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ADDITIVE MANUFACTURING IN THE FORGING PROCESS: PREFORM MANUFACTURING THROUGH MATERIAL DEPOSITION BY LOCALIZED FUSION USING LOW CARBON WIRE

Henrique Cechinel Casagrande[1]
Anderson Daleffe[2]
Carlos Antônio Ferreira[3]
Alexandre Milanez[4]
Gilson de March[5]
Lírio Schaeffer[6]

ABSTRACT

Objective: The objective of this study is to investigate the effects of hot forging on the microstructure and microhardness of a component manufactured by additive manufacturing (AM), specifically an eyebolt produced by the WAAM (Wire and Arc Additive Manufacturing) process, seeking to refine the grain size, relieve residual stresses and eliminate porosities.

Theoretical Framework: Additive manufacturing (commonly called 3D printing) has been gaining ground in the manufacturing of parts and components, allowing layer-by-layer construction, useful for complex designs and rapid prototyping. The WAAM process stands out for its high material deposition rate, although it presents lower surface precision, requiring finishing by machining. The microstructure of metals printed by AM, such as carbon steel, is characterized by coarse grains, residual stresses and porosities, which can compromise the performance of the final component.

Method: In this study, an eyebolt in carbon steel was manufactured by AM (WAAM process). Then, the component was subjected to hot forging. The analysis focused on evaluating the microstructure and microhardness of the samples before and after forging, seeking to verify the effect of the hybrid process (AM + forging).

Results and Discussion: The microstructural analysis revealed that the forged sample presented significantly smaller grains compared to the part that was only printed. Regarding microhardness, the values were also higher in the hybrid condition (207 HV) compared to the material that was only printed (161 HV), a result that was consistent with expectations, due to the grain refinement promoted by hot forging.

Research Implications: The results indicate that the combination of additive manufacturing with hot forging can mitigate metallurgical deficiencies typical of printed components, such as coarse grains and porosities, in addition to improving mechanical properties, such as hardness. In addition, the use of AM allows the manufacture of preforms, reducing material waste and the need for tools in the forming process.

Originality/Value: This work proposes an innovative hybrid approach, combining additive manufacturing and hot forging, as a strategy to improve the metallurgical and mechanical properties of metal components. This combination optimizes resources, promotes sustainability in the use of raw materials and expands the potential of AM for more demanding structural applications.

Keywords: Additive Manufacturing, Low Carbon, Welding and Forging.

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

MANUFATURA ADITIVA NO PROCESSO DE FORJAMENTO: CONFECÇÃO DE PRÉ-FORMA ATRAVÉS DA DEPOSIÇÃO DE MATERIAIS POR FUSÃO LOCALIZADA UTILIZANDO ARAME DE BAIXO CARBONO

RESUMO

Objetivo: O objetivo deste estudo é investigar os efeitos do forjamento a quente na microestrutura e microdureza de um componente fabricado por manufatura aditiva (MA), especificamente um olhal produzido pelo processo WAAM (Wire and Arc Additive Manufacturing), buscando o refino do tamanho de grão, alívio de tensões residuais e eliminação de porosidades.

Estrutura teórica: A manufatura aditiva (comumente chamada de impressão 3D) vem ganhando espaço na fabricação de peças e componentes, permitindo a construção camada por camada, útil para projetos complexos e prototipagem rápida. O processo WAAM destaca-se por sua alta taxa de deposição de material, embora apresente menor precisão superficial, exigindo acabamento por usinagem. A microestrutura dos metais impressos por MA, como o aço carbono, é caracterizada por grãos grosseiros, tensões residuais e porosidades, o que pode comprometer o desempenho do componente final.

Método: Neste estudo, foi fabricado um olhal em aço carbono por meio de MA (processo WAAM). Em seguida, o componente foi submetido a forjamento a quente. A análise concentrou-se na avaliação da microestrutura e da microdureza das amostras antes e após o forjamento, buscando verificar o efeito do processo híbrido (MA + forjamento).

Resultados e Discussão: A análise microestrutural revelou que a amostra forjada apresentou grãos significativamente menores em comparação à peça apenas impressa. Em relação à microdureza, os valores também foram superiores na condição híbrida (207 HV) em comparação ao material apenas impresso (161 HV), resultado condizente com o esperado, devido ao refino de grão promovido pelo forjamento a quente.

