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MICROSTRUCTURAL CHARACTERIZATION OF THE ALLOY TI-6AL-4V OBTAINED BY DIFFERENT MANUFACTURING PROCESSES

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Abstract. *The planning and the proper choice of the manufacturing process are of extreme importance for a good final result, since each process has its particularity, which can influence the costs or the final quality of the product. Ti-6Al-4V titanium alloy is one of the most used for medical and aerospace applications because of its excellent mechanical properties, high corrosion resistance and biocompatibility. This work aims to compare the microstructural characteristics of the Ti-6Al-4V alloy obtained by the processes of lamination, powder metallurgy and Direct Metal Laser Sintering (DMLS). For this, the microstructure obtained in each of the different manufacturing processes was analyzed through optical microscopy, scanning electron microscopy and Vickers microhardness tests. The results showed that the Ti-6Al-4V alloy produced by the rolling process had a homogeneous, pore-free equiaxial microstructure composed of the alpha and beta phases. The material produced by the powder metallurgy process presented a lamellar microstructure, also composed of the alpha and beta phases, presenting a large amount of pores from the process. The microstructure resulting from the DMLS manufacturing process is composed of the hexagonal (martensitic) and beta-retained phases.*

Keywords: *Ti-6Al-4V Alloy; Powder Metallurgy; Lamination; Direct Metal Laser Sintering*

1. INTRODUCTION

The new technologies developed for manufacturing processes have emerged to meet the needs of the industry, in terms of increasing production with efficiency and quality. Currently, there are several techniques of manufacturing a product, being that each process has its particularity in accordance with the final application.

As stated by Chiaverini (2001), the powder metallurgy is a metallurgical manufacturing technique that has presented high growth in recent years due to the innumerable possibilities of mixing materials. According to Galvani (2011), the process of powder metallurgy through the metallic powders and non-metallic has two main stages in the manufacturing process; the compaction and the sintering. In the compacting step the application of a pressure in the powders to the ambient temperature occurs, where the molds used generally correspond to the geometry and dimensional size desired in the final pieces, while in the sintering step the temperature used is below the melting temperature of the material suffering constantly temperature controls, time and ambient (Froes, 1984).

As said by Gonçalves (2010), the additive manufacturing process is linked to a set of methodologies developed to manufacture geometric models constructed from the 3D CAD system. As said by Smart (2008), Direct Metal Laser Sintering is an additive manufacturing technique, where the part is built layer by layer using the sintering of blends of 100% metallic powders through the use of a fiber laser. The construction methodology is based on geometric data obtained by the CAD 3D graphic system, making it possible to manufacture parts with complex shapes. DMLS technology enables significant reductions in costs and production time compared to other conventional manufacturing processes and still offers good mechanical properties (Greses, 2008).

According to Filho (1991), lamination is a process of mechanical conformation widely used in industries since it offers productivity and versatility with regard to geometric types and precision in dimensional control of the final product. As stated by Callister (2002), the lamination process consists of the passage of a work-piece between two cylinders rotating in opposite directions, resulting in a reduction in the thickness of the material this is caused by the compressive stresses exerted by the rollers. This deformation reduces the cross-section and increases the length and width of the piece body (Rodrigues, 2005).

The proper choice of the manufacturing process directly influences the efficiency and reliability in the production of a part, as each process technique can offer a different microstructure of the material.

With manufacturing processes, there are several types of materials and alloys on the market, as materials engineering constantly searches for materials that can offer greater strength, quality and efficiency in their application. Titanium and its alloys are included in this context, since it is a material with excellent mechanical properties.

Callister (2002) states that titanium, together with its alloys, is an innovative material and can be considered a new material in engineering due to its diverse applications. However, titanium alloys possess high cost in function of the requirement of specific techniques during improvement in the manufacturing process. According to Knoll (2006), titanium and its alloys can be applied in industrial aerospace, aeronautical, automotive and petroleum segments.

