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**COMPARATIVE ANALYSIS OF ABS TEST SPECIMENS PRODUCED
THROUGH ADDITIVE MANUFACTURING AND THERMOPLASTIC
INJECTION**

Vanessa Alonso Rodrigues

Roberto Giani Pattaro Junior

Faculdade de Tecnologia SENAI “Roberto Mange”

vanessa.alonso14@yahoo.com

pattarojunior@yahoo.com.br

Guilherme Paes de Souza

Faculdade de Tecnologia SENAI “Roberto Mange”

gui.paes1@outlook.com

Hugo Sakai Idagawa

Faculdade de Tecnologia SENAI “Roberto Mange”

hugo.sakai@sp.senai.br

***Abstract.** Injection molding is one of the most used processes for serial manufacturing of plastic products. When we have pilot parts validation or a product substitution that cannot be available on a market, the additive manufacturing can be an alternative, but the mechanical properties required through this process could be a problem, resulting on low reliability, making doubts that influence on the process choice. This study aims to mechanically characterize, through mechanical tests, the viability of such processes. Moreover, different printing parameters were tested to verify which are the most relevant.*

***Keywords:** 3D printing, Injection molding, Mechanical Properties, ABS.*

1. INTRODUCTION

Additive manufacturing (AM) is currently emerging as one of the main options for manufacturing polymeric parts or products and even capable of producing metallic ones. The techniques of fusion in extrusion of thermoplastic filaments through a heated nozzle can be applied in several areas in the industry, for physical visualization and validation of new parts or products, allowing it to manufacture complex geometries with greater ease. Global consumption of additive manufacturing systems, printing materials, parts or technology-related software totaled over \$12.6 billion in 2021. Furthermore, global spending on 3D printing is expected to have an annual growth rate of 22,5% in the coming years (Magazine Plástico Moderno, 2022).

One of the most used processes to manufacture plastic products is through injection molding. One of its main restrictions is a high initial investment required for the manufacture of the mold, usually metallic, and the use of an injection molding machine, being feasible only for high production volumes, making it completely unfeasible for the manufacture of small batches. Rapid prototyping, applied to validate pilot parts or replace products not available on the market, has been gaining more popularity due to its speed, ease and low cost, without the need to make a mold or other manufacturing processes, however, as the mechanical properties required by certain products can be a problem, originating from low reliability and generating doubts that directly affect the choice of this process.

This article has the general objective to compare the mechanical properties of ABS plastic formed through injection molding and rapid prototyping. To carry out these tests, ISO Test Specimens (CDP) were made and from these the tensile and compression tests were carried out.

2. ADDITIVE MANUFACTURING

There are several different technologies of Additive Manufacturing, each with its own particularity regarding the operation of the equipment. Although additive manufacturing technology is not recent, with the first equipment being marketed from 1987 (WOHLERS, 2014), it is only in recent years, with the reduction in equipment costs and patent expiration, that the technology has become popular. Additive Manufacturing can be classified into several categories according to the ISO/ASTM 52900:2015 standard, but Fused Deposition Filament (FDM) was used for the present study.

According to Sun et al (2021), Additive Manufacturing is the process of manufacturing parts layer by layer based on digital models of three-dimensional geometry, without the limitations of conventional forging, casting and machining processes. In conventional or reductive processes, the production of a part with more complex geometry requires a sequence of operations and tools, whereas in additive manufacturing this number of procedures is reduced, thus being a more direct process (Kumar et al, 2020). In summary, it is a set of technologies that work by successively adding material in layers, from a predefined digital model (Figure 1). This model is then “sliced” into layers with all the information and references so that the machine can start manufacturing the desired object.



Figure 1: Schematic representation of an AM process (Adapted from Moustafa, 2021).

2.1 Fused Deposition Filament (FDM)

Fused Deposition Filament (FDM) was developed by Stratasys in Eden Prairie, Minnesota. In this process, a plastic material is extruded through a nozzle that traces the cross-sectional geometry of the part, layer by layer (Figure 2). Also, the building material is usually supplied in filament form, but some configurations use plastic pellets fed from a hopper. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds with the layer below. Once a layer is built up, the platform lowers, and the extrusion nozzle deposits another layer (CustomPart.Net, 2023). The layer thickness is determined by the diameter of the extruder nozzle which varies from 0.1 to 1.2mm, and consequently the layer height can reach a resolution of 0.05mm. A variety of materials are available, including ABS, PLA, PETG, ASA, TPU, PA (NYLON), PP, Carbon Fiber, and more.