Implicações da pesquisa: Os resultados indicam que a combinação da manufatura aditiva com o forjamento a quente pode mitigar deficiências metalúrgicas típicas dos componentes impressos, como grãos grosseiros e porosidades, além de melhorar propriedades mecânicas, como a dureza. Além disso, a utilização da MA permite a fabricação de pré-formas, reduzindo desperdício de material e a necessidade de ferramentas no processo de conformação.

Originalidade/Valor: Este trabalho propõe uma abordagem híbrida inovadora, unindo manufatura aditiva e forjamento a quente, como estratégia para melhorar as propriedades metalúrgicas e mecânicas dos componentes metálicos. Essa combinação otimiza recursos, promove sustentabilidade no uso de matéria-prima e amplia o potencial da MA para aplicações estruturais mais exigentes.

Palavras-chave: Manufatura Aditiva, Baixo Carbono, Soldagem e Forjamento.

FABRICACIÓN ADITIVA EN EL PROCESO DE FORJA: FABRICACIÓN DE PREFORMAS MEDIANTE DEPÓSITO DE MATERIAL POR FUSIÓN LOCALIZADA UTILIZANDO HILO DE BAJO CARBONO

RESUMEN

Objetivo: El objetivo de este estudio es investigar los efectos del forjado en caliente en la microestructura y la microdureza de un componente fabricado mediante fabricación aditiva (FA), específicamente un cáncamo producido mediante el proceso WAAM (Fabricación Aditiva por Alambre y Arco), buscando refinar el tamaño de grano, aliviar tensiones residuales y eliminar porosidades.

Marco teórico: La fabricación aditiva (comúnmente llamada impresión 3D) ha ganado terreno en la fabricación de piezas y componentes, permitiendo la construcción capa a capa, útil para diseños complejos y prototipado rápido. El proceso WAAM destaca por su alta tasa de deposición de material, aunque presenta una menor precisión superficial, requiriendo acabado mediante mecanizado. La microestructura de los metales impresos mediante FA, como el acero al carbono, se caracteriza por granos gruesos, tensiones residuales y porosidades, que pueden comprometer el rendimiento del componente final.

Método: En este estudio, se fabricó un cáncamo de acero al carbono mediante FA (proceso WAAM). Posteriormente, el componente se sometió a forjado en caliente. El análisis se centró en evaluar la microestructura y la microdureza de las muestras antes y después del forjado, buscando verificar el efecto del proceso híbrido (FA + forjado).

Resultados y Discusión: El análisis microestructural reveló que la muestra forjada presentó granos significativamente más pequeños en comparación con la pieza impresa únicamente. En cuanto a la microdureza, los valores también fueron mayores en la condición híbrida (207 HV) en comparación con el material impreso únicamente (161 HV), un resultado consistente con las expectativas, debido al refinamiento del grano que promueve el forjado en caliente.

Implicaciones de la Investigación: Los resultados indican que la combinación de la FA con el forjado en caliente puede mitigar las deficiencias metalúrgicas típicas de los componentes impresos, como los granos gruesos y las porosidades, además de mejorar las propiedades mecánicas, como la dureza. Asimismo, el uso de la FA permite la fabricación de preformas, reduciendo el desperdicio de material y la necesidad de herramientas en el proceso de conformado.

Originalidad/Valor: Este trabajo propone un enfoque híbrido innovador que combina la fabricación aditiva y la forja en caliente como estrategia para mejorar las propiedades metalúrgicas y mecánicas de los componentes metálicos. Esta combinación optimiza los recursos, promueve la sostenibilidad en el uso de materias primas y amplía el potencial de la fabricación aditiva para aplicaciones estructurales más exigentes.

Palabras clave: Fabricación Aditiva, Bajas Emisiones de Carbono, Soldadura y Forja.

