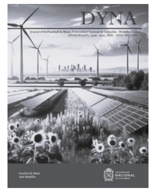
DYNA
http://dyna.medellin.unal.edu.co/



UNIVERSIDAD NACIONAL DE COLOMBIA

Exploring infill pattern and density effects on the tensile properties of 3D printed ABS

Bruno Leonardelli, Cesar Pandolfi, Gustavo Alberto Ludwig & Cristian Padilha Fontoura

Centro Universitário da Serra Gaúcha (FSG), Caxias do Sul, Brazil. brunoleonardelli@hotmail.com, cesar.pandolfi@fsg.edu.br, gustavo.ludwig@fsg.edu.br, cristian.fontoura@fsg.edu.br

Received: November 8th, 2024. Received in revised form: April 3rd, 2025. Accepted: April 11th, 2025

Abstract
Fused Deposition Modeling (FDM) is recognized as an efficient method for creating durable, complex parts quickly and affordably. This study examines how different infill patterns and densities affect the mechanical properties of ABS, with specimens produced via FDM for tensile testing. Fourier-transform infrared spectroscopy with attenuated total reflection (FTIR-ATR) identified the functional groups in ABS, while microscopic analysis assessed layer bonding. Results showed that tensile strength increased with higher infill densities and revealed that bonding characteristics of various infill patterns significantly impacted mechanical performance at densities from 25% to 100%. Interestingly, the same infill pattern displayed varied mechanical and bonding properties depending on density, highlighting the importance of selecting optimal infill configurations for specific applications.

Keywords: 3D printing; ABS; infill pattern; tensile strength.

Exploración del efecto del patrón y la densidad de relleno en las propiedades a tracción del ABS impreso en 3D

Resumen
El modelado por deposición fundida (FDM, por sus siglas en inglés) es reconocido como un método eficiente para fabricar piezas duraderas y complejas de forma rápida y económica. Este estudio analiza cómo los diferentes patrones y densidades de relleno afectan las propiedades mecánicas del ABS, con especímenes fabricados mediante FDM para ensayos de tracción. Se utilizó espectroscopia infrarroja por transformada de Fourier con reflexión total atenuada (FTIR-ATR) para identificar los grupos funcionales presentes en el ABS, mientras que el análisis microscópico permitió evaluar la adhesión entre capas. Los resultados mostraron que la resistencia a la tracción aumenta con mayores densidades de relleno, y evidenciaron que las características de unión de los distintos patrones de relleno influyen significativamente en el comportamiento mecánico, en un rango de densidad entre el 25% y el 100%. Curiosamente, un mismo patrón de relleno presentó propiedades mecánicas y de adhesión variables según la densidad, lo que resalta la importancia de seleccionar configuraciones de relleno óptimas para cada aplicación específica.

Palabras clave: impresión 3D; ABS; patrón de relleno; resistencia a la tracción.

1 Introduction

Additive Manufacturing (AM) is no longer a novelty, having become widely used across diverse fields, which include industrial settings, and extends to sophisticated biomedical applications. Among the various AM techniques, Fused Filament Fabrication (FFF) stands out as the most common extrusion process, with its widespread use extending even to domestic use. It consists of a process which deposits material layer by layer [1].

Understanding how various parameters influence the efficiency of printing a part or component continues to raise many questions, particularly regarding strength. It is crucial to recognize that 3D printing involves a multitude of variables, such as infill pattern, infill density, temperature, printing time, and layer height, all of which play a significant role in the outcome [2–4].

Many works have dealt with the influence of infill patterns, which are the internal structures of 3D printed objects. They play a

How to cite: Leonardelli, B., Pandolfi, C., Ludwig, G.A., and Fontoura, C.P., Exploring infill pattern and density effects on the tensile properties of 3D printed ABS. DYNA, 92(237), pp. 46-50, April - June, 2025.

crucial role in the mechanical properties of printed components. Different infill patterns, such as honeycomb, grid, triangle, and concentric, exhibit varying mechanical performances depending on the applied loads. Research has shown that infill pattern choice significantly affects not only the tensile strength but also the weight, flexibility, and energy absorption of printed parts [5,6]. For instance, the honeycomb pattern often provides a balance between strength and material usage, while grid patterns offer more isotropic mechanical behavior due to their uniform structure [5,7].

