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MECHANICAL ANALYSIS OF ER70S-6 WIRE IN PULSED ADDITIVE MANUFACTURING

Carlos Ferreira[1]
Anderson Daleffe[2]
Henrique Casagrande[3]
Gilson De March[4]
Hadrian Martins[5]
Lírio Schaeffer[6]

ABSTRACT

Objective: To investigate the influence of temperature on the behavior of carbon precipitation on the contact surface between the base plate and the layers deposited by additive manufacturing using pulsed electric arc.

Theoretical Framework: Additive manufacturing (AM) allows the creation of parts through the successive deposition of material in layers, with advantages such as raw material savings and the possibility of manufacturing complex or customized geometries — aspects that make it a promising alternative compared to traditional processes. However, in AM of metals by pulsed electric arc, the high temperatures required generate significant heat transfers, influencing microstructures and local properties.

Method: The consumable AWS A5.18 ER70S-6 was used. The mechanical characterization was performed by means of the Vickers microhardness test, and the structural evaluation by metallographic analyses.

Results and Discussion: The microhardness tests indicated that the base material and the deposited material have similar hardness. Metallographic analyses revealed a distinct band near the heat-affected zone, suggesting structural variations in this region, possibly related to carbon precipitation.

Research implications: Understanding the thermal influence on carbon precipitation contributes to the improvement of process parameters in pulsed-arc additive manufacturing, aiming at better microstructural control and mechanical performance of the parts produced.

Originality/value: This study addresses a specific and little-explored aspect in pulsed-arc metal additive manufacturing: carbon precipitation at the interface between base material and deposited layers, offering relevant experimental data for process optimization and quality control.

Keywords: Additive Manufacturing of Metals, Pulsed Arc, AWS A5, 18 ER70S-6 Wire.

[1] Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Rio Grande do Sul, Brazil.
E-mail: carlos.ferreira@satc.edu.br
[2] Centro Universitário do UNISATC, Criciúma, Santa Catarina, Brazil. E-mail: anderson.daleffe@satc.edu.br
[3] Centro Universitário do UNISATC, Criciúma, Santa Catarina, Brazil. E-mail: henrique_cechinel@hotmail.com
[4] Centro Universitário do UNISATC, Criciúma, Santa Catarina, Brazil. E-mail: gilson.march@satc.edu.br
[5] Centro Universitário do UNISATC, Criciúma, Santa Catarina, Brazil. -Email: hadrian.martins@hotmail.com
[6] Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Rio Grande do Sul, Brazil.
E-mail: schaefer@ufrgs.br

ANÁLISE MECÂNICA DO ARAME ER70S-6 EM MANUFATURA ADITIVA PULSADA

RESUMO

Objetivo: Investigar a influência da temperatura no comportamento da precipitação de carbono na superfície de contato entre a placa base e as camadas depositadas por manufatura aditiva utilizando arco elétrico pulsado.

Estrutura Teórica: A manufatura aditiva (MA) permite a criação de peças por meio da deposição sucessiva de material em camadas, com vantagens como economia de matéria-prima e possibilidade de fabricar geometrias complexas ou customizadas — aspectos que a tornam uma alternativa promissora em comparação a processos tradicionais. No entanto, na MA de metais por arco elétrico pulsado, as altas temperaturas exigidas geram significativas transferências de calor, influenciando microestruturas e propriedades locais.

Método: Foi utilizado o consumível AWS A5.18 ER70S-6. A caracterização mecânica foi feita por meio de ensaio de microdureza Vickers, e a avaliação estrutural por análises metalográficas.

Resultados e Discussão: Os testes de microdureza indicaram que o material base e o material depositado apresentam dureza semelhante. As análises metalográficas revelaram uma banda distinta próxima à zona termicamente afetada, sugerindo variações estruturais nessa região, possivelmente relacionadas à precipitação de carbono.

Implicações da pesquisa: A compreensão da influência térmica na precipitação de carbono contribui para o aprimoramento dos parâmetros de processo em manufatura aditiva com arco pulsado, visando melhor controle microestrutural e desempenho mecânico das peças produzidas.