1 INTRODUCTION

In 1981, at the Nagoya Research Institute in Japan, the term additive manufacturing, or 3D printing, was coined. Researcher Hideo Kodama, inspired by photohardened polymer technology, had the idea of making a three-dimensional impression. Despite this, the feat was accomplished 12 years later when MIT (Massachusetts Institute of Technology) developed the powder-bed process using the heads of an inkjet printer. That said, other terms have been introduced to describe this technique, such as additive manufacturing, rapid prototyping, free-form manufacturing, 3D printing and others (1) (3).

Abstract: The AM process using electric arc is known to produce large-scale metallic components with high deposition rates. However, when it is necessary to raise the temperature to the melting point of the steel, a greater amount of energy is used. Thus, deformations, residual stresses, porosity and cracks may be present in the structure of the printed material (2) (4).

The Wire Arc Additive Manufacturing (WAAM) technique is highlighted because it has high deposition rates and presents lower costs compared to other MA processes. It is believed that this technique will become a new leadership in the additive manufacturing industry (11).

Nevertheless, Hopper *et al*, report that 3D printing has great potential for the manufacture of high quality products used in critical situations, such as space and biomedical engineering. However, the acceptance of MA in these fields began to suffer retention due to lack of confidence in the consistency of the mechanical properties due to the occurrence of porosity, heterogeneous and large grains (5).

Therefore, high strength materials have been studied with the application of this technique in sectors that require properties free of defects. Thus, aerospace, war, mining, and even deep-sea submarine industries can all benefit from additive manufacturing. Therefore, ways to minimize the defects left after printing are studied (10).

Thus, there are studies initiated with the application of localized laser melting with metallic powder in 316L stainless steel with subsequent hot forging, the objective is to eliminate as much as possible the difficulties encountered when using the MA technique for the manufacture of the parts. Concomitantly the results were promising, with the junction of the hybrid process between MA and hot forging it was possible to obtain a structure with reduction in porosity, and the creation of a more robust structure, resulting in better mechanical properties (5).

For this study will be used the additive manufacturing technique by arc wire. However, when using the filler wire ER70S-6 in previous studies, the samples showed porosity between the union of the layers. However, this wire is known to have a low carbon content that thus, after microhardness evaluation, presented an average of 155 HV, which is consistent with a low carbon content material (6).

Therefore, for this study will be produced pieces in the form of an eye using the welding wire ER70S-6 with the MA technique for the manufacture of a preform, in the sequence the hot forging process will be carried out as a final form of the part, seeking to improve the metallurgical and mechanical properties of the material.

2 BIBLIOGRAPHIC REVIEW

This study evaluates an innovative manufacturing process called additive manufacturing along with the millennial manufacturing process, but widely used in industry as hot forging. In this chapter, a brief theoretical reference will be reported, basing the reader on these two technologies used in this work.

2.1 GMAW ADDITIVE MANUFACTURING

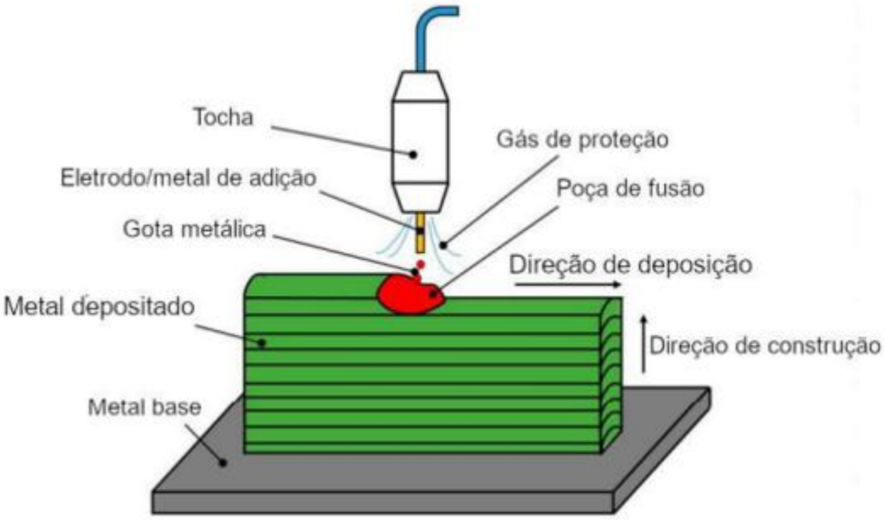
Within the WAAM process it is possible to have different localized fusion applications. As a combination of arc welding material and raw material, this technique has been used in the gas tungsten arc welding (GTAW) process, plasma arc welding (PAW), or the gas metal arc welding (GMAW) process, the latter used in this study (7).

