

TENSILE PERFORMANCE OF NON-PREFERENTIAL INFILL ARCHITECTURES IN FDM-MANUFACTURED ABS

DESEMPENHO SOB TRAÇÃO DE ARQUITETURAS DE PREENCHIMENTO NÃO PREFERENCIAIS EM ABS FABRICADO POR FDM

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Abstract

Fused deposition modeling (FDM) additive manufacturing has expanded its use in engineering applications because of its geometric flexibility, relatively low cost, and capacity for decentralized fabrication of polymeric components. However, the layer-by-layer nature of the process introduces mechanical anisotropy, particularly associated with raster orientation and interfacial bonding between adjacent deposited roads. This study evaluates the effect of non-preferential infill patterns on the mechanical performance of acrylonitrile butadiene styrene (ABS) specimens manufactured by FDM. Specimens with geometry based on the ASTM D638 Type I configuration were fabricated using four infill strategies: raster lines parallel to the tensile loading direction, raster lines perpendicular to the loading direction, Hilbert Curve, and Cross. The specimens were subjected to tensile testing in a universal testing machine, and ultimate tensile strength, yield strength, and strain were analyzed. The results showed that mechanical performance was strongly dependent on the deposition strategy. The parallel-line group presented the highest average ultimate tensile strength (23.46 MPa), closely followed by the Cross pattern (23.07 MPa), whereas the Hilbert Curve and perpendicular-line groups showed lower values, 14.64 MPa and 11.38 MPa, respectively. The Cross pattern reached 98.3% of the ultimate tensile strength obtained by

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the parallel reference group, indicating its potential to reduce the directional mechanical penalty typically observed in FDM without relying on favorable raster alignment. Non-preferential infill patterns may therefore represent a promising alternative for applications in which the predominant loading direction is unknown or variable, provided that the printing parameters are properly adjusted.

Keywords: ABS, Additive manufacturing, Anisotropy, FDM, Infill pattern.

Resumo

A manufatura aditiva por modelagem por deposição fundida (FDM, na sigla em inglês) tem ampliado seu uso em aplicações de engenharia devido à sua flexibilidade geométrica, custo relativamente baixo e capacidade de fabricação descentralizada de componentes poliméricos. Contudo, a natureza do processo, que ocorre camada por camada, introduz anisotropia mecânica — associada, em particular, à orientação das linhas de deposição (raster) e à união interfacial entre as trilhas depositadas adjacentes. Este estudo avalia o efeito de padrões de preenchimento não preferenciais no desempenho mecânico de corpos de prova de acrilonitrila butadieno estireno (ABS) fabricados por FDM. Os corpos de prova, com geometria baseada na configuração Tipo I da norma ASTM D638, foram produzidos utilizando quatro estratégias de preenchimento: linhas paralelas à direção de carregamento por tração, linhas perpendiculares à direção de carregamento, curva de Hilbert e padrão em cruz (Cross). As amostras foram submetidas a ensaios de tração em uma máquina universal de ensaios, sendo analisados a resistência à tração na ruptura, o limite de escoamento e a deformação. Os resultados demonstraram que o desempenho mecânico depende fortemente da estratégia de deposição. O grupo com linhas paralelas apresentou a maior resistência média à tração na ruptura (23,46 MPa), seguido de perto pelo padrão em cruz (23,07 MPa); por outro lado, os grupos com curva de Hilbert e linhas perpendiculares apresentaram valores inferiores, 14,64 MPa e 11,38 MPa, respectivamente. O padrão em cruz atingiu 98,3% da resistência à tração na ruptura obtida pelo grupo de referência (linhas paralelas), indicando seu potencial para reduzir a penalidade mecânica direcional — tipicamente observada em processos FDM — sem depender de um alinhamento específico e



favorável das linhas de deposição. Portanto, padrões de preenchimento não preferenciais podem representar uma alternativa promissora para aplicações nas quais a direção predominante de carregamento é desconhecida ou variável, desde que os parâmetros de impressão sejam devidamente ajustados.

Palavras-chave: ABS, Anisotropia, FDM, Manufatura aditiva, Padrão de preenchimento.

INTRODUCTION

Additive manufacturing has become an important fabrication technology because it enables components with high geometric freedom, reduced dependence on dedicated tooling, and considerable flexibility for adapting production to different shapes and scales (Volpato, 2017). Among the available processes, fused deposition modeling (FDM) stands out for its widespread use in academic, laboratory, and industrial environments, mainly because of the relatively low cost of equipment, the availability of thermoplastic polymers, and the ease with which process parameters can be adjusted (Tymrak; Kreiger; Pearce, 2014; Samykano et al., 2019). Within the context of Industry 4.0, additive manufacturing is also recognized as a technology associated with the transformation of production systems, since it enables three-dimensional objects to be fabricated from digital models through the successive addition of material (Kusma; Chirolì, 2021).

