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Effect of infill pattern in Fused Filament Fabrication (FFF) 3D Printing on materials performance

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ABSTRACT

Fused Filament Fabrication (FFF) is an Additive Manufacturing process popularized in the last decade due to its easiness of use and lower costs. However, despite its increasing popularity, the process itself has several gaps in knowledge, hindering further uses on more advanced objects. Also, the freedom of design allows significant variances in the printed parts, many influencing production and mechanical properties. This work studies the influences of the infill patterns in the mechanical response of printed parts. Using poly (lactic acid) (PLA), a widely used polymer in FFF process, the mechanical responses of parts printed with different infill patterns were analyzed. Rectilinear, Honeycomb, Triangle and Grid patterns were tested on impact resistance and tensile strength. Additionally, samples masses were measured and compared to the mechanical response. Results shown significant differences in the on tested properties. Tensile strength varied from 2.4 to 1.1 MPa, and impact resistance from 3.8 to 1.5 kJ/m² Also, measured mass was found to be significantly higher on the Honeycomb pattern. Considering mechanical response from both tensile and impact tests along with printed mass, Rectilinear pattern can be considered the most advantageous from the economic point of view.

Keywords: PLA, FFF, 3D printing.

1. INTRODUCTION

Additive manufacturing is a set of technologies that uses layer by layer building process to create objects directly from a computer model. It is a promising area of manufacturing as it is able to create functional components with intricate geometries at low cost and with minimal waste [1]. It is also user friendly and requires minimal supervision, being used to create products from biotechnology to engineering applications [2], [3] such as scaffolds and vehicle parts [4].

Fused Filament Fabrication (FFF) is an AM technology based on the extrusion of a melted polymer filament. It has grown in popularity in the last decade as the costs were lowered by an expanding community and open source devices. Compared to Selective Laser Sintering and Stereolithography, FFF offers the advantages of lower costs and wider diversity of available materials [5, 6].

In the FFF process, the polymer filament is melted in a heated nozzle and deposited in a building bed [7]. The objects geometry is created by the deposition of the melted material (Figure 1) as the head section moves above the printing surface in the XY plane [8] PEEK is a promising biomaterial that could potentially be used to replace traditional metal or ceramic parts for biomedical and aerospace applications. Compared to other processing technologies for manufacturing PEEK parts, fused deposition modeling (FDM. When one layer is finished, either the platform is moved down or the head moved up, to the height of a new layer. The speed limit of the FFF process is based on its ability to correctly melt and to correctly deposit the viscous material, whilst maintaining accuracy [9]. As the process of printing solid parts is time demanding, it is common in FFF to print parts with partial infill and few shell lines. Although complete infill is recommended for maximum mechanical resistance, it is solely needed, and partial infill offers a compromise between productivity and mechanical performance [10]. Besides lowering printing time, this also cuts materials costs and minimizes warping on the object edges.

Even though the FFF process is well known, it is still a complex process, as it is influenced by many parameters [11]. Extrusion temperature, extrusion speed, layer thickness, raster angles and width are some examples. Besides, it is occasional that more than one parameter interacts to influence a final propriety. Extrusion temperature and speed act together to determine, by the cooling process, the morphological characteristics of printed parts, such as the degree of crystallinity and

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the coalescence between deposited lines. Polymer coalescence is the process by which adjacent lines form necks and bond together [12]. It is driven by the diffusion of polymer chains at the interface, and it is dependable on the polymer's viscosity, surface tension and glass transition temperature. Coalescence is a key phenomenon to FFF, for it influences the strength of the printed parts and structural integrity. Ideally, coalescence would create a single structure. However, in reality, the process is incomplete, and voids are created between deposited lines. These voids are considered one of the reasons full infill printed parts have lower mechanical performance when compared to injection molding. Other factors such as differences in the cooling process also and higher pressure used in injection molding are also mentioned to contribute to differences.