Originalidade/valor: Este estudo aborda um aspecto específico e pouco explorado na manufatura aditiva de metais com arco pulsado: a precipitação de carbono na interface entre material base e camadas depositadas, oferecendo dados experimentais relevantes para a otimização do processo e controle de qualidade.

Palavras-chave: Manufatura Aditiva de Metais, Arco Pulsado, Arame AWS A5, 18 ER70S-6.

ANÁLISIS MECÁNICO DEL ALAMBRE ER70S-6 EN FABRICACIÓN ADITIVA PULSADA

RESUMEN

Objetivo: Investigar la influencia de la temperatura en el comportamiento de la precipitación de carbono en la superficie de contacto entre la placa base y las capas depositadas mediante fabricación aditiva mediante arco eléctrico pulsado.

Marco teórico: La fabricación aditiva (FA) permite la creación de piezas mediante la deposición sucesiva de material en capas, con ventajas como el ahorro de materia prima y la posibilidad de fabricar geometrías complejas o personalizadas, aspectos que la convierten en una alternativa prometedora en comparación con los procesos tradicionales. Sin embargo, en la FA de metales mediante arco eléctrico pulsado, las altas temperaturas requeridas generan transferencias de calor significativas, lo que influye en las microestructuras y las propiedades locales.

Método: Se utilizó el consumible AWS A5.18 ER70S-6. La caracterización mecánica se realizó mediante el ensayo de microdureza Vickers y la evaluación estructural mediante análisis metalográficos.

Resultados y discusión: Los ensayos de microdureza indicaron que el material base y el material depositado presentan una dureza similar. Los análisis metalográficos revelaron una banda distintiva cerca de la zona afectada por el calor, lo que sugiere variaciones estructurales en esta región, posiblemente relacionadas con la precipitación de carbono.

Implicaciones de la investigación: Comprender la influencia térmica en la precipitación de carbono contribuye a la mejora de los parámetros del proceso en la fabricación aditiva por arco pulsado, con el objetivo de lograr un mejor control microestructural y el rendimiento mecánico de las piezas producidas.

Originalidad/Valor: Este estudio aborda un aspecto específico y poco explorado en la fabricación aditiva de metal por arco pulsado: la precipitación de carbono en la interfaz entre el material base y las capas depositadas, ofreciendo datos experimentales relevantes para la optimización del proceso y el control de calidad.

Palabras clave: Fabricación Aditiva de Metales, Arco Pulsado, Alambre AWS A5, 18 ER70S-6.

1 INTRODUCTION

Additive metal manufacturing has revolutionized the industry, enabling the creation of complex parts from 3D CAD or through programming on specific machines. Unlike traditional machining methods, which remove material from a raw part, additive metal manufacturing builds the parts layer by layer, depositing material. This process offers several advantages, such as waste reduction, fast production times and the ability to fabricate complex geometries that would be difficult to produce with conventional methods.

Compared to traditional GMAW, which uses constant welding current, P-GMAW allows metal transfer by spraying with a lower average welding current. This is possible thanks to the use of a low current to maintain the arc and a high peak current to melt the electrode wire and separate the drop, resulting in an average current lower than the limit required for spray transfer (P. Zhu, 1997; F. Matsuda, 1984).

Studies have been focused on the real-time control of P-GMAW penetration, seeking relevant information for characterization and control of penetration through the detection of the molten pool morphology (Cruz JG, 2020; Jjn ZS, 2019).

2 THEORETICAL FRAMEWORK

2.1 WELDING ARC FUSION

According to (PAULO, 2012), the electric arc presents as characteristic the complex processes of mass transfer between the electrodes. This includes, in welding with consumable electrodes, the movement of the molten material from the wire-electrode to the part, and both in processes with consumable electrodes and in processes with non-consumable electrodes, the movement of gases through the arc, in the direction generally from the electrode to the part. These phenomena have great importance and influence several fundamental characteristics of the welding processes, such as the welding capacity in non-flat positions, the appearance of the metal cord, the amount of spatter and the stability of the process, the consistency of the electric arc, the absorption of gases in the weld pool, among others.