Despite these advantages, the use of FDM-printed parts in mechanically demanding applications remains limited by uncertainties related to repeatability, internal porosity, interlayer bonding, and mechanical anisotropy (Samykano et al., 2019; Tronvoll et al., 2019). Unlike conventional manufacturing processes, such as injection molding, FDM builds the component by sequentially depositing heated filaments (Volpato, 2017). Consequently, the final mechanical performance depends not only on the intrinsic properties of the polymer, but also on the internal architecture generated by slicing, raster orientation, deposition temperature, build-plate temperature, layer height, printing speed, infill percentage, and thermal history during solidification (Samykano et al., 2019; Zhang; Chou, 2008; Akhouni; Behraves, 2019).



Mechanical anisotropy is one of the main constraints on the structural use of FDM components (Tronvoll et al., 2019; Zarybnicka et al., 2020). Mechanically, this anisotropy arises from the difference between the strength along the deposited road and the strength of the interfaces formed between adjacent roads or successive layers (Tronvoll et al., 2019). When rasters are oriented parallel to the tensile load, the applied load is mainly carried by the deposited filament itself. When they are oriented perpendicular to the load, resistance depends more strongly on the bonding between filaments, which is often a critical region because of lower coalescence, higher probability of void formation, and greater sensitivity to cooling conditions (Samykano et al., 2019; Akhoundi; Behraves, 2019).

In this context, non-preferential infill patterns, such as Hilbert Curve and Cross, represent a technically relevant alternative. Previous studies have shown that infill patterns and raster angles significantly affect the mechanical strength of printed parts by altering porosity, interfacial bonding, and fracture paths (Akhoundi; Behraves, 2019; Galeja et al., 2020). By reducing the dominance of a single deposition direction, these patterns may mitigate the dependence between mechanical strength and loading direction. This feature is particularly important for applications in which components are subjected to multidirectional loads or to loading conditions that are not fully predictable. However, further evidence is needed to determine the extent to which these patterns can preserve mechanical strength when compared with configurations in which rasters are favorably aligned with the applied load.

The relevance of this topic to applied engineering is also supported by studies published in *Revista Principia*, in which 3D printing and additive manufacturing have been used for different technological purposes. Silva et al. (2017), for example, used rapid prototyping with ABS to develop a robotic finger, demonstrating the potential of 3D printing for functional applications in mechanical engineering. Dias et al. (2024), in a review of 3D printing applied to civil construction, highlighted the expansion of additive manufacturing in engineering sectors, particularly due to automation, geometric freedom, and computational control of the fabrication process.



Although the influence of raster orientation and conventional infill patterns on the mechanical behavior of FDM-manufactured polymers has been extensively investigated, comparatively less attention has been given to non-preferential architectures evaluated against well-defined favorable and unfavorable loading references. In particular, it remains relevant to determine whether patterns that distribute deposition trajectories in multiple directions can preserve tensile strength without depending on a single raster direction aligned with the applied load. Therefore, this study evaluates the mechanical performance of ABS specimens manufactured by FDM using Cross and Hilbert Curve infill architectures and compares their response with linear patterns oriented parallel and perpendicular to the tensile loading direction. The contribution of the study lies in experimentally examining the tensile response of these non-preferential architectures under a defined printing and loading condition, rather than in claiming a complete characterization of mechanical isotropy.

FDM ADDITIVE MANUFACTURING AND THE MECHANICAL BEHAVIOR OF PRINTED POLYMERS

Additive manufacturing comprises a set of processes in which a part is produced by the successive addition of material, usually from a three-dimensional model generated in a computational environment (Volpato, 2017). This principle is also emphasized by Kusma and Chiroli (2021), who describe 3D printing as a technology associated with Industry 4.0, based on the materialization of digital models by successive layer deposition. In FDM, the process involves converting the geometric model into a file compatible with slicing software, defining deposition parameters, generating machine code, and physically fabricating the component by extruding heated thermoplastic filament (Volpato, 2017).

FDM allows complex geometries to be produced with relative operational simplicity (Volpato, 2017), a feature that has favored applications in different engineering fields, from functional ABS prototypes, such as the robotic finger presented by Silva et al. (2017), to construction systems based on automated material deposition, as discussed by Dias et al. (2024). However, layer-wise construction



imposes microstructural characteristics that distinguish printed components from those obtained by conventional processes. These characteristics include voids between deposited roads, dependence on thermal bonding between rasters, the influence of cooling rate, and the effect of infill orientation on the load-transfer path (Samykano et al., 2019; Tronvoll et al., 2019; Zhang; Chou, 2008).