In this context, this works aims at exploring the effects of different infill patterns on tensile properties of 3D printed ABS.

2 Materials and Methods

In this work, a premium 3DLab filament was used, which has a cross-section of 1.75 mm in black color. For the printing, a Creality Ender 3 printer was used. It is currently the best-selling printer worldwide, and it possesses printing dimensions of 220 mm x 220 mm x 250 mm, with a heated bed, which can reach up to 110º C. The extruder assembly can reach up to 255º C, which means it is possible to print most available thermoplastic materials. For the design of the 3D models of the test specimens, Solidworks was used, and for the printer programming, open-source software Cura 5.5.0 was used. Table 1 displays printing parameters for the tested specimens.

Table 1.
Printing parameters.

Parameters	Value
Layer height [mm]	0.2
Extrusion nozzle diameter [mm]	0.5
Printing speed [mm/s]	40
Printing temperature [ºC]	240
Bed temperature [ºC]	95
Extrusion flow [%]	100
Infill orientation [º]	0/90
Top/bottom layers	5

Source: the authors.

To understand the relationship between infill density and pattern, coded samples were created as seen in Table 2.

Table 2.
Sample codification and properties.

Code	Infill density [%]	Infill pattern	Weight [g]	Printing time [min]
P1	25	Grid	10	42
P2	25	Cubic	10	43
P3	25	Lines	10	43
P4	50	Grid	12	50
P5	50	Cubic	12	50
P6	50	Lines	12	51
P7	75	Grid	14	58
P8	75	Cubic	14	56
P9	75	Lines	14	57
P10	100	Grid	16	63
P11	100	Cubic	16	62
P12	100	Lines	16	63

Source: the authors.

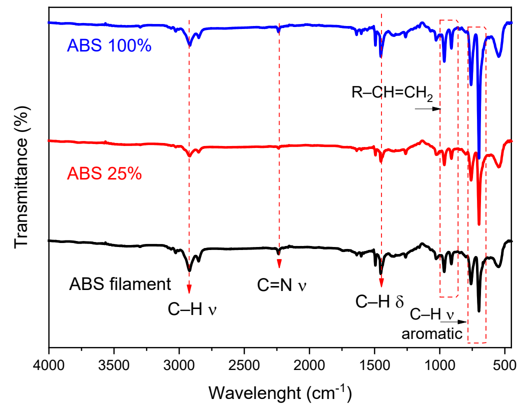


Figure 1. Infrared spectra for pristine ABS, 25% and 100% infill samples.
Source: the authors.

After the fabrication of the test specimens, tensile tests were performed on a testing machine DL-30000 EMIC with a maximum load capacity of 300 kN, using a clamp system with a load cell with a 5 kN capacity, which was used during the test. A test speed of 5 mm/min was used, in accordance with ASTM D 638-02a standard. To ensure repeatability, the tensile tests were performed on three specimens fabricated using identical printing parameters.

Fourier-transform infrared spectroscopy with attenuated total reflection (FTIR-ATR) was performed to identify the functional groups present in ABS both before and after printing. The analysis was conducted using a PerkinElmer Spectrum 400 spectrometer. The spectra were acquired in the range of 4000 to 400 cm^{-1}, with a nominal resolution of 4 cm^{-1} and 32 scans. Three conditions were studied: pristine ABS filament, ABS with 25% of density and ABS with 100% density.

3 Results and Discussion

3.1 Fourier Transfom Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) was performed to test the chemical stability of ABS after printing the specimens. With this analysis, it was possible to verify the functional groups existing in the copolymer chain.

It was noted, according to Fig. 1, that there was no change in functional groups, oxidation, or breaking of chemical bonds, indicating that the polymer has good chemical stability under the extreme conditions of 25% and 100% filling. It is possible to observe the typical absorption bands for ABS, as seen in previous works [8].