As said by Suryanarayana (1991), the Ti-6Al-4V alloy is an alpha-beta alloy containing 6% aluminum and 4% vanadium, exhibiting excellent mechanical properties allied with the corrosion and tensile strength. The Ti-6Al-4V alloy is widely used to manufacture medical devices and aeronautical items, as it has excellent biocompatibility, as well as low weight and high melting point (Gonçalves, 2012).

This work has as main objective to compare the microstructures obtained from three different manufacturing processes for the same Ti-6Al-4V alloy. The processes used were Lamination, Powder Metallurgy and Direct Metal Laser Sintering.

2. MATERIALS AND METHODS

The material used to perform this work was the Ti-6Al-4V alloy. The samples were produced by three different processes in the form of cylindrical bars (Figure 1).

The Samples made by the Direct Metal Laser Sintering process were produced from EOS Titanium Ti-6Al-4V pre-bonded commercial powder (Figure 2), using the EOSINT M 270 additive manufacturing equipment of the EOS GmbH (Electro Optical System). The processing parameters used in the samples production were laser beam power of 170 W, scanning speed of 1250 mm/s, line spacing of 0.1 mm, layer thickness of 0.03 mm and scanning angle of 45^{o} C.

In the Powder Metallurgy process, the samples were made by cold uniaxial pressing using a force of 2 tons and cold isostatic pressing of 450 MPa, followed by sintering in a high vacuum oven at a temperature of 1000 ° C per two hours.

The Samples manufactured by the Lamination process were purchased commercially, and no further details of the methodology of the sample preparation process were reported.

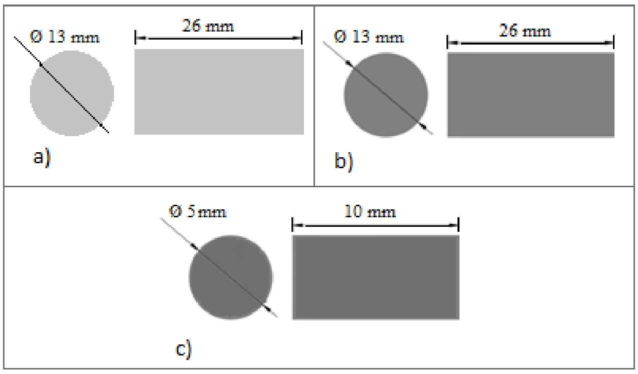

Figure 1. Samples manufactured by the processes of: (a) Powder Metallurgy, (b) DMLS and (c) Lamination

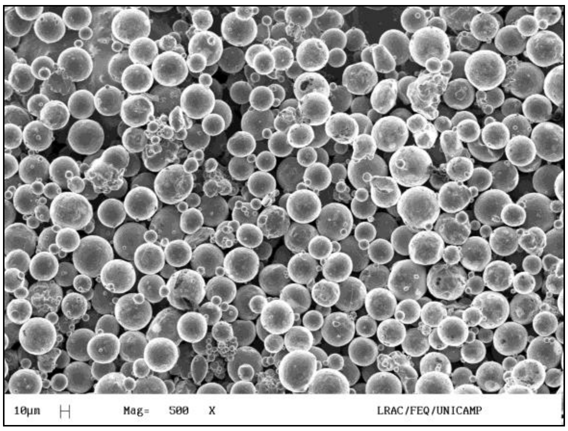

Figure 2. Commercial powder of the Ti-6Al-4V alloy used for the manufacture of DMLS samples.

The samples were analyzed by the Leica optical microscope, Le IL DM model LED, and by scanning electron microscope (SEM) Zeiss model EVO MA15. The Vickers Microhardness tests were performed using the Shimadzu digital microdurometer, model HMV-2. Twenty measurements were performed in each sample applying a force of 500 gf for 15 seconds and the results presented are the mean values.

3. RESULTS AND DISCUSSIONS

3.1 Microstructural analysis

In Figure 3 it is possible to observe the micrographs of the longitudinal and transverse sections of the sample made by the Powder Metallurgy process. The microstructure in both sections are practically identical. It is possible to visualize several pores formed by the powder metallurgy process and also to observe that the structure of the biphasic region ($\alpha + \beta$) is homogeneously distributed, where the light area represents the alpha phase (α), and the dark area the beta phase (β). The alpha phase (α) has a relatively coarse lamellar structure and no orientation, whereas the beta phase (β) has an intergranular structure.

