Study of reliability parameters and mechanical performance for automotive components fabricated by additive manufacturing

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RESUMO

Additive manufacturing, especially 3D printing, has been gaining traction in the automotive sector, going beyond the production of prototypes to integrate structural components into vehicles. This technological advancement requires assessment of reliability, repeatability, and reproducibility, criteria already consolidated in traditional methods such as machining and casting. Among 3D printing techniques, FDM (Fused Deposition Modeling) stands out for its accessibility and versatility. However, parts manufactured by FDM and other additive manufacturing processes face challenges related to lack of homogeneity and isotropy, resulting in significant variations in mechanical properties, such as strength and elasticity, depending on the orientation and deposition strategy of the layers. For the automotive sector, this variability directly impacts the structural performance of critical components. Density, for example, is an essential parameter for finite element computational simulations (FEA), used to predict the behavior of parts under different loading conditions. Porosometry tests indicated density close to the values indicated by the manufacturers, while tensile tests with 100% filled specimens showed variations in the modulus of elasticity. To ensure reliable application in automotive components, it is essential to invest in methods for characterizing and standardizing the mechanical properties of parts manufactured by additive manufacturing.

1. INTRODUCTION

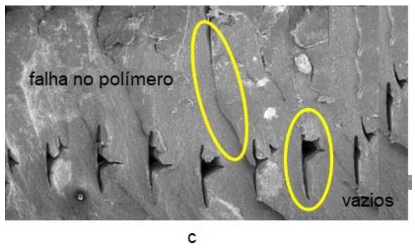
Additive manufacturing (AM), especially through fused deposition modeling (FDM), has gained relevance in structural applications, including in the automotive industry. The possibility of manufacturing parts with porous structures allows for mass reduction and customization of mechanical performance. However, for applications that require rigidity and durability, it is essential to ensure reliability through the correct characterization of properties such as density and modulus of elasticity [1]. These parameters are essential for data input in finite element simulations (FEA). Widely used materials include PLA, ABS, PET, among others. 3D printing, now accessible even in the home environment, is advancing with trends such as bioprinting and hybrid manufacturing [2], [3]. The process, illustrated in Figure 1, involves steps that include defining the density of the part at the slicing stage.

Figure 1. Manufacturing steps in AM

Source: VITALE *et al*. [33]

Although AM is effective for prototyping, its functional application requires attention. FDM parts exhibit anisotropy due to the layer-by-layer process. Figure 2 shows examples of internal failures even at 100% infills with a triangular pattern, affecting tensile strength [4].

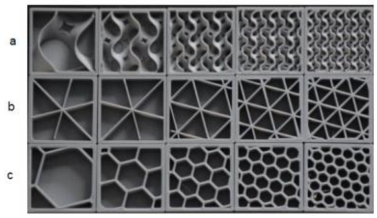
Figure 2. Deposition failures and cross-section micrograph



Source: CALVALNTE [4], KARAD [5].

Different types of infill, such as gyroid, triangular and honeycomb, are illustrated in Figure 3. Each pattern influences final mechanical properties.

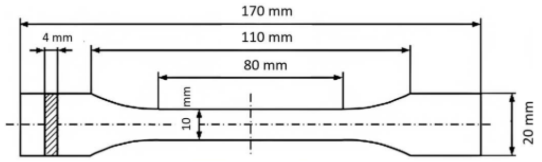
Figure 3. Common types of fill



Source: AL KHAWAJA [6].

Standardization of test specimens is hampered by the number of printing parameters. Settings such as layer thickness, temperature, and speed impact density and stiffness [7]. The ASTM D638 Type I standard test specimen, shown in Figure 4, is widely used in mechanical testing.

Figure 4. Standardized geometry for tensile testing.



Source: MORADI *et al*. [26]

Even with similar geometries, internal porosity and imperfections can cause significant variations. The modulus of elasticity of the printed part often differs from the value of the filament [8]. This discrepancy can compromise the representativeness of computational models, requiring standardization of density and specific stiffness control. AM, already integrated into the production chain [9], also requires normative standardization, as provided for in ISO/ASTM 52900, 52915, 52910, 52930 and ASME Y14.46 [10]. Therefore, it is essential to develop methods that establish density as a reliable input parameter in structural analyses using finite elements.

General Objective: To establish density as a reliability parameter for structural analysis by FEA in AM parts.

Specific Objectives:

• Characterize density and modulus of elasticity;

• Evaluate the influence of porosity on structural integrity;

• Propose a density measurement criterion in FDM parts;

• Compare the properties of the filament with the values obtained in the manufactured parts.

