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COMPARATIVE STUDY OF THE MECHANICAL PROPERTIES OF Ti-6Al-4V ALLOY MANUFACTURED BY ADDITIVE MANUFACTURING USING THE ELECTRON BEAM MELTING (EBM) PROCESS AND BY CONVENTIONAL METHODS

Lucas Carlos Sousa

Federal Institute of São Paulo, São Paulo, SP, Brazil.
lc.sousa.1994@gmail.com

Caique Movio Pereira de Souza

Mackenzie Presbyterian Institute, São Paulo, SP, Brazil
caiquemovio@gmail.com

Rene Ramos de Oliveira

Nuclear and Energy Research Institute, São Paulo, SP, Brazil
rolivier@ipen.br

Vanessa Seriacopi

Maua Institute of Technology, Maua, SP, Brazil
vanessa.seriacopi@maua.br

Rogério Daniel Dantas

Federal Institute of São Paulo, São Paulo, SP, Brazil.
rogerio.dantas@ifsp.edu.br

Wilson Carlos da Silva Junior

Federal Institute of São Paulo, São Paulo, SP, Brazil.
wilsoncarlos@ifsp.edu.br

Abstract. The Ti-6Al-4V alloy has existed for many decades, and its utilization has been increasing in recent years, particularly in the automotive, aerospace, and medical equipment sectors. Conventional processes such as casting, machining, and forging have limitations in manufacturing parts with complex geometries, increasing the product weight. Additive manufacturing (AM) has gained popularity due to its ability to produce customized parts with less mass and complex, varied geometries. The Electron Beam Melting (EBM) additive manufacturing process is widely used in the medical field and will be the focus of this study. It is necessary to investigate whether the mechanical properties of parts manufactured by EBM are comparable to those produced by conventional methods. Mechanical and microstructural characterizations of parts manufactured by EBM were performed through a series of mechanical tests, including hardness, tensile, Charpy impact tests, and X-ray diffraction analysis. The results obtained from the tensile test show that the samples meet the current ASTM F136 standard, with an average yield strength of 897.45 MPa and a maximum stress of 1054.92 MPa. The impact tests yielded an average value of 27.83 J/m, higher than that found in parts manufactured using conventional methods. The microstructural characterization indicates a phase transformation in both manufacturing processes, with the presence of α' martensite phase. The EBM-fabricated samples exhibit an α -Widmanstätten microstructure in the beta matrix with columnar grains.

Keywords: ASTM F136, EBM, Charpy impact test, tensile test.

1. INTRODUCTION

Layer-based geometry construction techniques have been developed since the mid-1980s (BRANDL, 2011). Additive manufacturing (AM) enables the creation of unique shapes through a CAD file, where this virtual model in .stl format is sliced into multiple cross-sectional layers by the software, resulting in coordinates for each layer. This point mesh is interpreted by the machine, which then builds three-dimensional objects layer by layer, stacking them on top of each other until the completion of the part (HERZOG et al., 2016).

Currently, AM offers layer deposition techniques for these same products at competitive economic values, and it is also possible to obtain parts with variable porosity surfaces (DUVAIZEM, 2009).

In the biomedical field, AM is widely employed for orthopedic implants, where metals gain prominence due to their favorable biological properties for interacting with complex changes and reactions in the human body. In one application example, metallic prostheses should be made from a metal or metallic alloy classified as a biomaterial (WANG, 2016). Titanium alloys are preferred in the biomedical industry, specifically in the field of implants, due to their good mechanical properties, biological compatibility, and corrosion resistance (PUEBLA et al., 2011). The biomedical field extensively utilizes additive manufacturing across a wide range of applications (COX et al., 2016) because each patient has unique anatomy and specific needs. In this context, AM enables the production of personalized implants tailored to the patient's anatomy, which reduces postoperative time and healing duration. Additionally, it allows for manipulation of the external and internal structures as well as the porosity of the implant to maximize the osteointegration process (JARDINI et al., 2014). Based on this scenario, the characterization of the mechanical properties of these materials becomes crucial, and laboratory tests such as tensile, hardness, and Charpy impact tests are commonly performed. The AM process needs to be better understood and supported to further develop this technique.