Figure 4 shows the micrograph of the longitudinal and transverse sections of the sample made by the DMLS process. It is not possible to observe modifications in the structure of the material between these sections, only difference in the directions of the lamellas. This manufacturing process presented a fine structure with phase alpha (α) and beta (β) of the acicular type.

Finally, Figure 5 shows the micrograph of the longitudinal and transverse sections of the sample made by the Lamination process, where it was observed that this process has a well-refined and homogeneous microstructure.

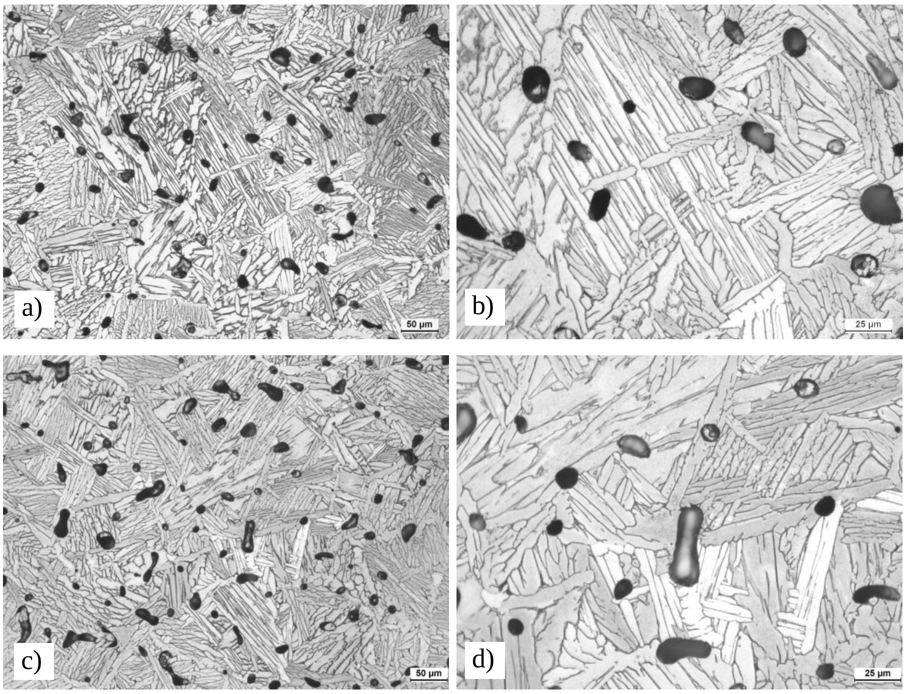

Figure 3. Optical microscopy of the sample made by the powder metallurgy process. Longitudinal section: (a) Increase of 200X and (b) 500X. Cross section: (c) Increase of 200X and (d) 500X.