However, a molten metal pool is supported by the formation of an electric arc between a consumable wire and a base metal. The consumable is fed into the melting pool and protected by a gas shield, adding three-dimensional movements to the torch when a path is traveled and a geometry is printed layer by layer (2).

Figure 1 details the GMAW 3D printing process, where the deposition is carried out through an automatic equipment, where this consumable has gas protection, which can be with active or inert gas. The figure also highlights the horizontal direction of deposition and the direction of construction, both programmed according to geometric need. It is worth mentioning the use of a base metal to initiate the deposition of material (2).

Figure 1

Additive manufacturing process.



Source: Adapted from Ding *et al* (2016) (2).

The use of the GMAW process is adopted due to the high rate of deposition of raw material, which can reach up to 5 kg/h (2).

2.2 HOT FORGING PROCESS

Different ways of handling the metal have emerged over time. However, the use of forging for mechanical conformation stands out due to its ability to homogenize the structure of the material being worked, increasing its reliability for extreme applications (8).

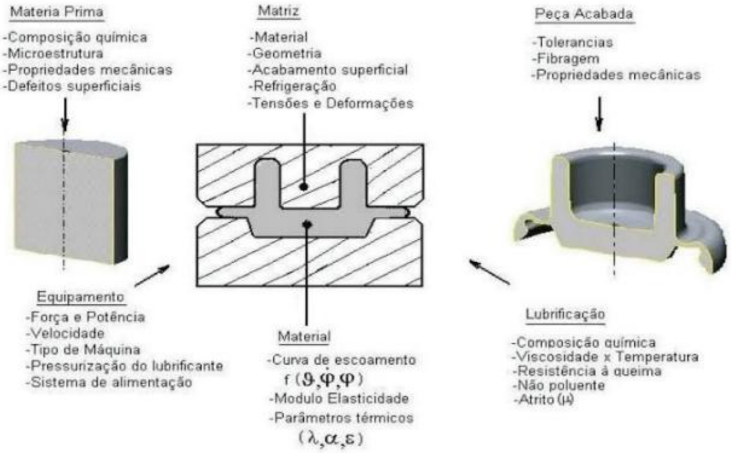
Thus, to forge a material, it is necessary to have prior knowledge of the raw material, the tooling to be used and the final geometry, as shown in Figure 2.

Therefore, the most commonly used material in the industry for forming is steel. This can be deformed cold or hot, which will change the application is the equipment available, production cost, mechanical strength, metallurgical among others (9).

That said, by raising the temperature of a metal it is possible to reduce the resistance to deformation, thus reaching large deformations with relatively low force values (9).

Figure 2

Parameters for forging process



Source: SCHAEFER., (2001). (8).

It should be noted that when heating the material to be forged, a homogeneous structure is obtained, where simple parts are transformed into complex geometries with excellent metallurgical and mechanical characteristics (12).

2.3 METALLOGRAPHY AND MICROHARDNESS

Understanding the properties of materials is crucial to ensure compliance of specific products. This allows the analysis of aspects such as microstructure, pore formation, potential defects and areas affected by heat treatments or welding processes (13). A metallographic essay can be divided into two main categories: macrography and micrography.

As for the hardness test, it consists of applying a load that on a surface occurs a surface deformation. Hardness is a mechanical property where a material when pressed by another material of higher hardness, or by standardized markers, presents a risk or formation of a permanent mark (14).

2.4 CHEMICAL COMPOSITION ER70S-6 WIRE AND BASE METAL

Studies carried out with the aid of the additive manufacturing technique using the ER70S-6 wire were developed with the objective of studying the deposited material and base metal (substrate). Therefore, Table 1 shows the values referring to the chemical characterization for these materials (15).

Table 1

Chemical composition ER70S-6 and SAE 1020

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)	0.010	<0.0030
Chromium (Cr)	0.020	0.020
Molybdenum (Mo)	0.014	0.0096
Copper (Cu)	0.093	0.0045
Iron (Fe)	Bal.	Bal.

