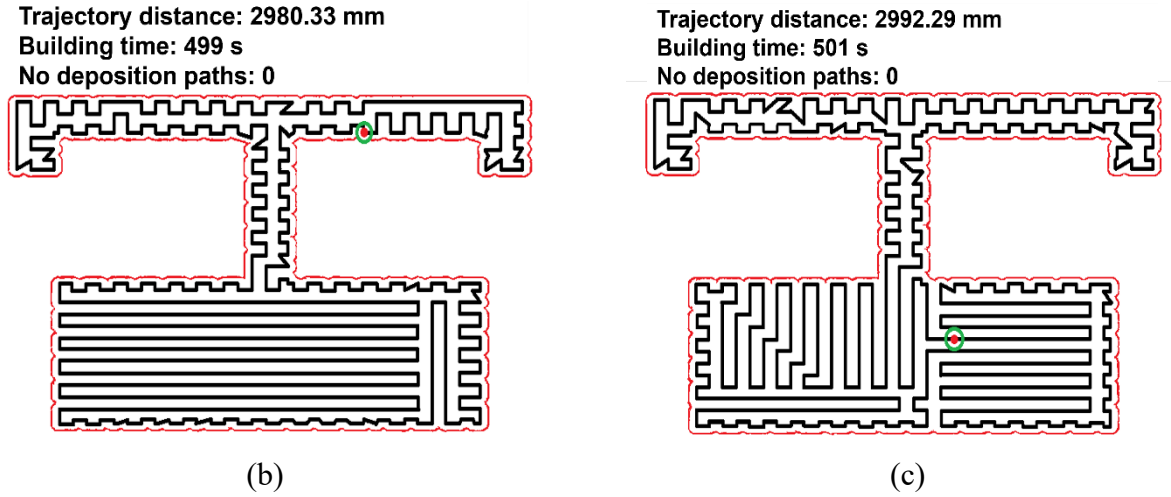


Fig. 4 Toolpaths used during the printing process: (a) odd layer adopted in both toolpath strategies; (b) even layer corresponding to the Basic Pixel strategy; and (c) even layer corresponding to the Interleaved Pixel strategy.

2.2.1. Printing Time

Analyzing the toolpaths used for printing the even and odd layers together, the total printing time of the components can be observed for both printing strategies, Basic and Interleaved. The deposition times of the toolpaths were very similar, with the Interleaved strategy requiring 3024 seconds, or 50 minutes and 24 seconds, and the Basic strategy requiring 3018 seconds, or 50 minutes and 18 seconds. This represents a difference of only 6 seconds between the two strategies. Therefore, the strategies effectively differ by approximately only 0.2% in terms of toolpath distance, indicating a practically negligible difference, as also observed for the toolpath length.

2.2.2. Trajectory Distance

From the comparison of the toolpath distances, it can be observed that the strategies used to print the even and odd layers share one identical deposition layer, differing only in the layer responsible for generating the overlapping effect, shown in Fig. 4(a). As a result, both printing strategies, Basic and Interleaved, exhibited very similar toolpath distances, with the Interleaved strategy presenting a total distance of 18,009.72 mm and the Basic strategy 17,973.84 mm. This corresponds to an effective difference of approximately only 0.2% between the two toolpath distances, demonstrating a practically negligible variation. Consequently, the Basic Pixel strategy presented the shortest toolpath distance, although not significantly shorter than that of the Interleaved Pixel strategy.

2.2.3. Number of Stops

Regarding non-deposition movements, these are not observed when the Pixel toolpath planning strategy is used. This occurs because the strategy employs a mesh of points, or nodes, which are interconnected to define the entire deposition path through an optimization algorithm [13, 15].

3. Operational Effectiveness

3.1. Methodology

Effectiveness is defined as the ability of the process to manufacture components with adequate mechanical performance, structural integrity, and dimensional conformity relative to the design specifications. To assess the mechanical performance and structural integrity associated with the two investigated strategies, namely Basic Pixel and Interleaved Pixel, the printed components were characterized through microhardness measurements and microstructural analysis using optical microscopy.

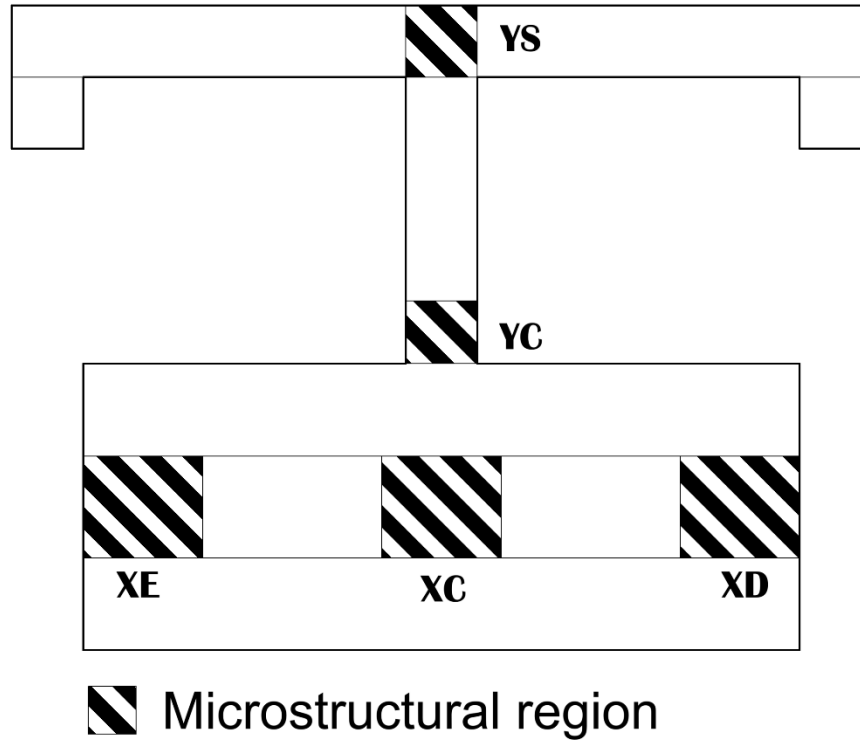
With respect to structural integrity, both the surface condition and the internal features of the manufactured components were evaluated. Initially, external defects were identified and quantified, followed by the investigation of internal discontinuities using appropriate inspection techniques. This methodology enabled the correlation of microstructural characteristics and microhardness measurements with the overall structural quality of the fabricated components. In addition, the dimensional conformity of the samples was verified in relation to the design model in order to ensure the geometric accuracy of the component. The details of all these analyses are described in the following sections.

3.1.1. Sample extraction strategy

Additionally, to ensure a comprehensive and representative characterization of the components produced by additive manufacturing, specimens were extracted as illustrated in Fig. 5. Table 3 presents the chemical composition of both the substrate material and the filler metal, AWS ER90S-B3 wire. Figure 5 also shows the distribution of the sampling regions selected for microstructural and microhardness analyses.

Table 3 Chemical composition

%	C	Si	P	Mn	Cr	Mo	S
AWS ER90S-B3 (filler material)	0.09	0.55	-	0.60	2.55	1.05	-
SAE 1020 Carbon Steel (substrate)	0.18- 0.23	0.15- 0.35	0.030	0.30- 0.60	-	-	0.050

**Fig. 5** Sampling regions within the printed component.

To investigate the microstructure at different locations within the component, five regions of interest were defined, as indicated by the diagonal hatching patterns shown in Fig. 5. From each region, two specimens were extracted, one from the XY plane, enabling the analysis of bead morphology within the same deposited layer, and another from the transverse XZ plane, allowing the evaluation of layer morphology along the build direction.

3.1.2. Hardness

For the Vickers microhardness analysis, systematic measurements were carried out on all specimens prepared for microstructural characterization. In each specimen, ten indentations were performed along the X direction to evaluate hardness uniformity both across the surface and along the build direction of the component. A vertical line of equally spaced indentations

(0.5 mm) was made with 980.7mN, an admissible speed of ≤ 0.200 mm/s and 15 s of holding time in each region. This approach allows the identification of local variations potentially associated with the anisotropic nature of the additive manufacturing process. Furthermore, the indentation layout was designed to cover the entire region of interest, thereby ensuring greater representativeness and reliability of the obtained results.

3.1.3. Thermography

A FLIR A325 thermographic camera was used to capture the global temperature distribution of the components during the deposition process. The equipment has a resolution of 320×240 pixels, an acquisition rate of up to 60 Hz, and an accuracy of ± 2 °C, allowing reliable measurements under dynamic conditions. In addition, the camera is capable of operating at high temperature ranges, with a measurement limit of up to 2000 °C, making it suitable for applications in wire arc additive manufacturing.

The experimental system was configured as shown in Fig. 6, with the camera positioned laterally to the quasi-immersion cooling system tank. A mirror inclined at 45° was used to enable image acquisition of the deposition process from a top-view perspective. This configuration allowed adequate process monitoring, even with the limitations associated with direct camera positioning. The regions of interest illustrated in Fig. 5 were analyzed using FLIR Research Studio software, enabling the reconstruction of the thermal cycles associated with each evaluated region.