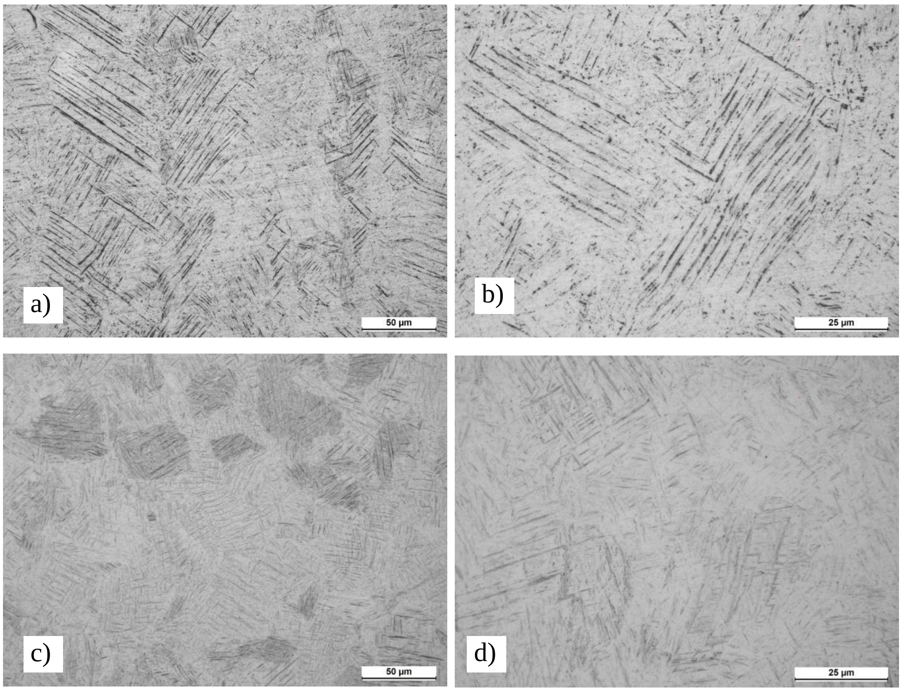

Figure 4. Optical microscopy of the sample made by the DMLS process: Longitudinal Section: (a) 200X magnification and (b) 500X. Cross Section: (c) 200X increase and (d) 500X.

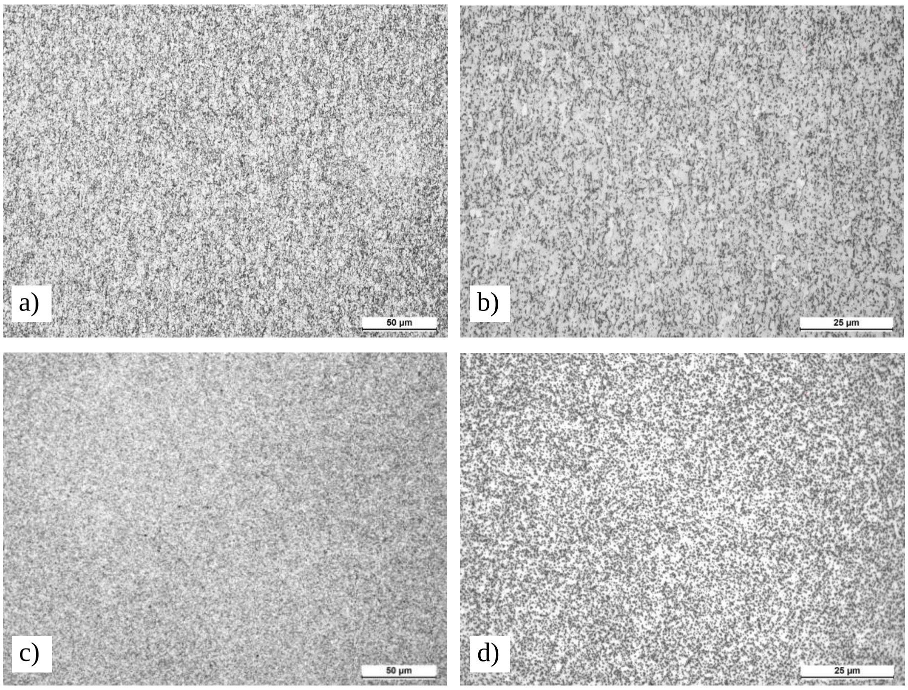

Figure 5. Optical microscopy of the sample made by the Lamination process. Longitudinal Section: (a) increase of 200X and (b) 500X. Cross Section: (c) increase of 200X and (d) 500X.

The ASTM F136 was used to verify and compare whether or not the main chemical compositions of the sample elements were within the established standard. Using the resource of element analysis of the scanning electron microscope (SEM), the elements identified were titanium, aluminum, and vanadium; each sample in proportions provided for in ASTM F136 according to the results shown in table 1.

Table 1. Chemical composition of samples elements x ASTM F136 Standard.

Elements	**ASTM F136 Standard** Composition, % (mass/mass)	**Powder Metallurgy** Composition, % (mass/mass)	**DMLS** Composition, % (mass/mass)	**Lamination** Composition, % (mass/mass)
Aluminum	5,5 – 6,50	4,60	6,16	5,72
Vanadium	3,5 – 4,5	4,48	3,98	3,57
Titanium	-	90,92	89,86	90,71

The micrographs obtained by scanning electron microscopy are presented.