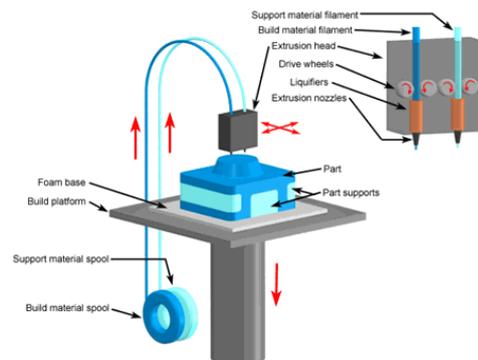


Figure 2: Additive Manufacturing Process (Adapted from CustomPart.Net, 2023).

3. INJECTION MOLDING

Injection molding, according to Zheng et al. (2011), is a cyclic process where identical products are produced through a mold, being highly used for polymer parts. The main advantage of this process is its repeatability, and the possibility of manufacturing complex geometries at high production rates.

The cost of labor is relatively low with parts that do not require finishing or almost none. According to Fuh et al. (2004) about 70% of the products produced worldwide employ this process: from computers, toys, housewares, equipment for the healthcare industry and components for the automotive industry.

The plastic resin injection machine (Figure 3) is an equipment used in the manufacture of mass produced injected products from the injection process of polymeric material. Its structure is basically formed by a mold mechanism and a heated cylinder where the polymer is homogenized and subsequently injected into the mold (Accorsi, 2020).

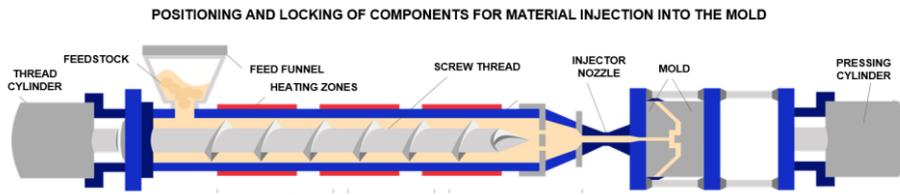


Figure 3: Injection Molding Process and equipment (Sulpast, 2023).

4. PROCESSES FOR OBTAINING THE INJECTED TEST SPECIMEN

For the manufacture of injected specimen, some adjustments of a mold previously used for the manufacture of tensile and impact tests were necessary. Electrodes were made for roughing and finishing the compression cavities and plates to cover cavities not used in the tests (Figure 04)

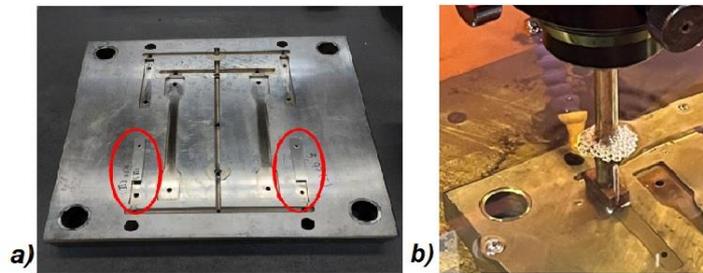


Figure 4: Injection mold adaptations: a) Installation of produced plates; b) Electro erosion of the compression CDP cavity.

4.1 Injection

For the injection of the test specimens, a ROMI Primax 65R Injector, owned by Faculdade de Tecnologia SENAI “Roberto Mange”, was used. Specimen were injected (Figure 5), using the same material as the ABS filament applied in 3D printing, with the injection parameters given in Table 1.

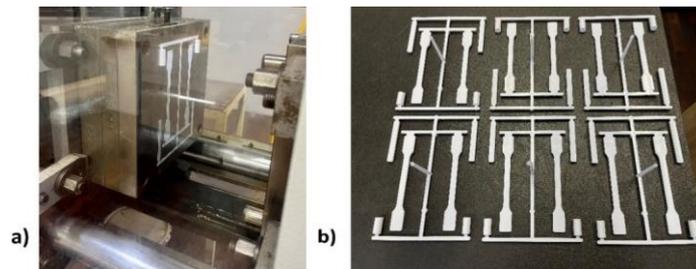


Figure 5: a) Test specimen injection process; b) Injected specimens.

