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Effect of infill percentage and pattern on compressive behavior of FDM-printed GF-CF PA6 composites

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Abstract. The present paper aims to assess the effect of different infill percentages and patterns on the compressive mechanical properties of specimens in Polyamide PA6 reinforced with 20% glass fibers (GF) and 10% carbon fibers (CF) printed using the Fused Deposition Modeling (FDM) technology. According to the ASTM D695-15 standard, cylindrical specimens were designed and processed through slicing software, configuring infill percentages and patterns. Three different typologies of infill pattern and two infill percentages were considered: a 100% grid infill, a 50% grid infill, a 100% concentric infill and a 50% honeycomb infill were printed. Then, compression tests were performed at room temperature to evaluate the properties of the different specimens. The comparison between the stress-strain compression curves has shown that the infill percentages and patterns significantly affect the mechanical compression properties of 3D printed components.

Introduction

In recent years, Additive Manufacturing (AM) has gained increasing relevance in different manufacturing sectors due to its capability to produce lightweight components with complex geometries, which are challenging to achieve through traditional techniques [1,2]. The AM approach also offers high efficiency, reducing raw materials costs, labor, and material waste, enabling on-demand manufacturing and subsequently reducing storage and logistical costs [3,4]. Furthermore, additive manufacturing promotes rapid and iterative design, allowing engineers and designers to swiftly test and refine their prototypes. This technology also holds potential to reduce energy demand, production process complexity, manufacturing lead times, and time to market. This industrial progress is reshaping production paradigms in different sectors, from aerospace, to automotive, biomedical, sports, and others [5].

Among various AM methodologies, Fused Deposition Modeling (FDM) has emerged as one of the most versatile and widely adopted techniques [6]. Its popularity derives from its simplicity, user-friendliness, and especially its extensive material flexibility, allowing the printing of a wide range of materials. Traditionally, FDM-printed parts primarily employ polymers, yet there is a growing interest in utilizing high-performance composite materials. Composites are produced by combining two or more constituent materials, characterized by dissimilar chemical or physical properties, in order to obtain a material with enhanced properties with respect to the individual elements. Specifically, fiber-reinforced polymer (FRP) composites, consisting of fibers, as reinforcing phase, embedded into a polymeric matrix, offer superior mechanical properties as compared with traditional metallic materials, such as higher tensile strength–weight ratio and modulus, making them suitable for many structural applications. Such materials can be also 3D printed using the FDM technology. Different studies have demonstrated that FDM process allows obtaining a significant fiber alignment in the longitudinal direction when short fiber-reinforced polymers are printed by means of a material extrusion-based process [7,8]. Such result demonstrates that the design of the printing process and, consequently, the deposition direction can significantly affect the mechanical properties of the 3D printed components in short FRP composites. The growing advancement of FDM technology in composite materials leads to the need of characterizing the printed materials performances, and to understand the effect of the process printing parameters on the mechanical properties of the additive manufactured components [9–12]. Current research is mainly focused on the influence of printing parameters, such as print speed, infill percentage, temperature, layer height, and infill geometry, on tensile, flexural and impact resistance behaviours of FRP components printed using FDM process. Lee & Wu [13] investigated the influence of printing parameters on the mechanical properties of carbon fiber reinforces PLA, identifying the printing bed temperature as the most significant parameter on tensile strength. They also demonstrated that parts printed at a 45° orientation exhibit superior mechanical properties as compared to those printed at 90°. The increase in infill density enhances strength. The impact of nozzle and print bed temperature, print speed, and layer thickness on the tensile and flexural behavior of CF/PEEK and GF/PEEK samples was studied by Wang et al. [14], highlighting that the increase in print speed and layer thickness negatively affect the mechanical properties. Kovan et al. [15] analysed the effect of orientation angle. Peng et al. [16] discovered that CF/PA6, printed along the tensile loading direction, exhibits higher tensile properties as compared to orientations at 45°/-45° and 90°, indicating strong anisotropy in mechanical properties linked to printing orientation. From the study conducted by Ramalingam et al. [17] on the effect of infill density (30%, 40%, and 50%) with various infill patterns (hexagonal, triangular, and rectangular) on 3D printed onyx glass fiber composites subjected to impact tests, it was found that there is an increase in energy absorption rate in the hexagonal pattern and 50% infill density model.