Source: Ferreira *et al.*, 2024. (15).

It should be noted that the concentrated carbon content for the two materials is very close, which justifies the use of the adopted base metal.

It is noteworthy that by raising the carbon content in the material, higher temperatures are required for hot forging, which implies costs (9).

3 EXPERIMENTAL PROCEDURE

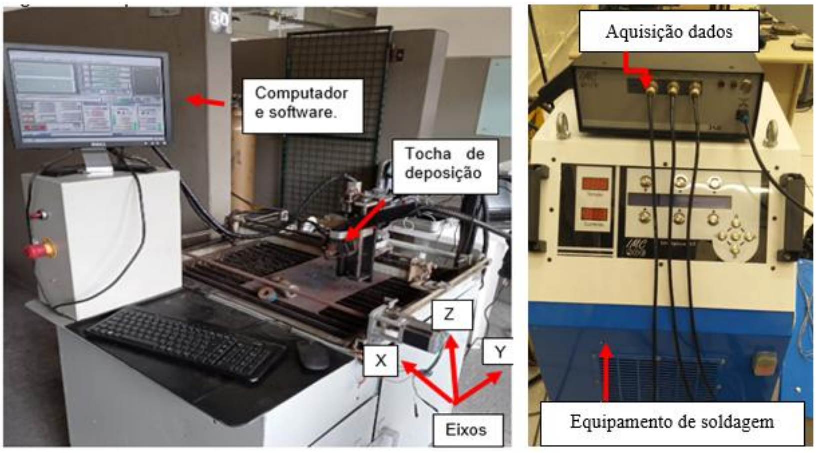
Next, it will be detailed how the practical part of this study was carried out, as well as the parameters and techniques used to make the pieces in eye shape.

3.1 ADDITIVE MANUFACTURING EQUIPMENT

The equipment used for 3D printing of the samples is a junction between welding machine and device with CNC coordinates (Computer Numerical Center). The welding machine is made by IMC model DIGplus A7. However, this device stands out for having a tool for data acquisition of the welding process called SAP 3SR.

Figure 3

Additive manufacturing equipment



Source: FERREIRA *et al*., 2024. (15).

The data acquisition equipment is shown in Figure 3, as well as the welding machine and the device for moving the torch. The latter has coordinates in three axes, longitudinal, transverse and vertical, X, Y and Z, respectively. The equipment also has a software for MACH 3® programming, using the G programming language.

3.2 SPECIMENS MANUFACTURED BY MA

Figure 4 shows the manufacture of the part under study. It stands out as AM the part produced by Additive Manufacturing, and for the sample with the hybrid process titled AM and FORGE.

Figure 4

Eye manufactured by additive manufacturing (MA), eye manufactured by the hybrid process (MA + Forge).

The parameters used to manufacture the samples are shown below. The use of the SAP 3SR tool for welding data acquisition is emphasized.

Table 2

Welding parameters.

Parameters:	Values:
Current (A)	**138**
Voltage (V)	**18**
Gas flow rate (L/min.)	**12.5**
Wire speed (m/min.)	**5**
Argon (%)	**85**
Carbon dioxide (%)	**15**
CNC Displacement (mm/min.)	**350**

As previously mentioned, the programming was performed using G language with the aid of Mach 3® software. However, an advance of 350 mm/min and an increase of 2.5 mm were used at each deposition.

3.3 HOT FORGING

The mechanical forming process took place in the FKL - Hydraulic Machines brand press, applying compression of 100 tons on the tooling provided by the UniSATC university. For forging, the specimens were heated to 1200 °C for 60 minutes in the JUNG muffle furnace. In short, a total of four samples were prepared, two only by Additive Manufacturing and the other two by Additive Manufacturing followed by the hot forging process, both for metallographic comparison and Vickers microhardness profile.

3.4 VICKERS MICROHARDNESS TEST

A SHIMADZE® HMV-2TADW microhardness tester was used following the ABNT NBR ISO 6507 standard. The test was carried out on a specimen applying a force of 4,903N and a distance of 1 millimeter at each indentation.