Table 1. Injection Parameters

Parameters	Values
Holding pressure	250 bar
Injection pressure	350 bar
Volume flow	80 cm ³
Dosing speed	400 mm/s
Mold closing force	58 ton
Injection volume	55 cm ³
Switching volume	5 cm ³
Holding time	3 s
Cooling time	30 s
Temperature	220 °C
Injection Time	10 s

5. PROCESSES FOR OBTAINING THE PRINTED SPECIMEN

The additive manufacturing process adopted was Fused Filament Fabrication (FFF), configured for printing at 50mm/s and layer thickness of 0.2mm by heating the ABS filament to 225°C in the nozzle and 100°C on the table. 100% infill was used, with 1 perimeter turn and 0.4 extrusion width. For the printing process, a 0.4mm nozzle was used.

For the study, the orientation of the impression was taken into account, therefore, specimen were produced at five different angles for tensile and only one direction for the compression test. The printing orientation of the specimen can be seen in Figures 6 and 7.

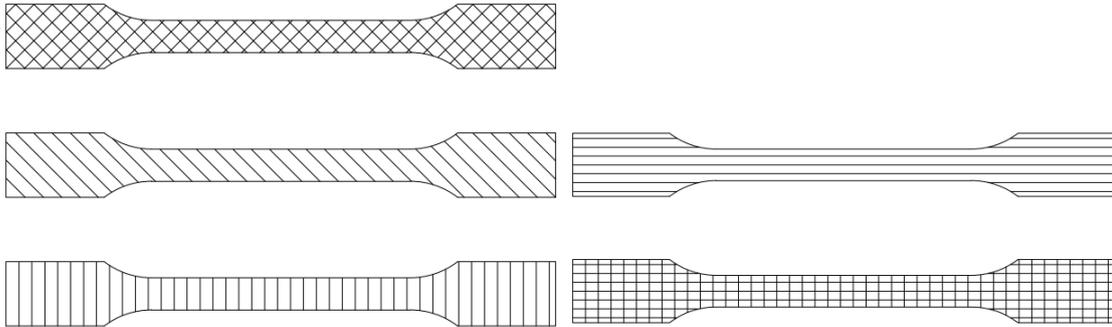


Figure 6: Printing orientation of the tensile specimens.

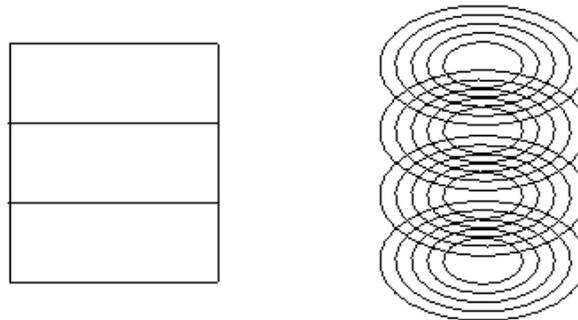


Figure 7: Printing orientation of the compression specimens

6. MECHANICAL STRENGTH TESTS

6.1 Tensile Test

To carry out the tensile test, we used the specimen in accordance with ISO Standard 527 (2012), with Type A CDP (Figure 8).

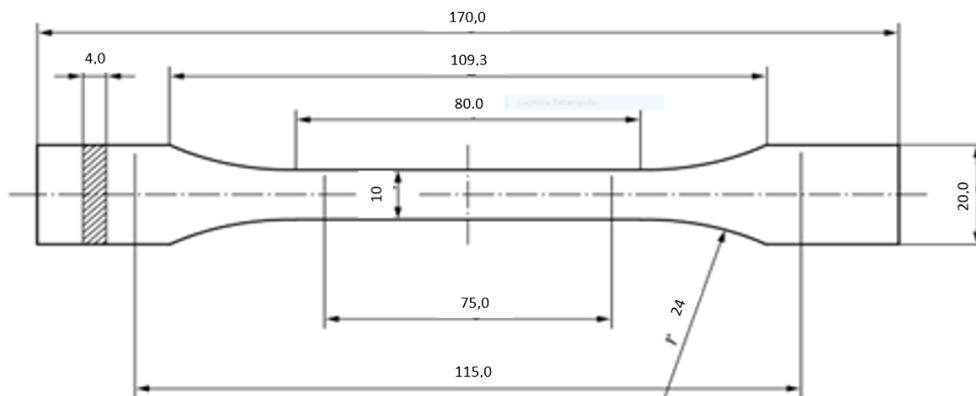


Figure 8 - Type 1A test samples (ISO, 2012).

