RGSA – Journal of Social and Environmental Management
ISSN: 1981–982X
Submission date: 2/26/2025
Acceptance date: 4/25/2025
DOI: https://doi.org/10.24857/rgsa.v19n5-138
Organization: Interinstitutional Scientific Committee
Chief Editor: Ana Carolina Messias de Souza Ferreira da Costa
Assessment: Double Blind Review by SEER/OJS

ADDITIVE MANUFACTURING BY ARC DEPOSITION: STUDY OF MECHANICAL AND CHEMICAL PROPERTIES WITH STAINLESS STEEL ELECTRODE ER 310

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ABSTRACT

Objective: The objective of this study is to analyze additive manufacturing by metal deposition, mechanically validating the efficiency of ER 310 stainless steel, in order to understand its metallurgical and structural behavior, in addition to establishing ideal operating parameters for layer-by-layer deposition.

Theoretical Framework: Additive manufacturing (AM) is a growing manufacturing technique, known for reducing material waste and improving delivery times, in addition to contributing to sustainability by reducing the carbon impact. The technique involves the superposition of metal layers, integrating knowledge from mechanical engineering, metallurgy, welding and automation. ER 310 stainless steel, used in this study, is widely applied due to its high resistance to oxidation and heat.

Method: The metal deposition process was performed using a CNC arm programmed to operate with continuous and controlled movement, forming a wall composed of several successive layers. Material characterization included chemical analysis by optical emission spectrometry and Vickers microhardness testing with 15 indentations. Metallographic analysis was also performed to observe the microstructure and thermal monitoring of the molten pool during deposition.

Results and Discussion: The results demonstrated that the chemical composition of the deposited material is within the expected limits for ER 310 wire. The average microhardness was 191 HV, revealing uniformity throughout the layers. The metallographic analysis indicated a predominantly austenitic microstructure, with small dark spots attributed to the possible formation of chromium carbide, due to the high chromium content of the material. Thermal monitoring indicated temperatures in the molten pool around 1900 °C, gradually decreasing with each pass, which influences the thermal stability and the final microstructure.

Research Implications: This study provides important subsidies for the development of technical parameters in the additive manufacturing of stainless alloys, especially in applications where thermal control and metallurgical integrity are essential. The implications include sectors such as advanced metallurgy, manufacturing of corrosion-resistant and high-temperature components, and contributes to the optimization of processes with less material waste.

Originality/Value: This research contributes to the literature by exploring the deposition of ER 310 stainless steel using additive manufacturing with real-time thermal monitoring, offering unprecedented data on the hardness, microstructure, and thermal stability of the process. The value of the research lies in the possibility of establishing new sustainable and technically viable manufacturing routes for high-performance industrial applications.

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Keywords: Additive Manufacturing, ER310 Stainless Steel, Characterization of Printed Materials, Localized Fusion, Arc Deposition.

MANUFATURA ADITIVA POR DEPOSIÇÃO A ARCO: ESTUDO DAS PROPRIEDADES MECÂNICAS E QUÍMICAS COM ELETRODO INOXIDÁVEL ER 310

RESUMO

Objetivo: O objetivo deste estudo é analisar a manufatura aditiva por deposição metálica, validando mecanicamente a eficiência do aço inoxidável ER 310, a fim de compreender seu comportamento metalúrgico e estrutural, além de estabelecer parâmetros ideais de operação para deposição camada por camada.

Referencial Teórico: A manufatura aditiva (MA) é uma técnica de fabricação em crescente expansão, conhecida por reduzir o desperdício de material e melhorar os prazos de entrega, além de contribuir para a sustentabilidade por meio da diminuição do impacto de carbono. A técnica envolve a sobreposição de camadas metálicas, integrando conhecimentos de engenharia mecânica, metalurgia, soldagem e automação. O aço inoxidável ER 310, utilizado neste estudo, é amplamente aplicado devido à sua elevada resistência à oxidação e ao calor.