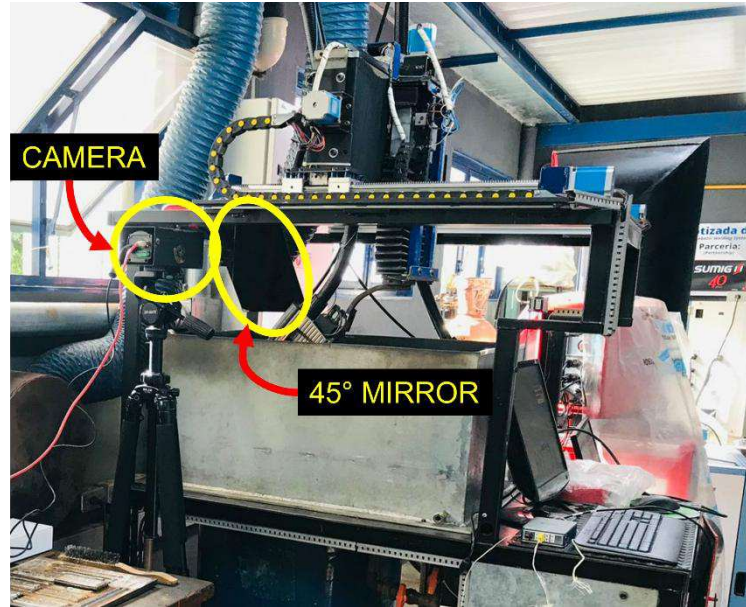


Fig. 6 Thermographic camera positioning configuration within the experimental setup.

3.1.4. Microscopy

Microstructural characterization was conducted by metallographic optical microscopy using magnifications ranging from $50\times$ to $500\times$, selected according to the requirements of each analysis. Micrographs acquired at different magnification levels enabled a detailed assessment of microconstituent morphology, grain distribution, and phase evolution across the analyzed regions. This technique enables the identification of microstructural variations directly associated with the thermal history imposed during the deposition process, particularly regarding grain refinement mechanisms and the prevalence of specific microconstituents. Moreover, the microstructural analysis provided a fundamental framework for interpreting the microhardness results, enabling correlations between local hardness variations and the thermal conditions experienced throughout the manufacturing process.

3.1.5. Analysis of Internal and External Defects in Printed Parts

A visual analysis was performed to identify the presence of both external and internal defects in the printed components. The inspection of external defects considered aspects such as surface irregularities, visible discontinuities, open porosity, and geometric deformations. For the detection of internal defects, it was necessary to machine the component surface to a depth of 5 mm, allowing the exposure of internal layers and enabling the assessment of possible flaws, such as pores, internal cracks, or lack of fusion between layers.

3.1.6. Analysis of the Dimensional Conformity of the Printed Part and the CAD

For the dimensional conformity analysis, the printed components were digitized using a HandyScan 3D™ scanner from Creaform, selected due to its high accuracy in capturing complex surfaces. The meshes obtained from the scanning process were compared with the original CAD model using VXEelements software, from the same company, which provides advanced tools for aligning and evaluating discrepancies between physical and virtual models. In addition to these steps, a Python program was specifically used to perform detailed analyses along the sample lines, as shown in Fig. 7. This program was used to identify dimensional variations and evaluate the geometric accuracy of the components in critical regions, contributing to a more in-depth analysis of process quality. For example, the sample lines 1 and 2 cross specific regions of the T-intersection, identified by [16] as areas with a higher probability of presenting geometric deviations. Sample line 4 extends longitudinally along the component, covering both the thin-wall region, or slender area, and the bulky region.

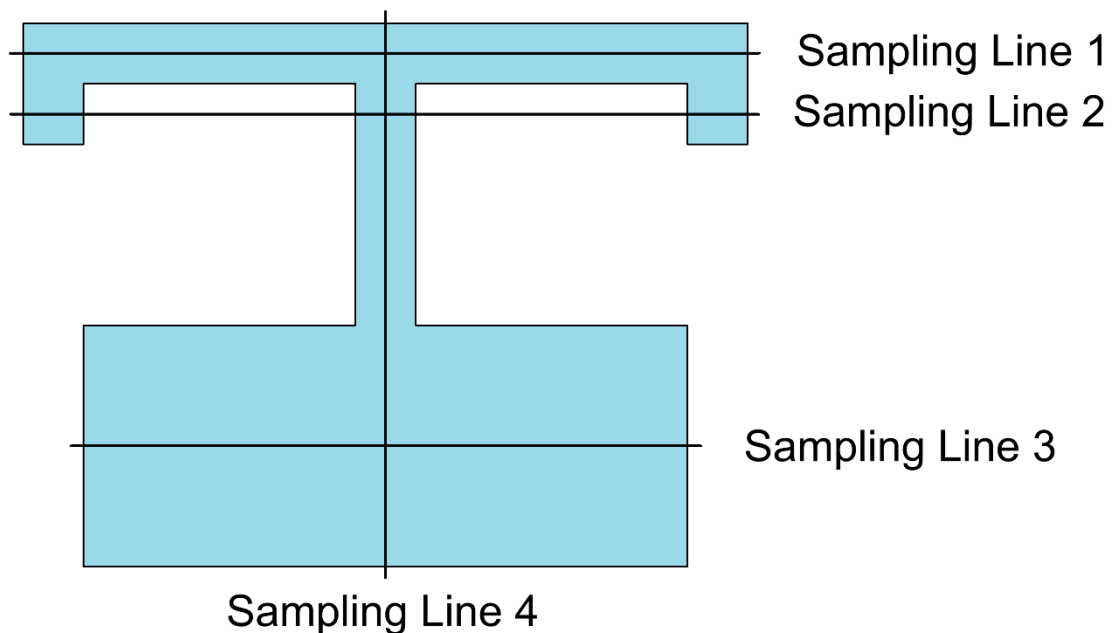


Fig. 7 Sample lines for dimensional analysis

The waviness analysis of the component was performed using the digitized meshes of the printed parts. These meshes were converted into point clouds, and a Python program was used to evaluate the surface waviness of the printed components along the sample lines presented in Fig. 7.

3.2. Results and Discussion

3.2.1. Microhardness

3.2.1.1. Basic Pixel

The microhardness distribution presented in Fig. 8 reveals significant variations among the analyzed samples. Sample YS exhibited the highest average microhardness, reaching 396 HV, whereas sample XD showed the lowest value, corresponding to 321.7 HV. Samples XE (368.8 HV) and YC (369.1 HV) also demonstrated relatively high hardness levels. In contrast, samples XC (333.2 HV), ZXD (324.9 HV), and ZYC (323.7 HV) presented lower microhardness values, approaching the minimum range observed within the dataset. Meanwhile, samples ZXE (356.6 HV), ZYS (349.2 HV), and ZXC (355.6 HV) exhibited intermediate hardness levels, positioned between the upper and lower extremes identified in the analysis.

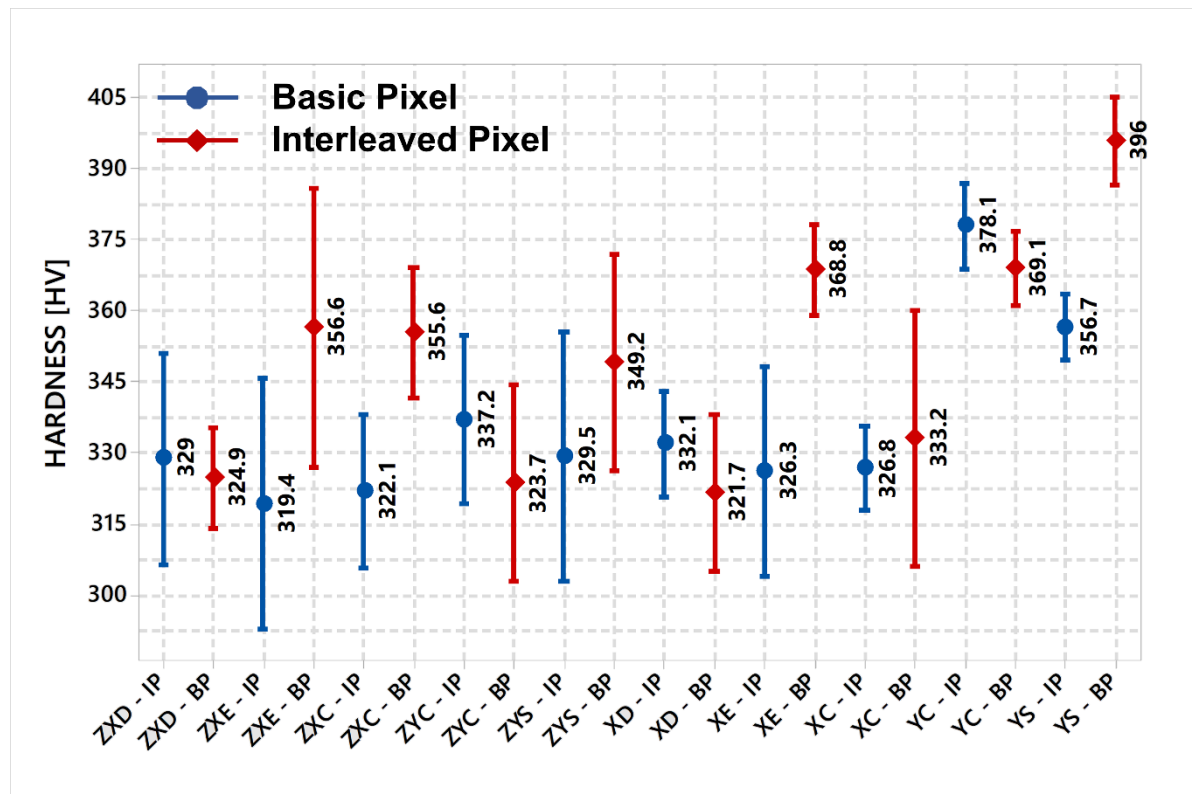


Fig. 8 Hardness of Basic Pixel (BP) vs. Interleaved Pixel (IP)

The results highlight the pronounced microhardness heterogeneity throughout the component, a behavior directly associated with the thermal anisotropy inherent to the WAAM process. Samples exhibiting higher hardness values, such as YS, XE, and YC, suggest the predominance of refined microstructures, potentially consisting of bainite and acicular ferrite formed under higher cooling rates. This interpretation is consistent with the findings reported

by Teixeira et al. [17], who demonstrated the strong influence of arc energy and thermal history on the evolution of microstructure and microhardness in WAAM-fabricated components, particularly in thin-wall structures.