Unfortunately, few studies on the influence of process parameters on the compressive mechanical properties of 3D printed short fiber-reinforced composites are available in scientific literature. Fisher et al. [18] investigated that nylon samples reinforced with 14% by weight of short carbon fibers is characterized by an increase in compression strength by up to 130% when the printing path aligns parallel to the loading direction. Mei et al. [19] demonstrated that the yield load and elastic modulus of PLA and CF/PLA printed specimens increase with decreasing layer thickness.

In this framework, the effect of printing parameters on compressive mechanical properties needs to be further investigated. To this purpose, the present study focuses on optimizing the mechanical properties of polyamide PA6 reinforced with 20% glass fibers (GF) and 10% carbon fibers (CF) composite material. The influence of different filling percentages and patterns on the compression strength and on specific compression strength of cylindrical samples obtained through FDM was investigated. This approach aims to provide a deeper understanding of the relationships between filling geometries and mechanical performances, crucial for optimizing of the utilization of such composite materials in different industrial applications. Furthermore, this investigation is significant for the optimization of the balance between weight, durability, and production costs to meet the specific needs of industrial applications.

Materials and methods

3D printer and material

The composite material investigated in this study is the polyamide PA6 reinforced with 20% short glass fiber and 10% short carbon fibers (PA6 CF-GF), provided by Tagin3D company in the form of a 1.75 mm diameter filament.

As reported in the technical datasheet, the material is characterized by a density of 1.27 g/cm^3, and mechanical properties higher than a not reinforced PA6.

Compression cylindrical specimens were sized according to ASTM D695 standard with a diameter of 12.7 mm and a height of 25.4 mm. The model was designed using CAD software and then exported in STL format. It was imported into Simplify 3D slicing software, through which the main printing parameters, such as infill percentage and pattern, were defined.

The Roboze One* 400 3D, equipped with Fused Deposition Modeling (FDM) technology, was used to produce the compression cylinders. Extrusion of the PA/6 CF-GF filament was carried out at a temperature of 250°C, using a nozzle of 0.4 mm in diameter. The temperature of the building plate was set at 70°C to enhance the adhesion of the specimens. Table 1 summarizes the main processes parameters.

Table 1: Printing parameters.

Processes parameters	
Nozzle diameter	0.4 mm
Extrusion temperature	250 °C
Printing plate temperature	70 °C
Average printing speed	50 mm/s
Layer height	0.25 mm
Outer layer	2 (0.8mm)

Four different configurations were analyzed, obtained from the combination of three different types of infill patterns with two fill percentages: 100% concentric infill, 100% grid infill, 50% grid infill, and 50% honeycomb (Figure 1). For grid and honeycomb infill pattern specimens, 3D printing was performed with deposition layers alternating between raster angle of +- 45°, while a straight external infill (0°, 90°) was chosen for first and last 2 layers (external infill was not necessary in the concentric configuration).

Due to the high hygroscopic nature of polyamide, the filament was preheated in an oven for four hours at 100°C, 15°C below the softening temperature, to ensure better print quality and reduce void formation caused by moisture absorption. Furthermore, during the printing phase, the filament spool was stored in a dedicated dryer at a temperature of 50°C. To enhance adhesion, the print bed was coated with an adhesive film (blue tape).