The figure 6 shows the longitudinal and transverse sections of the sample made by the powder metallurgy process. The resulting microstructure in this manufacturing process is homogeneous and presents lamellas of phase α and phase β retained.

Since the temperature employed in the sintering process (1000° C) was greater than the β (Tβ = 995° C) transition temperature, the 100% β-phase structure was reached. As recrystallization and grain growth occurred during the cooling, the material presents the same morphology in the longitudinal and transverse sections. With cooling from Tβ, formation and growth of α-phase lamellas occurred. Part of the β phase of the initial matrix was retained between the lamellas, resulting in a lamellar microstructure composed of the phases α (dark phase) and β (light phase). It is possible to observe the presence of pores with approximately 17.63 μm.

Figure 7 shows the microstructure of the sample made by the DMLS process, where it is possible to observe that the microstructure consists of the hexagonal α-martensite phase with acicular morphology, formed from the β phase during the fast cooling process.

Finally, Figure 8 shows the microstructure of the sample manufactured by the Lamination process. In this figure it is possible to observe that the samples of the lamination process did not present porosity in their structure. The β (light) phase is homogeneously distributed in the grain boundaries of the α (dark) phase.

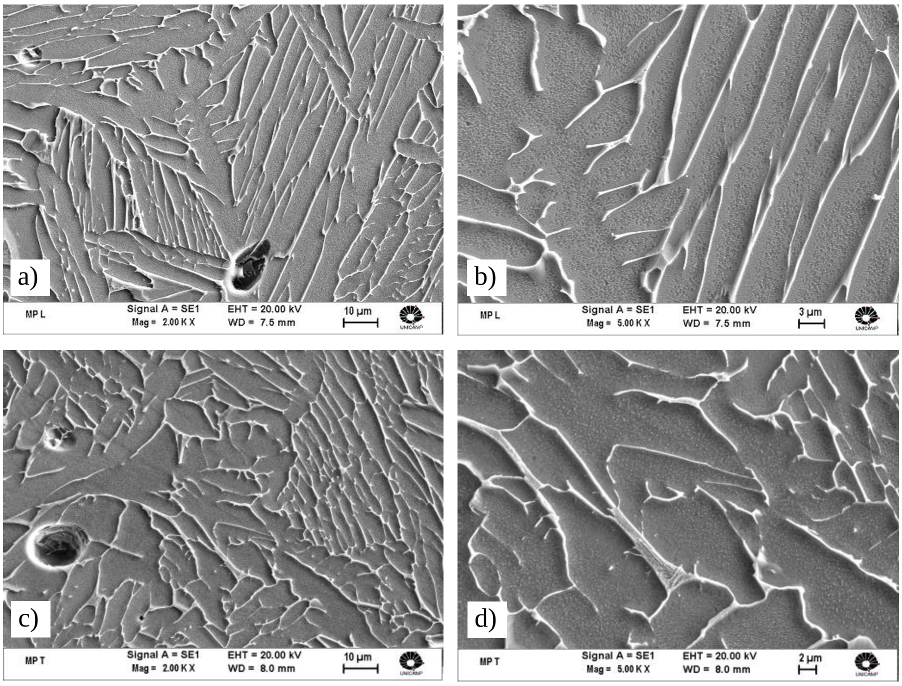

Figure 6. SEM of the sample made by the Powder Metallurgy process: Longitudinal Section: (a) 2000X magnification and (b) 5000X. Cross Section: (c) 2000X magnification and (d) 5000X.