Método: O processo de deposição metálica foi realizado utilizando um braço CNC programado para operar com movimento contínuo e controlado, formando uma parede composta por várias camadas sucessivas. A caracterização do material incluiu análise química por espectrometria de emissão óptica e ensaio de microdureza Vickers com 15 endentações. Também foi realizada análise metalográfica para observação da microestrutura e monitoramento térmico da poça de fusão durante a deposição.

Resultados e Discussão: Os resultados demonstraram que a composição química do material depositado encontra-se dentro dos limites esperados para o arame ER 310. A microdureza média foi de 191 HV, revelando uniformidade ao longo das camadas. A análise metalográfica indicou uma microestrutura predominantemente austenítica, com pequenas manchas escuras atribuídas à possível formação de carboneto de cromo, em função do alto teor de cromo do material. O monitoramento térmico indicou temperaturas na poça de fusão em torno de 1900 °C, diminuindo gradualmente em cada passe, o que influencia a estabilidade térmica e a microestrutura final.

Implicações da Pesquisa: Este estudo fornece subsídios importantes para o desenvolvimento de parâmetros técnicos na manufatura aditiva de ligas inoxidáveis, especialmente em aplicações onde o controle térmico e a integridade metalúrgica são essenciais. As implicações abrangem setores como metalurgia avançada, fabricação de componentes resistentes à corrosão e à alta temperatura, além de contribuir para a otimização de processos com menor desperdício de material.

Originalidade/Valor: Esta pesquisa contribui para a literatura ao explorar a deposição de aço inoxidável ER 310 utilizando manufatura aditiva com monitoramento térmico em tempo real, oferecendo dados inéditos sobre dureza, microestrutura e estabilidade térmica do processo. O valor da pesquisa reside na possibilidade de estabelecer novas rotas de fabricação sustentável e tecnicamente viável para aplicações industriais de alto desempenho.

Palavras-chave: Manufatura Aditiva, Inox ER310, Caracterização de Materiais Impressos, Fusão Localizada, Deposição a Arco.

FABRICACIÓN ADITIVA POR DEPOSICIÓN POR ARCO: ESTUDIO DE PROPIEDADES MECÁNICAS Y QUÍMICAS CON ELECTRODO DE ACERO INOXIDABLE ER 310

RESUMEN

Objetivo: El objetivo de este estudio es analizar la fabricación aditiva por deposición metálica, validando mecánicamente la eficiencia del acero inoxidable ER 310, con el fin de comprender su comportamiento metalúrgico y estructural, además de establecer los parámetros operativos ideales para la deposición capa a capa.

Marco Teórico: La fabricación aditiva (FA) es una técnica de fabricación en auge, conocida por reducir el desperdicio de material y mejorar los plazos de entrega, además de contribuir a la sostenibilidad al reducir la huella de carbono. La técnica consiste en la superposición de capas metálicas, integrando conocimientos de ingeniería mecánica, metalurgia, soldadura y automatización. El acero inoxidable ER 310, utilizado en este estudio, se aplica ampliamente debido a su alta resistencia a la oxidación y al calor.

Método: El proceso de deposición metálica se realizó mediante un brazo CNC programado para operar con movimiento continuo y controlado, formando una pared compuesta por varias capas sucesivas. La caracterización del material incluyó análisis químico mediante espectrometría de emisión óptica y pruebas de microdureza Vickers con 15 indentaciones. También se realizó un análisis metalográfico para observar la microestructura y monitorizar térmicamente el baño de fusión durante la deposición.

Resultados y Discusión: Los resultados demostraron que la composición química del material depositado se encuentra dentro de los límites esperados para el alambre ER 310. La microdureza promedio fue de 191 HV, lo que reveló uniformidad en todas las capas. El análisis metalográfico indicó una microestructura predominantemente austenítica, con pequeñas manchas oscuras atribuidas a la posible formación de carburo de cromo, debido al alto contenido de cromo del material. El monitorizado térmico indicó temperaturas en el baño de fusión cercanas a los 1900 °C, que disminuyen gradualmente con cada pasada, lo que influye en la estabilidad térmica y la microestructura final.