In ABS, a polymer widely used in 3D printing, these issues are particularly relevant because of thermal shrinkage and the sensitivity of the material to cooling conditions (Divyathej; Varun; Rajeev, 2016; Kuo et al., 2019). Inadequate build-plate or chamber temperatures may intensify warpage, delamination, and residual stresses, compromising both dimensional accuracy and mechanical performance (Kuo et al., 2019; Choi et al., 2016). Thermal control is therefore essential to obtain specimens with comparable properties and lower experimental scatter.

The literature also indicates that small variations in process parameters can significantly alter final properties. Layer height affects the contact area between deposited filaments, printing speed modifies the time available for thermal diffusion, and extrusion temperature influences material viscosity, wetting of the previously deposited surface, and the degree of interfacial bonding. Comparisons between infill patterns must therefore be conducted under controlled conditions, keeping the main parameters constant whenever possible and reporting the unavoidable differences associated with the use of different slicing software. Processing conditions and internal material architecture can substantially affect the mechanical response of polymer-based materials, reinforcing the need to consider manufacturing parameters when interpreting their strength behavior (Rane et al., 2019; Çakan et al., 2021).

Another relevant aspect is the actual density of deposited material. For some infill patterns, the value configured in the software does not directly represent the same mass or solid fraction obtained with other patterns. This issue is particularly important in comparative studies, because specimens with different masses may show mechanical performance influenced not only by internal architecture, but also by the effective amount of load-bearing material in the cross section.



ANISOTROPY, RASTER ORIENTATION, AND INFILL PATTERNS

Raster orientation is one of the most relevant parameters governing the mechanical performance of FDM-printed parts, since changes in deposition direction alter the load-transfer mechanism and the relative contribution of filament strength and inter-raster bonding (Tronvoll et al., 2019; Galeja et al., 2020; Bhuiyan; Khanafer, 2026). When the load is applied in the same direction as the deposited roads, the component tends to exhibit higher tensile strength because the load is transferred along the continuous filament. Conversely, when loading occurs transverse to the rasters, fracture tends to be governed by the strength of the interfaces between filaments, which usually present lower cohesion (Tronvoll et al., 2019; Naveed, 2021).

In addition to deposition angle, the infill pattern influences material distribution, the continuity of resistant paths, stress concentration, and local thermal history (Akhoundi; Behraves, 2019; Galeja et al., 2020). Linear patterns favor performance when aligned with the applied load, but may exhibit lower performance when loaded transversely (Samykano et al., 2019; Tronvoll et al., 2019). Nonlinear or non-preferential patterns, in turn, tend to distribute deposition directions throughout the section, which may reduce the directional dependence of mechanical properties.

The Hilbert Curve pattern has been discussed in the literature because it presents continuous trajectories and frequent changes in direction, which may favor deposition over short distances and reduce the cooling time between adjacent rasters (Akhoundi; Behraves, 2019). The Cross pattern also presents an internal geometry without a single dominant direction, combining recurrent changes in direction with high local deposition density. In both cases, the underlying hypothesis is that the absence of a single dominant deposition direction may distribute load-bearing paths more broadly within the specimen plane. However, this geometric characteristic should not be interpreted as evidence of mechanical isotropy, which can only be established by testing equivalent specimens under multiple orientations. (Tronvoll et al., 2019; Akhoundi; Behraves, 2019; Domínguez-Rodríguez et al., 2018).



The analysis of non-preferential patterns is particularly important because optimizing printed components only through favorable raster orientation may be insufficient for parts subjected to complex loading. In real components, the direction of loading may vary over time or between different regions of the part, making it desirable to adopt an internal architecture capable of distributing load-bearing paths in multiple directions. Thus, comparing linear and non-oriented patterns helps determine whether infill strategy can be used as a mechanical design resource rather than merely as a secondary printing parameter.

Nevertheless, the adoption of non-preferential patterns does not, by itself, guarantee improved performance. Nozzle path, filament continuity, abrupt changes in direction, heat accumulation, and weak interfaces may generate preferential fracture paths. Experimental evaluation of each pattern therefore remains necessary to verify whether the internal geometry proposed by the slicing software effectively reduces anisotropy or merely redistributes weak regions throughout the section.

MATERIALS AND METHODS

This section describes the experimental design, the materials used, the fabrication parameters of the specimens, and the procedures adopted for tensile testing and data analysis.

All specimens were manufactured using black ABS+ filament in a Creality Ender 3 printer operated inside a closed chamber. The nominal layer height was 0.20 mm, the printing speed was 40 mm/s, the build-plate temperature was 100 °C, and the nozzle temperature was 260 °C. Two side perimeters were used, while top and bottom solid walls were disabled so that the mechanical response was predominantly associated with the evaluated internal architecture. The same printer and filament material were used throughout the experimental campaign.



STUDY CHARACTERIZATION

This research was conducted as an applied experimental study aimed at evaluating the effect of different infill patterns on the mechanical properties of ABS specimens manufactured by FDM. The main independent variable was the infill strategy used in specimen fabrication. The dependent variables were ultimate tensile strength, yield strength, and strain obtained from tensile testing (Garcia, Spim and Santos, 2012).