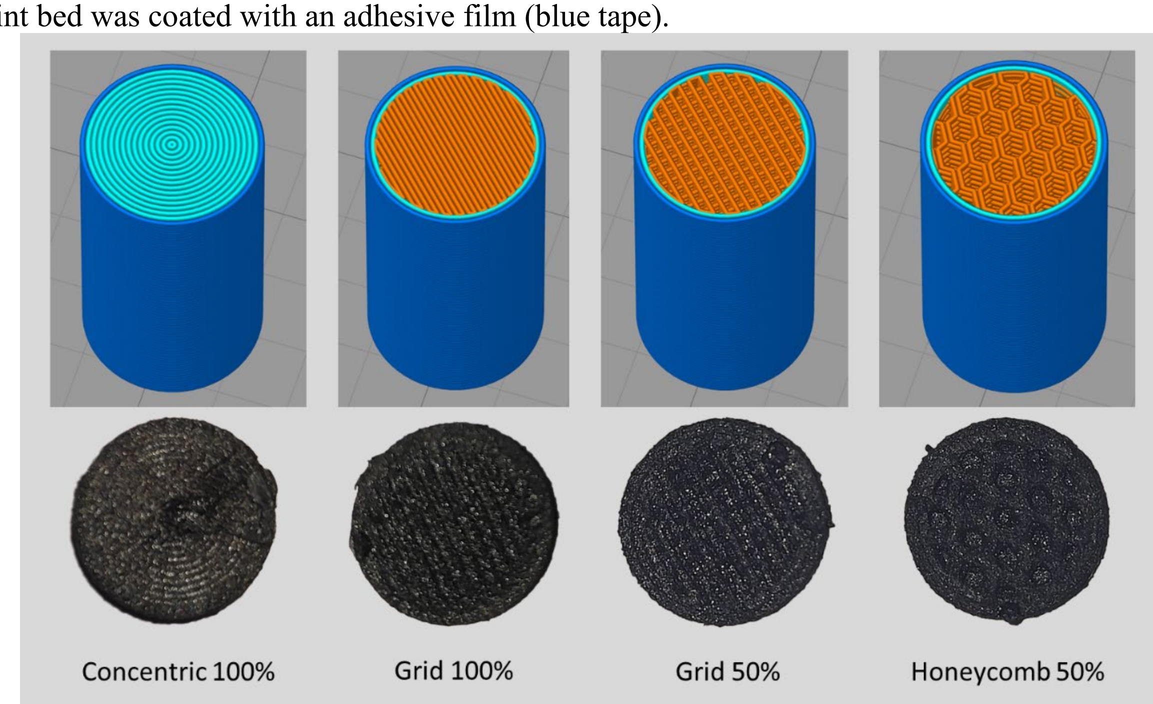

Figure 1: Rapresentation of the four configurations studied, and comparison between the slicing images and the real sections of the 3D printed specimens.

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Compression test
Compression tests of 3D printed cylindrical specimens in polyamide PA6 reinforced with short carbon and glass fibers were performed using the MTS 810 servo-hydraulic testing machine, at a speed of 0.5 mm/s, following ASTM D695 standards. Load and displacement along the loading direction were captured using a load cell and a variable linear displacement transducer (LVDT). The results obtained by compression tests were plotted as stress-strain curves. To ensure result repeatability, five compression tests were performed for each specimen configuration.

The specific strength of the material was calculated as ratio between the strength of material and its density. To this purpose, before the compression tests, the average masses of the specimens were measured using an analytical balance; similarly, the average size of each specimen was measured. The density of each structure was calculated as ratio between the average mass and volume.

Results and discussion
Figure 2 shows nominal compression stress-strain curves obtained by short glass and carbon fiber reinforced polyamide specimens with the different infill patterns and percentages, produced through FDM printing process. Irrespective of the infill percentage and pattern, it can be observed that the typical compression stress-strain curve is characterized by an increase in compression stress with strain until a peak value. Then, the stress tends to decrease with rising strain until reaching a minimum value at which the stress tends to further rise. By comparing the two 100% configurations, no differences in terms of maximum compression strength and strain at the peak can be observed. However, a reduction of about 19% in the compression modulus appears when transitioning from 100% grid infill to the 100% concentric infill. There is no substantial difference in the yield point. Analyzing the results obtained from the 50% infill samples, the configuration with the highest compression strength is the grid arrangement. However, the maximum peak strain is about 50% honeycomb infill, which is only 2.3% lower than that of the 100% grid specimens.

