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A REVIEW OF 3D PRINTED CARBON FIBER REINFORCED PLA COMPOSITES IN FUSED FILAMENT FABRICATION

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Abstract. *Additive manufacturing (AM) has evolved significantly and expanded its use in a wide range of applications over the past few decades. Fused filament fabrication (FFF), which is based on filament extrusion, is a widely used AM process technique, especially when it comes to polymers. One of the methods to overcome the limitations and specially increase the mechanical properties of thermoplastic printed parts in FFF is the use of short and continuous fiber reinforced polymer composites (CFPRCs), especially carbon fibers. Research in this area is mainly based on the examination of mechanical and other properties, as well as influential factors, on printed parts made of these composites. Printing parameters are particularly interesting influential parameters and thus are most often examined. This paper will provide an overview and results of available research related to the use of short and continuous carbon fiber reinforced polylactic acid (PLA) composites (CFRPLAC) in the FFF technique.*

Key words: *FFF, Carbon fiber, PLA, CFRPLA composites*

1.INTRODUCTION

The term "additive manufacturing (AM)" refers to various technologies in which a three-dimensional object is built from a computer-aided design (CAD) model, usually by successively adding material layer by layer. AM enables the production of parts that have complex geometry and that are either very hard or impossible to produce with traditional production processes.

Fused filament fabrication (FFF), also known as fused deposition modeling (FDM™), is an extrusion-based AM technology that uses filament as the row material. In the FFF technology, the part is produced by selective disposal of the molten material on the building platform through the nozzle, layer by layer, according to the path defined on the basis of the loaded CAD model.

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It is one of the most widely used AM technologies, especially when it comes to polymeric materials. This is primarily due to the low cost, ease of use, and large number of commercially available materials. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most common polymers used in FFF printers.

Polylactic acid (PLA) is a thermoplastic biobased, biodegradable, and biocompatible polymer that is derived from renewable resources such as corn starch or sugar cane. PLA extrusion temperatures range from 180 to 230°C, tensile strength from 37 to 65 MPa, Young's modulus from 2.3-3.5 GPa, and flexural strength from 52-115.1 MPa [1, 2, 3], [4]. PLA has a relatively low glass transition temperature and deforms quickly under heat, making it unsuitable for high-temperature applications. It is also hygroscopic, i.e., it tends to absorb moisture from the air, making it difficult to print in humid conditions.

Pure thermoplastics, such as PLA, have limitations in terms of low strength and stiffness, as well as becoming soft at high temperatures. In addition, the mechanical properties of printed parts are weaker than those of parts made with other manufacturing methods (e. g. injection molding). One way to improve the properties of printed parts made of PLA (and other pure thermoplastic materials) is by adding reinforcement to the polymer and forming suitable composites. Different types of reinforcement materials are used in composite filaments. Depending on the types of reinforcement, we distinguish between *particulate composites, fiber composite filaments,* and *nanocomposites*. This review paper aims to summarize the available published research involving the use of carbon fiber reinforced PLA (CFRPLA) composites for the printing of parts using the FFF technology.

2. FIBER REINFORCED POLYMER COMPOSITES

In fiber reinforced polymer composites, natural or synthetic fibers are mixed as reinforcements in the polymeric matrix, Fig. 1.

Fig. 1 Fiber reinforced polymer composites (FRPCs)

The most used fibers are carbon and glass [5, 6]. The purpose of using fiber composites is to increase the possibility of applying FFF in various fields by improving the mechanical, thermal, and electrical properties and biocompatibility of printed parts. Fiber reinforced polymer composites (FRPCs) are known as high-performance composite materials that offer a high strength-to-weight ratio and excellent properties, such as high durability [7-10].

The properties of these composites depend primarily on the properties of the fibers and the polymer matrix, the interfacial bond between the fibers and the matrix, the void content, the fiber volume fraction, the alignment of the fibers, the relative fiber content, and the direction of the carbon fiber. No less important is the influence of printing parameters such as layer height, extrusion width, printing temperature, building orientation, raster angle, printing speed, pattern infill, etc.

Reinforcing fibers in composite materials can be in the form of short (discontinuous or chopped) fibers or continuous fibers. Accordingly, fiber reinforced composites can be divided into short fiber reinforced composites (length of fibers < 1 mm) and continuous fiber reinforced composites (l > 50 mm) based on the length [11], Fig. 2.