In contrast, samples XC, ZYC, and ZXD, which exhibited lower microhardness values, reflect regions subjected to greater heat accumulation and successive reheating cycles, favoring microstructural coarsening and the formation of more stable constituents, such as polygonal ferrite, in addition to possible tempering effects. According to Teixeira et al. [17], variations in heat input, mainly controlled by the deposition parameters, tend to modify the local thermal cycle, directly influencing microstructural evolution and, consequently, the mechanical properties of the material.

Samples exhibiting intermediate microhardness values, such as ZXE, ZYS, and ZXC, correspond to regions of microstructural transition, where a balance exists between the cooling and reheating effects inherent to the layer-by-layer deposition process. In these regions, the successive thermal cycles are insufficiently severe to promote pronounced microstructural coarsening, yet not rapid enough to produce highly refined microstructures, resulting consequently in intermediate mechanical properties. This behavior further reinforces the strong correlation between process parameters, thermal history, and microstructural evolution in wire arc additive manufacturing.

3.2.1.2. Interleaved Pixel

As shown in Fig. 8, samples YC and YS exhibited the highest average microhardness values, reaching 378.1 HV and 356.7 HV, respectively, whereas sample ZXE presented the lowest average value, corresponding to 319.4 HV. The remaining samples displayed behavior comparable to that observed for ZXE, with no significant differences among them. Specifically, the measured values were 326.8 HV for XC, 326.3 HV for XE, 332.1 HV for XD, 329.0 HV for ZXD, 321.1 HV for ZXC, 337.2 HV for ZYC, and 329.5 HV for ZYS, indicating relatively low microhardness variation within this group.

The variation observed in the microhardness values is associated with the microstructural anisotropy induced by the WAAM process, which is an inherent characteristic of additive manufacturing process. During fabrication, the material is subjected to successive thermal cycles of heating and cooling resulting from layer-by-layer deposition, promoting directional thermal gradients and different solidification rates along the build directions.

In addition to the thermal history, the local deposition geometry exerted a significant influence on microstructural evolution. Regions YC and YS, as well as ZYS and ZYC, were

produced under geometric conditions resembling thin-wall structures, which favor enhanced heat dissipation and higher cooling rates. Such conditions promote microstructural refinement and the formation of finer constituents, particularly bainite, thereby resulting in increased hardness values, as also reported by Teixeira et al. [17].

In contrast, regions manufactured with a larger material volume tend to exhibit greater heat accumulation and lower thermal dissipation efficiency, resulting in more intense and prolonged reheating cycles during the deposition of subsequent layers. This behavior is directly associated with the positive thermal balance inherent to the WAAM process, in which the heat input exceeds the heat extraction capacity, leading to a progressive increase in the preform temperature throughout the manufacturing process, as discussed by Santos [18].

As a consequence, this thermal history promotes grain growth, microstructural coarsening, and the development of regions characterized by coarser microstructures, thereby reducing the density of interfaces that act as barriers to dislocation motion. Furthermore, the successive reheating cycles may induce localized tempering effects and partial spheroidization of microconstituents, contributing to a reduction in local mechanical strength. Consequently, these regions tend to exhibit lower microhardness values, as observed in the samples associated with bulkier geometries.

This behavior is consistent with findings reported in the literature, which indicate that, in WAAM processes, regions containing larger material volumes are typically associated with lower cooling rates and the formation of more stable and long-lasting molten pools. Such conditions favor the development of coarser microstructures and, consequently, lower hardness values when compared with regions characterized by lower thermal mass.

3.2.1.3. Comparison between Basic Pixel and Interleaved Pixel

When comparing the microhardness results obtained for the two deposition strategies, as presented in Fig. 8, it can be observed that the Basic Pixel strategy exhibited a broader microhardness distribution, with values ranging from 321.7 to 396 HV. Under this condition, pronounced hardness peaks were identified in samples YS (396 HV), XE (368.8 HV), and YC (369.1 HV), whereas substantially lower values were observed in regions such as XD (321.7 HV).

In contrast, the Interleaved Pixel strategy exhibited a more homogeneous microhardness distribution, with values ranging from 319.4 to 337.2 HV. Nevertheless, samples YC and YS remained among the regions with the highest average hardness values, reaching 378.1 HV and 356.7 HV, respectively. However, compared with the Basic Pixel strategy, a reduction in the

maximum hardness peaks was observed, accompanied by a greater number of statistically equivalent regions.

Overall, the microhardness values obtained in this study are relatively high when compared with those reported by Dirisu et al. [19] and Preecha et al. [20], who investigated the same material using similar additive manufacturing processes. However, these values are consistent with the work of Teixeira et al. [17], who used passive NIAC cooling and the same ER90S-B3 filler material.

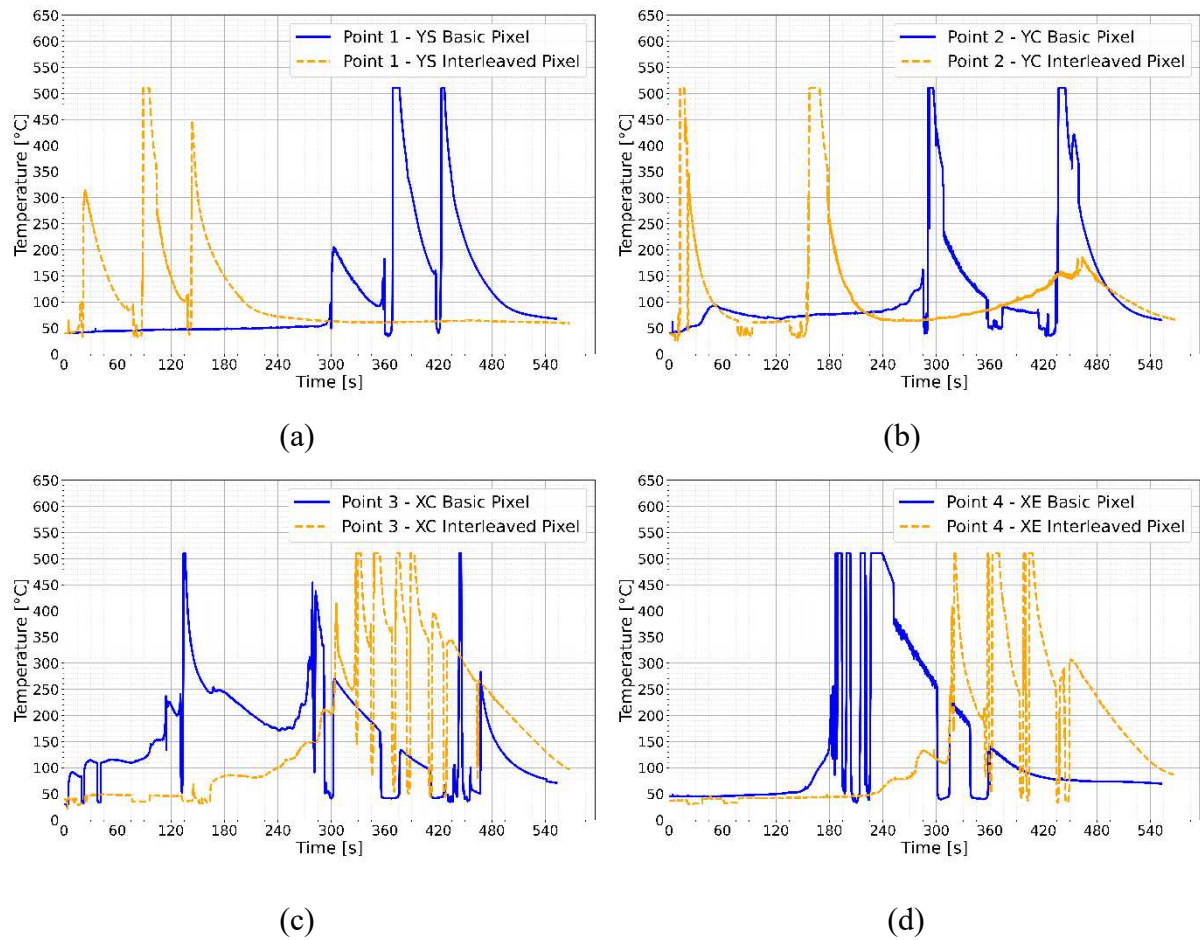
From a thermal perspective, the results indicate that the Interleaved Pixel strategy promotes a redistribution of heat input and repeated reheating cycles throughout the deposition process. However, this dynamic does not lead to a more uniform thermal history, instead, it intensifies local thermal variations between adjacent regions. As a consequence, the process exhibits a more heterogeneous thermal evolution, favoring the development of microstructural heterogeneity along the component. Although this condition may contribute to an apparent convergence of average hardness values in certain regions, it is intrinsically associated with a less homogeneous thermal history characterized by more pronounced local thermal fluctuations.