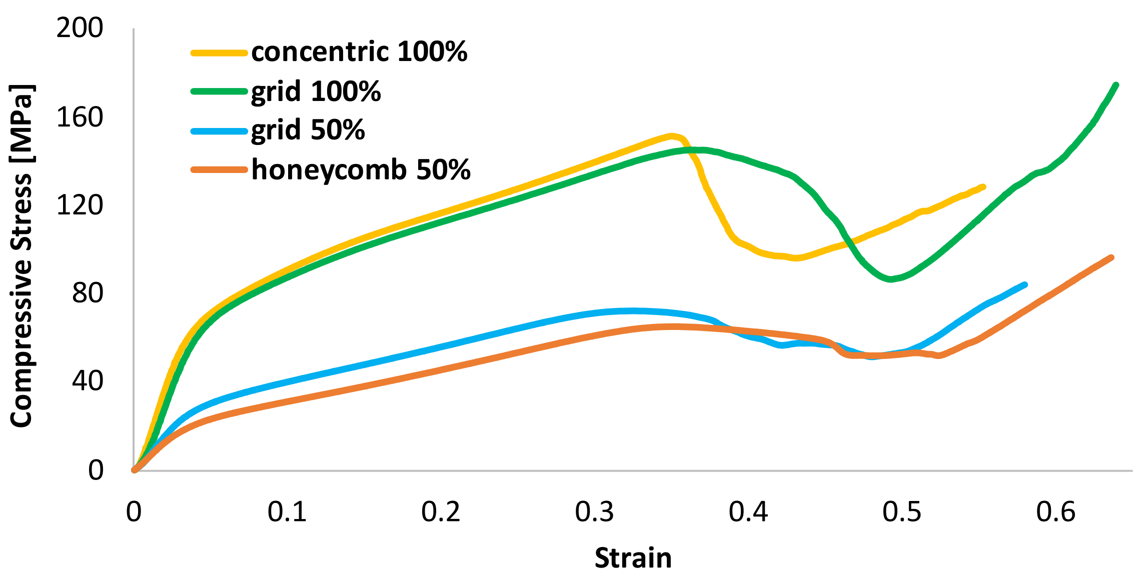

Figure 2: Effect of the infill percentage and pattern on typical nominal compression stress-strain curves of 3D printed specimens in polyamide PA6 reinforced with 20% short glass fiber and 10% short carbon fibers.

As far as the infill percentage is concerned, it can be observed that the strength levels reached by specimens printed at 100% infill are higher than those obtained by specimens printed at 50% infill. As a matter of fact, a reduction in compression strength and compression modulus of about 57% and 60%, respectively, can be observed as the infill percentage decreases from 100% to 50%.

With regard to the yield stress analysis, the maximum value reached at the 100% grid setting is 61% higher than the minimum value measured in the case with 50% honeycomb infill. The yield point difference between the 50% grid condition and the 50% honeycomb condition, about 5.5 MPa lower than the former case, is also not significant. Table 2 summarizes the main results achieved.

Table 2: Compression results summary (averages, n=5).

	Compression Modulus [MPa]	Compression Strength [MPa]	Compression Yield (0.2%) [MPa]	Strain at the peak stress
Concentric 100%	2157.8	151.2	53.0	0.3501
Grid 100%	1754.1	144.8	58.3	0.3624
Grid 50%	869.2	72.3	22.5	0.3247
Honeycomb 50%	653.1	65.1	16.1	0.3542

Figure 3 shows the maximum specific strength values achieved in each configuration. It becomes evident that samples exhibiting the highest specific strength are always those with 100% concentric configuration. By comparing the data gathered from the four studied cases, it emerges that the difference in terms of compression specific strength between the 100% and 50% infill structures is reduced as compared to the results obtained by Figure 2, in which the stress levels were evaluated without considering the density of the 3D printed specimens. This suggests that the advantage in terms of strength with doubling the infill is mitigated by the structure's weight. Specifically, cylindrical specimens with 50% honeycomb infill exhibit a reduction in specific stress compared to concentric cylinders of 37.4%.