The tensile tests were performed with a Kratos KE20.000 equipment. In the software the test parameters were set according to the ISO standard: the displacement speed was set to 5mm/min, the maximum allowed time for the test completion was 5 min and the load cell with a maximum capacity of 20000 kgf was used. The position of the CDP was done manually with pneumatic claws (upper and lower) that were both checked for alignment (Figure 9).



Figure 9: Tensile test specimen positioned in the machine.

6.2 Compression Test

The compression tests for thermoplastic polymers were based on the ISO Standard 604 (2002) standard. In general, the mechanical behavior in compression is measured using a low and constant load rate throughout the test, therefore it is a monotonic test. The determination of the characteristics through the compression test is extremely relevant, especially when the component to be designed will be subjected to this loading mode in its real application. From a normative point of view, this test can determine the modulus of elasticity and the yield stress or focus on obtaining the ultimate breaking strength stress.

The compression test was also carried out using the KE 20.000 model machine from Kratos Equipamentos along with its software. Initially, it was necessary to replace the grips that are used in the traction tests with the compression device (Figure 10). The compression parameters were also based on the standard, with a displacement speed of 1.3 mm/min and a load cell with a maximum capacity of up to 20000 kgf.



Figure 10: Compression test specimen positioned in the machine.

7. RESULTS AND DISCUSSIONS

7.1 Tensile Tests Results

The results for the tensile tests of the injected (Figure 11) and 3D printed (Figure 12) specimen are shown in the following graphs and the average values are presented in Table 2.

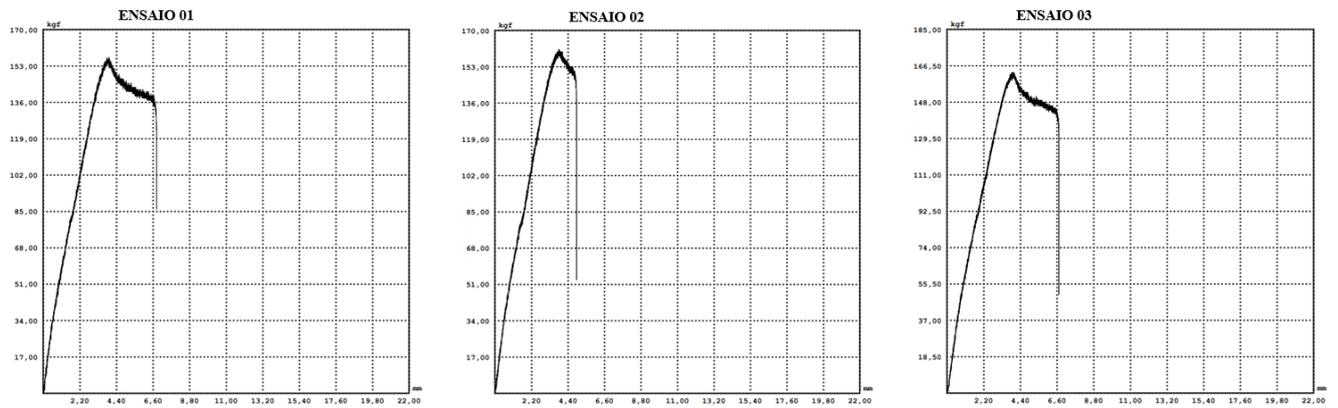


Figure 11: Tensile test results for the injected specimen.