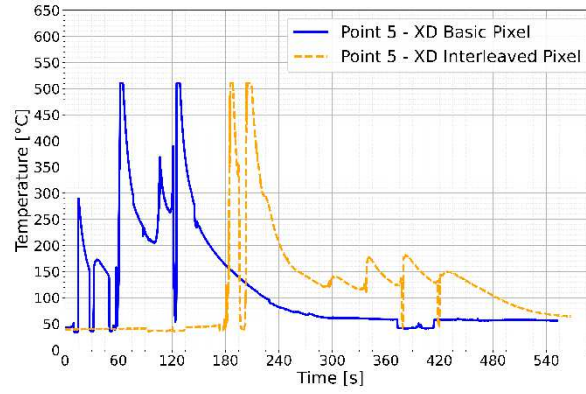
As a consequence, localized increases in interpass temperature occur, accompanied by reductions in the local cooling rate and intensified heterogeneous thermal cycling, conditions that favor grain growth and promote relative material softening. This behavior is consistent with the findings reported by Gil Plazas et al. [21], who demonstrated that repeated reheating during the WAAM process increases interpass temperature and decreases cooling rates, thereby modifying the phase balance and promoting recrystallization phenomena as well as ferrite stabilization at the expense of harder microconstituents formed under higher cooling rates.

Additionally, the geometric analysis presented in Fig. 5 helps explain why samples YC and YS consistently exhibited the highest hardness values for both deposition strategies. Regions characterized by lower thermal mass, analogous to thin-wall structures, display greater heat dissipation efficiency, resulting in higher cooling rates and favoring the formation of refined microstructures. In contrast, bulkier regions tend to accumulate larger amounts of heat during the manufacturing process, intensifying reheating cycles and promoting microstructural coarsening and grain growth, which ultimately contribute to hardness reduction. This behavior is in agreement with the findings reported by Gil Plazas et al. [21] for arc-based additive manufacturing processes subjected to repetitive thermal cycling.

3.2.2. Thermal Cycles

The analysis of the thermography results presented in Fig. 9 highlights significant differences in the thermal cycles between the Basic Pixel and Interleaved Pixel deposition strategies. These results allow not only the direct interpretation of the thermal histories, but also the establishment of physically consistent correlations with the microhardness results and with the microstructural findings that will be discussed subsequently. This behavior is characteristic of WAAM processes, in which layer-by-layer deposition imposes successive and complex thermal cycles on the material [5, 22].





(e)

Fig. 9 Thermal history of the samples: (a) Point 1 – YS; (b) Point 2 – YC; (c) Point 3 – XC; (d) Point 4 – XE; (e) Point 5 – XD

The thermal profiles exhibit abrupt temperature drops followed by rapid increases. However, these fluctuations do not represent the actual thermal behavior of the material, but rather artifacts associated with the measurement procedure. Such disturbances occur when the deposition torch momentarily passes in front of the thermographic camera, interfering with the acquisition of infrared radiation. Once the torch moves away from the camera's field of view, the temperature readings rapidly return to their actual values. Therefore, these oscillations should be interpreted as experimental artifacts rather than physical variations in the thermal cycle.

At locations corresponding to bulkier regions, such as XC, XE, and XD, illustrated in Fig. 9(c), Fig. 9(d), and Fig. 9(e), the differences between the deposition strategies become even more pronounced. The Interleaved Pixel strategy exhibits a markedly intensified sequence of thermal peaks, indicating that these regions undergo repeated reheating before completing their cooling cycle. This thermal behavior reveals the presence of repetitive and heterogeneous thermal cycles associated with successive reheating events and progressive heat accumulation. From a physical standpoint, this condition is directly related to elevated interpass temperatures and cumulative thermal buildup throughout the deposition process, phenomena widely recognized in the literature as key factors governing microstructural evolution in WAAM [23-24].

From a metallurgical standpoint, this behavior promotes the development of harder and more heterogeneous microstructures, particularly through an increased fraction of bainitic constituents. As discussed by Müller et al. [25], elevated interpass temperatures combined with

repeated thermal cycling favor the formation of such phases, resulting in increased mechanical strength, although often accompanied by reductions in ductility and toughness.

The presence of repetitive thermal cycles and greater heat accumulation favors the formation of more brittle and heterogeneous microstructures, reducing the material's energy absorption capacity. This behavior is consistent with classical WAAM studies, in which high tensile properties coexist with reduced ductility and toughness due to the microstructural heterogeneity induced by thermal cycling [19, 26].

Furthermore, the correlation with the microhardness results reinforces this interpretation, in which bulky regions associated with greater heat accumulation tend to exhibit lower hardness values due to grain growth and prolonged reheating effects. This behavior is directly related to the reduction in the density of barriers to dislocation motion, resulting in relative softening of the material in these regions.

In contrast, in these same bulky regions, the Basic Pixel strategy exhibits more isolated thermal peaks and longer cooling intervals, indicating lower thermal overlap between passes and greater efficiency in heat dissipation. This behavior results in a more stable and predictable thermal history, with lower heat accumulation and lower interpass temperature. Consequently, more balanced microstructures with lower heterogeneity may be formed, favoring a better compromise between strength and ductility. As discussed by Cota et al. [24], more controlled thermal conditions and lower interpass temperatures favor the formation of more homogeneous microstructures and improve the overall mechanical response of the material.

In thin-wall regions, such as YS (Fig. 9(a)) and YC (Fig. 9(b)), the thermal behavior presents distinct characteristics, mainly due to the lower thermal mass and greater heat dissipation efficiency. In the case of the Interleaved Pixel strategy, these regions maintain intermediate temperatures for longer periods after the thermal peaks, indicating heat accumulation and a reduction in the cooling rate.

From a microstructural perspective, this condition favors the occurrence of more intense reheating cycles, promoting grain growth and possible partial tempering effects. These phenomena are widely observed in multipass welding processes, as shown by Borba et al. [27], and contribute to reducing the microstructural hardening of the material, resulting in lower microhardness values in the regions subjected to this thermal history.

On the other hand, in the Basic Pixel strategy, the thin-wall regions exhibit faster cooling after the thermal peaks, indicating higher thermal gradients and more rapid solidification. This behavior favors microstructural refinement and the formation of more homogeneous structures, with a higher fraction of refined constituents, such as fine bainite. As a consequence, these

regions present improved toughness properties and greater mechanical stability, as widely reported in the literature by Dirisu et al. [19].

In general, it is observed that the Interleaved Pixel strategy presents a higher frequency of thermal peaks distributed over time, whereas the Basic Pixel strategy exhibits more widely spaced peaks and longer cooling intervals. This difference in thermal behavior directly influences microstructural evolution and, consequently, the mechanical properties of the material.

3.2.3. Microstructural Characterization

The thermography results show that regions associated with geometries of lower thermal mass, such as YC in the Interleaved Pixel strategy (Fig. 10(a)) and YS in the Basic Pixel strategy (Fig. 10(b)), exhibited higher hardness values. In these regions, a more refined microstructure is observed, predominantly composed of bainite (B) and acicular ferrite (AF), formed under conditions of faster cooling. This microstructural refinement increases the density of interfaces and barriers to dislocation motion, hindering plastic deformation and resulting in higher hardness values.

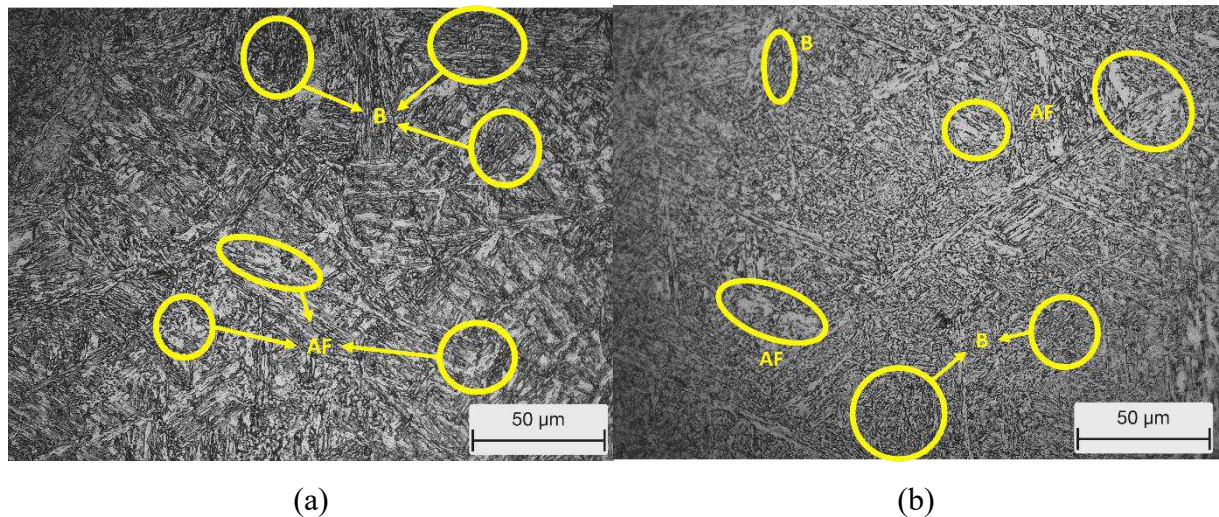


Fig. 10 Microstructure: (a) YC – Interleaved Pixel; (b) YS – Basic Pixel

This microstructural condition is also directly related to the results obtained from the microhardness tests. The presence of bainite and acicular ferrite contributes to increased hardness, since these phases exhibit a refined morphology and a high density of boundaries. As a result, higher microhardness values are observed in regions where these microconstituents are

predominant, highlighting the strong relationship between microstructural refinement and the increase in the local strength of the material.

Similar results were reported by Dirisu et al. [19] and Preecha et al. [20], who also observed predominantly bainitic and ferritic microstructures in components produced by arc-based additive manufacturing. These microstructures were associated with high levels of mechanical strength and local variations in toughness resulting from the anisotropy and thermal cycles inherent to the process.