The objective of this study is to perform mechanical characterizations of Ti-6Al-4V alloy manufactured by Additive Manufacturing using Powder Bed Fusion - Electron Beam Melting (PBF-EBM) and compare its mechanical properties with those of the same alloy fabricated using conventional methods.

2. MATERIALS AND METHODS

The raw material used in the fabrication of the samples is a titanium alloy known as Ti-6Al-4V in powder form. The Ti-6Al-4V - Grade 23 powder supplier is AP&C, a manufacturer under GE Additive Company. This powder is obtained through plasma atomization with particle size distributions of 15-45 μm , 15-63 μm , 45-106 μm , 45-150 μm , and 106-180 μm . These powders have a highly spherical geometry, virtually no porosities, and minimal satellite content, resulting in excellent flow ability and packing density.

The mechanical properties were evaluated through Vickers Microhardness tests, tensile tests, and Charpy impact tests. In general, Vickers microhardness tests were conducted by ASTM E384 standard (2022). Tensile tests were performed using a Schenck-Trebel RM 1000 testing machine, following the ASTM E8M standard (2022). Charpy impact tests were conducted according to ASTM E23 standards (2023), and seven specimens were fabricated. The tests were carried out using a Wolpert PW30 universal impact-testing machine.

Microstructural characterization via optical microscopy (MO) was performed following the ASTM E3-11(2017) standard. The test specimens from the AM-fabricated part were cut in both transverse and longitudinal directions, and Figure 1 shows the embedded samples.

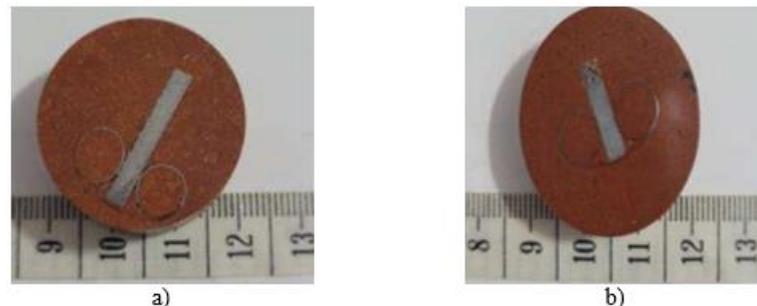


Figure 1. a) Cross section and b) longitudinal section.

For the tensile tests, seven specimens fabricated using the EBM additive manufacturing process with Ti-6Al-4V alloy were used. Among these specimens, four were subjected to surface anodization treatment, while three were not anodized. The dimensions of the specimens are shown in Figure 2. The testing speed was set at 0.38 mm/min, using a 20,000 kN load cell.

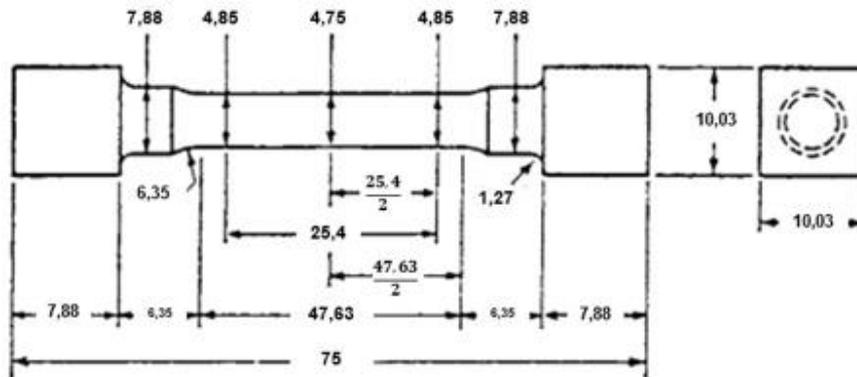


Figure 2. Specimen dimensions adapted from the ASTM E8M standard for tensile testing.