3.5 METALLOGRAPHIC ANALYSIS

The metallographic test was performed following the ABNT NBR 15454 standard, which defines the terms used in metallography of iron-carbon alloys, using an Olympus microscope model SC30. To reveal the phases present in the samples, 2% nital acid was used for a period of 15 seconds.

4 RESULTS AND DISCUSSIONS

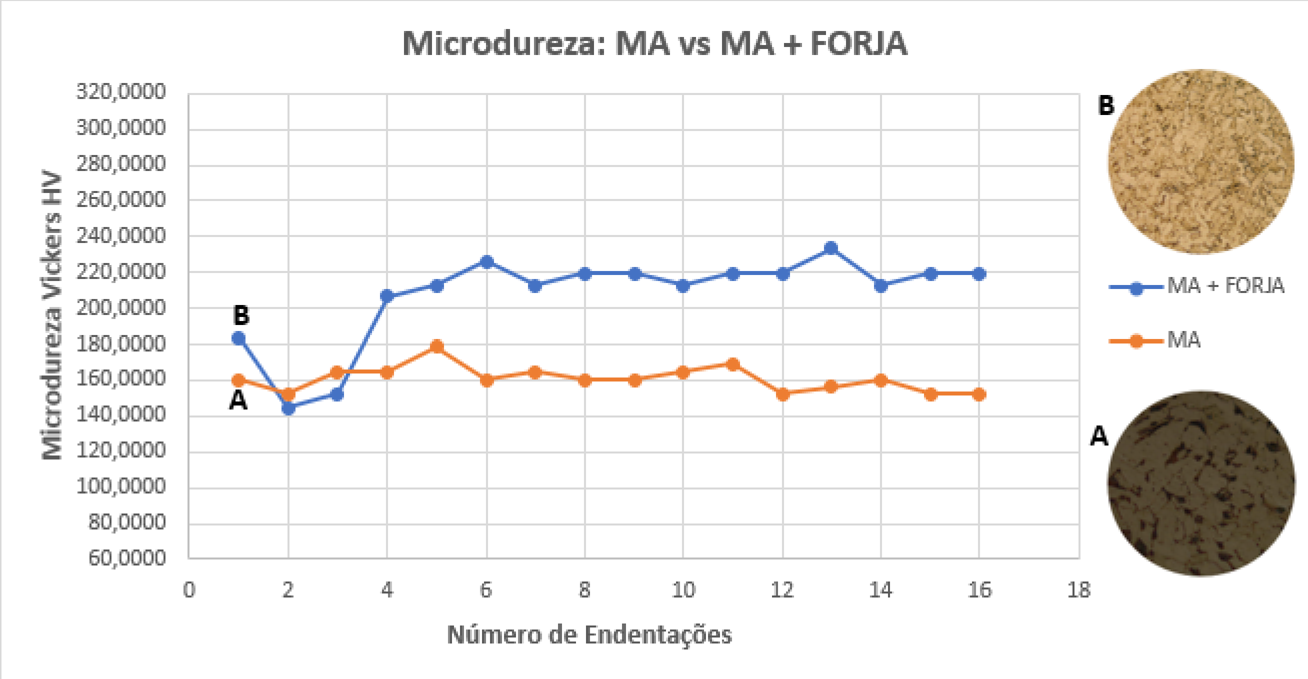
It seeks to understand the metallurgical effects with the hybrid manufacturing process between Additive Manufacturing and subsequent Hot Forging. The GMAW layer-by-layer welding technique with low carbon consumable (wire) is used. It will then be presented and discussed the results obtained throughout this study.

4.1 VICKERS MICROHARDNESS TEST

Figure 6 shows the results for the Vickers microhardness test in profile, that is, 16 indentations were performed in the sample with a distance of 1 millimeter between each indentation.

Figure 6

Vickers microhardness test.



Thus, the sample called MA, where only the 3D printing process was applied, presented lower hardness compared to the hybrid process. However, it should be noted that the MA process obtained greater uniformity between indentations, presenting an average of 161 ± 7 HV.