In contrast to the regions discussed previously, areas associated with geometries exhibiting higher thermal mass, such as ZXE in the Interleaved Pixel strategy (Fig. 11(a)) and XD in the Basic Pixel strategy (Fig. 11(b)), presented lower microhardness values. These regions exhibited relatively coarser microstructures predominantly composed of bainite (B), polygonal ferrite (PF), and acicular ferrite (AF). This behavior is directly associated with greater heat accumulation and more severe thermal cycling inherent to these geometries, which promote elevated reheating conditions and lower cooling rates during deposition. Consequently, these thermal conditions favor microstructural coarsening and grain growth, ultimately leading to reduced microhardness values.

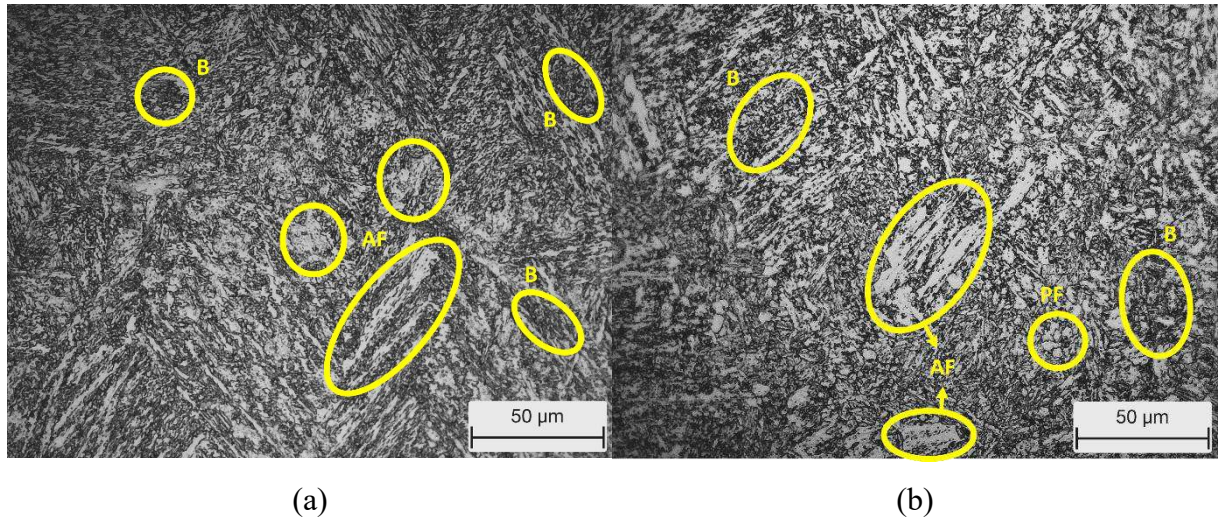


Fig. 11 Microstructure: (a) ZXE – Interleaved Pixel; (b) XD – Basic Pixel

The more gradual cooling reduces the degree of microstructural refinement and promotes the growth of ferritic and bainitic phases, resulting in a lower density of grain boundaries and interfaces capable of acting as barriers to dislocation motion. Consequently, a local reduction in microhardness is observed, in agreement with the results obtained from the microhardness mapping and with the overall mechanical behavior discussed previously.

This type of microstructural variation is frequently observed in components produced by WAAM using low-alloy steel wires, such as ER90S-B3. According to recent studies, the cyclic nature of heat input in the process promotes heterogeneous thermal gradients throughout the component, resulting in the formation of microstructures with different morphologies and degrees of refinement. In the work of Begum et al. [28], for example, the simultaneous presence of fine and coarse grains, as well as dendritic structures distributed throughout the component, was observed, highlighting the direct influence of local thermal variations during deposition. In addition, the occurrence of repeated heating and cooling cycles between layers favors distinct microstructural transformations in different regions, contributing to the anisotropy and heterogeneity of the material.

These results are consistent with the findings reported by Dirisu et al. [19] and Kessler et al. [29], who described the formation of bainitic and ferritic microstructures with different degrees of refinement as a function of the thermal history and component geometry. In particular, regions subjected to greater heat accumulation and reheating tend to exhibit coarser microstructures, associated with lower cooling rates and, consequently, slightly lower hardness values. These results reinforce that the thermal distribution throughout the component plays a fundamental role in defining the microstructure and mechanical properties of additively manufactured components.

3.2.4. Analysis of Internal and External Defects in Printed Parts

Regarding the evaluation of printing quality in terms of process effectiveness, the component manufactured using the Basic Pixel strategy, shown in Fig. 12(a), exhibited some lack-of-fusion discontinuities during the filling process, particularly in the thin-wall regions, where the conditions are more critical for maintaining material integrity. In comparison, the component produced using the Interleaved Pixel strategy, shown in Fig. 12(b), also presented a considerable number of lack-of-fusion discontinuities, which were more pronounced than those observed in the Basic Pixel component. These discontinuities were identified not only in the thin-wall regions but also in portions of the bulkier geometry, especially near the arc start-stop locations.

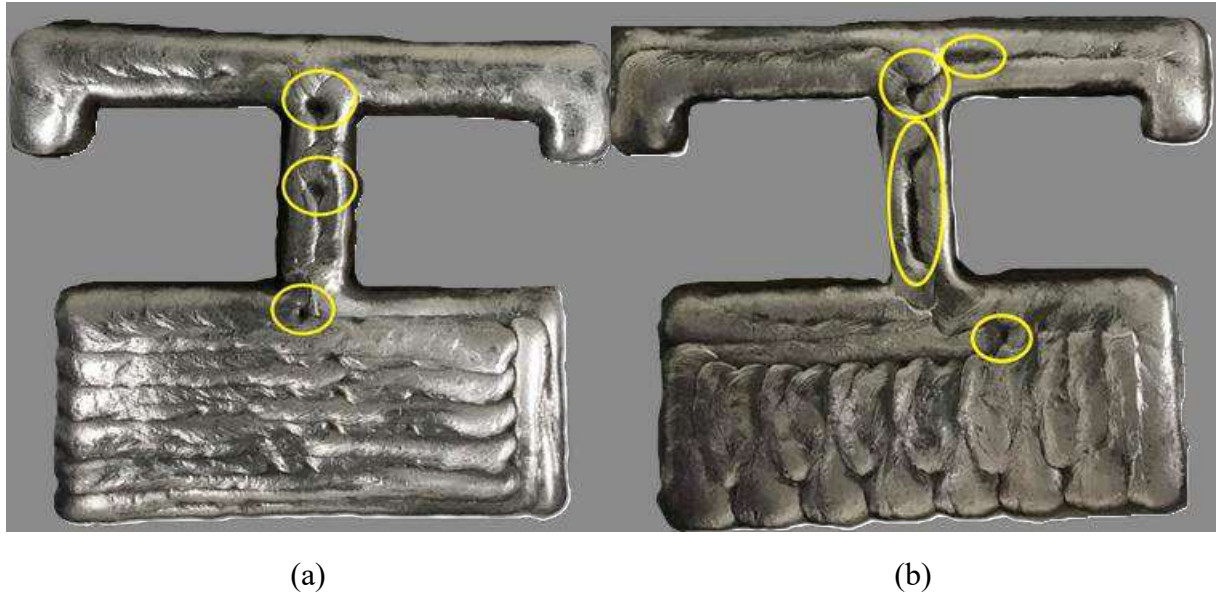


Fig. 12 Components printed using the Pixel toolpath planning strategy: (a) Basic Pixel; (b) Interleaved Pixel.

After the machining step performed to expose potential internal discontinuities, a more detailed evaluation of the component surfaces became possible. The component manufactured using the Basic Pixel strategy, shown in Fig. 13(a), did not exhibit apparent deposition-related surface discontinuities, such as porosity, indicating a relatively stable and uniform deposition process without visible defects. In contrast, the component produced using the Interleaved Pixel strategy, shown in Fig. 13(b), exhibited more pronounced surface defects. These defects may be associated with typical instabilities observed in pulsed MIG deposition, particularly in the central region of the bulkier geometry, where pore formation was identified, as highlighted in Fig. 13(b). Some pores were relatively large and clearly visible, whereas others were smaller and less readily distinguishable in the image

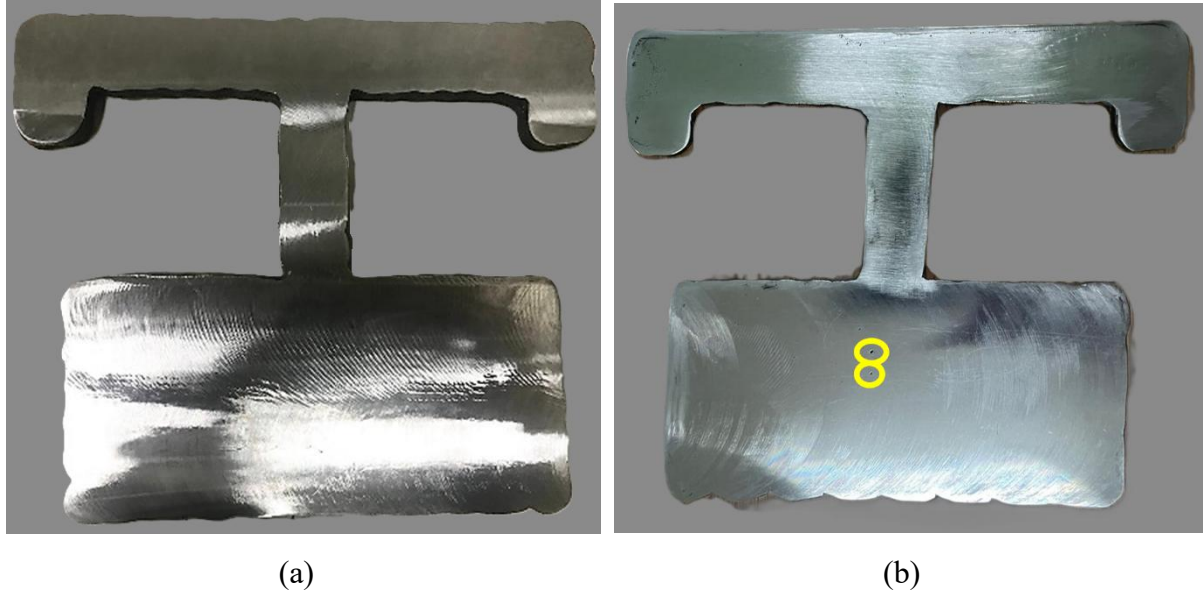


Fig. 13 Machined components manufactured using the Pixel-based toolpath planning strategies: (a) Basic Pixel strategy; and (b) Interleaved Pixel strategy.