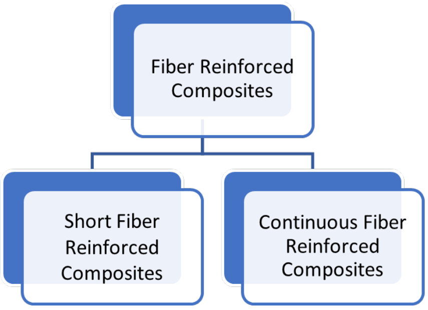

Fig. 2 Types of fiber reinforced composite filaments

The fiber aspect ratio (length/diameter = l/d) is often used as a measurement of the relative length of the fiber. The fiber length is much larger than its diameter. Continuous fibers have long aspect ratios, while discontinuous fibers have short aspect ratios [12]. Continuous fiber composites have a preferred orientation, while short fibers have a random orientation, Fig. 3.

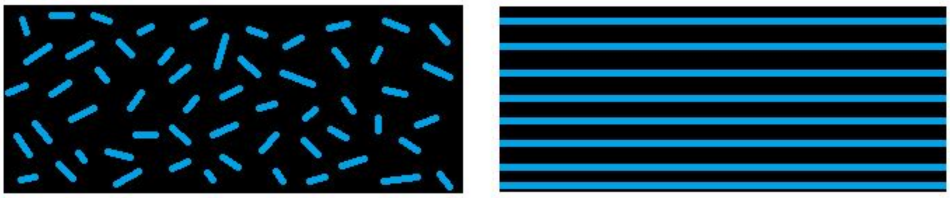

Fig. 3 Short fiber composites (left), continuous fiber composites (right)

3. CARBON FIBERS AS REINFORCEMENTS

Carbon fibers are of great importance as reinforcements, because they have many advantages, such as high tensile strength, low weight, high stiffness, high-temperature tolerance, and high chemical resistance. Carbon fiber reinforced polymer composites (CFRP) have significant advantages over metals in several important properties: they are lightweight, resistant to corrosion and fatigue, and have high rigidity and strength. Thus, a combination of carbon fiber and thermoplastic can increase the thermal stability of the work and reduce warping during printing. Carbon fibers allow printed models to withstand high temperatures and prevent model deformation. Many studies have shown that fibers with standard and medium modulus show the best performance because the tensile strength of fibers with these modules is the highest. Many researchers have examined and published the results of the influence of different parameters of the printing process on the mechanical properties of carbon fiber reinforced composites to achieve the best performance of printed parts [13-20, 6, 21]. It has been shown that by changing the process parameters for the same material and the printer, the mechanical characteristics of the manufactured parts vary significantly. Fiber properties, length, CF content, volume fraction, and fiber orientation also play an important role in the tensile and impact properties of printed parts [22-24]. The carbon fiber filament usually contains 5-35% carbon fiber.

Due to the properties and superior structural characteristics in relation to metals and their alloys, the use of CFRP in the aerospace, defense, and automotive industries is significant.

3.1 Production of 3D printed Carbon Fiber Reinforced Composites

As was previously mentioned, a short fiber reinforced polymer (SCFRP) composite is a mixture of polymer matrix and short fibers. Typically, polymers and short carbon fibers are blended first in a blender and then extruded in an extruder to obtain filament. This filament is then used in a standard FFF printer. This process is simple, and there is no need for the modification of a commercial 3D printer.

Continuous fiber reinforced PLA composites have been widely used in the automobile, aircraft, and space industry because of their lightweight, high specific strength, and modulus compared to metals and alloys. Production of 3D printed continuous carbon fiber reinforced PLA (continuous CFRPLA) (as well as other composites) can be summarized mainly by the following approaches: in-nozzle impregnation of fiber and dual nozzle extrusion of a matrix and fibers [25-28], (Fig. 4). Additionally, significant modifications must be incorporated into the extruding head.

In the first approach, the matrix (thermoplastic filament) and the fibers (in this case, carbon fiber) are supplied separately to the printing head. CF fibers are preheated before entering the nozzle, and the thermoplastic filament is melted above its melting point by the heater inside the printer head. Then they are impregnated in the nozzle forming a reinforced thermoplastic filament which is then extruded through a nozzle and deposed onto the printing bed.

In the case of the two nozzles process, i.e., ex situ prepreg (pre-impregnation composite filament), one nozzle prints the thermoplastic, and the other prints the continuous fiber [29-32]. This approach consists of two separate phases. The first phase is the production of the pre-impregnated filament by means of a separate extrusion system by joining thermoplastics and fibers. In the next phase, the filament made in this way is rolled into a spool and enters the printing process. This approach requires special printers like those produced by Markforged (Massachusetts, USA). MarkOne was the first commercially available 3D printer in the world that produced pre-impregnated continuous fiber reinforced composites with two print nozzles in a print head. One nozzle prints the thermoplastic filament, and the other prints the pre-impregnation composites filament.