Implicaciones de la Investigación: Este estudio proporciona importantes apoyos para el desarrollo de parámetros técnicos en la fabricación aditiva de aleaciones inoxidables, especialmente en aplicaciones donde el control térmico y la integridad metalúrgica son esenciales. Las implicaciones incluyen sectores como la metalurgia avanzada y la fabricación de componentes resistentes a la corrosión y a altas temperaturas, y contribuye a la optimización de procesos con menor desperdicio de material.

Originalidad/Valor: Esta investigación contribuye a la literatura al explorar la deposición de acero inoxidable ER 310 mediante fabricación aditiva con monitorización térmica en tiempo real, lo que proporciona datos sin precedentes sobre la dureza, la microestructura y la estabilidad térmica del proceso. El valor de la investigación reside en la posibilidad de establecer nuevas rutas de fabricación sostenibles y técnicamente viables para aplicaciones industriales de alto rendimiento.

Palabras clave: Fabricación aditiva, Acero inoxidable ER310, Caracterización de Materiales Impresos, Fusión Localizada, Deposición por Arco.

1 INTRODUCTION

The industry has always been in constant evolution and adaptation, with its history marked by the continuous search for innovation and improvement of production methods.

Currently, Industry 4.0, also called the fourth industrial revolution, a term that describes new methods of intelligent manufacturing, there is an integration between physical and virtual processes, allowing the creation and development of new products with greater agility, expanded production, superior quality and improved precision (1).

The Boston Consulting Group (BCG) report identifies nine emerging technologies that make up Industry 4.0: automated robots, additive manufacturing, simulation, horizontal and vertical integration of systems, internet of industrial things, big data and analytics, cloud computing, cyber security and augmented reality, as pointed out by Tadeu and Santos (2).The results of this study suggest that the use of technologies in the management of industrial robots, such as robots, is essential for the development of new technologies.

In this context, additive manufacturing, or 3D printing, is revolutionizing the production of parts with complex geometries, using the addition of raw material and offering the possibility of using various materials (3).

According to Cerqueira, Diéguez and Camacho (4), by using the additive manufacturing procedure of metals by localized fusion, it is possible to take advantage of the material more efficiently, to introduce automated processes, to achieve a higher production speed than other additive methods or conventional manufacturing techniques, to produce parts without the need for tools and to manufacture metals that are difficult to machine.

In the addition of material layer by layer by means of arc and wire, it is essential to perform mechanical and microstructure tests. This is because, during the process, melting, rapid cooling, solidification and reheating phases occur, which directly affect the final properties of the part (5).

High temperatures generated during the welding process can significantly alter the properties of stainless steel, resulting in decreased ductility, toughness, electrical resistivity, impact and corrosion resistance, and increased hardness. The microstructure is also affected, with grain growth causing cracks in the molten zone, depending on the classification of the material. These changes in properties limit the application of stainless steel in welded structures. However, stainless steel continues to be widely used in various sectors, such as the food and chemical industries, turbine components, pump rotors and oil pipes, kitchen utensils, among others. Its wide use is due to its excellent resistance to oxides and to stress corrosion, besides its good manufacturing characteristics and ease of cleaning (6).

Given the growing interest in additive manufacturing, it is essential to understand in detail the deposition process and the characteristics of the resulting material when using the welding method. Therefore, this work aims to analyze the deposition process in the additive manufacturing of the 310 stainless steel material evaluating the mechanical and structural properties of the metal deposited by localized fusion.