3.2.5. Analysis of the Dimensional Conformity Between the Printed Component and the CAD Model

The dimensional conformity analysis revealed that the component manufactured using the Interleaved Pixel strategy exhibited reduced geometric accuracy, particularly in the thin-wall regions. This behavior can be observed in Fig. 14, where the scanned component is compared with the reference CAD model. As shown in Fig. 14(b), the scanned geometry presented extensive areas with significant negative dimensional deviations, represented by the blue regions, predominantly along the sample-line areas indicated in Fig. 7 and within the thin-wall sections. These results indicate that the component failed to achieve the expected dimensional accuracy requirements.

This behavior may have occurred because the interleaved beads, as they are deposited in the valleys of the previous layer, may have compromised the layer height, resulting in regions with negative dimensional deviations. Even in the bulky region, which would theoretically be less susceptible to dimensional variations, negative dimensional deformations were observed at the edges, which are typical of components produced by WAAM.

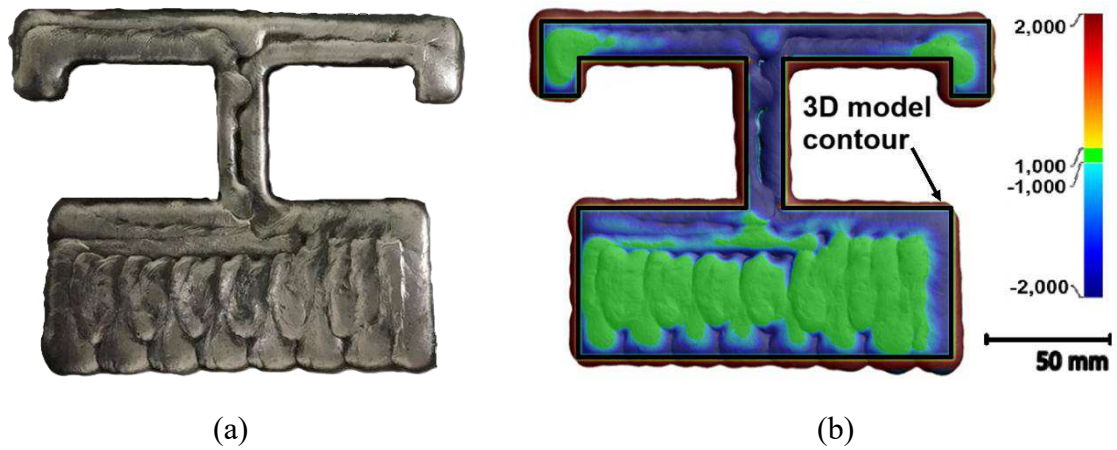


Fig. 14 Component manufactured using the Interleaved Pixel toolpath planning strategy: (a) printed component; and (b) 3D-scanned mesh used for dimensional conformity analysis.

In contrast, the component manufactured using the Basic Pixel strategy, shown in Fig. 15, presented much better performance in terms of dimensional conformity, represented by the green region in Fig. 15(b). Across the entire surface, the component exhibited higher accuracy, with minimal dimensional variations. Although a slight negative deviation was still observed at the edges of the component, this variation was less pronounced and did not compromise the overall integrity. On the other hand, the component also exhibited positive dimensional deviations, represented by the red region, in some parts of the bulkier area and, to a lesser extent, in the thin-wall regions. This behavior can be explained by the approach used during printing, in which the beads are deposited directly on top of one another, generating a greater volume in the overlapping regions. This effect does not occur in the same way with the Interleaved strategy.

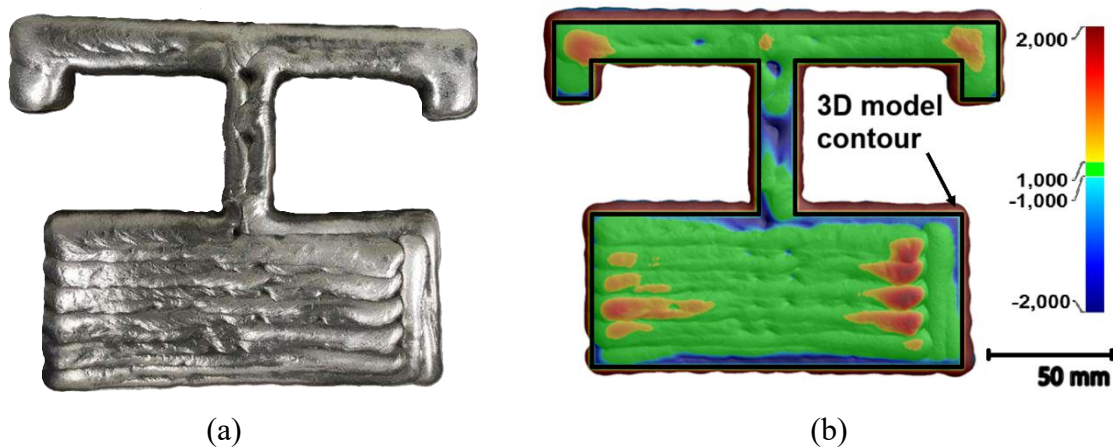


Fig. 15 Component manufactured using the Basic Pixel toolpath planning strategy: (a) printed component; and (b) 3D-scanned mesh used for dimensional conformity analysis.

The dimensional conformity analysis can also be observed in Fig. 16, which presents side views of the manufactured components. Figure 16(a), corresponding to the component produced using the Interleaved Pixel strategy, reveals a noticeable gap between the CAD model and the 3D-scanned mesh, highlighted by the red arrow, particularly in the thin-wall region located at the center of the component.

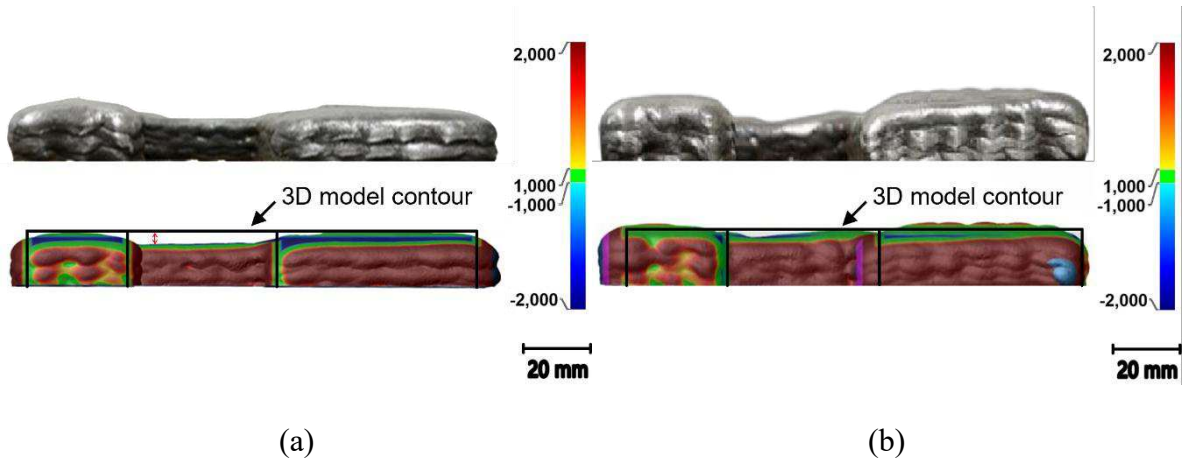


Fig. 16 Components printed using the Pixel toolpath planning strategy in side view: (a) Component printed with Interleaved Pixel; (b) Component printed with Basic Pixel.

In Fig. 16(b), corresponding to the component manufactured using the Basic Pixel strategy, superior dimensional conformity is observed compared with the Interleaved Pixel strategy, as evidenced by the black contour line representing the CAD model geometry. Although localized regions of dimensional deviation are still present, associated with either material deficiency or excess material deposition, the component produced using the Basic Pixel strategy exhibits greater overall agreement with the reference geometry, indicating improved dimensional accuracy.

The profiles of the sampling lines are presented in Fig. 17 to provide a more detailed evaluation of the surface characteristics associated with both deposition strategies. Sampling line 1 indicates that the Basic Pixel strategy produced a slightly smoother surface compared with the Interleaved Pixel strategy, with minimum measured heights of 10.65 mm and 8.53 mm, respectively. The Basic Pixel strategy exhibited a more uniform profile characterized by fewer surface depressions, whereas the Interleaved Pixel strategy showed more pronounced depressions in the central region of the sampling line. Similar behavior was observed for sampling line 3; however, in this case, both strategies demonstrated improved dimensional conformity relative to the previous condition.