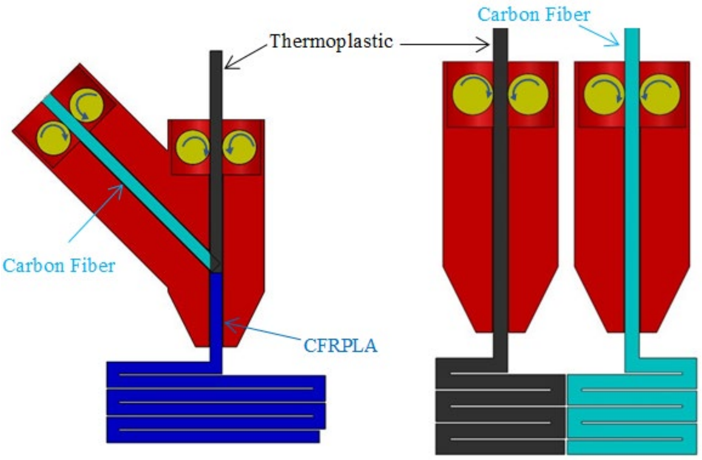

Fig. 4 In-nozzle impregnation of fibers (left), dual nozzle extrusion of matrix and fibers (right)

4. CARBON FIBER REINFORCED PLA COMPOSITES - CFRPLA

PLA, as a material that is widely used for 3D printing, primarily due to the ease of printing, biodegradability, and being an environmentally friendly filament, has disadvantages such as low heat resistance, lower tensile strength, compared to other thermoplastics, and being hygroscopic. Having in mind the good characteristics of carbon fibers, one of the ways to improve the disadvantages of PLA is to reinforce them with carbon fibers and to make appropriate PLA reinforced carbon fiber composite filaments.

Many researchers have published papers in which they analyzed the possibilities of production and determining the properties of short or continuous CFRPLA composites, as well as examining which factors have a significant influence on the characteristics and quality of CFRPLA printed parts [6, 13-15, 20, 21, 33-36]. Many pointed out the advantages and disadvantages of different approaches and selection of important parameters, and some of them gave suggestions for improving the observed shortcomings. In this paper, we will discuss the conclusions reached in these published studies.

4.1 Literature review of short CFRPLA

Within the literature related to the CFRPLA research with short carbon fibers, the influence of certain printing parameters on the mechanical properties of printed CFRPLA parts was mainly investigated [6, 20, 21]. Fig. 5 shows the most frequently investigated printing parameters.

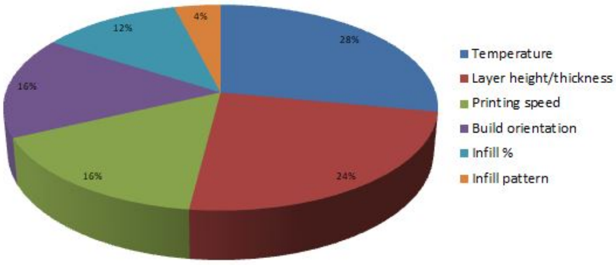

Fig. 5 Most frequently investigated printing parameters for short CFRPLA

Ding et al. [20] analyzed the influence of build orientations on mechanical and frictional properties, and the effect of printing temperature, printing speed, and layer thickness on the mechanical properties of CFRPLA parts printed on the U-print machine A8. It turned out that X-build-oriented samples showed the best mechanical properties and those printing parameters had a significant impact on the mechanical properties of Y and Z-oriented samples but not on X-oriented samples. It was also shown that the orientation of carbon fibers in the direction of deposition gives the best strength values. Ferreira et al. [34] investigated a CFRPLA filament and compared it to a standard PLA filament, both printed on BQ Prusa i3 Hephestos. They found a decrease in the tensile strength in CFRPLA compared to PLA samples from 54.7 MPa for PLA to 53.4 MPa for CFRPLA. On the contrary, the tensile modulus increased in CFRPLA to 7.5 GPa compared to PLA where the tensile modulus was found to be 3.3 GPa. The problem confirmed here is a problem that has been observed in other studies related to CFRPLA with short carbon fibers and that is poor adhesion between PLA and CF, causing short carbon fibers to not improve the mechanical properties of CFRPLA composite parts.