2.2 HEAT INPUT AND PULSED WELDING

Thermal input is a crucial consideration in the context of metal structures, especially in welding. It refers to the amount of heat that is supplied to the part during the welding process. This heat affects several properties of metallic structures, such as their microstructure, resistance, toughness and distortion. For the amount of heat introduced during the welding process, known as thermal input or welding energy, it determines the cooling rate and, consequently, the grain size and phase formation in the material (Yin, Zhang & Yu, 2018). MODENESI also mentions that the thermal input is the result of the energy transferred to the base material by the length of the weld bead.

According to DebRoy et al. The control of the thermal input through pulses in metallic additive manufacturing processes is essential to obtain the desired microstructures and to improve the mechanical properties of the parts produced, since in turn when the thermal input occurs, a large amount of energy is introduced in each layer addition, one of which affects the shape of the grain and the weld bead itself is the time variable, where when opening the electric arc in a very prolonged period raises the temperature above the same location causing the bead to spread.

2.3 ADDITIVE MANUFACTURING

AM (Additive Manufacturing) is consolidated with a new and innovative method for the modeling of metal parts in a way that tends to be more efficient and practical compared to previous methods. This method starts from the principle of layers where one layer overlaps the other to form a final geometric shape. It consists of transforming a 3D CAD model into layers, and from these data to determine the trajectory and the deposition methods, which are later triggered by four basic components: CNC software, displacement method, power supply, and a material deposition system (GIBSON et al., 2010).

In this context, MA follows a line of procedures in eight steps. They are: 3D CAD modeling; conversion to STL file (STL format is a way to represent the part only with geometry information, the faces of the model are approximated by meshes), upload to the machine (when the format and scale of the part is verified, check the file storage location, use of software); Preparation of the equipment (calculation of materials and calibration of parameter of use for the equipment); Construction (after the program is given the construction of the layers); Removal and cleaning (removal and cleaning of the surface is required to be subject to a certain application); Post processing (when it is necessary to complete the project, such as cutting, sanding, polishing and among others); and application (followed by post processing the printed parts will be ready for application), (COTTELEER, 2016.

2.4 WIRE WS A5.18 ER70S-6

The wire used in the manufacture of the specimens (cp) was WS A5.18 ER70S-6. According to CASAGRANDE, H.C., in turn, has a low carbon content. It used to be used for the manufacture of metallic structures and for general use in metallurgy for the bonding of low carbon materials such as SAE 1020 steel, due to its low cost compared to other alloys. Table 1 shows the chemical composition according to the [11].

Table 1:

Characterization ER70S-6

Element	ER70S-6 (%)
Carbon (C)	**0.06**
Silicon (Si)	**0.80**
Manganese (Mn)	**0.04**
Phosphorus (P)	**0.025**
Sulfur (S)	**0.035**
Chromium (Cr)	**0.15**
Molybdenum (Mo)	**0.15**
Copper (Cu)	**0.5**
Iron (Fe)	**Bal.**

Source: AWS A5.18.

3 MATERIALS AND METHODS

Through the experimental tests developed, the main objective was to produce specimens and analyze the microstructural behavior after the additive manufacturing method. In this sense, initial experiments were carried out that sought to obtain a geometry, without there being inclusions in the formed object. For the beginning of the process, a MIG/MAG welding machine coupled to a CNC system was used to form the geometry. After the manufacturing process, it was placed in a grinding machine to plan the faces and leave the uniform thicknesses so that, for the tests to be standard. Then the sanding process was carried out to polish and finally metallography test and hardness test to study the behavior of the deposited material.

3.1 LOCALIZED MELTING WITH CNC MACHINE

In the production of the presented study, a machine that uses the Cartesian plane of 3 (three) axes Fig.1 was used, which through programming applied in a machining software was inserted data of the route to be covered. The equipment uses the mach3 programming, which through coordinates in the plane created the coordinates of the torch trajectory. To perform the localized fusion, a GMAW process machine was used.