Sampling line 2 corresponds to the thin-wall regions of the components. Along this line, both strategies exhibited greater dimensional conformity on the right side, whereas the central and left regions presented deviations of approximately 1.5 mm between their lowest measured points. Sampling line 4, which encompasses both the bulkier and thin-wall regions of the analyzed component, similarly demonstrated higher conformity on the right side, corresponding to the bulkier geometry. In contrast, the left side exhibited lower dimensional conformity, particularly for the Interleaved Pixel strategy, which reached a minimum value of 5.61 mm.

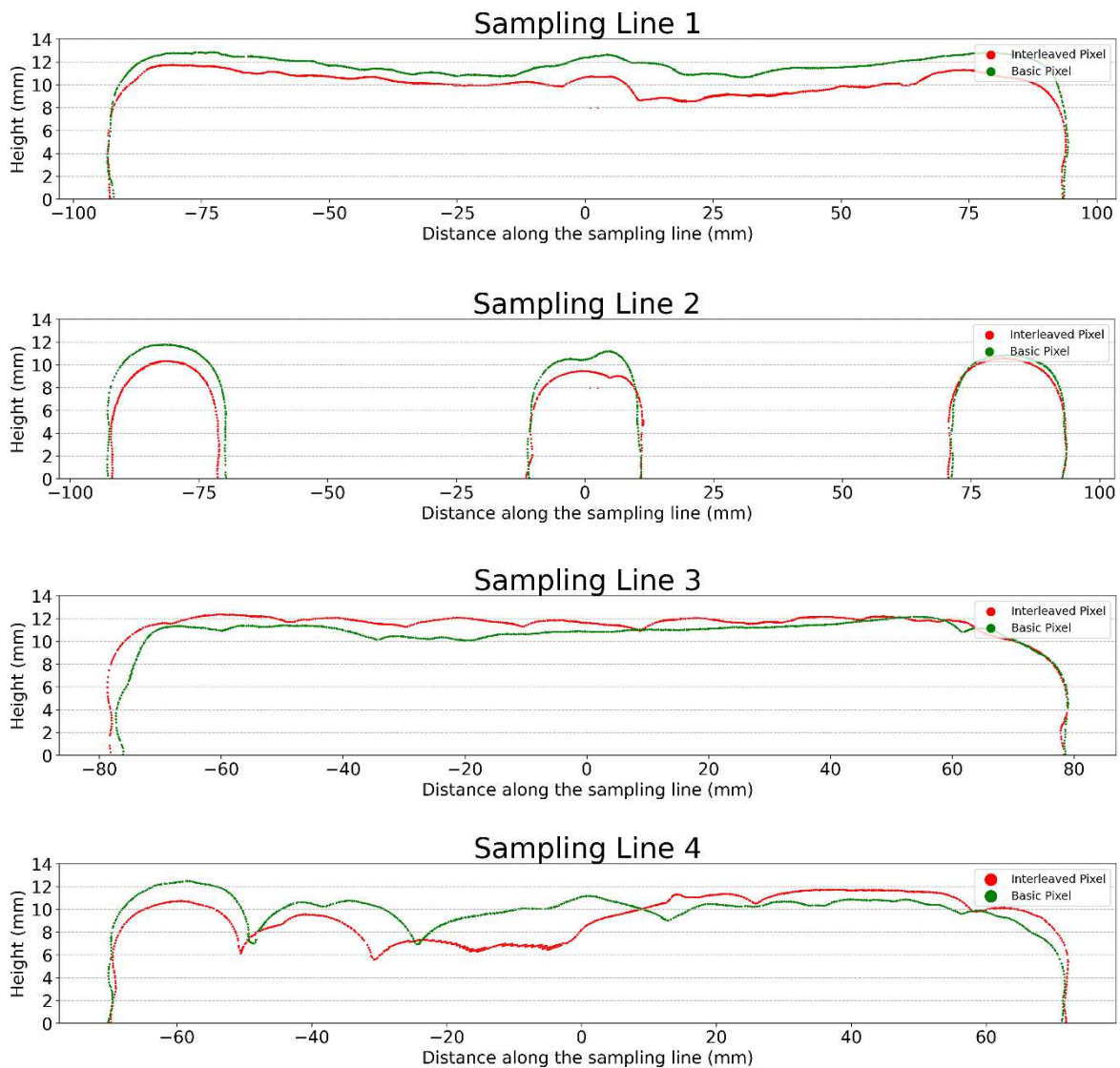


Fig. 17 Two-dimensional contours along the sampling lines defined in Fig. 7

In general, the Interleaved Pixel strategy exhibited greater surface nonconformities throughout the printed component. Although several studies in the literature have proposed the use of interleaved bead deposition as a means of improving interlayer filling, the present results

indicate that, from a practical manufacturing perspective, this approach may not represent the most suitable strategy for fabricating complex components.

One possible explanation for this behavior is the occurrence of arc instability during deposition. Ideally, in the interleaved approach, the arc should be precisely positioned within the valley formed between two adjacent beads from the previous layer. However, due to the inherently unstable and dynamic nature of the welding arc, the deposited material may not be accurately directed toward the center of the valley, compromising wall formation and dimensional stability, particularly in thin-wall regions. Figure 18(a) illustrates the deposition behavior associated with the Basic Pixel strategy, in which the arc is positioned directly over the previously deposited bead, resulting in more stable deposition conditions. In contrast, Fig. 18(b) schematically represents the Interleaved Pixel strategy, where the arc exhibits a more erratic behavior and the deposited material is not consistently directed toward the valley between adjacent beads, but instead tends to accumulate preferentially along the side of one of the beads. This behavior contributes to geometric deviations and reduced dimensional conformity in the manufactured component.

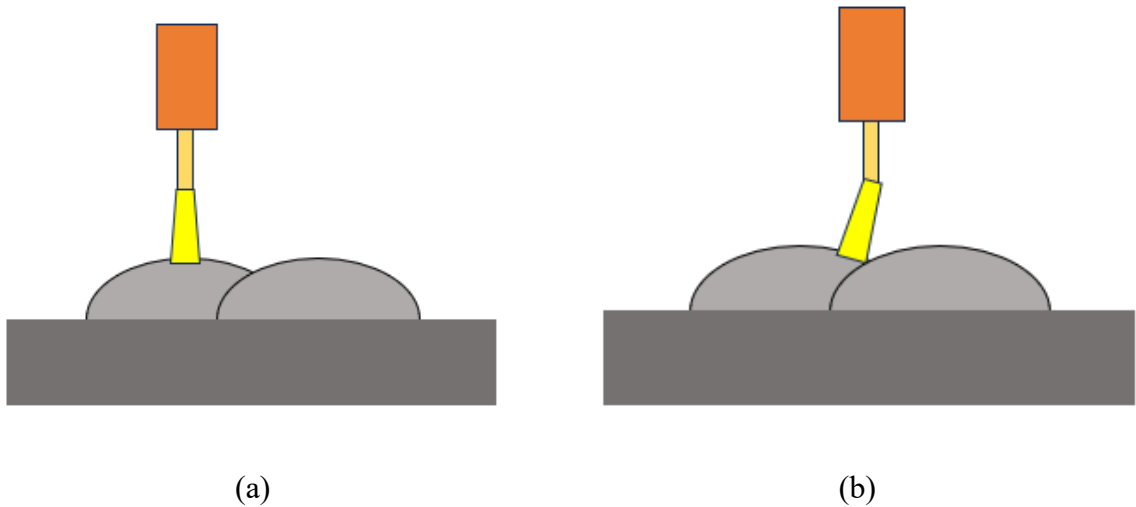


Fig. 18 Deposition scheme associated with the investigated toolpath strategies: (a) Basic Pixel; and (b) Interleaved Pixel

4. Conclusions

This study investigated the influence of Basic Pixel and Interleaved Pixel interlayer toolpath strategies on the efficiency and effectiveness of manufacturing complex components by WAAM. From the operational efficiency perspective, the two investigated strategies can be considered equivalent in terms of toolpath distance and total printing time, with differences of

only approximately 0.2% in both metrics. Similarly, no significant differences were observed regarding the number of arc interruptions, since the toolpath generation methodology inherent to the Pixel strategy minimizes the occurrence of arc stops during the component fabrication process.

In terms of process effectiveness, both strategies exhibited higher hardness values in regions subjected to faster cooling rates, highlighting the direct influence of microstructural refinement and increased interface density on the enhancement of local mechanical strength. The microstructural analyses revealed the predominance of bainite, acicular ferrite, and polygonal ferrite, with finer microstructures observed in regions of lower thermal mass, whereas coarser microstructures developed in regions subjected to greater heat accumulation and successive reheating cycles.

Regarding dimensional control, the Basic Pixel strategy demonstrated superior accuracy, producing components with lower geometric deviations relative to the design specifications. This performance was confirmed by the higher dimensional conformity between the manufactured component and the reference 3D model, highlighting the effectiveness of this strategy in reproducing geometric features with greater precision. Furthermore, the components produced using the Basic Pixel strategy exhibited superior surface quality, with fewer fusion-related discontinuities and a lower incidence of typical welding defects, such as porosity.

In contrast, the Interleaved Pixel strategy exhibited greater susceptibility to thermal variations throughout the manufacturing process, likely associated with arc instabilities during deposition. These effects negatively impacted dimensional accuracy and contributed to a higher occurrence of regions presenting inadequate geometric conformity.

Therefore, it can be concluded that the Basic Pixel strategy represents the most suitable approach for WAAM component fabrication when the objective is to achieve a balanced combination of geometric accuracy, surface quality, and mechanical performance. Although both strategies exhibited equivalent operational efficiency, the Interleaved Pixel strategy did not demonstrate satisfactory performance when applied to the fabrication of a real complex component. In contrast, the Basic Pixel strategy produced more consistent hardness distributions and exhibited a lower incidence of both internal and external defects, indicating greater process robustness and manufacturing reliability.