1.1 Finite Element Analysis: principles and applications

Finite Element Analysis (FEA) is a computer-aided numerical technique (CAE) used to investigate the behavior of bodies and structural media under specific operating conditions. The method consists of discretizing a continuous medium into finite elements that preserve the original properties, creating a discrete approximation of continuous quantities with simple functions defined in subdomains. In the context of additive manufacturing (AM), especially through the FDM process, the application of FEA requires adaptations, since the bodies produced have characteristics that are different from traditional materials. It is important to consider the degrees of freedom, the contact conditions between layers, the presence of porosity and anisotropy. The model must include orthotropic or transversely isotropic properties, respecting the printing orientation, as indicated by . Behseresht and Park (2024) [11]. Furthermore, the accuracy of the simulation depends on the input data, especially the characterization of the elastic modulus and density, which must be obtained through experimental tests. FEA is also useful for modeling delamination between layers and validating elastoplastic behaviors in nearly realistic geometries, making it essential for analyzing the structural performance of porous parts produced by AM..

1.2 Additive manufacturing: concepts and techniques

Additive manufacturing, or 3D printing, has been consolidated in the industry due to its flexibility in prototyping and production of parts. Among the available techniques, the most widespread is Fused Deposition Modeling (FDM), due to its accessibility, low cost and ease of operation [12]. The process begins with 3D modeling in CAD software, followed by conversion of the model to formats such as STL, AMF or 3MF, which are interpreted by "slicers" that generate the G-code for printer operation. Other relevant techniques include Stereolithography (SLA), which uses UV laser to cure liquid resin with high resolution; Selective Laser Sintering (SLS), which fuses powdered materials by laser, suitable for high-strength applications; and Direct Metal Laser Sintering (DMLS), used in the manufacture of metal parts with excellent mechanical properties. All of these techniques are constantly being developed, seeking greater precision, repeatability and scalability. Despite technological advances, it is essential to ensure the traceability and certification of manufactured products, since there are still challenges related to reliability, especially for structural applications [10].

1.3 Density measurements of porous bodies

Porosity directly affects the mechanical performance of AM-manufactured parts, especially in terms of stiffness and strength. Pores can be interlaminar (between layers) or intralaminar (within layers), and their formation depends on parameters such as temperature, printing orientation, and filling density [13]. The density of porous bodies can be assessed by direct and indirect methods. Apparent density is obtained considering the total volume, including pores, which can lead to underestimations. True density considers only the solid volume, and is obtained by techniques such as gas pycnometry [1], mercury porosimetry, computed tomography, and vacuum sealing. In this work, mercury porosimetry will be used to determine the density of test specimens manufactured by FDM using PLA. According to Ashby (2010, p.34) [14], when relating specific stiffness and strength, PLA is close to engineering polymers, although it presents slightly lower values. The analysis of these . parâmetros é crucial para estabelecer a aplicabilidade estrutural de peças AM.

2. LITERATURE REVIEW ON PERFORMANCE OF BODIES CONSTRUCTED BY ADDITIVE MANUFACTURING

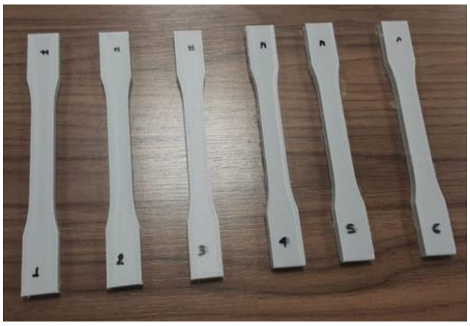
The structural evaluation of models built by additive manufacturing (AM), through Finite Element Analysis (FEA), arouses technical and economic interest, especially in the context of numerical validation. However, several factors influence the correspondence between physical and simulated models. [12] observed significant discrepancies between simulated models and real bodies subjected to compression, attributing them to anisotropy, porosity and internal voids. [15] analyzed ASTM D638 Type I bodies produced by FDM and UV curing, varying the printing orientation from 0° to 90°, and observed divergences in the modulus of elasticity attributed to the infill pattern. Wang, 2020 [16] also detected inconsistencies due to interlaminar resistance, printing angle and thermal degradation. Pitjamit, 2024 [17], using SLA, observed good agreement between simulations in ANSYS® and experimental results, but with localized variations, suggesting adjustments in the input parameters. The systemic approach proposed by Jumle, 2024 [18] with the Ishikawa diagram identified the influence of thickness, infill density and air gap. Scapin, 2021 [19] with nonlinear simulation of FDM bodies, confirms the intrinsic anisotropic nature of these parts, even with the adoption of elastic models. Matúš, 2023 [20] highlights the importance of considering mesoscale geometric errors and microscale anisotropies in topological optimizations. The standardization of terminology according to ISO/ASTM 52900:2021 [21] is an important factor. Urbaite [3] highlights the regulatory challenges, while. Yadollahi [22] and Decker [23] reinforce that the microstructure and the infill pattern (e.g., gyroid) directly influence the structural integrity. Bacak [24] applied statistical analysis (96% confidence level) to compare patterns such as elliptical, diagonal, grid and cross 3D, evidencing variation in specific resistance. Eryildiz [25] and Derise [26] also observed significant variations associated with infill density, demonstrating the importance of parameterization. Moradi [27], using response surface methodology, identified stability in the modulus of elasticity up to 40% infill. Harpool [28] used simulations with ANSYS® and concluded that the geometric pattern of the infill has a greater impact than the absolute density. Racza [29], when studying patterns such as ±45°, triangular and honeycomb in ABS, found that some of them configure an error above 20% in the modulus of elasticity, even when 100% dense. Pernet [30] tested 14 different patterns and showed wide variation in the compressive modulus in ASTM D695 bodies, confirming that infill geometry affects performance. Cavalcante [4] proposed adjusting the G-code to optimize the contact between filaments, reinforcing the importance of controlling anisotropy and the interlayer contact area.