Figure 1:
CNC machine

3.2 PARAMETERIZATION OF THE CORD

To determine the parameters of voltage, current, wire feed, gas flow rate, as well as other parameters, a weld bead is performed and the behavior of the weld pool is analyzed in order to finish the most suitable method and then create the ER70s-6 bead wall. During the process, the IMC DIGIplus A7 MIG/MAG welding machine.

3.3 RECTIFICATION

In this operation the bead wall was inserted into the rectified Mello brand, where the part is attached to a magnetic surface such that a grinding wheel when passing through its surface removes material in order to plan the wall surface by removing the present ripples, formed by the deposition of the material in the melting pool, in order to homogenize the surfaces, which subsequently favor in other processes.

3.4 MICROSCOPIC ANALYSIS

In the process of preparation for visualization of the microstructure, the material was sanded, polished and attacked with a solution of 2% of Nital. In this phase, the objective was to acquire the necessary characteristics of the metallography test and to visualize the formation of the grains in the Olympus microscope model SC30, in which it follows the ABNT NBR 15454 standard.

3.5 VICKERS MICROHARDNESS TEST

The Vickers microhardness test in profile was performed for mechanical evaluation. For this purpose, the SHIMADZE® microdurometer, model HMV-2TADW, was used. The applied load was 9.806 Newtons with application time of 10 seconds for the sample core, according to ABNT NBR NM ISO 6507.

4 RESULTS

4.1 SPECTROMETRY FOR SAE 1020 STEEL AND ER70S-6 WIRES

According to Table 3, the carbon content for both materials is close, which justifies the application of the SAE 1020 base material.

Table 2

Spectrometry data.

Element	ER70S-6 (%)	SAE 1020 (%)
Carbon (C)	0.104	0.107
Silicon (Si)	0.657	<0.0050
Manganese (Mn)	1,259	0.465
Phosphorus (P)	0.014	0.016
Sulfur (S)	0.01	<0.0030
Chromium (Cr)	0.020	0.020
Molybdenum (Mo)	0.014	0.0096

Copper (Cu)	**0.093**	**0.0045**
Iron (Fe)	Bal.	Bal.

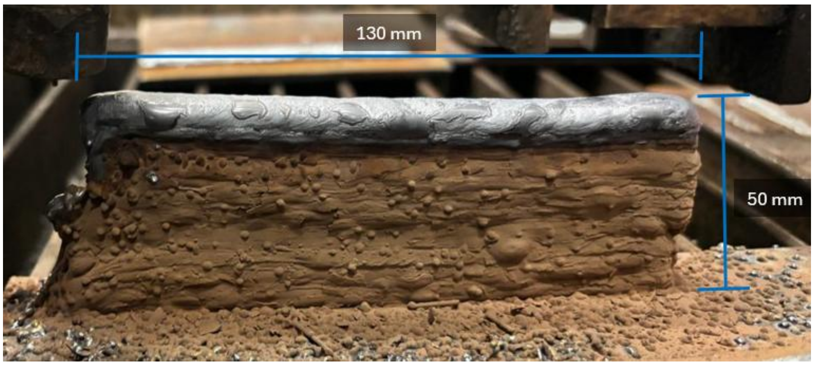
Other components are part of the structure of these materials, highlighting the use of manganese as a deoxidant and desulphurizer. When manganese is present in concentrations below 1%, it does not adversely affect weldability, although it can increase the hardness of the material. At concentrations above 1%, manganese can increase the propensity to cracks during the welding process. [13] [14] [15].

4.2 SAMPLE MANUFACTURED BY ADDITIVE MANUFACTURING

First, the parameter adjustment of the wire in question was performed in the machine itself.

Figure 2

3D printing



The manufactured wall is approximately 130 mm long, 50 mm high and 13 mm thick. Printing was performed with double cord laterally. The increment for each pass, that is, the value that the machine moved vertically for each layer was approximately 1.85 mm, totaling 27 layers.

After manufacturing the samples, they were cut and ground in a band saw from Franho FM 18S and a flat grinder from Mello P36, respectively.