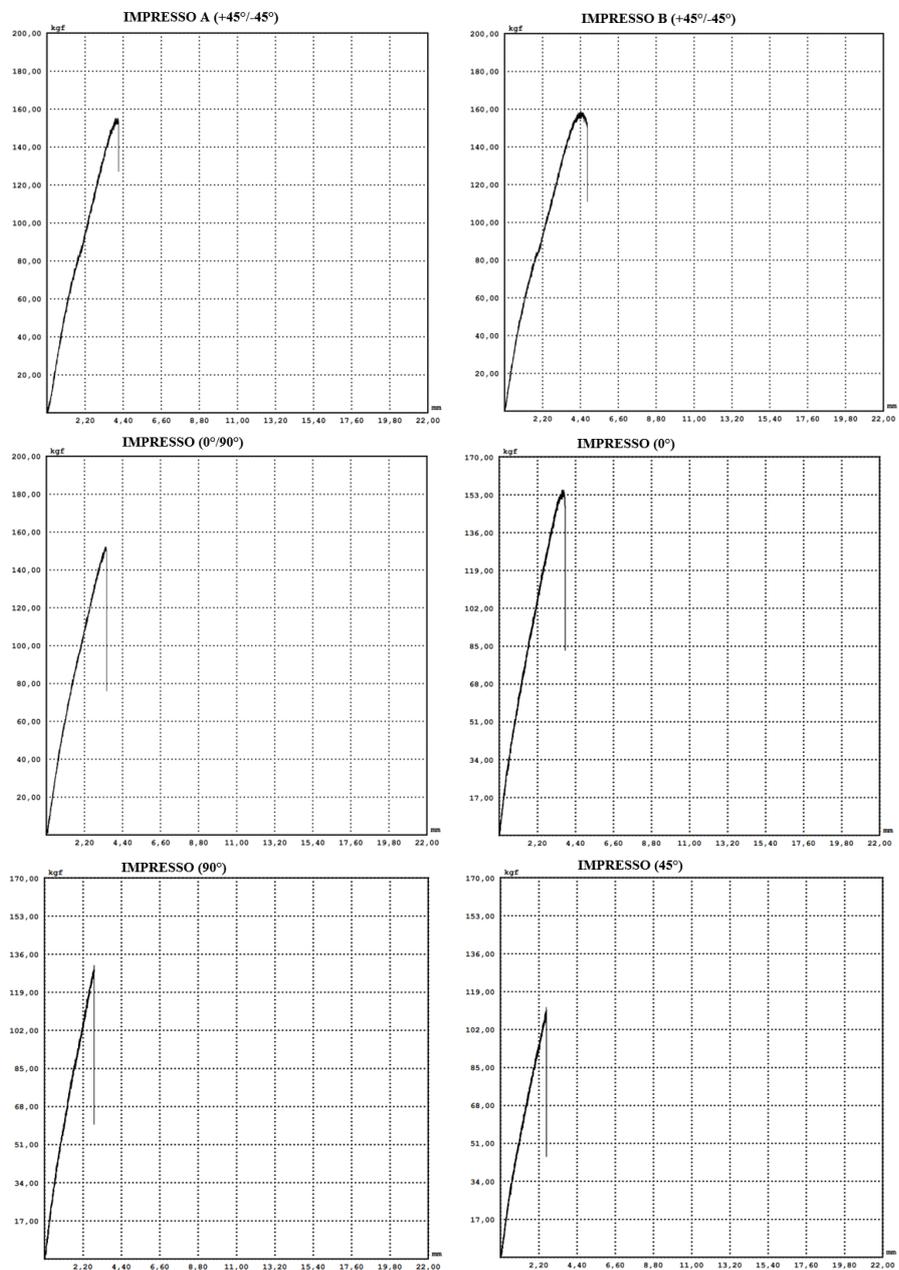


Figure 12: Tensile test results for the CDP manufactured by additive manufacturing.
Table 2: Comparative results obtained for all the tensile tests.

Samples	Maximum force (kgf)	Tensile Strength (kgf/mm ²)	Yield Strength (kgf/mm ²)	Elongation (%)	Linear Elongation (mm)
Test 01 (Injected)	157,00	3,93	3,50	8,53	6,82
Test 02 (Injected)	161,00	4,03	3,88	6,15	4,92
Test 03 (Injected)	163,00	4,08	3,34	8,40	6,72
Average Results of Injected Tests	160,33	4,01	3,57	7,69	6,15
45°/-45°_a (Printed)	155,00	3,88	2,93	5,18	4,14
45°/-45°_b (Printed)	159,00	3,98	2,88	6,01	4,81
Average results of tests at 45°/-45° (Printed)	157,00	3,93	2,90	5,59	4,49
0°/90° (Printed)	152,00	3,80	2,95	4,35	3,48
0° (Printed)	155,00	3,88	3,41	4,76	3,81
90° (Printed)	131,00	3,28	2,90	3,56	2,85
45° (Printed)	112,00	2,80	2,35	3,31	2,65

Regarding the injected CDP (Figure 13a) it was observed that the samples present similar results throughout their elastic phase, followed by a drop in maximum force of approximately 10% until failure. These tests showed an average tensile strength of 4.01 kgf/mm² and a maximum variation of 2%, yield strength of 3.57 kfg/mm² and a maximum variation of 8.7%. An average elongation of 7.69% was also observed. The values obtained in the tests were very close to the values provided in the ABS datasheet, which confirms the data obtained in the tests.