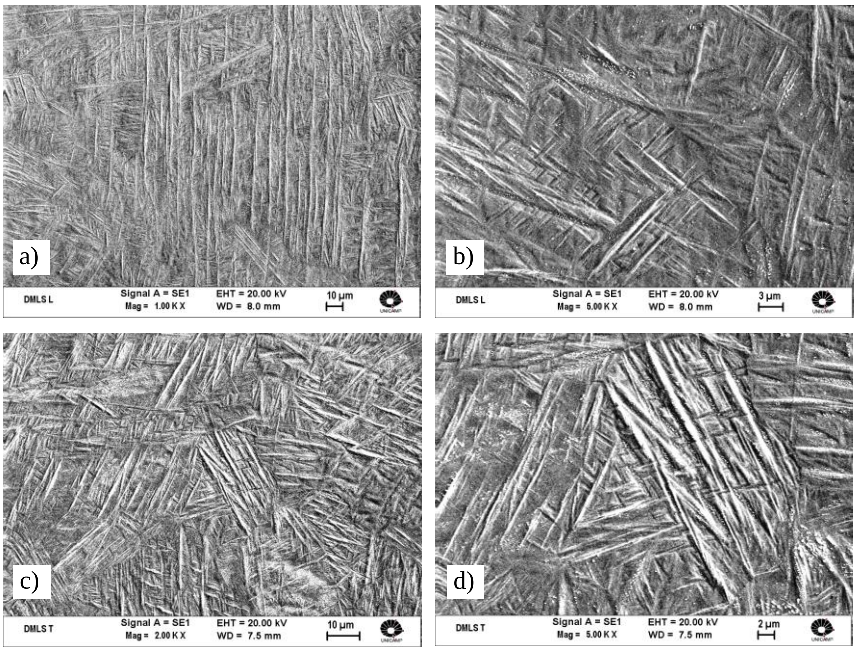

Figure 7. SEM of the sample made by the DMLS process: Longitudinal Section: (a) 2000X magnification and (b) 5000X. Cross Section: (c) 2000X magnification and (d) 5000X.

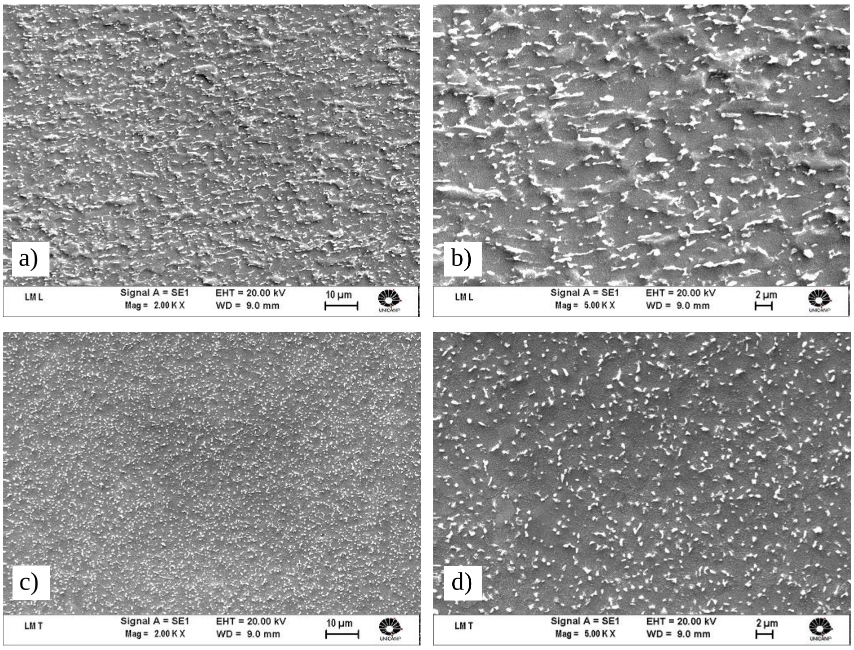

Figure 8. SEM of the sample manufactured by the Lamination process: Longitudinal Section: (a) 2000X magnification and (b) 5000X. Cross Section: (c) 2000X magnification and (d) 5000X.

3.2 Microhardness

Figure 9 shows the results obtained in the Vickers microhardness tests. It is observable that the material produced by the powder metallurgy process presents the value of approximately 250 HV, while the materials obtained by the lamination and DMLS processes present higher values, around 350 HV and 370 HV, respectively. The low value of microhardness obtained in the process of powder metallurgy can be explained by the fact that the material has a coarser microstructure and also due to the presence of pores.