2 BIBLIOGRAPHIC REVIEW

This work aims to evaluate the additive manufacturing process of stainless steel ER310 addressing the welding parameters and temperature during the process, also evaluating the microstructure and hardness of the material after the deposited material.

2.1 ADDITIVE MANUFACTURING

Abstract: The additive manufacturing process is a technology that allows the deposition of materials layer by layer, offering greater freedom in the creation of complex geometries compared to traditional technologies, which use standardized tools. One of its main application areas is manufacturing with complex geometries for the aerospace and automotive industries (7); (8).

In the WAAM (Wire Arc Additive Manufacturing) process, it is possible to apply different localized fusion techniques. This is because the process combines the arc welding material with the raw material. In the case of this study, the gas metal arc welding (GMAW) process was used, which allows significant flexibility in the creation of complex and customized components (9).

2.2 PARAMETERIZATION

Defining the appropriate welding parameters is a fundamental step in the planning of the additive manufacturing process, as these parameters directly influence the quality, precision and final properties of the deposited material (10)

The waiting times between the actions are important to avoid excessive melting in the areas already deposited, as well as the definition of essential welding parameters, such as wire feed speed, voltage and current. In addition, to improve the quality of the finish and the efficiency of the operation, it is essential to adjust the flow rate of the shielding gas according to the material to be used, maintaining the stability of the arc and reducing spatter. (11); (4).

2.3 DEPOSITION LAYERS.

In metal deposition during the additive manufacturing process, heat is inevitably generated by reheating due to overlapping of the layers, making the area more critical or in the region closest to it, which may cause internal structural changes in the material (4); (12).

The thermal cycle of this procedure involves rapid heating, followed by rapid solidification of the deposited material. Subsequent layers keep the material still heated, resulting in reheating and cooling with each deposition (13).

2.4 VICKERS METALLOGRAPHY AND MICROHARDNESS TEST

Metallographic tests are categorized into two main areas: macrography and micrography, to understand the properties of materials is essential to ensure that products meet the desired specifications. This knowledge allows the evaluation of several aspects, such as the microstructure, the presence of pores, possible defects and the areas impacted by thermal treatments or welding processes (14).

In the case of the hardness test, the technique involves applying a load on the surface of the material, causing a surface deformation. Hardness, a mechanical property, is measured by the resistance of the material to the formation of permanent marks when pressed by a material of greater hardness or by specific markers (15).

2.5 CHEMICAL COMPOSITION OF RAW MATERIAL

The choice of welding raw material in additive manufacturing is fundamental to ensure the quality and desired properties of the final component (16).

Materials such as wires are widely used, as they allow controlled melting and solidification during the layer-by-layer construction process. These materials offer flexibility in the creation of complex parts and the use of specific alloys, although they require strict control of welding parameters to maintain the structural integrity and dimensional accuracy of the final product (17); (18).

Studies performed with the additive manufacturing technique using ER 310 wire were developed to analyze the deposited material. Table 1 shows the values referring to the chemical characterization of this material.

Table 1

Chemical Composition Stainless Wire ER310 (19)

Components	% by weight
Carbon (C)	0.08 – 0.15
Silicon (Si)	0.30 – 0.65
Manganese (Mn)	1.0 – 2.50
Chromium (Cr)	25.0 – 28.0
Nickel (Ni)	20.0 – 22.5
Molybdenum (Mo)	0.75
Phosphorus (P)	0.03
Sulfur (S)	0.03
Copper (Cu)	0.75

The welding process with solid wire ER 310 of 1.0 mm diameter is suitable for joining and coating cast alloys, and is characterized by its resistance to heat at high temperatures (19).