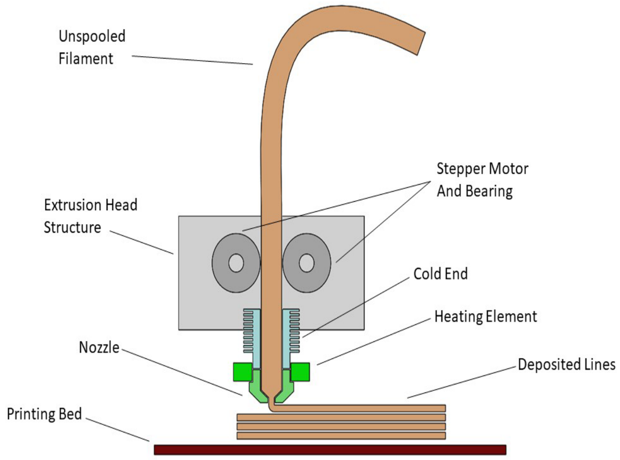

Figure 1: Fused deposition process representation.

Exception to small objects, the infill becomes the predominant factor as it takes more volume than the perimeter shell [13, 14]. When lower infill degrees are used, the infill patterns influence becomes much higher, as it creates the internal structure, responsible for the parts integrity. The infill pattern itself can be rendered from different geometries, from simple lines to hexagons. These patterns have direct effect on the mechanical properties of the printed parts, as studied by [15]. Also, they can be used to create metamaterials, drastically changing mechanical response. At least one study, [16], discuss the differences in the deformation among infill patterns, presenting diverse responses associated to the patterns internal geometric structure. For simple linear infill patterns, studies approximate to the classical laminate theories [17, 18, 19], along consistent experimental results [20]. Variances in the tensile strength are reported by [21, 22]. In these studies, tensile strength varied with the infills angle, from a maximum at axial direction [21, 22, 23] to a minimum at transverse direction.

Similar results were also found in previous works regarding impact resistance. Impact resistance was found to be higher when orienting deposition lines on axial orientation and lower on transverse orientation. Similar results also reported by [24, 25]. These differences are attributed to distinct fracturing mechanisms, transversal to filament strands and between strands, the latter absorbing less energy [26, 27].

Poly (lactic acid) (PLA) is a biodegradable thermoplastic and is considered a renewable resource. It can be easily processed by extrusion, molding, into films and fibers. Also, depending on the isomer ratio, it can be made amorphous or semi crystalline [28]. Usually having a glass transition and melt temperature of 60 ºC and 170 ºC respectively, it can be effortlessly processed in the temperature range of 180 to 200 ºC [9]. However, it suffers degradation at temperatures higher than 200 ºC. Degradation causes changes in molecular weight and mechanical properties, causing PLA to have a very narrow processing window [29]. However, for the FFF process, the polymer remains at processing temperatures for a very limited time, as it enters the extrusion head and is promptly extruded, minimizing polymer degradation. Lastingly, due to its high surface energy, PLA has good coalescence properties, fundamental to the FFF process. These features made PLA a popular choice, along with acrylonitrile butadiene styrene (ABS), for 3D printer filaments [11].

On mechanical performance, PLA is considered to have high strength and high stiffness, although also considered brittle [30]. Usual mechanical responses are in the range of 3-4 GPa elastic modulus, 50-70 MPa tensile strength [31] and 20-30 kJ/m² impact strength for the injection molded process [32]. These are usually lower on FFF process due to internal voids. Also, to minimize production time, the use of lower infill degrees promote much lower mechanical responses [33]. On a rheological perspective, PLA has a relatively modest Melt Flow Index (MFI), ranging from 3 to 15 g/10min. Nevertheless, it has a low melt viscosity, and in consequence, low processing pressure [30]. Additionally, its viscosity quickly declines with a small increase in temperature, making it an ideal subject to FFF process.