The figure 10 shows the Vickers profile of microhardness, in which it is possible to observe a greater variation in the values measured in the material produced by powder metallurgy.

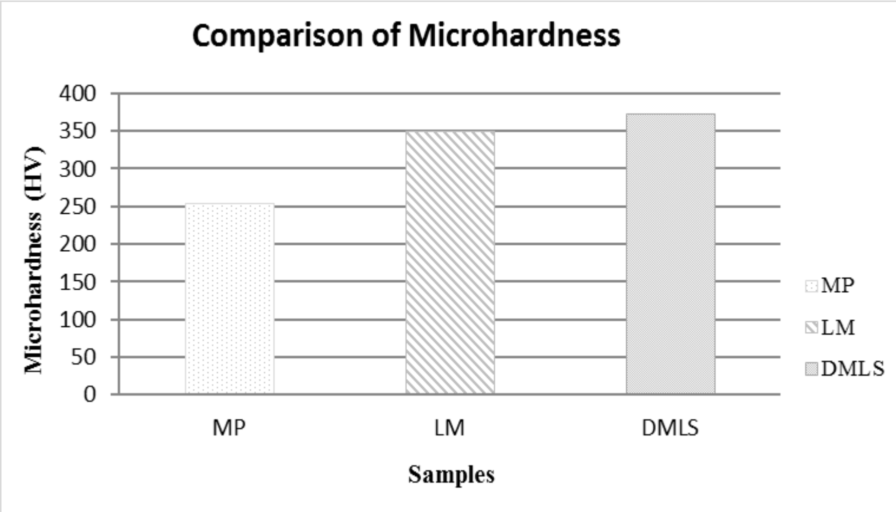

Figure 9. Comparative graph of the microhardness test.

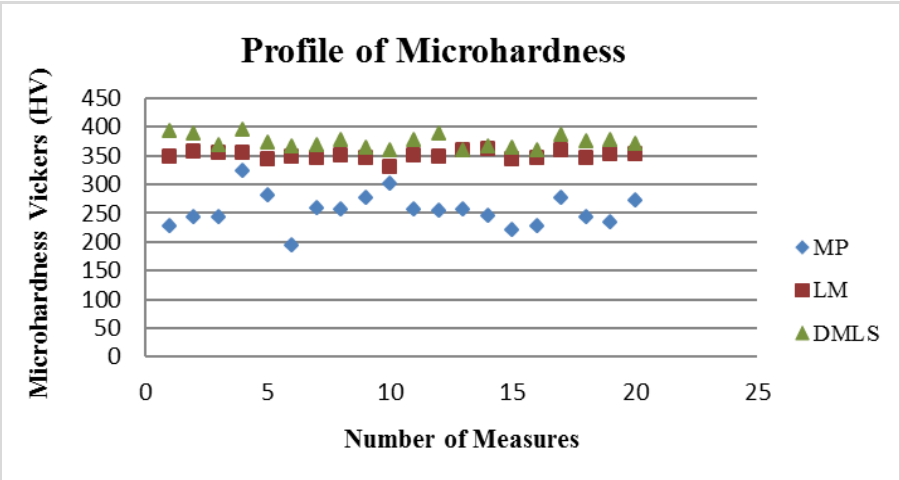

Figure 10. Profile of Microhardness Vickers.

4. CONCLUSIONS

This work proved that the different manufacturing processes interfere directly in the microstructure of the material and in its microhardness. It then reinforces the importance of choosing the suitable process for each application.

The powder metallurgy manufacturing process allows the manufacturing of custom parts, presenting a lower cost when compared to the processes of DMLS and Lamination. On the other hand, the material obtained by this process will have a lower mechanical resistance and still cannot yet be applied in the area of biomedicine, since it has a very high amount of pores, which can cause infiltrations and infections to the patients.

With the DMLS process, it is possible to construct parts with complex geometries for different applications. The material has a refined microstructure, excellent mechanical properties, however, but it will have a high cost when compared with the powder metallurgy and lamination processes.

Meanwhile, the lamination process may also offer excellent mechanical strength at a lower cost compared to the DMLS process, but there is a manufacturing limitation of shapes that are simple and straight.

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