The longitudinal axis of the reduced section of each tensile specimen was taken as the reference tensile-loading direction. In the PA group, the principal linear deposition roads were oriented parallel to this axis, so that the tensile load was predominantly transferred along the deposited roads. In the PE group, the principal linear roads were oriented transverse to the tensile axis, increasing the contribution of inter-road interfaces to load transfer. In the CR and HI groups, the toolpaths repeatedly changed direction within the printing plane and therefore did not present a single dominant raster orientation with respect to the tensile axis.

Four experimental groups were compared: Cross pattern (CR), Hilbert Curve pattern (HI), linear pattern parallel to the loading direction (PA), and linear pattern perpendicular to the loading direction (PE). The PA and PE groups were used as reference conditions representing, respectively, favorable and unfavorable orientations of the deposited roads with respect to the tensile load.

SPECIMEN FABRICATION

The specimens were fabricated using black ABS+ filament in a Creality Ender 3 printer placed inside a closed printing chamber. The chamber was used to reduce thermal variations during printing, which is relevant for controlling warpage and promoting better interlayer bonding in ABS parts.

The specimen geometry was based on the ASTM D638 Type I configuration, with a nominal thickness of 3.2 mm (ASTM International, 2010). The ASTM geometry was used as the dimensional reference for specimen preparation and tensile testing. Accordingly, the present study refers to specimens



based on the ASTM D638 Type I geometry rather than claiming dimensional certification of each printed specimen. The specimens were printed with a 0.20 mm layer height, 40 mm/s printing speed, 100 °C build-plate temperature, and 260 °C nozzle temperature. To reduce the interference of external contours on the analysis of internal patterns, two side perimeters were used and the top and bottom walls were removed from the printing profiles.

Two slicing software programs were required because the evaluated infill architectures were not available within a single slicing environment used in the experimental campaign. PrusaSlicer 2.4.2 was used to generate the Hilbert Curve specimens, whereas Ultimaker Cura 4.13.1 was used for the Cross and linear-reference specimens. The printer, filament material, layer height, nominal printing speed, nozzle temperature, build-plate temperature, and specimen geometry were maintained according to the defined experimental conditions. Nevertheless, because slicing software may differ in toolpath generation, deposition sequence, extrusion commands, and interpretation of infill parameters, complete equivalence between the generated internal trajectories cannot be assumed. Accordingly, slicer implementation is treated as a potential confounding factor and is considered in the interpretation of the results. Table 1 summarizes the experimental groups adopted in the study. The groups were defined to enable comparison between infill patterns with defined orientation and patterns without preferential orientation.

Table 1

Evaluated printing strategies

Group	Infill pattern	Orientation	Infill	Software
CR	Cross	No preferential orientation	142%	Ultimaker Cura
HI	Hilbert Curve	No preferential orientation	100%	Prusa Slicer
PA	Lines	90°	100%	Ultimaker Cura
PE	Lines	0°	100%	Ultimaker Cura

Source: prepared from experimental data.



TENSILE TESTING

Tensile tests were performed using an EMIC DL10000 universal testing machine with Tesc software, version 3.04. Three specimens were tested for each group, totaling twelve specimens. Individual values of ultimate tensile strength, yield strength, and strain were obtained from the tests. The results were then grouped by printing strategy and analyzed comparatively. For each experimental group, arithmetic means and sample standard deviations were calculated for ultimate tensile strength, yield strength, and strain. Because only three specimens were available per condition, these descriptive statistics were used exclusively to characterize the observed experimental dispersion and were not interpreted as supporting population-level statistical inference.

During the experimental stage, the initially produced PE specimens were found to present a weakened region associated with the starting point of the infill pattern. This issue was corrected by enabling the function that connects infill lines, allowing continuous deposition with the starting point shifted to one end of the specimen. The strain value was also corrected because of the difference between the gauge length configured in the testing-machine software and the effective gauge length of the specimens.

The results were evaluated comparatively, considering differences between groups and the relationship between the performance of non-preferential patterns and that of the linear reference patterns. Because of the limited number of specimens per group, the analysis was conducted as an exploratory experimental comparison, without broad statistical generalization.

RESULTS

This section presents the tensile-test results for the four experimental groups, including individual values, group means, and the graphical comparison of the evaluated mechanical properties.



TENSILE TEST RESULTS

Table 2 presents the individual results obtained for the twelve tested specimens. The values indicate expressive differences between infill strategies, especially when comparing the linear conditions parallel and perpendicular to the loading direction.