Mathematical modeling based on this area has proven to be more effective for predicting strength. Jin et.al [31] evaluated FDM printed bodies with ultrasonic elastography, revealing anisotropic differences and variation in Young's modulus. Tronvoll [32] used computed tomography to characterize internal voids, highlighting the importance of high-resolution tools for validating structural models in AM parts..

3. METHODOLOGY

All specimens were manufactured in the architectural design laboratory of the School of Architecture, using an Ender 3 PRO FDM printer. The printing speed was 90.0 mm/s, as recommended by the manufacturer, and the extrusion temperature for the PLA material was 230.0 ºC. Standard ASTM D638-14 (Type I) samples were printed, in addition to cylindrical and cubic specimens, following the ASTM D695, ASTM C109 or ISO 604 standards, as applicable for polymers in additive manufacturing [32], [27], [5] and [6]. The internal filling strategy of the specimens adopted orthogonal layers, while the external frame was printed with the same process, but using lines in the longitudinal direction, as described by Pyka et al. [33]. The samples were analyzed in a mercury intrusion porosimetry test performed on a cubic PLA sample with a 10.0 mm edge, using the AutoPore IV equipment - Micromeritics, Technological Characterization Laboratory of USP, in accordance with ISO 15901-1/2005. The technique was based on the Washburn equation, which relates the applied pressure to the pore diameter through the surface tension and contact angle of mercury. A parallel test with helium gas intrusion pycnometry on a Micromeritics equipment, model AccuPcy II 1340, was performed to determine the specific mass. Four test specimens were prepared for analysis. Two were cubic with a 10.0 mm edge and two were cylindrical with a height of 25.0 mm and a diameter of 14.0 mm. For the tensile test, six specimens were prepared, three with radial filling and three with longitudinal filling. Figure 5 shows the specimens. Specimens 1 to 3 were printed horizontally with the filament being melted from one end to the other and braided in the width direction and repeatedly until the final thickness of 5.0 mm was obtained. Specimens 3 to 6 were printed vertically (standing up) with the filament being melted in the width direction and returning in the thickness direction, thus until the final length was obtained..

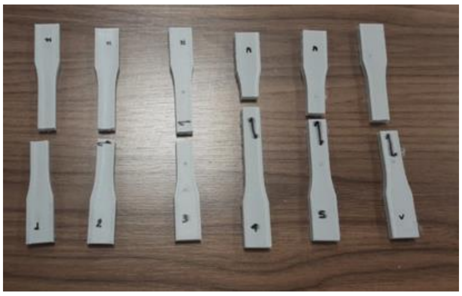
Figure 5. Test specimens according to ASTM D638-14 TYPE I



Source: authors' collection

The samples were tested on a ZwickRoell Z050 universal tensile testing machine with a tensile speed of 5.0 mm per minute. The test room was at 23 °C with a relative humidity of 50%. The specimens ruptured with brittle fracture characteristics. Figure 6 shows the appearance of the specimens after the tensile test.