3 METHODOLOGY

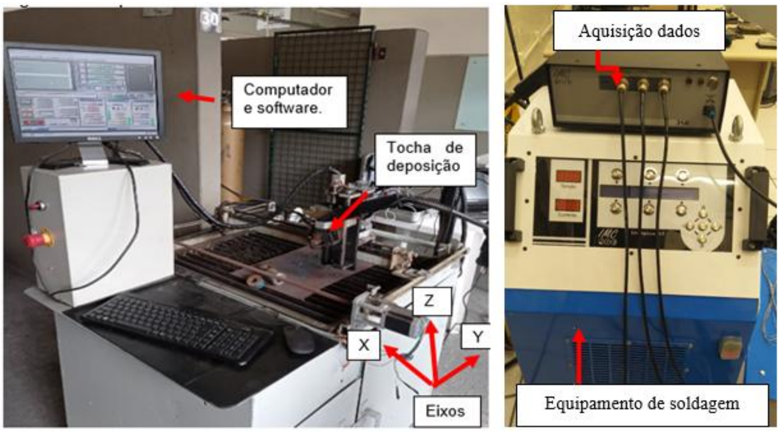
The following work will detail the steps used in the manufacture of the part, including the techniques applied and the parameters adopted throughout the process.

3.1 MANUFACTURING EQUIPMENT

The system used for printing the samples combines a welding machine with a CNC (Computer Numerical Center) device, controlled by a MACH 3® programming software, which uses the G programming language. The welding machine, model DIGplus A7 from IMC, is equipped with a tool for data acquisition of the welding process, known as SAP 3SR.

Figure 1

Additive manufacturing equipment



In Figure 1, it is possible to visualize the data acquisition equipment, the welding machine and the torch movement device. This device operates on three axes - longitudinal, transverse and vertical, identified as X, Y and Z, respectively, allowing constant movement.

3.2 SPECIMENS.

For the realization of the specimen, a wall with approximately 120mm in length, 35mm in height and 10mm in width was designed. In the programming of the deposition strategy represented in figure 2, 18 passes were performed with a distance of approximately 5mm between the torch and the deposited cord. The layers were manufactured one subsequent to another according to figure 3 below.

Figure 2

Deposition strategy

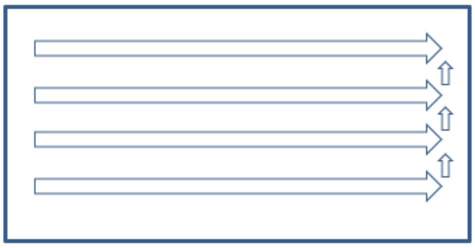


Figure 3

Manufactured part

3.3 PARAMETERS OF ADDITIVE MANUFACTURING.

The deposition parameters used in the sample manufacturing are shown in Table 2. The SAP 3SR tool is used for the acquisition of welding data.

Table 2

Welding parameters

Parameters:	**Values:**
Current (A)	110
Voltage (V)	19.8
Gas flow rate (L/min.)	16.0
Wire speed (m/min.)	5.8
Argon (%)	85
Carbon dioxide (%)	15
CNC Displacement (mm/min.)	300

For temperature acquisition during the additive manufacturing process, an OPTRIS PI 08M thermographic camera was used, capable of capturing thermal images from 575 to 1900ºC, allowing to monitor and record temperature variations during material deposition.

3.4 OPTICAL EMISSION SPECTROMETRY

In the optical emission spectrometry test, the BRUKER Q2 ION model equipment was used, operating at a power of 400 Watts for 30 seconds.

3.5 METALLOGRAPHIC ANALYSIS

The test of the structure is important to reveal the material under study. For this, an Olympus microscope and model SC30 were used according to the BNT NBR 15454 standard. In the case of the material under analysis, an attack was carried out with Nitál with 2% and with electrode within 30 minutes to reveal the phases of the stainless wire ER310.

3.6 VICKERS MICROHARDNESS TEST

The test was performed using a microdurometer model HMV-2TADW SHIMADZE®, according to ABNT NBR ISO 6507. The force applied to the specimen was 9.807N, performing 15 indentations with a distance of 1 millimeter between each application.