Table 2

Individual tensile test results

Specimen	Ultimate tensile strength (MPa)	Yield strength (MPa)	Strain (%)
CR1	19.52	12.37	4.30
CR2	25.46	20.40	6.13
CR3	24.22	17.86	5.96
HI1	15.35	8.54	4.34
HI2	10.47	2.19	2.71
HI3	18.10	12.27	4.84
PA1	26.26	21.32	8.54
PA2	21.11	17.21	7.19
PA3	23.00	18.00	8.19
PE1	10.11	0.00	2.44
PE2	12.24	3.09	2.82
PE3	11.80	2.96	2.85

Source: prepared from experimental data.

Table 3 presents the average values by experimental group. The comparison of mean values allows the performance hierarchy among the evaluated strategies to be directly observed.



Table 3

Mean mechanical properties by group

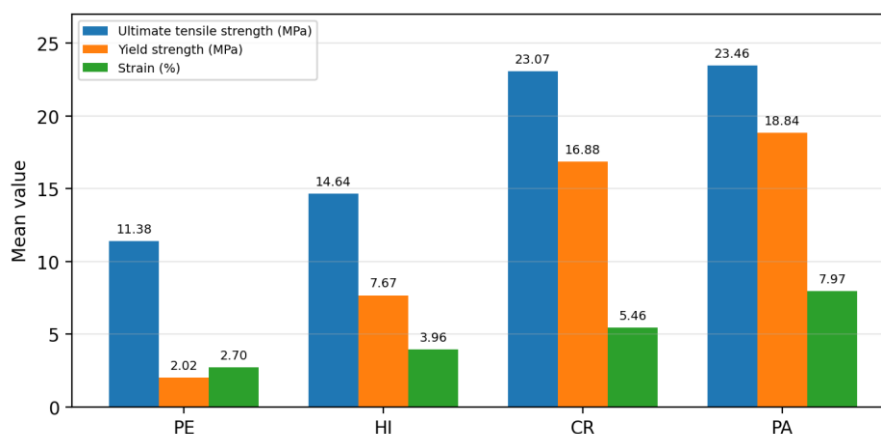
Group	Mean ultimate tensile strength (MPa)	Mean yield strength (MPa)	Mean strain (%)
PA	23.46	18.84	7.97
CR	23.07	16.88	5.46
HI	14.64	7.67	3.96
PE	11.38	2.02	2.70

Source: prepared from experimental data.

The mean ultimate tensile strength was 23.46 MPa for PA, 23.07 MPa for CR, 14.64 MPa for HI, and 11.38 MPa for PE. Mean yield strength followed the same descending order (18.84, 16.88, 7.67, and 2.02 MPa, respectively), while mean strain was 7.97% for PA, 5.46% for CR, 3.96% for HI, and 2.70% for PE. Figure 1 summarizes the differences among the experimental groups.

Figure 1

Mean mechanical properties by printing method.



Source: experimental data adapted from the source study.

Among the evaluated groups, PA presented the highest mean ultimate tensile strength, with CR showing a similar value. HI presented an intermediate mean value, and PE showed the lowest mean ultimate tensile strength. The same general ranking was observed for yield strength and strain.



DISCUSSION

EFFECT OF DEPOSITED-ROAD ORIENTATION

The comparison between the PA and PE groups confirms the typical anisotropic behavior of FDM. Whereas the PA group reached an average ultimate tensile strength of 23.46 MPa, the PE group reached only 11.38 MPa, corresponding to approximately 48.5% of the performance obtained in the parallel condition. This difference demonstrates that, when tensile load is applied transverse to the rasters, failure is governed by interfacial adhesion between deposited roads rather than by the longitudinal strength of the filament.

This result is consistent with the FDM literature, which identifies deposition orientation as a determining factor in the mechanical behavior of printed polymeric components (Samykanó et al., 2019; Tronvoll et al., 2019; Galeja et al., 2020). In real applications, this dependence is problematic because the predominant loading direction is not always known or constant. Components subjected to complex loads may have regions loaded in different directions, making an infill strategy optimized for a single axis insufficient.

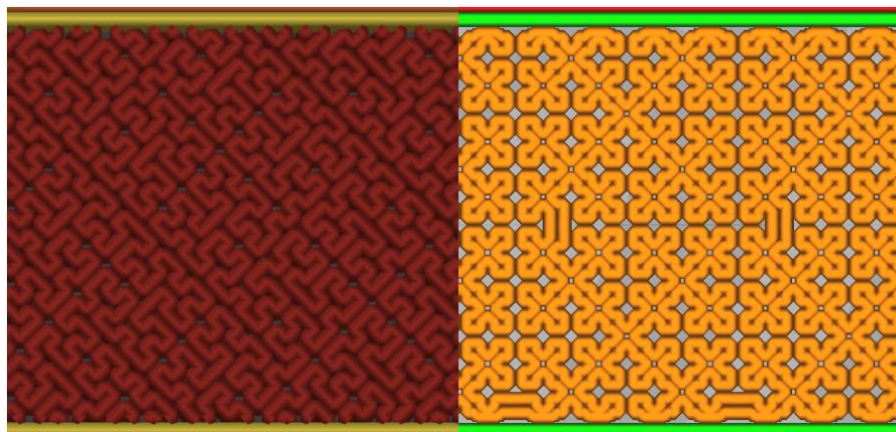
In addition to ultimate tensile strength, strain was also affected by orientation. The PA group presented an average strain of 7.97%, whereas the PE group reached only 2.70%. This difference indicates that loading perpendicular to the rasters not only reduces strength, but also anticipates failure, decreasing deformation capacity before fracture. This behavior is relevant for engineering applications, since components with low allowable strain may fail suddenly under service conditions.