Despite increasing amount of research on the subject, mechanical performance of FDM parts has only been partially explored [33]. Mechanical performance is crucial to a functional end use part and is greatly affected by the selected variables. This paper aims at filling some gaps in knowledge related to available infill patterns in the FFF process. In this study, different infill patterns are used to create groups of printed PLA samples. Tensile response and impact resistance are tested, along the sample's final masses. These responses are compared to the fractured samples and conclusions are drawn about the pattern's effects.

2. MATERIALS AND METHODS

2.1 FFF equipment and filament material

The 3D printer used in this study was a Prusa i3 model, built in house. While not as productive as commercial models, it is cost efficient and allows machine customization. The equipment uses a standard 0.4 mm nozzle, J-Head type, mounted on a direct drive extruder. The firmware Marlin was used to control the equipment. During the printing process, the room temperature was kept at 20 ºC, with no direct air flow to the equipment.

The material used in the experiment, PLA, was purchased from Cliever Ltda., in the form of a 1 kg blue filament roll. The material was tested as having a MFI of 10 g/min at 190 ºC.

2.2 Printing parameters and design of experiment

The experiment required impact and tensile specimens. These were modeled accordingly to ASTM 256 and ASTM D638 standards and then transferred to Slic3r v1.3.0, in order to generate the G-Codes. During this step, the processing parameters were established. Printing speed was set to 20 mm/s, printing temperature to 200º C and layer thickness to 0.3 mm. Only a single perimeter wall was used, to minimize its influence on the sample's mechanical performance. Using an infill degree of 20 %, four infill types were used in this study.

The four infill types studied are Rectilinear, Grid, Honeycomb and Triangle (Figure 2) and were oriented along the sample's axis, used in the tensile tests. Grid pattern is a spaced sprout of rectilinear. While grid prints vertical and horizontal lines on the same layer, rectilinear alternates between horizontal and vertical each layer, leading to closer lines. Infill orientation was set to 0º, using Sclic3r standard orientation. Using a 90º orientation to align Triangle pattern lines resulted in incomplete triangles inside the infill, and lower mechanical performance, being thus, disconsidered.

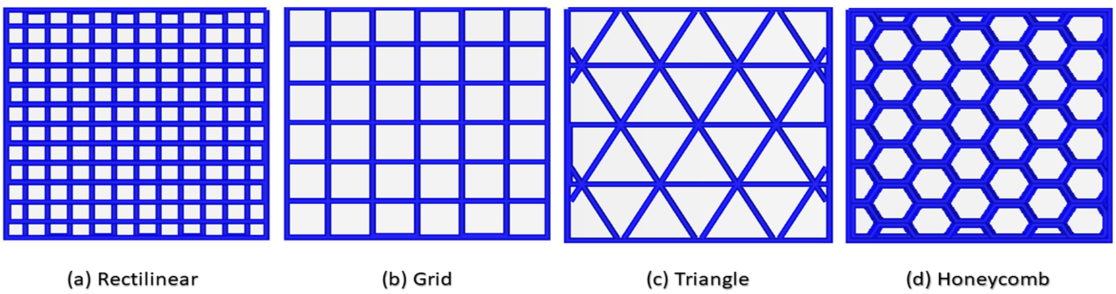

Figure 2: Infill patterns rendering for Rectilinear (a), Grid (b), Triangle (c) and Honeycomb (d).

2.3 Izod impact strength

Izod impact strength test was performed on a CEAST Impact Izod using a 2.75 J hammer. Specimens were designed to ASTM 256 standard, resulting in 10 layers per sample. Samples were tested unnotched, as the notching would cause rupture of deposited lines and a printed notched specimen would change the infill patterns.

2.4 Tensile testing

Tensile testing of printed samples was performed on an Instron Emic 23 D at a speed of 2 mm/min, along a load cell of 5 kN. A pressure of 1 bar was used on the grips to minimize specimens slipping without fracturing the samples. Tensile specimens were dimensioned and tested according to ASTM D638, accordingly to specimens' type V specifications, resulting in 11 layers per sample.