For the 3D printed CDP (Figure 13b–c) some variations were observed in regards to the way in which they were printed. The samples printed at +45°/-45° presented a greater tensile strength in relation to the other tests. In comparison to the 0°/90°, 0°, 90°, 45° samples, a decrease was verified during the tests of approximately 3.2%, 1.2%, 16.5% and 28.5%, respectively.

The values obtained for maximum forced proved to be quite disperse for the samples tests printed at 90° and 45°, presenting a drop of up to 28.75% in tensile strength. In comparison, the other tests were very close, reaching only 3.30% for the 0°/90° sample and 1.2% for 0°. For the yield strength property, it was achieved a 17.5% increase in the 0° test and a 18.9% drop in the 45° test in comparison to the +45°/-45° test. Finally, the elongation was also evaluated, noting a variation of up to 40.9% when comparing the +45°/-45° sample to the 45° sample.

Compared to the injected samples, it is possible to observe that the printing direction is a crucial factor for the final properties. The sample printed at +45°/-45° produced values of maximum force during the elastic phase very close to those of the injected samples, varying only 2% between them. One of the main discrepancies found was the size of the plastic phase, where the 3D printed samples was visibly lower than the injected ones, in terms of elongation in millimeters, this difference could represent up to 27% less. When it comes to the tensile strength, the observed differences reached only 2% and for the yield strength, the observed difference was 18.7%.

In relation to the plastic phase until failure, it is possible to observe that all of the 3D printed samples presented only a small plastic region, which shows a very low ductility of the printed specimen.

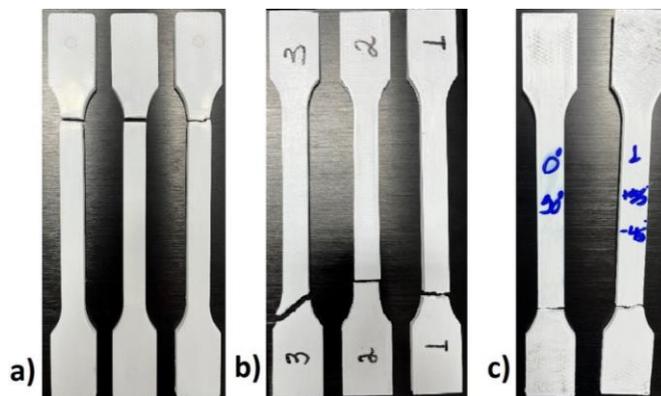


Figure 13: a) Injected tensile samples after the test; b) 3D printed samples after the test (printed orientations: 1 = 0°, 2 = 90°, 3 = 45°); c) 3D printed samples after the test (0°/90°, 45°/-45°).

7.2 Compression Tests Results

The results obtained for the compression tests of the injected and printed specimens can be seen in Figures 14 and 15, respectively.

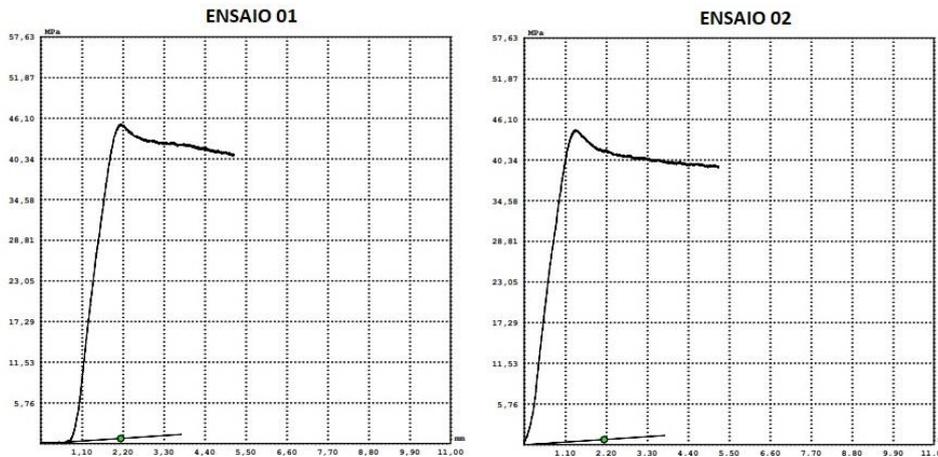


Figure 14: Compression test results for the injected samples.