PERFORMANCE OF NON-PREFERENTIAL INFILL PATTERNS

Figure 2

Representation of the Hilbert Curve and Cross patterns used during slicing.



Source: experimental data adapted from the source study.

Among the non-preferential patterns, Cross presented substantially higher performance than Hilbert Curve. The average ultimate tensile strength of the CR group was 23.07 MPa, whereas the HI group reached 14.64 MPa. This represents an approximately 57.6% higher value for Cross compared with Hilbert Curve. For yield strength, the difference was even more expressive: 16.88 MPa in the CR group against 7.67 MPa in the HI group, corresponding to an increase of approximately 120%.

The most relevant result of the study, however, lies in the comparison between the CR and PA groups. The Cross pattern reached 98.3% of the average ultimate tensile strength of the parallel linear pattern, although it does not rely on a single raster orientation to resist the applied load. Under the investigated loading configuration, this result shows that the Cross architecture was capable of reaching an ultimate tensile strength close to that of the favorable parallel reference. Because only one specimen orientation was tested, this result should not be interpreted as evidence of mechanical isotropy. Instead, it indicates that, for the investigated configuration, the Cross pattern preserved tensile strength without requiring a single linear raster direction aligned with the applied load.

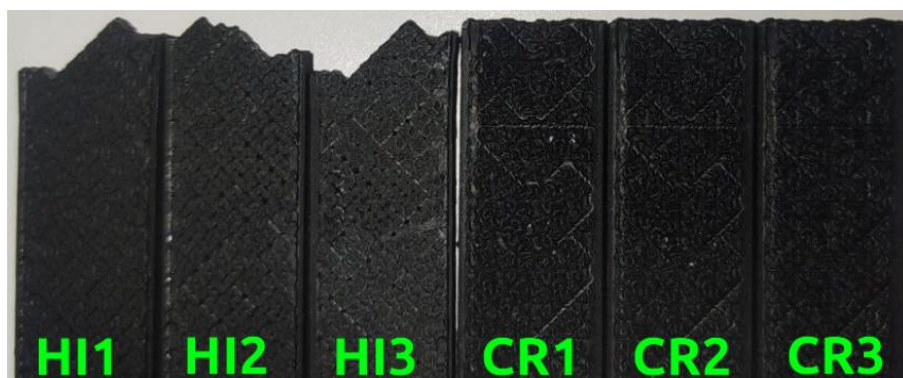
Strain, on the other hand, was lower in the CR group than in the PA group. While the parallel pattern presented an average strain of 7.97%, the Cross pattern presented 5.46%. Thus, although ultimate



strength was almost equivalent, the Cross pattern resulted in lower ductility. This difference is important for engineering applications because it shows that infill selection should consider not only ultimate strength, but also the allowable deformation regime before failure.

Figure 3

Fracture appearance of specimens from the HI and CR groups.



Source: author.

The lower performance of Hilbert Curve indicates that the absence of preferential orientation is not sufficient to ensure high mechanical strength. Although this pattern distributes the deposition trajectory in multiple directions, its geometry may generate local discontinuities, vertices, and regions of weaker interfacial bonding that act as preferential sites for crack initiation and propagation. Thus, the effectiveness of non-oriented patterns depends on the internal architecture generated by the slicer and on how this architecture interacts with the applied load ().

MECHANICAL INTERPRETATION OF THE RESULTS

The superiority of the Cross pattern over Hilbert Curve may be associated with greater continuity of deposition paths, a more efficient distribution of internal trajectories, and a possible reduction in the cooling interval between adjacent rasters. Since bonding between filaments in FDM depends on local temperature, time between depositions, and thermal diffusion at the interface, patterns that promote



nearby depositions within a shorter time interval tend to favor coalescence between roads (Akhoundi; Behraves, 2019; Kuo et al., 2019; Choi et al., 2016; Dalfré et al., 2022).

Although the literature indicates that Hilbert Curve may improve bonding by promoting short-distance deposition, the results obtained in this study show that its specific configuration was not sufficient to achieve performance close to the parallel pattern or the Cross pattern. The irregular fracture observed in the HI specimens suggests the existence of preferential fracture paths associated with regions of lower interfacial strength. This behavior may be related to the formation of internal lines or vertices that act as stress concentrators or regions of lower structural continuity.