2.5 Mass

The mass of each printed impact specimen was evaluated before impact using a Marte, AY220 model, electronic balance with 0.1 mg resolution.

2.6 Statistical analysis

Tensile and impact testing results were submitted to both ANOVA and Turkey's test at α=0.05 for comparison on each group of infill pattern. Testing was performed using five samples per group for the tensile tests and ten samples per group for the impact test.

3. RESULTS

3.1 Impact resistance

Firstly, impact resistance is found to be much lower than reported to injection molded PLA, as it presents internal structures, and, in the present study, lower infill quantity. As shown in Figure 3, impact resistance from different infill patterns differ significantly. Triangular pattern presented the lowest impact resistance among the groups. This lowest resistance can be attributed to the simpler structure created by the infill pattern, with no internal redundancies. It is also more susceptible to failure as cracks would create much higher strains in the internal structure [26].

Meanwhile, the other three groups (Grid, Rectilinear and Honeycomb) have similar impact resistance, at a higher level than Triangular pattern. A statistical analysis revealed Rectilinear pattern to uphold a higher impact resistance than Grid pattern. However, due to the higher standard deviation, the statistical analysis found no statistical differences between Honeycomb and Grid patterns or Honeycomb and Rectilinear patterns. The higher impact performance of Grid and Rectilinear patterns when compared to the Triangle pattern can be related to the transversal geometry, creating more redundancies in the infill. These would absorb more energy during crack propagation Although Honeycomb pattern possess similar characteristics to Triangle, it has higher internal angles and the samples have higher masses. That could better distribute internal strains. Also, Grid, Rectilinear and Honeycomb patterns present higher symmetry, effectively combining direct and transversal orientations (vertical and horizontal), which allows for more energy absorption [25]. This behavior is similar to the composite materials.

A higher standard deviation can be noted from the Honeycomb pattern. This can be associated to different breaking mechanisms in the internal structure. While other patterns are created by transversal continuous lines, this pattern is created by a zig-zag movement, which generates bonds of adjacent lines. These bonds are known to be weaker than the lines themselves and could induce failure [24, 27].

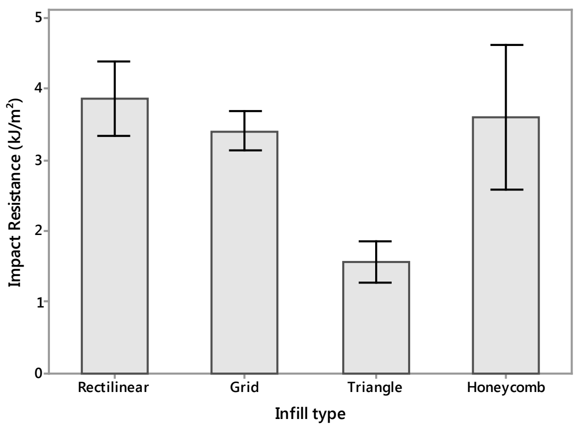

Figure 3: Mean impact resistance of infill groups.

3.2 Tensile tests

Similarly, to impact resistance results, tensile strength and elastic modulus were found to be much lower than those of injection molded PLA. This is related to both infill degree and the printing process, as also reported by [22]. Tensile tests show more diversity on the results between infill patterns, as to each property (Figure 4). Elastic modulus was found to be higher to Grid pattern, followed by Rectilinear, while Honeycomb and Triangular were found to have lower modulus. Albeit with much lower infill, and thus much lower properties, Rectilinear and Grid patterns could be related to the laminate theory used for describing the behavior of FFF parts [19]. As both Grid and Rectilinear patterns have a higher number of deposited strands aligned along the tensile axis, it allows them to absorb stresses directly akin to a column and preventing structure deformation [20]. On the other side, Honeycomb and Triangle patterns are crated having angular lines in the internal structure. These lines are more easily deformed by applied forces, acting similarly to a cantilever beam and may be approximated by Timoshenko's beam theory [16]. This easier deformation leads to a lower elastic modulus and could be also predicted.