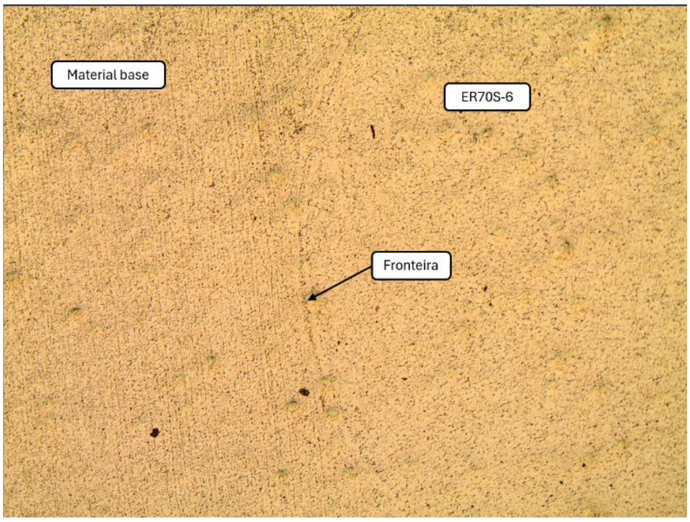
4.3 METALLOGRAPHIC TEST

At the 50x magnification to the left one can notice the arrangement of perlite in bands, which comes from the direction of lamination that occurs during the manufacture of the sheet

(COLPAERT Metallography of common steel products). On the right, we note that this provision is not present, since the material from there comes from melting and solidification.

Figure 3

Border metallography

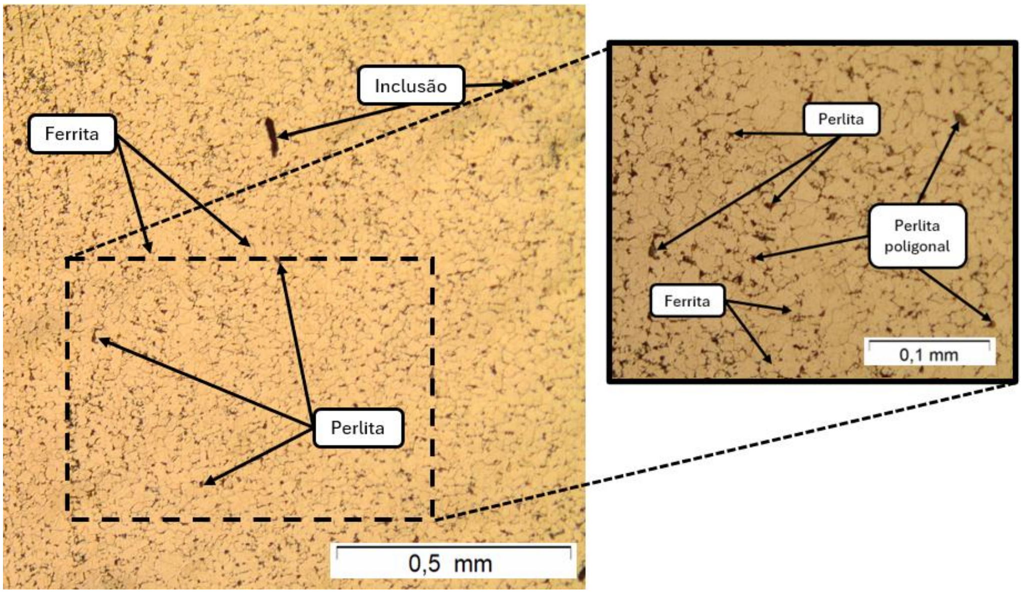


It is also noted that at the transition boundary welding base material occurs an accumulation of carbon, from the high temperature made by the welding process. It is also noted that the carbon migrated more from the welding material itself than from the plate, this should occur due to the high temperature at which the deposited material was facilitated the internal displacement of carbon.

Figure 4 details the metallography for the wire, where it can be seen that this material showed carbon precipitation to the contact surface. However, it has a similar structure compared to the base material, since for the region of material deposition it is composed of the ferrite phase and the microconstituent perlite.

Figure 4

Connection line between deposited material and base.