4 RESULTS AND DISCUSSIONS

The results obtained in this study seek to understand the occurrences in the manufacturing process by additive manufacturing through deposition of the ER 310 stainless wire.The results obtained in this study will be presented and discussed below.

4.1 OPTICAL EMISSION SPECTROMETRY.

Table 3 presents in detail the chemical composition of the wire with manufacturer data and spectrometry analyzed in the laboratory after 3D printed part, it is observed that most of the alloying elements of the chemical composition of the 3D part is largely consistent with the

ER310 wire, although nickel is slightly below expectations, and molybdenum and copper are smaller, which can affect the final properties of the material.

Table 3

Comparison of chemical composition of wire and 3D piece

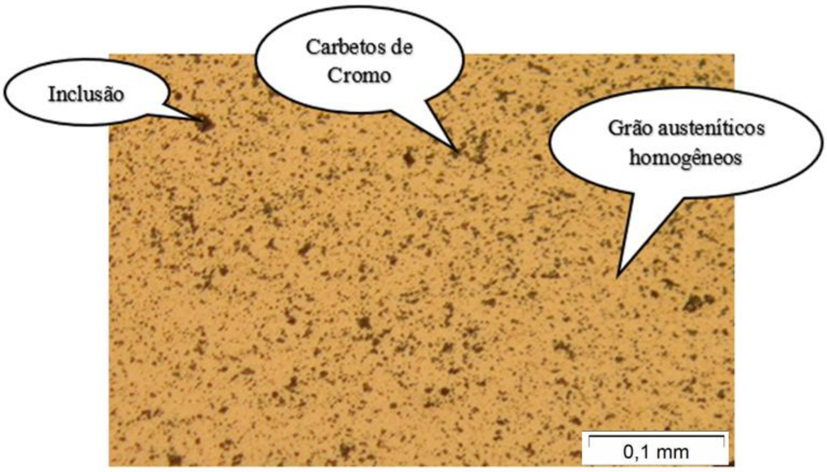
Components	ER310 Wire (%)	3D part (%)
Carbon (C)	0.08 – 0.15	0.11
Silicon (Si)	0.30 – 0.65	0.47
Manganese (Mn)	1.0 – 2.50	1.34
Chromium (Cr)	25.0 – 28.0	26.58
Nickel (Ni)	20.0 – 22.5	19.75
Molybdenum (Mo)	0.75	0.14
Phosphorus (P)	0.03	0.02
Sulfur (S)	0.03	0.01
Copper (Cu)	0.75	0.36

4.2 METALLOGRAPHIC TEST

In the metallographic analysis presented in Figure 4, it is possible to observe a microstructure composed mainly of homogeneous austenitic grains, with small dark spots distributed throughout the matrix that can be represented by chromium carbides and small inclusions of impurities in the procedure. The homogeneity of the grains represents a relatively uniform distribution, possibly due to the cooling process after the deposition of 3D printing.