3.2 Tensile tests

Tensile tests yielded valuable insights into the mechanical behavior of 3D-printed ABS with various infill patterns. For comparative analysis, Fig. 2 presents the tensile stress-strain curves of two contrasting samples, P3 and P12, which exhibited the lowest and highest ultimate tensile strengths,

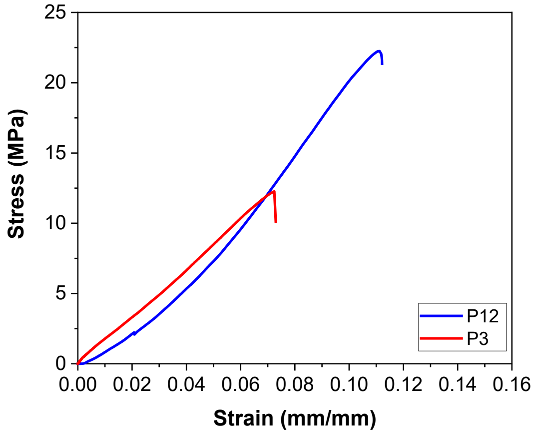


Figure 2. Comparative stress-strain curves for conditions P3 and P12.
Source: the authors.

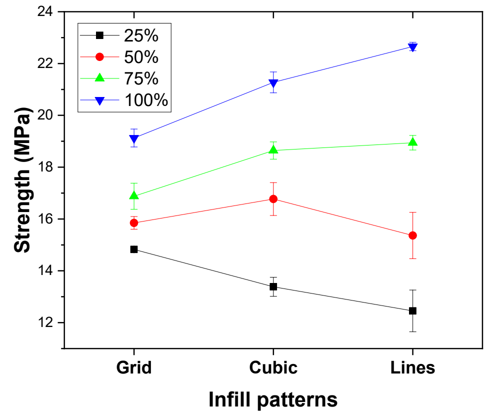


Figure 3. Tensile strength dependance on infill patterns and percentage.
Source: the authors.

respectively. Notably, the cross-sectional area used to calculate tensile strength was based on the total nominal cross-section, without accounting for the voids between the printed layers. This approach, while consistent with standard testing protocols, can lead to an underestimation of the material's effective resistance, as observed in similar studies in the literature [9,10].

Previous research has shown that different infill patterns, such as honeycomb or grid, significantly influence the overall tensile strength of 3D-printed materials [11]. The results obtained here align with these findings, confirming that denser, more uniform infill patterns tend to provide superior mechanical properties. However, the interplay between infill pattern and density remains complex, and this study offers additional insights by examining this relationship in ABS specifically. The highest-performing infill patterns in this study, such as P12, demonstrated enhanced tensile strength in line with the results found, who also reported that optimized infill patterns could improve the mechanical performance of printed components.

For further evaluation, Fig. 3 compares ultimate tensile strength of different infill patterns with different densities. As expected, higher infill densities generally resulted in increased tensile strength [12,13]. Interestingly, the grid pattern exhibited the smallest margin of improvement in tensile strength between the lowest and highest densities, indicating a more consistent performance across densities. In contrast, the line pattern showed the greatest increase in tensile strength, highlighting its sensitivity to changes in infill density. Lines pattern, in comparison to cubic and grid, displayed increased tensile strength in previous works as well [14], which can be attributed to the increased material deposition due to the direct load paths created.

Another interesting point is that the specific strength (in MPa g^{-1}) or strength to mass ratio, which accounts for the weight the specimens have, displays different behaviors. Interestingly, grid infill pattern at 25% density displayed highest efficiency. However, it significantly drops at greater densities. For line pattern, specific strength increases according to density, while for cubic it reaches a maximum specific strength at 50% density.

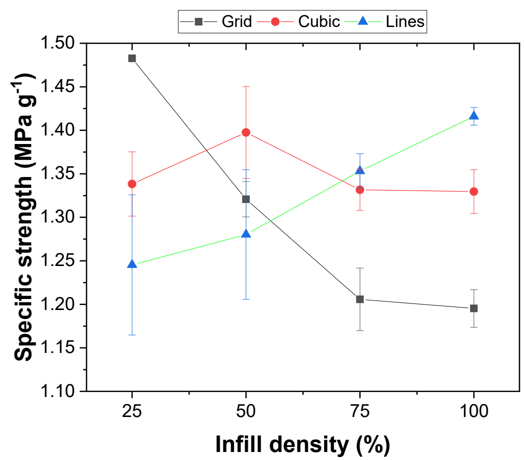


Figure 4. Specific strength dependance on infill density.
Source: the authors.