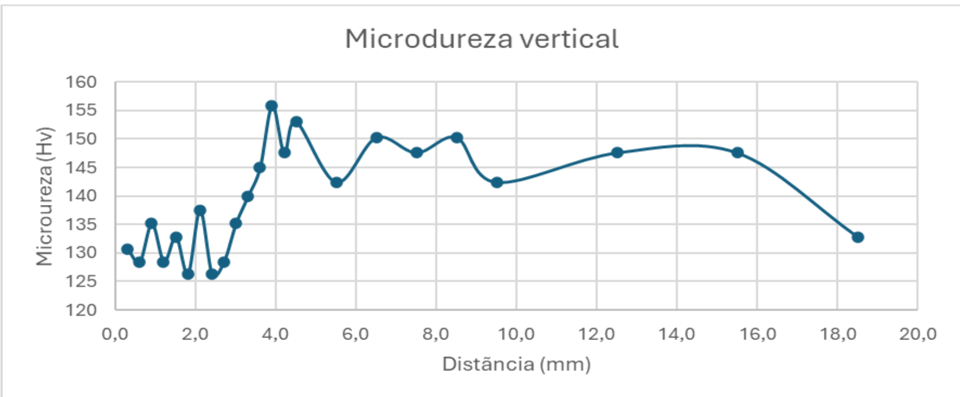


4.4 VICKERS MICROHARDNESS TEST

Fig.5 shows the results relevant to the microhardness test. In this test, the indentations begin in the base material (SAE 1020), approximately 2 mm from the heat affected zone (ZTA), with a pass between 0.3 mm indentation, in which it varies between 126.28 and 137.5 HV. For the binding region, the microhardness obtained measurements with approximately 155 HV. After passing the ZTA, perform four more tests at a distance of 0.3 mm, it is used 1 mm between 5 subsequent indentations and finish with 3 more data at a distance of 3 mm each, which shows values between 150.28 and 132.83 HV

Figure 5

Microhardness vertical direction.

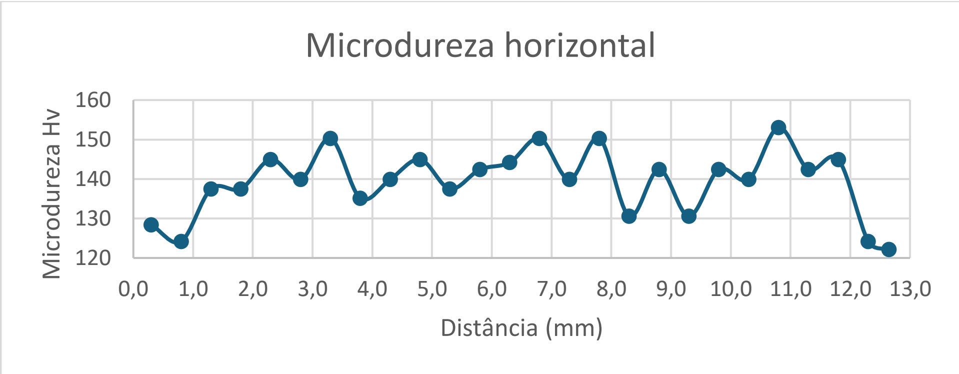


In this test it can be observed that the microhardness in the plate is slightly higher than the microhardness in the deposited material, which can be explained by the band structure of the plate material [12].

The horizontal graph shows the difference in microhardness between the center and the periphery of the specimen, explained due to the different cooling speed that impacts on pearlite and grain growth ..

Figure 6

Horizontal microhardness



Due to the relatively low microhardness difference between the edges at the center, the welding process presents a good quality product by providing a considerable material homogeneity.

5 CONCLUSION

Subsequently, the metallographic analysis was possible to verify that for the region in which the ER70S-6 material was deposited based on SAE 1020, there is a migration of carbon from the base metal to the deposited material, however, the migration layer is very close to the base, which can be eliminated by separating the printed part from the base metal.

When evaluating the microhardness data, the ER70S-6 wire was more influenced by the temperature in the peripheries due to the cooling that resulted in a difference in microhardness of approximately 16%.

Thus, when evaluating the microhardness of the material deposited in the deposition region was 137 HV. The increase in microhardness may be linked to the amount of manganese associated with chromium present in the study material.

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