Rao et al. [6] tested the impact at the 3 levels of layer thickness, printing temperature, and infill pattern on the tensile strength of CFRPLA. This involved testing the impact of 3 different values for the layer thickness (0.1, 0.2, and 0.3mm), 3 different infill patterns (Cubic, Cubic subdivision, and Quarter cubic), and 3 temperatures (205, 215 and 225°C). The results showed that the interaction between the layer thickness and the infill as well as the interaction between the filling pattern and the extrusion temperature had a considerable effect on the tensile strength of printed parts. It was shown individually that layer thickness has the greatest and most significant impact on the value of the strength of printed parts. The lowest value of the layer thickness (0.1 mm) gave the highest value of the tensile strength. The best results for tensile strength (26.59 MPa) were obtained for a printing temperature of 225°C, the layer thickness of 0.1 mm, and a cubic infill pattern.

The effect of building direction, infill percentage and layer thickness on the tensile and impact strength of CFRPLA printed parts with chopped CFs was also the subject of interest of Kamaal et al. [21]. They tested the influence of different infill percentages (20, 50 and 80%), building direction (x, y, z) and layer thickness (0.2, 0.25 and 0.3mm) on mechanical properties of printed CFRPLA parts. The influence of building orientation and infill percentage proved to be more significant than the influence of layer thickness on the values of tensile strength of printed samples. The Z building direction showed the worst results. As the layer thickness and infill percentage increase, the tensile strength also increases. The recommendation for optimal results of tensile strength according to their results would be the direction of X construction, the layer thickness of 0.25 mm, and the infill percentage of 80%.

In addition to standard printing parameters, Calles et al. [37] also examined the influence of the number of parameters. They found that the number of parameters has the greatest influence on the tensile strength and that with increasing its value, the tensile strength also increases. On the other hand, reinforced PLA with short carbon fibers did not show better mechanical properties.

A comparative analysis of the creep behavior of PLA and CFRPLA samples made by the FFF technology (at three different printing orientations and three different layer thicknesses, under different stresses) was presented in the paper by Tezel et al. [38]. Again, poor adhesion between PLA layers in CFRPLA caused the creep strength of the PLA to be higher than that of CFRPLA with all values of layer thicknesses. For higher stresses, the influence of layer thickness and orientation on CFRPLA creep properties is greater. The best creep strength values were obtained with samples with a printing orientation of 90°. The results obtained indicate the need for additional research on creep properties for different materials and under different conditions to establish a reliable conclusion.

Another study on the effect of short carbon fiber reinforcement of the PLA matrix and post-printing annealing procedure (at temperatures of 30, 60, and 90°C above the glass transition temperature) on the mechanical properties of parts printed on an open-source 3D printer (RoVa3D 5 Extruder MEAM 3D) was the subject of research in Ivey at al. [39]. They concluded that CFRPLA samples have higher values of elastic modulus than PLA samples. Annealing of the PLA and CFRPLA prints increased crystallinity, up to 30%, but did not increase the modulus of the same material. The ultimate strength did not change significantly by annealing, nor was there a significant difference between PLA and CFRPLA, while the ultimate strain was slightly higher in PLA than in CFRPLA but without a significant effect of annealing on these values. Microstructural analysis showed the existence of larger voids in the CFRPLA printed parts.

A comparative analysis of the influence of build orientation on tensile and flexural strength and interlaminar shear strength of CFRPLA and PLA samples, as well as the effect of carbon fiber reinforcement, was conducted in Reverte et al. [40]. The flat CFRPLA samples showed the best values of modulus of the tensile strength (73.5 MPa), flexural strength (105.5Mpa) and stiffness compared to PLA and other build orientations, but lower strain than the PLA specimens (Table 1).

The authors in Guduru et al. [41] examined the effect of post-processing (heat treatment and chemical treatment) on printed CFRPLA samples. Chemical treatment showed better results, that is, an increase in tensile strength from 70 to 80 MPa, while heat treatment gave an increase of only 6% (74 MPa).