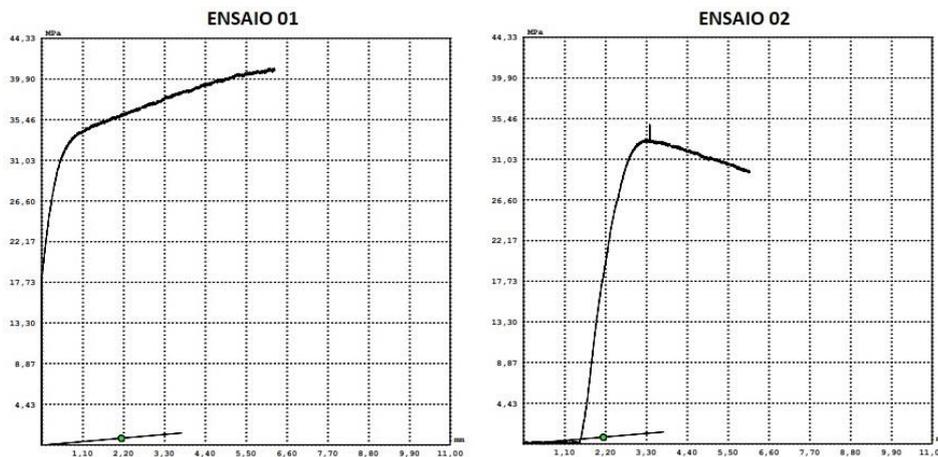


Figure 15: Compression test results for the 3D printed samples.

The test results for the maximum strength are presented in Table 3:

Table 3: Results obtained for the compression tests.

Samples	Maximum Compression Strength (MPa)	Maximum force (kgf)
Test 01 (Injected)	45,29	613,3
Test 02 (Injected)	44,63	604,3
Average of Injected Tests	44,96	608,8
Test 01 (Printed)	41,08	556,3
Test 02 (Printed)	34,80	471,2
Average of Printed Tests	37,94	513,7

It was observed that there was a variation of approximately 15.5% in relation to the strength between the specimens, thus the injected samples were more resistant.

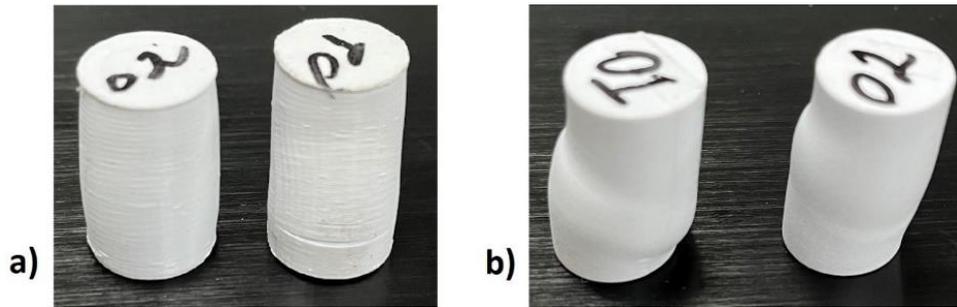


Figure 16: a) 3D printed compression sample after the test; b) Injected compression sample after the test.

8. CONCLUSIONS

Based on the results presented, it was possible to verify that for printed samples subjected to tensile forces, the printing direction was an extremely important factor, and if it is strategically configured, by analyzing the direction of the applied forces in the part, it is possible to reach very close values to injected samples. This was possible to visualize not only in the 45°/-45° samples but also in the 0° one, since the printing direction adopted was similar to that of the displacement force of the equipment during the test, the maximum force on the analyzed sample was superior to the others. This also applies to the rest of the evaluated data, where it was possible to observe a decrease in all the properties due to the printing orientation. It was also possible to observe that printed samples do not have good ductility compared to injected ones.

In compression, the printed specimen showed lower results than injected ones, but still satisfactory, since it supported 84.5% of the injected capacity.

Thus, it is possible to obtain good mechanical characteristics of parts manufactured through 3D FDM printing, where, combined with a load analysis of the body to be printed to determine in a more assertive way the orientation of the printed layers. In this way, it could be possible to provide the final item with the desired characteristics.

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