Figure 4

Surface of HI3 and CR1 specimens after image processing.



Source: experimental data adapted from the source study.

The comparative analysis shows that the absence of preferential orientation alone does not guarantee improved mechanical performance. The positive effect depends on the effective geometry of the infill, material density, continuity of deposition trajectories, and quality of the interfaces formed



during printing. Therefore, non-preferential patterns should be evaluated not only according to their nominal geometry, but also according to how they are implemented by the slicer, the final mass of the specimen, and the interaction between deposition path and thermal history.

It is also important to consider that the Cross group was produced with a configured infill of 142%, an adjustment required to approximate its mass to that of the other groups. This methodological decision reduces mass differences between specimens, but also shows that equivalence between infill percentages configured in different patterns and software programs is not direct. Future studies should record the individual mass of specimens and, whenever possible, normalize mechanical properties by mass or apparent density, allowing a more refined comparison between internal architectures.

The within-group dispersion should also be considered when interpreting the results. The standard deviation was particularly relevant for the Hilbert Curve group and for the yield-strength response of some configurations. In FDM manufacturing, such variability may be associated with local differences in filament deposition, inter-road bonding, extrusion stability, cooling history, void distribution, and the geometry of the generated toolpath. Although nominal printing temperatures, layer height, and printing speed were maintained according to the defined processing conditions, these local phenomena were not independently monitored during fabrication. Consequently, the present dataset does not allow the individual contribution of each mechanism to the observed experimental scatter to be isolated.

IMPLICATIONS FOR ENGINEERING APPLICATIONS

The results have practical implications for the fabrication of polymeric components by FDM. When the loading direction is known and predominantly uniaxial, aligning the rasters with the load remains an efficient strategy for maximizing tensile strength. However, this strategy restricts design freedom and may be inadequate for parts subjected to multidirectional loads.

In this context, the Cross pattern presents a potential advantage: it maintains ultimate strength close to the favorable orientation condition while not relying on a single unidirectional linear raster



aligned with the applied tensile load. This feature may be useful in functional prototypes, supports, auxiliary components, and applications in which the loading direction is not fully controlled. Nevertheless, the lower strain observed requires caution in applications demanding high ductility or energy absorption before failure.

From a scientific perspective, the study reinforces the need to analyze infill patterns as internal architectures capable of altering the load-transfer path, rather than merely as secondary slicing settings. Infill selection should be understood as a mechanical design decision, especially for parts intended for functional use.

For engineering practice, the results suggest that infill pattern selection should be performed together with assessment of loading direction, expected stress level, and admissible failure mode. In low-structural-responsibility parts, the Cross pattern may offer a favorable combination of strength and reduced directional dependence. In critical components, however, its application should be preceded by complementary testing and safety criteria compatible with the function of the part (Gordelier et al., 2019; Guessasma, Belhabib and Nouri, 2019).

STUDY LIMITATIONS AND METHODOLOGICAL RECOMMENDATIONS

Although the results indicate promising mechanical behavior for the Cross pattern, their interpretation should consider the limitations inherent to the experimental design. The first limitation concerns the number of specimens per group. Using three specimens allows an exploratory comparison between printing strategies, but it does not provide a sufficient statistical basis for robust inferences regarding population variability, confidence intervals, or significance between means.

The second limitation concerns the use of two slicing software programs. Although this choice was necessary because of the availability of the evaluated patterns, it introduces implementation differences that may influence the actual deposition path, infill sequence, extrusion control, and final