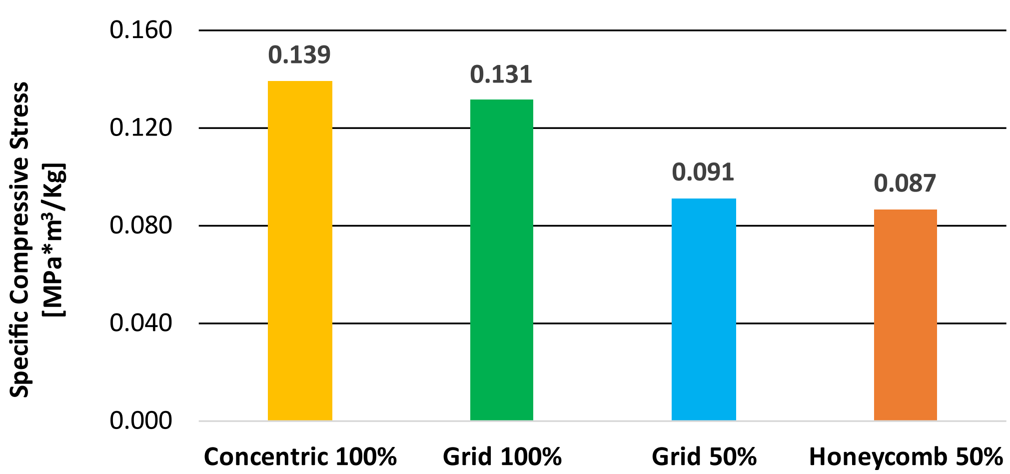

Figure 3: Effect of the infill percentage and pattern on maximum specific strength of 3D printed specimens in polyamide PA6 reinforced with 20% short glass fiber and 10% short carbon fibers.

Similarly to the results shown in Figure 2, there are no substantial differences in specific strength between the two 100% infill structures. Furthermore, the comparison between specimens with 50% grid infill and 50% honeycomb infill shows that a negligible difference in specific strength appears.

Conclusions

In this paper, the effect of different infill percentages and patterns on the compression behaviour of cylindrical specimens produced in Polyamide PA6 reinforced with 20% glass fibers and 10% carbon fibers, printed using the Fused Deposition Modeling technology, was investigated. Different infill percentages, equal to 100% and 50%, and patterns (grid, concentric, and honeycomb) were chosen.

The main results can be summarized as follows:

- The nominal compression stress-strain curves are significantly affected by the infill percentages, in particular in terms of strength level.
- The difference in specific strength between the 100% and 50% infill structures is less marked.
- The 100% concentric configuration demonstrates the highest specific compression strength. Among the 100% infill configurations, no substantial differences emerge in maximum compression strength. However, a reduction of approximately 19% in the compression modulus is observed between the 100% grid and 100% concentric specimens, with a higher peak deformation observed in the grid configuration.
- The 50% infill configuration shows high variability in mechanical properties depending on the infill geometry.
- Among the 50% infill configurations, the grid pattern exhibits the highest compression strength and a superior modulus. Maximum deformation is observed in the 50% honeycomb configuration, with a value only slightly lower than that of the 100% grid samples.

This study provides a deep understanding of the relationships between infill geometries and mechanical performances, crucial for optimizing the utilization of 3D printed composites in different industrial applications. Further research should focus on advanced characterization of mechanical properties and process parameter optimization to further enhance the performance of these composites in additive manufacturing. Nevertheless, the results offer valuable insights for optimizing the production of 3D printed components for various industrial applications.

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