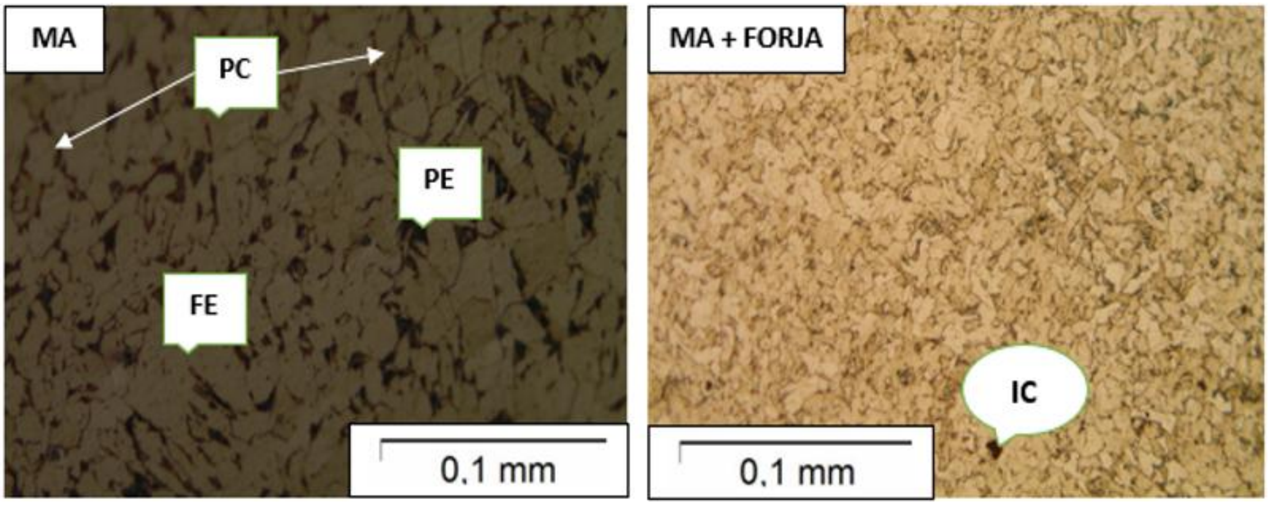
For the hybrid process, the average was 207 ± 25 HV. A larger standard deviation is observed in relation to the MA process. This is due to the fact that the first three indentations oscillate from 182 HV decaying to 142 HV and then rising to 200 HV, which followed in this line.

4.2 METALLOGRAPHY TEST

Figure 7 details the metallographic evaluation between the Additive Manufacturing process and the hybrid process between AM and FORJA. That said, nomenclatures are used to understand the phases and microconstituents present in the structure. Thus, CP stands for Grain Contour Perlite, PE Perlite and FE ferrite, as well as CI for Inclusion.

Figure 7:

Metallographic analysis between MA and MA + FORJA.



The printed sample presented pearlite represented in dark color, and ferrite in light color. However, the situations where the perlite was concentrated in the ferritic grain boundary. It is worth mentioning that the ferrite phase consists of iron, since the microconstituent perlite has two phases, ferrite and cementite, the latter formed by iron carbide, responsible for increasing the hardness of the metals.

For the hybrid process, a refinement in the grain size was obtained, however, the pearlite is noted in lower concentrations, but dissolved in the ferritic matrix. The refining in the grains explains the increase in hardness compared to the material produced by additive manufacturing. Nevertheless, it was evidenced an inclusion after hot forging. What can become a porosity of the welding process.

5 CONCLUSIONS

The samples produced by Additive Manufacturing presented higher hardness in relation to the hybrid process. As shown in Figure 6, the microhardness for MA was 161 ± 7 HV, however, the hybrid process increased the microhardness characteristic of the material to 207 ± 25 HV, due to the hot forging process to refine the grain size and improve the mechanical properties, according to the literature. However, after forging, an inclusion in the structure was evidenced, which can be a porosity of the welding process.

However, the results of the forged samples reached the expected. Thus, it is concluded that the hybrid process between Additive Manufacturing and Forging can be a valuable tool, and thus improve the mechanical and metallurgical characteristics of printed metals. It is worth mentioning that using the AM process the part is in the form of a preform, reducing the waste of raw material and the excessive use of dies for forging. Thus improving production spending as well as improving sustainability.

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