The dimensional requirements of ASTM E23 standard (2023) were followed for the fabrication of Charpy impact test specimens. The specimen dimensions are presented in Figure 3. Seven specimens were manufactured using the EBM method and subsequently machined to improve the surface finish. Before conducting the tests, all specimens underwent dimensional verification to ensure compliance with the current standard recommendations for comparison purposes.

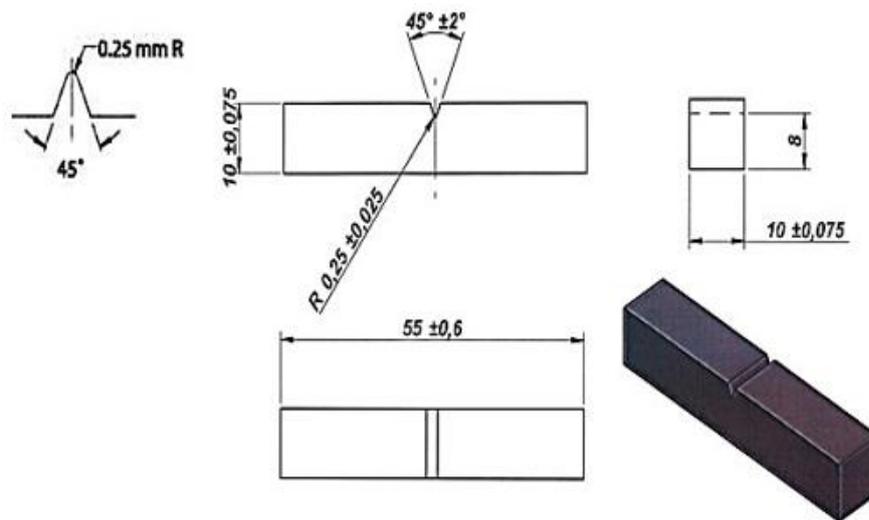


Figure 3. Specimen dimensions adapted from the ASTM E23 standard for Charpy impact test.

The impact tests were conducted using a Wolpert PW30 impact-testing machine. Before the tests, all necessary procedures were carried out to ensure the equipment was properly zeroed. The machine was connected to a data acquisition and processing system through software. The impact velocity was set at 5.52 m/s, and the testing temperature was maintained at 23°C. The striking edge of the hammer had a radius of 2 mm.

3. RESULTS AND DISCUSSIONS

Figure four shows the stress-strain curve obtained from the tensile tests, revealing an average maximum stress of 1054.92 MPa, which is higher than the values reported in the literature. The average yield strength was 958.15 MPa, which is suitable for use in implants, and the toughness was measured at 100.90 MJ/m³.

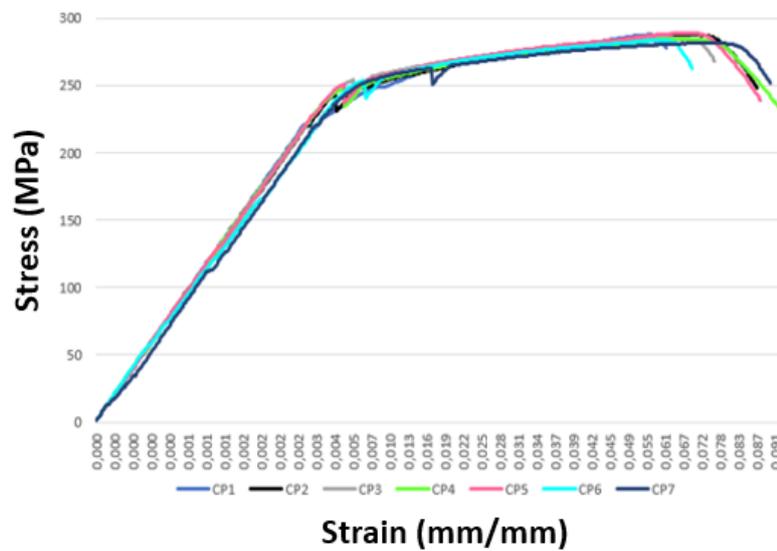


Figure 4. Stress x strain graph of all specimens by EBM.