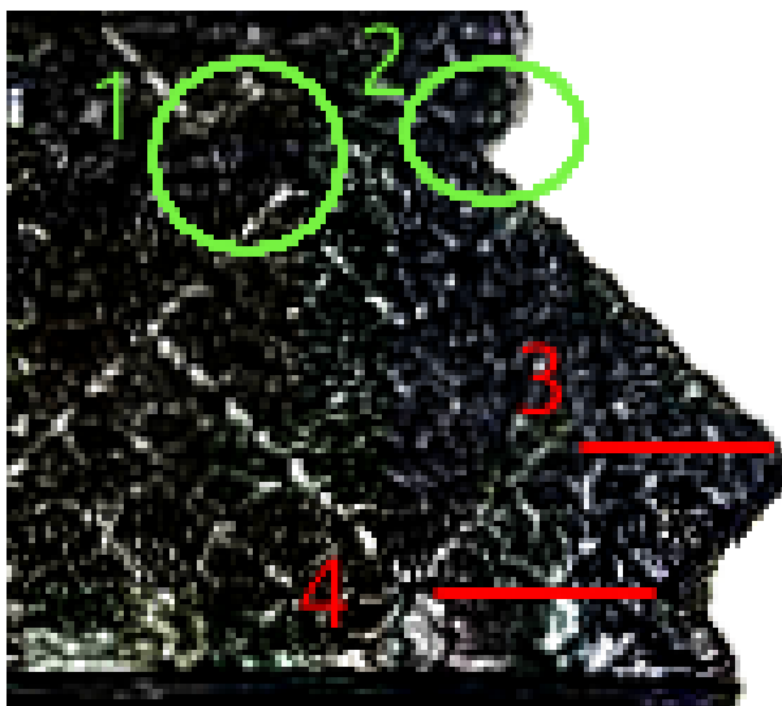


specimen mass. Future investigations should isolate this factor by using a single slicing environment or by validating in detail the machine code generated for each condition.

The third limitation is related to microstructural characterization. This study interprets fracture behavior based on mechanical results and visual inspection of the fracture surfaces, but it does not include scanning electron microscopy, quantitative porosity analysis, or apparent density measurements. These procedures would be important to verify whether the superior performance of the Cross pattern is associated with higher deposition continuity, lower void content, improved coalescence between rasters, or a combination of these factors.

Figure 5

Detail of the HI3 specimen fracture and possible preferential fracture paths.



Source: author.

The detail shown in Figure 5 reinforces the need to integrate mechanical and morphological analyses in studies on infill patterns. Abrupt changes in fracture direction suggest that certain regions of the Hilbert Curve pattern may act as preferential paths for crack propagation. This observation does not



invalidate the potential of the pattern, but indicates that its efficiency depends on the local geometry of the rasters and on the quality of the interfaces formed during deposition.

Future studies should also evaluate other infill percentages and compare results in both absolute terms and normalized by specimen mass. This approach would allow gains associated with internal architecture to be distinguished from gains resulting simply from a greater amount of deposited material. In engineering applications, this distinction is relevant because infill selection may involve trade-offs between strength, mass, manufacturing time, and material consumption.

Another methodological possibility is to expand the experimental program to flexural, impact, and fatigue testing. Tensile testing provides essential information on axial strength, but functional FDM parts are often subjected to combined loads. Complementary tests would allow evaluation of whether the Cross pattern maintains its mechanical advantage under different loading conditions or whether its response is specific to uniaxial tensile loading.

A further limitation concerns the assessment of anisotropy. The Cross and Hilbert Curve architectures were tested under only one specimen and loading orientation. Therefore, the present results do not allow their degree of mechanical isotropy to be quantified. A rigorous assessment would require equivalent specimens to be manufactured and tested at different orientations while maintaining material, infill architecture, printing parameters, and testing conditions constant.

Finally, incorporating inferential statistical analysis, such as ANOVA or multiple-comparison tests, would increase the scientific robustness of the results. With a larger number of specimens, it would be possible to determine whether the observed differences between patterns are statistically significant and to estimate the variability associated with each printing strategy. These improvements would strengthen the applicability of the results and expand the contribution of the study to the design of polymeric components manufactured by FDM.



CONCLUSIONS

This study evaluated the effect of non-preferential infill patterns on the mechanical performance of ABS specimens manufactured by FDM. Based on the tensile tests performed, the deposition pattern was found to exert a determining influence on ultimate tensile strength, yield strength, and strain.

The comparison between linear patterns demonstrated the typical anisotropy of the FDM process. Specimens with rasters parallel to the loading direction presented an average ultimate tensile strength of 23.46 MPa, whereas those with perpendicular rasters reached only 11.38 MPa. This result confirms that mechanical strength is strongly dependent on raster orientation with respect to the applied load.

Among the non-preferential architectures, Cross presented the highest average ultimate tensile strength, reaching 23.07 MPa, equivalent to 98.3% of the mean value obtained for the favorable parallel linear reference. Under the specific printing and loading condition investigated, this result indicates that the Cross architecture was able to preserve tensile strength without relying on a single linear raster aligned with the applied load. However, because only one specimen orientation was evaluated, the present results do not demonstrate mechanical isotropy or quantify the directional sensitivity of the Cross pattern.

As a limitation, the reduced number of specimens per group restricts more robust statistical analyses. Future studies should increase the number of specimens, include inferential statistics, evaluate other infill percentages, investigate the influence of different chamber temperatures, and perform microscopic characterization of fracture surfaces. The evaluated patterns should also be compared under flexural, impact, and fatigue loading to verify the applicability of the results under conditions closer to real use.

It is concluded that non-preferential infill patterns should not be assessed only by the absence of a dominant direction, but by their effective ability to maintain structural continuity, promote bonding between rasters, and distribute load-transfer paths. Under the experimental conditions investigated, the Cross pattern presented the most promising tensile response among the evaluated non-preferential



architectures. Further testing under multiple build and loading orientations is required before conclusions regarding mechanical isotropy or orientation-independent performance can be established.

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