Figure 6. Specimens after tensile test, according to ASTM D638-14 Type I standard



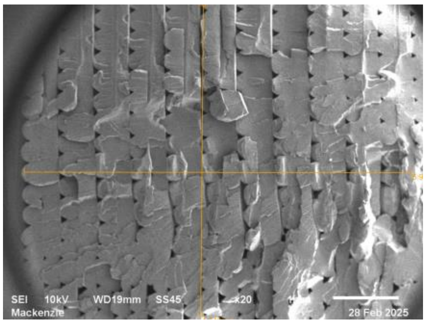
Source: authors' collection

The rupture faces of the specimens were analyzed by electron microscopy at the Materials Characterization Laboratory of the University. The samples were prepared with a standard gold deposition process on the face where the rupture occurred in the tensile tests. A scanning microscope model JSM-6510 was used for this test. The specimens were evaluated with the "vertical" reference for the specimen printed "standing up" in the increasing direction of the z axis based on the xy plane and horizontal for the specimen printed "lying down" in the xy plane and the thickness in the increasing direction of the z axis. In Figure 8, specimens 1 to 3 were printed vertically, while specimens identified as 4 to 6 were printed horizontally. For microscopy, one specimen from each manufacturing situation was chosen.

4. RESULTS AND DISCUSSION

The samples viewed through the electron microscope presented the voids described in the literature with the same intensity and dimensions. The discontinuities and lack of adhesion between superimposed layers are also evident and can be seen in Figure 7 in the "horizontal" sample with a magnification of 20,000 times.

Figure 7. Voids and discontinuity of the sample on the failure face.



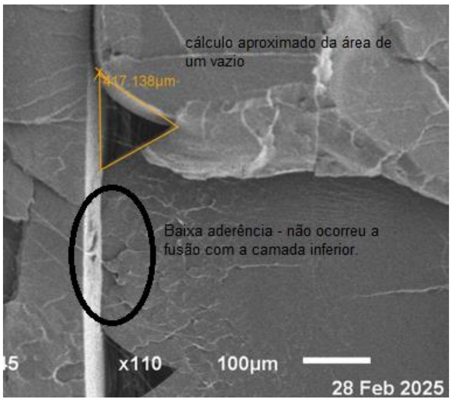
Source: authors' collection

With greater magnification, it is possible to observe the dimensions of the voids and the lack of adhesion in superimposed layers. In Figure 8, one can see how the voids were estimated.

The void was estimated with an edge of 0.417.10-3 m, approximated as an isosceles triangle, its area was calculated at 0.8.10-8 m2. Performing a count of 150 voids, in Figure 8, this represents 0.02% of the cross-sectional area of the section observed under the microscope in the sectioned area of the test specimen, which was calculated at 50.10-6 m2.

The data obtained by pycnometry with helium gas intrusion (PHE 0007-25 and PHE 008-25 reports) indicated 1.2682 g/cm3 for the cylindrical sample and 1.2551 g/cm3 for the cubic sample. The data obtained by mercury intrusion show the relationship between the applied pressure and the pore diameter. According to report PHG 006-25, from LCT - Technological Characterization Laboratory, it indicates that the pore size distribution shows a typical mesopore curve, with a peak around 10.0 nm and that the accumulated intruded volume curve shows a rapid initial increase, followed by a stabilization at higher pressures, indicating a relatively homogeneous internal structure with a regular pore distribution. Table 1 shows the summary of the values obtained in the test.

Figure 8. Appearance of the splitting surface performed in the tensile test.



Fonte: Acervo dos autores

Table 1. Results of the mercury intrusion porosimetry test performed on a cubic PLA sample.

Table 1. Summary of results obtained in laboratory tests and trials

Resultado	Valor
Volume máximo de intrusão	0,0881 mL/cm^3
Área total de poros	39,5180 m²/g
Diâmetro mediano dos poros	10,0700 nm
Densidade aparente	1,2012g/cm^3
Porosidade total	9,6%

Source: authors' collection

5. CONCLUSIONS

The experimental analysis demonstrated that the presence of porosity negatively affects the modulus of elasticity and mechanical strength of parts manufactured by FDM. Despite this, the “uniform” distribution of pores indicates that the printing process was well controlled. The measured apparent density (1.2012 g/cm³) was close to the typical density of PLA (1.24 g/cm³), suggesting good structural integrity of the manufactured samples. The pycnometry results with helium gas revealed real densities between 1.2551 g/cm³ and 1.2682 g/cm³, values slightly higher than the theoretical value, which can be attributed to the presence of additives or the effect of specific thermal conditions during printing. The predominance of pores in the 10.0 nm range confirms that the material has a mesoporous nature, which may benefit applications involving heat exchange or interaction with fluids, due to the high specific surface area (39.5 m²/g) observed. In structural terms, although the parts present satisfactory mechanical stability, the existence of pores and variations associated with printing orientation require caution for applications in critical components. Anisotropy and dimensional variability confirm the need for specific characterizations for each printing condition. Finally, the tests performed, although restricted to a laboratory environment and limited sampling, point to the potential reliability of FDM additive manufacturing in the production of structural parts. However, it is recommended to expand the studies with more statistically representative samples and to incorporate constitutive models that explicitly consider the effects of porosity and anisotropy in computational simulations.

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