In the study by Liu (2019), the average maximum stress of 960 MPa was found for Ti-6Al-4V alloy samples manufactured by additive manufacturing, while Debroy et al. (2018) reported maximum stress of 1041 MPa for the same type of sample. Another important mechanical property of samples intended for healthcare applications, such as implants, is the yield strength recommended by the ASTM F136 standard (2021), which is 828 MPa (SOUZA et al., 2022).

Work hardening is a mechanical property that refers to increased material strength after plastic deformation. Ti-6Al-4V alloys exhibit a high level of work hardening. The work-hardening values found in this study are similar to those reported in the literature, such as Johnson (1989), who found an n -value of 0.34. In this study, the average value was 0.31. The work-hardening values of the samples and other mechanical properties are presented in Table 1.

Table 1. Results of the translation test.

Sample	Maximum Stress (MPa)	Elastic Limit (MPa)	Yield Stress (MPa)	Elongation (%)	Resilience Coefficient (MPa)	Work Hardening Coefficient	Toughness (MJ/m ³)
1	1056.78	895.28	902.87	8.40	268.41	0.30	85.34
2	1056.78	900.70	858.43	12.00	267.60	0.29	112.87
3	1055.70	993.92	902.87	10.50	260.16	0.32	102.36
4	1049.19	981.99	901.79	12.70	270.40	0.35	120.10
5	1062.20	931.05	885.53	12.20	259.53	0.30	112.26
6	1053.53	1002.59	926.72	9.40	264.45	0.32	78.78
7	1050.28	1001.50	903.95	10.50	273.52	0.31	94.61
Mean	1054.92	958.15	897.45	10.81	267.60	0.31	100.90
Standard Deviation	4.41	47.76	20.98	1.58	5.20	0.02	15.35

The Ti-6Al-4V alloy is known for its excellent toughness, and this mechanical property is of utmost importance for materials subjected to impacts or cyclic loads. The toughness of the Ti-6Al-4V alloy is attributed to its microstructure and resulting mechanical properties. The alloy consists of fine grains of α phase, which contribute to its mechanical strength and toughness, while the presence of β phase in small amounts helps increase the ductility and toughness of the alloy. In this study, an average value of 100.90 MJ/m³ was obtained, which is within the expected range for Ti-6Al-4V alloy samples.

The average yield strength of the samples manufactured by EBM was 897.45 MPa, which is higher than the value established by the ASTM F136 standard for materials fabricated by conventional methods. The resilience of a material refers to its ability to absorb energy in the elastic regime. Therefore, when the material's load is removed, resilience allows the release of the absorbed energy during loading, causing the material to return to its original dimensions. Graphically, resilience corresponds to the area under the stress-strain curve in the elastic regime and is characterized by the associated Resilience Modulus, which represents the energy per unit volume required to stress the material from zero to its yield strength. The average resilience value found in the samples is 3.52 MJ/m³.

Compared to studies that conducted tensile tests on Ti-6Al-4V alloy produced by the casting method, the results obtained can be seen in Table 2.

Table 2. Comparison of manufacturing processes.

	Additive Manufacturing	Hot Forging
Maximum stress (MPa)	1054.92	1064.02
Yield Strength (MPa)	897.45	1040.36

Based on the data, it is noticeable that the values obtained by the additive manufacturing sample were lower, as in the study by Souza (2022), the average yield strength was 1040.36 MPa, while in this study, it was 897.45 MPa. Similarly, the maximum stress in Souza (2022) was 1064.02 MPa, a value 0.8% higher than the one found in this study.

The Charpy impact tests showed an average energy absorption of 2.83 kgf.m or 27.7528 J.m, with a percentage variation of the standard deviation about the mean of 9.87% for these tests.

Table 3 presents the results of the Charpy impact test, including the data obtained from the test. The average values of absorbed energy and brittleness index, as well as the standard deviations, were calculated.

Table 3. Results obtained in the Charpy impact test.