3.3 Microscopic analysis

Microscopy analysis was also performed, to investigate cross section properties of tested specimens. While cross-section in 3D printed components is complex and may not be precisely estimated, microscopic analysis may provide an insight on resistance area. Fig. 5 displays differences between grid, cubic, lines with 25% density and their counterparts with 100% density.

It is important to note that even at 100% infill density, voids and gaps remain, which reduce the effective load-bearing area. For instance, in the grid pattern, interlayer gaps persist, while the cubic pattern becomes significantly more densely packed at 100% density compared to 25% density. This can be perceived by seeing printing paths on Cura software (Fig. 6). For further analysis, the images were processed to obtain quantitative data of filling for each scenario in a Python based script. The script excluded pixels that did not correspond to the characteristic color of the filled regions. Both visual and numerical basis results are displayed in Fig. 6 as well.

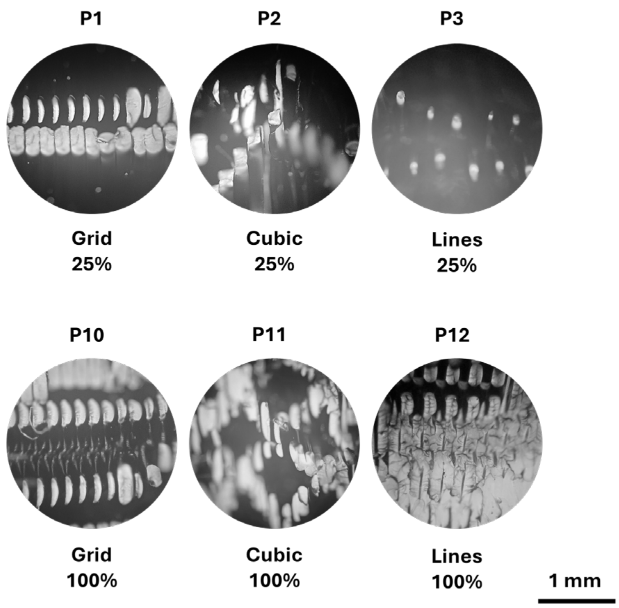


Figure 5. Micrographs displaying the fracture cross-section of three types of infill at an infill density of 100%.
Source: the authors.

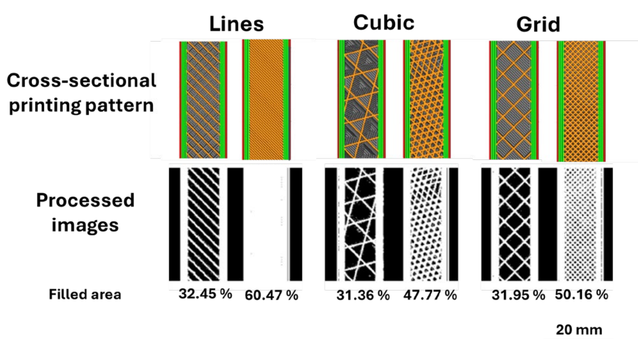


Figure 6. Top row: Representative cross-sectional views of the printed specimens for each infill pattern. Bottom row: Image-processed binarized sections used to calculate the effective filled area. The percentage indicates the fraction of the cross-section occupied by material, allowing direct comparison of infill efficiency across different geometries.
Source: the authors.

The line pattern shows the most substantial increase in effective resistant areas, a result that aligns with the observed tensile test performance. According to Popescu [4], who conducted a review on process parameter influence on mechanical properties, filament bonding determines strength, so the bonding of the layers is favored in more closely packed infill patterns, such as the one in P12. This is also supported by other works [11,15], where it is argued that the inter-layer bonding between consecutive layers. Additionally, while an increase in density leads to a higher mass, it does not directly correlate with a proportional increase in strength. This highlights the importance of selecting the appropriate infill pattern to optimize component performance, balancing both mechanical properties and material efficiency. Such analyses have gained attention in recent years, particularly when ultralight components come into play [16].