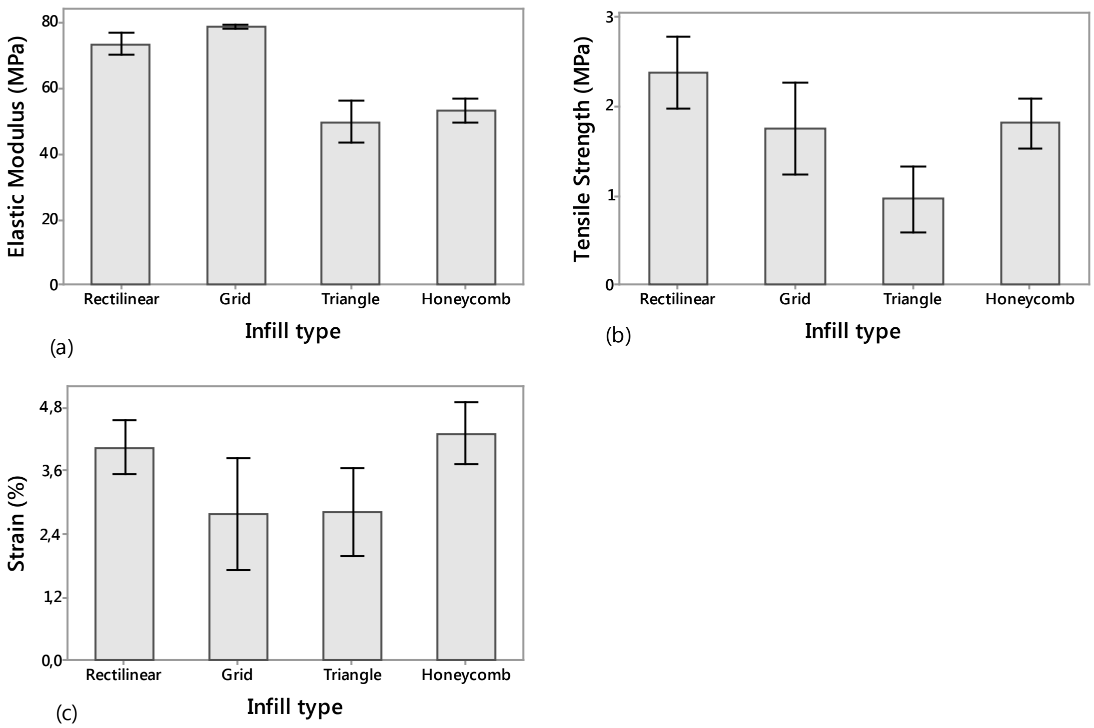

Figure 4: Elastic Modulus (a), tensile strength (b) and tensile strain (c) of infill groups.

Tensile strength was found to be higher for the rectilinear pattern, at 2.4 MPa. This is somehow expected as part of the deposited lines are in direct orientation to the applied stress, and is consistent to other studies [34]. Following the same premises as to Elastic Modulus, Grid pattern should have similar tensile strength to Rectilinear ones, contrary to results. An explanation may be inferred by analyzing fractured specimens of the four infill types (Figure 5). While Rectilinear, Triangle and Honeycomb patterns presented fracture points in the specimen's middle zone, all samples from the Grid group presented fracture on the necking region. This could be related to an ineffective stress transfer inside the structure as it is more spaced, creating areas of high stress concentration. Triangular pattern also showed the lower tensile strength, at only 1.1 MPa, less than half than the strongest pattern. It is possible the failure of a region inside the structure leads to a progressive increase in internal forces, as reported by [15] for impact resistance. It can be noted Figure 5 (c) that Triangle patterns exhibited fractures near joint points, as opposed to the deposited lines. It could be theorized these joints are more prone to stress concentration, creating weak spots inside the structure. Honeycomb pattern shares this resemblance, as could be expected by the geometry. A more thoroughly analysis of the failure mechanism of both patterns is needed. Differently, Rectilinear and Grid patterns exhibited more disperse fracture points along deposited lines, much like failing fibers. While authors have used laminate models for full infill printed parts [17], it is possible these could be extended to partially infill parts.