5. Declarations

- Funding - This work was supported by the Foundation for Research and Scientific and Technological Development Support of Maranhão (FAPEMA) (Call No. 01/2022 FAPEMA/IFMA; Grant No. BM-09118/24).
- Ethics approval - Not applicable.
- Consent to participate - Not applicable.
- Consent for publication - Not applicable.
- Conflicts of interest - The authors declare no competing interests.
- Author contribution - All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Carlos Eduardo Ferreira Bezerra and Lucas Gabriel Silva Lobato. The first draft of the manuscript was written by Carlos Eduardo Ferreira Bezerra and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.”

6. References

1. Alfaify, A., Saleh, M., Abdullah, F. M., & Al-Ahmari, A. M. (2020). Design for additive manufacturing: A systematic review. In *Sustainability (Switzerland)* (Vol. 12, Number 19). MDPI. <https://doi.org/10.3390/SU12197936>
2. Raut, L. P., & Taiwade, R. V. (2021). Wire Arc Additive Manufacturing: A Comprehensive Review and Research Directions. In *Journal of Materials Engineering and Performance* (Vol. 30, Number 7, pp. 4768–4791). Springer. <https://doi.org/10.1007/s11665-021-05871-5>
3. Suryakumar, S., Karunakaran, K. P., Bernard, A., Chandrasekhar, U., Raghavender, N., & Sharma, D. (2011). Weld bead modeling and process optimization in Hybrid Layered Manufacturing. *CAD Computer Aided Design*, 43(4), 331–344. <https://doi.org/10.1016/j.cad.2011.01.006>
4. Cao, Y., Zhu, S., Liang, X., & Wang, W. (2011). Overlapping model of beads and curve fitting of bead section for rapid manufacturing by robotic MAG welding process. *Robotics and Computer-Integrated Manufacturing*, 27(3), 641–645. <https://doi.org/10.1016/j.rcim.2010.11.002>

5. Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). *Robotics and Computer-Integrated Manufacturing*, 31, 101–110. <https://doi.org/10.1016/j.rcim.2014.08.008>
6. Xiong, J., Zhang, G., Gao, H., & Wu, L. (2013). Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing. *Robotics and Computer-Integrated Manufacturing*, 29(2), 417–423. <https://doi.org/10.1016/j.rcim.2012.09.011>
7. Hu, Z., Qin, X., Li, Y., Yuan, J., & Wu, Q. (2020). Multi-bead overlapping model with varying cross-section profile for robotic GMAW-based additive manufacturing. *Journal of Intelligent Manufacturing*, 31(5), 1133–1147. <https://doi.org/10.1007/s10845-019-01501-z>
8. Zhou, X., Qin, J., Fu, Z., Wang, M., Yuan, Y., Fu, J., Zhang, H., & Hosseini, S. R. E. (2024). An Innovative Finite Element Geometric Modeling of Single-Layer Multi-Bead WAAMed Part. *CMES - Computer Modeling in Engineering and Sciences*, 138(3), 2383–2401. <https://doi.org/10.32604/cmes.2023.029249>
9. Foorginejad, A., Zarei, M., Emam, S. M., & Hosseini Baghdadabadi, S. M. J. (2026). A novel multi-bead overlapping model for wire arc additive manufacturing (WAAM) processes with dissimilar beads area strategy. *International Journal of Advanced Manufacturing Technology*, 142(1–2), 309–328. <https://doi.org/10.1007/s00170-025-17036-y>
10. Li, L., Xu, G., Ji, H., Liu, Y., Li, X., Cai, H., Zhao, S., & Zou, B. (2026). A level set-based process planning method for the additive and subtractive hybrid manufacturing of a flow channel with an inner cavity. *Scientific Reports*, 16(1). <https://doi.org/10.1038/s41598-025-29360-0>
11. Rodrigues, T. A., Duarte, V., Miranda, R. M., Santos, T. G., & Oliveira, J. P. (2019). Current status and perspectives on wire and arc additive manufacturing (WAAM). *Materials*, 12(7). <https://doi.org/10.3390/ma12071121>
12. Liu, B., Shen, H., Zhou, Z., Jin, J., & Fu, J. (2021). Research on support-free WAAM based on surface/interior separation and surface segmentation. *Journal of Materials Processing Technology*, 297. <https://doi.org/10.1016/j.jmatprotec.2021.117240>
13. Ferreira, R. P., & Scotti, A. (2021). The concept of a novel path planning strategy for wire + arc additive manufacturing of bulky parts: Pixel. *Metals*, 11(3), 1–22. <https://doi.org/10.3390/met11030498>

14. Ferreira, R. P., Vilarinho, L. O., & Scotti, A. (2022). Development and implementation of a software for wire arc additive manufacturing preprocessing planning: trajectory planning and machine code generation. *Welding in the World*, 66(3), 455–470. <https://doi.org/10.1007/s40194-021-01233-w>
15. Bezerra, C. E. F., Ferreira, R. P., & Scotti, A. (2025). *PLANEJAMENTO DE TRAJETÓRIAS NA MANUFATURA ADITIVA POR DEPOSIÇÃO A ARCO (MADA): UMA ANÁLISE DE UM MÉTODO UTILIZANDO PASSES INTERCALADOS ENTRE CAMADAS*.
16. Nguyen, L., Buhl, J., & Bambach, M. (2020). Continuous Eulerian tool path strategies for wire-arc additive manufacturing of rib-web structures with machine-learning-based adaptive void filling. *Additive Manufacturing*, 35. <https://doi.org/10.1016/j.addma.2020.101265>
17. Teixeira, F. R., Scotti, F. M., Vilarinho, L. O., da Mota, C. A. M., & Scotti, A. (2022). Transferability of the working envelope approach for parameter selection and optimization in thin wall WAAM. *International Journal of Advanced Manufacturing Technology*, 119(1–2), 969–989. <https://doi.org/10.1007/s00170-021-08326-2>
18. Santos, M. (2022). *Caracterização de pré-formas de aços 2,25Cr1Mo fabricadas via manufatura aditiva por deposição a arco com e sem resfriamento ativo por quase-imersão* [Universidade Federal de Uberlândia]. <https://doi.org/10.14393/ufu.di.2022.83>
19. Dirisu, P., Ganguly, S., Mehmanparast, A., Martina, F., & Williams, S. (2019). Analysis of fracture toughness properties of wire + arc additive manufactured high strength low alloy structural steel components. *Materials Science and Engineering: A*, 765. <https://doi.org/10.1016/j.msea.2019.138285>
20. Preecha, K., Chaideesungnoen, S., & Muangjunburee, P. (2024). Microstructure and Fatigue Behavior of Cr-Mo Steel Weld Joints with Automatic TIG Welding. *Chiang Mai Journal of Science*, 51(2). <https://doi.org/10.12982/CMJS.2024.021>
21. Gil Plazas, A. F., Amaya Villabón, T. A., Ramírez Vargas, D. A., Rubiano Buitrago, J. D., & Herrera Quintero, L. K. (2025). Influence of interlayer thermal cycling on microstructural evolution in WAAM processed carbon steel. *Welding in the World*. <https://doi.org/10.1007/s40194-025-02227-8>
22. Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire + Arc additive manufacturing. *Materials Science and Technology (United Kingdom)*, 32(7), 641–647. <https://doi.org/10.1179/1743284715Y.00000000073>

23. Jorge, V. L., Teixeira, F. R., & Scotti, A. (2022). Pyrometrical Interlayer Temperature Measurement in WAAM of Thin Wall: Strategies, Limitations and Functionality. *Metals*, 12(5). <https://doi.org/10.3390/met12050765>
24. Cota, B. S., Amendoeira, D. A. E., Farias, F. W. C., Fonseca, P. P., Oliveira, J. P., Moreno-Uribe, A. M., Viebranz, V. F., Hassel, T., Santos, T. G., & Duarte, V. R. (2024). High-strength low-alloy steel fabricated by in situ interlayer hot forging arc-based directed energy deposition assisted with direct cooling: Microstructural and mechanical properties evaluation. *Journal of Manufacturing Processes*, 129, 273–291. <https://doi.org/10.1016/j.jmapro.2024.08.064>
25. Müller, J., Hensel, J., & Dilger, K. (2022). Mechanical properties of wire and arc additively manufactured high-strength steel structures. *Welding in the World*, 66(3), 395–407. <https://doi.org/10.1007/s40194-021-01204-1>
26. Martina, F., Colegrove, P. A., Williams, S. W., & Meyer, J. (2015). Microstructure of Interpass Rolled Wire + Arc Additive Manufacturing Ti-6Al-4V Components. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, 46(12), 6103–6118. <https://doi.org/10.1007/s11661-015-3172-1>
27. Borba, T. M. D., & Modenesi, P. J. (2019). Influence of welding thermal cycle on grain growth, microstructural transformations and MA formation on CGHAZ of TMCP steel. *Soldagem e Inspecao*, 24. <https://doi.org/10.1590/0104-9224/SI24.06>
28. Begum, S. R., Samprashanth, R., Vasumathi, M., Vigneshwaran, K., & Venkateshwaran, N. (2025). Mechanical, Thermal, and Microstructure Characterization of ER90S-B3 on SS347 Substrate Wire Arc Additive Manufacturing. *Journal of Materials Engineering and Performance*. <https://doi.org/10.1007/s11665-025-12257-4>
29. Kessler, H. D., & Sherman, R. J. (2024). Tension and Charpy V-notch impact properties of wire arc additively manufactured ER80S-Ni1. *Structures*, 61. <https://doi.org/10.1016/j.istruc.2024.106134>