Figure 4

ER 310 metallographic image

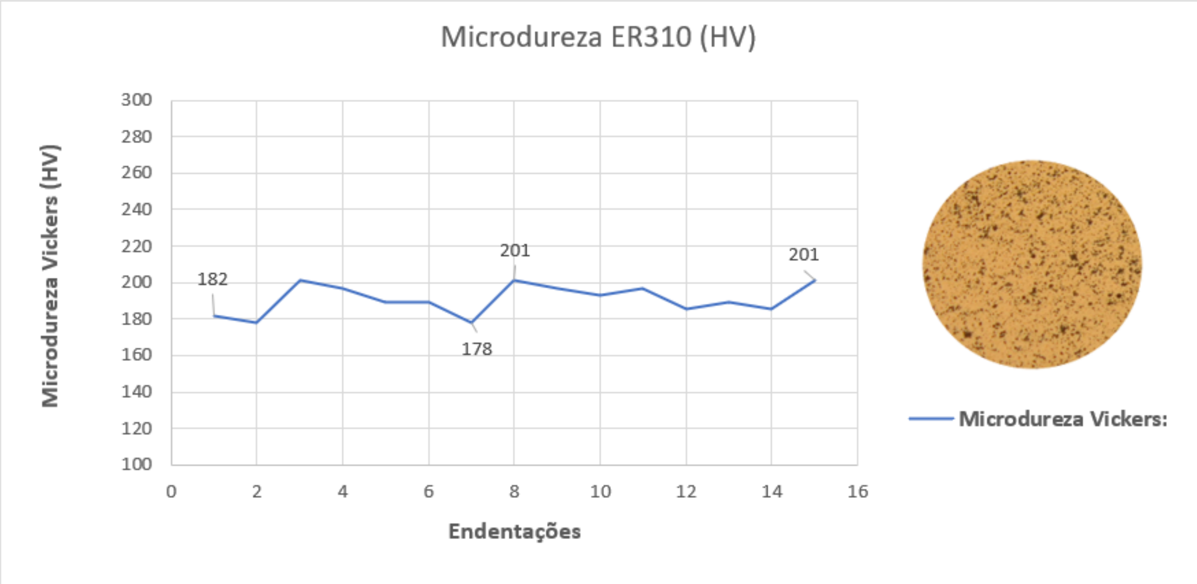


4.3 VICKERS MICROHARDNESS TEST

Figure 5 shows the results for the Vickers microhardness test along the manufactured part with 15 indentations with a distance of 1mm from each indentation.

Figure 5

Vickers Microhardness Chart After Printed Part



The 3D printed sample presented an average hardness of 191 ± 8 HV, which remained within the expected range compared to the manufacturer's data, which indicate a hardness below 200 HV. This level of hardness is characteristic of stainless steels, due to their high content of Chromium and Nickel, which contributes to the impact resistance and abrasive wear, besides preserving their mechanical properties at high temperatures.

4.4 THERMOGRAPHIC ANALYSIS.

The thermographic images captured during the additive manufacturing process show the temperature distribution in both the horizontal and vertical directions of the sample as shown in Figure 6.