4 Conclusions

This study investigated the combined influence of infill pattern and infill density on the mechanical strength of 3D-printed components, offering insights into design considerations for improved performance. Key findings include:

- The experimental design effectively demonstrated the interaction between infill pattern and infill density, providing valuable insights into their combined effects on material strength.
- All infill patterns showed increased tensile strength with higher densities. To enhance comparison, specific strength (MPa g^{-1})—tensile strength normalized by mass—was also analyzed. It revealed distinct trends: the grid pattern showed a decrease, the lines pattern an increase, and the cubic pattern exhibited no consistent behavior, with values falling within the margin of error.
- The resistant area formed by each infill pattern significantly impacts the mechanical response. Even at 100% density, some patterns (e.g., grid and cubic) resulted in voids or gaps that reduced overall strength.
- For efficient and application-specific design, both mass and strength must be considered. If possible, a targeted study should be conducted to identify the most suitable infill pattern for the intended use case.

References

[1] Ebel, B., Sinnermann, T., Fabrication of FDM 3D objects with ABS and PLA and determination of their mechanical properties, [Online]. RTejournal, (1), pp. 1–9, 2014. Available at: https://rtejournal.de/rte/article/view/2014_3
[2] Alagheband, M., Zhang, Q., Jung, S., Investigating the influence of infill patterns and mesh modifiers on fatigue properties of 3D printed polymers. International Journal of Fatigue, 187, art. 108463, 2024. DOI: https://doi.org/10.1016/j.ijfatigue.2024.108463.
[3] Dizon, J.R.C., Espera, A.H., Chen, Q., Advincula, R.C., Mechanical characterization of 3D-printed polymers, Additive Manufacturing, (20), pp. 44–67, 2018. DOI: https://doi.org/10.1016/j.addma.2017.12.002.
[4] Popescu, D., Zapciu, A., Amza, C., Baciu, F., Marinescu, R., FDM process parameters influence over the mechanical properties of polymer specimens: a review. Polymer Testing, (69), pp. 157–66, 2018. DOI: https://doi.org/10.1016/j.polymertesting.2018.05.020.
[5] Dudescu, M.C., Racz, L., Popa, F., Effect of infill pattern on fatigue characteristics of 3D printed polymers, Materials Today: Proceeding, 78(2), 2023, pp. 263–9. DOI: https://doi.org/10.1016/j.matpr.2022.11.283.
[6] Sriya-Ambati, S., Ambatipudi, R., Effect of infill density and infill pattern on the mechanical properties of 3D printed PLA parts, Materials Today: Proceeding, 64(1), 2022, pp. 804–7. DOI: https://doi.org/10.1016/j.matpr.2022.05.312.
[7] Din, S., Xu, W., Cheng, L.K., Dirven, S., A Stretchable Multimodal Sensor for Soft Robotic Applications, IEEE Sensors Journal, 17(17), pp. 5678–5686, 2017. DOI: https://doi.org/10.1109/JSEN.2017.2726099.
[8] Fiorio, R., Díez, S.V., Sánchez, A., D'hooge, D.R., Cardon, L., Influence of different stabilization systems and multiple ultraviolet a (UVA) aging/recycling steps on physicochemical, mechanical, colorimetric, and thermal-oxidative properties of ABS, Materials, 13(1), pp.1–14, 2020. DOI: https://doi.org/10.3390/ma13010212.
[9] Appalsamy, T., Hamilton, S.L., Kgaphola, M.J., Tensile Test Analysis of 3D Printed Specimens with Varying Print Orientation and Infill Density, Journal of Composites Science, 8(4), pp. 1–15, 2024. DOI: https://doi.org/10.3390/jcs8040121
[10] Hozdić, E., Characterization and Comparative Analysis of Mechanical Parameters of FDM- and SLA-Printed ABS Materials, Applied Sciences (Switzerland), 14(2), pp. 1–22, 2024. DOI: https://doi.org/10.3390/app14020649