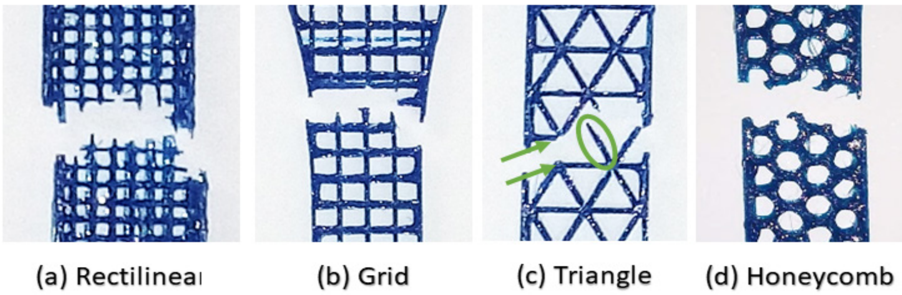

Figure 5: Fracture region of tensile specimens after tensile test of Rectilinear (a), Grid (b) and Triangle (c) samples.

Lastingly, the higher tensile strain was observed on the Honeycomb type infill pattern at 4.3 %. This could be anticipated as, in theory, the angled structure would allow more internal deformation [16]. Rectilinear pattern presents the same level of tensile strain, having no statistical difference from Honeycomb pattern due to standard deviations. Again, Triangle pattern shows lower strain, at 2.8 %, pointing again to a less sturdy internal structure. Also, Grid pattern exhibits low tensile strain, with no statistical difference from Triangle and lower than both Rectilinear and Honeycomb. This could be attributed to the failure at the necking point, as previously stated, strengthening the hypothesis. The origin of the necking failure may be related to Slic3rs pattern design routine, and not by Grid pattern itself. As the infills design algorithm is based on equally spacing extruded lines up to the desired filling degree (occupied space), it is unable to balance geometric changes to better mechanical performance. Hence, some internal parts may be subjected to unwanted stresses and prone to failure, if infill geometry is not properly reviewed.

3.3 Gravimetric analysis

The correlation between samples masses, printing time and impact resistance, brings out hidden differences between patterns [10]. This is shown in Figure 6. Processing time and samples mass are clearly related, as could be expected as the printing speed is set to constant. As deposition occurs, printing time becomes proportional to the time needed for the extruder conclude the patterns path. Grid pattern samples had lower mass values and printing times than their peers. Rectilinear pattern values were slightly higher. Honeycomb pattern presented the highest values, more than 20 % higher than Grids values, due to the pattern intricacy and due to being created with adjacent strands. These strands are created in order to keep extrusion constant as the extruder moves, creating each hexagon side, as seen in Figure 2 (d). A constant extrusion mitigates an under extrusion due to oozing on resuming it. It must be noted that the software seems to relate infill degree to internal area, not printed mass, leading to differences among certain patterns. Also, it seems to prioritize internal symmetry and border alignment instead of extreme mass precision in order to create a less anisotropic infill. Triangle pattern samples presented mass and processing time between Honeycomb and Grid patterns. Despite being simple as a structure, it needs slightly longer toolpaths. Also, mass deviation from infill patterns groups are minimal, within measurement error and slicer prediction, highlighting the accuracy of the FFF process.