Specimen	Energy Absorbed (J/m)	Fracture Toughness (%)	Fracture Type
1	27.8	30	Ductile
2	26.9	50	Ductile
3	28.4	40	Ductile
4	29.4	50	Ductile
5	27.5	40	Ductile
6	23.5	40	Ductile
7	31.3	50	Ductile
Mean	27.83	40	-
Standard Deviation	2.63	7.56	-

Based on the data presented in Table 3, two results draw attention, which are the values of specimens 6 and 7, as they showed the minimum and maximum values of the test. The studies by Grell et al (2017) and Pixner et al (2020) report an average value of 20 J/m for samples fabricated by the electron beam melting (EBM) process in impact tests. Therefore, the results obtained in this study are higher than those found in the literature for similar works.

The microscopic analysis revealed the presence of two phases ($\alpha+\beta$), as shown in Figure 5. However, the microstructure of Widmanstätten was observed along with the matrix of the β phase, together with the α phase lamellae. This microstructure is likely derived from the nucleation of lamellae at the grain boundary of the β phase. The α phase

dominates the microstructure. The α phase lamellae within the β phase matrix with Widmanstatten structure exhibit a "basketweave" morphology. In Figure 5b, it can be observed that the α lamellae have different orientations. This randomness in orientation is a result of the manufacturing process, which involves a 90° rotation in each layer. The temperature during the manufacturing process ranges between $650\text{-}750^\circ\text{C}$, which prevents the transformation of the α phase into α' martensite (Sena, 2022).

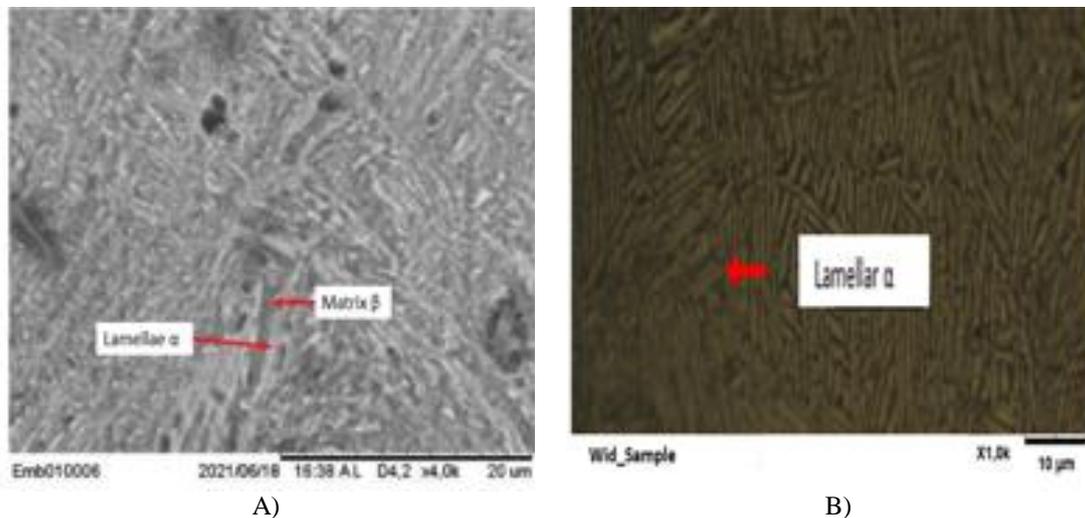


Figure 5. a) microscope obtained by SEM and b) Microscopy of sample 1 etched for 20 seconds.

4. CONCLUSIONS

The objective of this study was to characterize the mechanical properties of the Ti-6Al-4V titanium alloy produced by Electron Beam Melting (EBM) additive manufacturing. From the tensile tests, the average yield strength obtained was 897.45 MPa, which meets the requirement of the ASTM F136 standard. The maximum stress obtained was higher than values found in some studies, but remained below those using the casting manufacturing process, with a value of 1054.92 MPa falling within the range specified by the standard. In the Charpy impact test, the samples showed an average result of 27.83 J/m, which is higher than the values reported in the literature. Based on the obtained results, it can be concluded that the test specimens exhibited satisfactory performance within the requirements of the standards, as well as within the magnitude observed in related literary works.

5. ACKNOWLEDGMENTS

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