[11] Qamar-Tanveer, M., Mishra, G., Mishra, S., Sharma, R., Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts- a current review, Materials Today: proceedings, 62(1), pp. 100–8, 2022. DOI: https://doi.org/10.1016/j.matpr.2022.02.310.
[12] Tzotzis, A., Manavis, A., Efkolidis, N., García-Hernández, C., Kyratsis, P., Analysis of the Influence of Structural Characteristics on the Tensile Properties of Fused Filament Fabricated ABS Polymer Using Central Composite Design, Applied Mechanics, 5(1), pp. 20–35, 2024. DOI: https://doi.org/10.3390/applmech5010002.
[13] Daly, M., Tarfaoui, M., Bouali, M., Bendarma, A., Effects of Infill Density and Pattern on the Tensile Mechanical Behavior of 3D-Printed Glycolyzed Polyethylene Terephthalate Reinforced with Carbon-Fiber Composites by the FDM Process, Journal of Composites Science, 8(4), pp. 1–15, 2024. DOI: https://doi.org/10.3390/jcs8040115.
[14] Sharma, S., Gupta, V., Mudgal, D., Effect of infill pattern on the mechanical properties of polydopamine-coated polylactic acid orthopedic bone plates developed by fused filament fabrication, Polymer Engineering and Science, 63(2), pp. 353–65, 2023. DOI: https://doi.org/10.1002/pen.26210.
[15] Agrawal, A.P., Kumar, V., Kumar, J., Paramasivam, P., Dhanasekaran, S., Prasad, L. An investigation of combined effect of infill pattern, density, and layer thickness on mechanical properties of 3D printed ABS by fused filament fabrication. Heliyon, 9(6), art. 16531, 2023. DOI: https://doi.org/10.1016/j.heliyon.2023.e16531.
[16] Calleja-ochoa, A., Gonzalez-barrio, H., de Lacalle, N.L., Martínez, S., Albizuri, J., Lamikiz, A., A new approach in the design of microstructured ultralight components to achieve maximum functional performance, Materials, 14(7), pp. 1–12, 2021. DOI: https://doi.org/10.3390/ma14071588.

B. Leonardelli, obtained the BSc. Eng. in Mechanical Engineering in 2024 from the Centro Universitário da Serra Gaúcha (FSG), Brazil. His experience includes automation of manufacturing processes and 3D printing.
ORCID: 0009-0007-6258-0353

C. Pandolfi, received the BSc. Eng. in Mechanical Engineering in 1998 from the Universidade de Caxias do Sul), Brazil. He obtained the MSc. in Production Engineering in 2003 and the PhD. in Production Engineering in 2017, both from the Universidade Federal do Rio Grande do Sul, Brazil. Since then, he has been a professor at the Centro Universitário da Serra Gaúcha (FSG), teaching undergraduate courses in production engineering, statistics, and operations research, as well as graduate-level courses in applied statistics and quality control. He also serves as coordinator of the Center for Technology and Innovation and oversees the undergraduate programs in Production, Electrical, and Mechanical Engineering at FSG. His research interests include quality and process engineering, statistical process control, measurement system evaluation, and institutional assessment in engineering education.
ORCID: 0009-0009-9563-1991

G.A. Ludwig, received the BSc. Eng. in Mechanical Industrial Engineering in 2011 from the Universidade Feevale, and the MSc. In 2013, and PhD. In 2020 in Engineering with a focus in Materials Science and Technology from the Universidade Federal do Rio Grande do Sul, Brazil. He worked as a researcher at LAPEC, focusing on electrochemistry and protective coatings against corrosion, as well as ceramic coatings for wear resistance and mechanical testing. He is currently a professor at Centro Universitário da Serra Gaúcha (FSG). His research interests include materials engineering, protective and functional coatings, and mechanical behavior of materials.
ORCID: 0000-0002-8692-7514

C.P. Fontoura, received the BSc. Eng. in Mechanical Engineering in 2017, the MSc. in Materials Science and Engineering in 2019, and the PhD. in Materials Science and Engineering in 2024, all from the Universidade de Caxias do Sul, Brazil. His research experience includes surface modification techniques such as plasma nitriding, thin film deposition, and ion implantation. He is currently a professor of Mechanical Engineering and faculty member at Centro Universitário da Serra Gaúcha (FSG), where he teaches undergraduate courses. His research interests include biomaterials, surface engineering, additive manufacturing, and soft robotics.
ORCID: 0000-0002-0700-1853