An estimative of effectiveness can be established by comparing impact resistance and samples mass. This gives an economic view of production costs [3]. The resulting efficiency is very low for the Triangle pattern, as it has very poor mechanical performance. On the other side, Rectilinear pattern becomes the most efficient, along the similar structured Grid pattern. Both Rectilinear and Grid presented no statistical difference, and both presented as having statistically higher means than Honeycomb pattern. Honeycomb turns as having intermediate effectiveness, due to having high impact resistance, but also having heavier samples. The same logic could be extended to other results, as tensile strength for example. Rectilinear pattern would still be the most efficient as, in this case, as patterns showed similar response to tensile strength and impact resistance

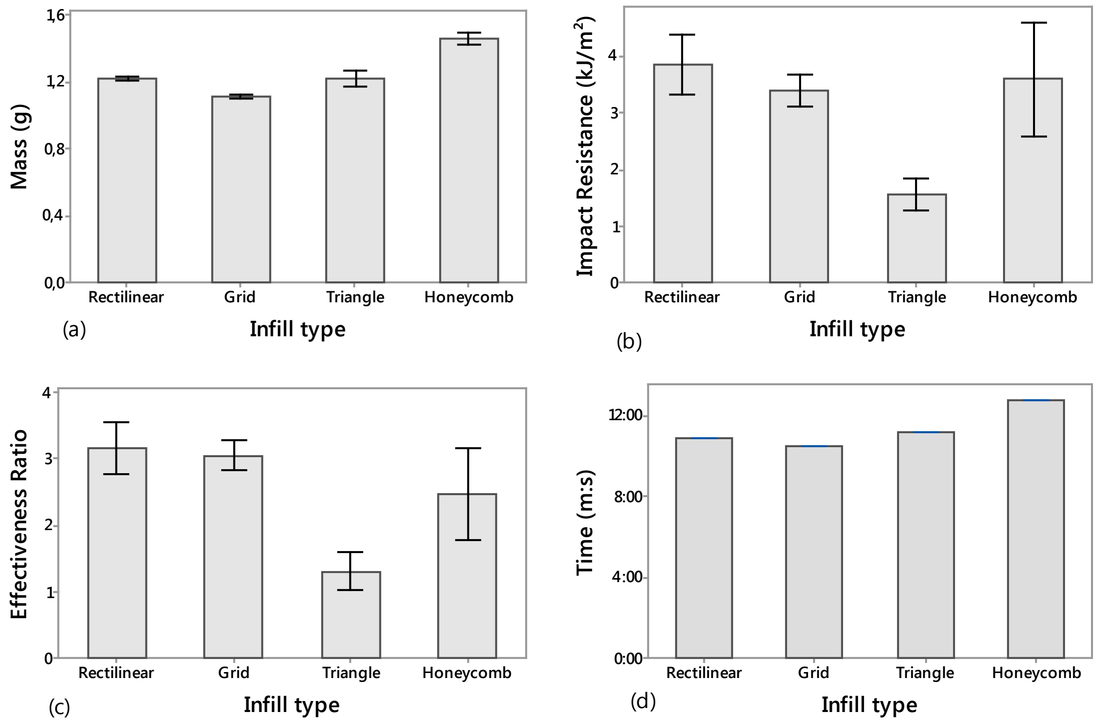

Figure 6: Mean samples mass (a), impact resistance (b), efficiency ratio (c) and printing time (d) for infill groups.

While Rectilinear pattern might be more time and cost effective from a simple production point of view and mechanical performance, it must also be noted the differences between patterns could serve various purposes, as in creating metamaterials or creating materials with higher elongation break. Hence the chosen infill pattern would be defined by the final product's needs. Also, it would be possible in 3D printing, for optimization purposes, to combine different infill patterns for different regions, creating a fully customized structure.

4. CONCLUSION

The results show significant differences in the mechanical performance of 3D printed objects of different infill patterns. Compared to the others studied infill patterns, Rectilinear pattern presented best performance, having a high Elastic Modulus, tensile strength and impact resistance. It also presented as the most economic and mass efficient, among the four patterns, consuming less material and having low printing time whilst having good mechanical performance. Triangular pattern was found to have much lower mechanical performance than other tested patterns. This is attributed to the more fragile internal structure. Also Honeycomb pattern presented the highest processing time and samples mass, it also presented a higher braking strain. It can be concluded the chosen infill pattern should not only be chosen based on mechanical performance but also on printing time and material costs.

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