Figure 6

Thermographic Image in 3D Printing

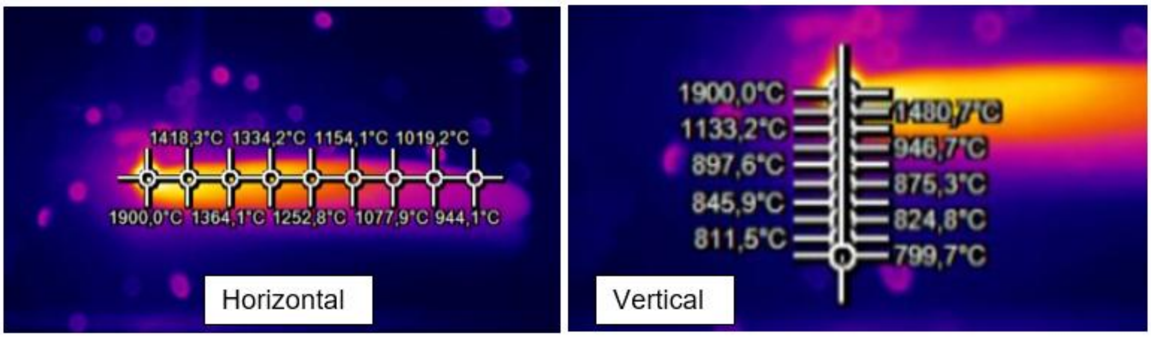
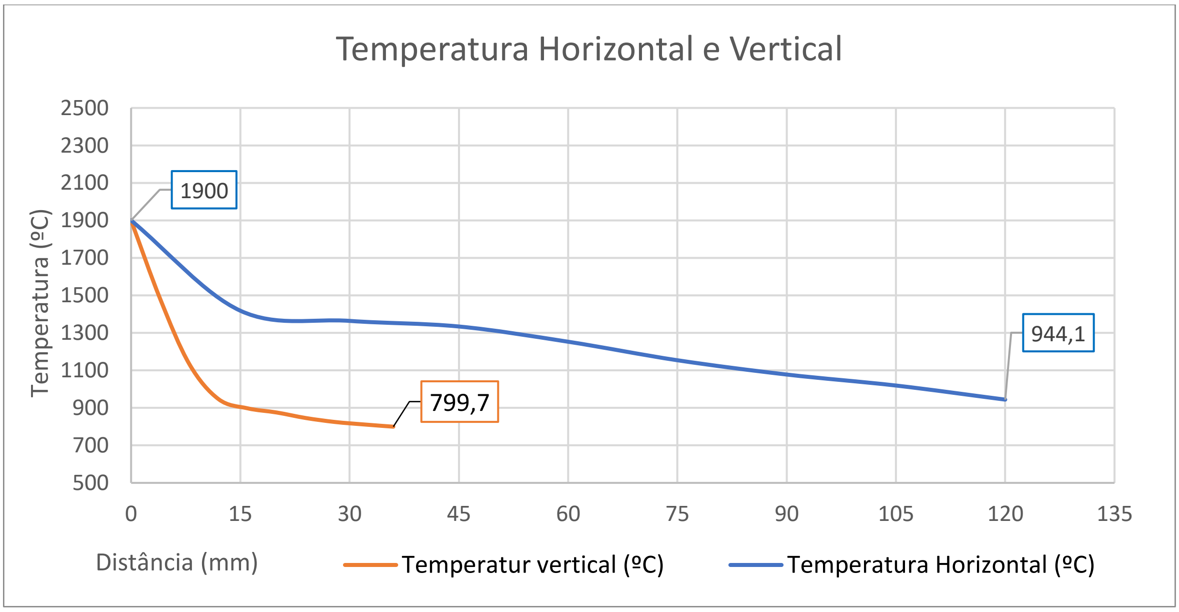


Figure 7 shows the horizontal temperature curve, which ranges from 1900.0 °C to 944.1 °C during printing, with the highest temperature recorded directly under the welding torch. This distribution illustrates how heat dissipates laterally along the surface, with a gradual decrease as it moves away from the starting point. Similarly, in the vertical analysis, temperatures also reach a peak of 1900.0 °C, but show a more pronounced variation along the height of the part, with values ranging from 1900.0 °C at the top to 799.7 °C at the base.

Figure 7

Horizontal and Vertical temperature graph.



This thermal pattern indicates that heat accumulates predominantly in the upper part of the part, with a gradual reduction in the lower layers, which can affect both the microstructure and the mechanical properties of the final material.

5 CONCLUSIONS

Sampling produced by manufacturing the ER310 wire compares the chemical composition revealing that most alloying elements are consistent between them. However, nickel, molybdenum and copper have slightly lower levels in the 3D part, which can influence the final properties of the material.

In the metallographic test it reveals an austenitic microstructure with homogeneous distribution of grains and with small dispersed dark inclusions that represent secondary phases of chromium carbides and impurities.

As for the Vickers Microhardness test, the sample presented an average of 191 ± 8 HV, consistent with the manufacturer's data (below 200 HV), suggesting good impact and wear resistance due to the high chromium and nickel content.

During printing, temperatures vary constantly with each material deposition pass, with higher temperatures in the melting pool and gradual decrease in the lower layers maintaining a homogeneous grain microstructure.

ACKNOWLEDGMENTS

The authors thank the UNISATC University Center for its support with the infrastructure of the laboratories, the Federal University of Rio Grande do Sul (UFRGS) for its collaboration with its research network, and the Foundation for Research and Innovation Support of the State of Santa Catarina (FAPESC) for its financial support in the acquisition of equipment and inputs for research.

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