Table 1 Literature regarding short CFRPLA composites

Paper	Material	Machine	Input parameters	Output parameters
Overview and results				
Ding et al. (2020) [20]	20% CF	U-print machine A8	***Temperature*** 190, 200, 210, 220, 230°C ***Layer thickness*** 0.1, 0.2, 0.3, 0.6, 0.7, 0.8 mm ***Printing speed*** 20, 30, 40, 50 mm/s	Tensile properties Impact strength Elongation at break Friction Wear

Effect of build orientations on mechanical and frictional properties and effect of printing parameters on mechanical properties of CFRPLA parts. The X-build-orientation specimen showed the best mechanical properties. Carbon fiber orientation, print orientation of specimens, bonding strength, and density of specimens effect mechanical properties of printed parts.				
Ferreira et al. (2017) [34]	15% CF	BQ Prusa i3 Hephesto	***Nozzle extrusion temperature*** 190°C, ***Heat bed temperature*** 70°C ***Layer thickness*** 0.3 mm, ***Printing speed*** 3000 mm/min ***Raster angle***: specially oriented specimens printed at 0, 90 and ± 45° ***Infill pattern*** rectilinear	Tensile properties In-plane shear Shear properties Poisson ratios
Mechanical properties and micrography of 3D printed PLA and short CFRPLA. The tensile modulus in the deposition direction for CFRPLA was more than two times higher than in PLA (3.37 GPa vs 7.54GPa). Short CFs give the greatest increase in the stiffness of CFRPLA in the printing direction. Poor adhesion between PLA and CF causes that short CF did not change the mechanical properties of CFRPLA compared to pure PLA (tensile strength for 0°: 53.4 MPa vs 54.7 MPa)				
Ivey et al. (2017) [39]	15% CF	RoVa3D 5	***Nozzle temperature*** 200°C ***Bed temperature*** 85°C ***Print speed first layer*** 30 mm/s ***Layer height*** 0.1 mm ***Infill percentage*** 100% ***Infill pattern*** 90° ***Infill pattern*** rectilinear Infill was printed by alternating 0° and 90° layers	Tensile properties Microstructural analysis Dimensional accuracy
The mechanical properties of printed parts made from PLA and short CFRPLA material were analyzed, as well as the effect of applying a post-printing annealing procedure on the mechanical properties of the same parts. CFRPLA samples have higher values of elastic modulus than PLA samples. Annealing of both materials increased crystallinity, up to 30%, but did not increase the modulus of the same material.				
Rao et al. (2019) [6]	/	DRONA C300D	***Layer Thickness*** 0.1, 0.2, 0.3 mm ***Infill Pattern*** cubic, cubic sub division, quarter cubic ***Temperature*** 205, 215, 225°C	Tensile properties
Effect of printing parameters on mechanical properties of CFRPLA. Analysis of variance (ANOVA) was performed. The results showed that layer thickness has the greatest impact on strength. The interaction between the layer thickness and the infill, as well as the interaction between the infill pattern and the extrusion temperature, has a significant effect on the tensile strength.				
Tezel et al. (2019) [38]	15% CF	Zmorph	***Temperature*** 195°C ***Printing bed temperature*** 65°C	Creep behavior Deformation curves

<table>
<tr><td></td><td></td><td></td><td><i>Printing speed</i> 40 mm/s</td><td></td></tr>
<tr><td colspan="5">Determination of creep behavior of 3D printed PLA and CFRPLA parts at three different printing orientations and three different layer thicknesses, under different stresses, and to set up time-dependent deformation curves using different printing parameters.
The creep strength of the PLA is higher than that of the CFRPLA with all values of layer thicknesses. With increasing layer thickness, the creep resistance increases with CFRPLA and decreases with PLA.
For higher values of stresses, the influence of layer thickness and orientation on CFRPLA creep properties is greater. Samples with a 90° printing orientation had the best creep strength values.</td></tr>
<tr><td>Kamaal et al (2021) [21]</td><td>5.5% CF</td><td>Ypanx Falcon 3D printer</td><td><i>Infill percentage</i> 20, 50, 80%
<i>Layer height</i> 0.2, 0.25, 0.3 mm
<i>Build orientation</i> x, y, z
<i>Temperature</i>: 210°C
<i>Printing speed</i> 60 mm/s</td><td>Tensile strength,
Impact strength,
TOPSIS analysis</td></tr>
<tr><td colspan="5">Effect of printing parameters on mechanical properties. Tensile strength increases with the increase in the layer height and infill percentage. Layer thickness has the smallest effect on strength in contrast to build orientation and infill percentage. Recommendation from TOPSIS and experimental results for good results of tensile strength: 80% infill, 0.2 mm layer height, and X building direction.</td></tr>
<tr><td>Guduru et al. (2020) [41]</td><td>15% CF</td><td>/</td><td><i>Printing temperature</i> 220°C
<i>Orientations</i> 90°
<i>Layer thickness</i> 0.2 mm</td><td>Tensile strength</td></tr>
<tr><td colspan="5">Influence of post processing treatment (chemical and heat treatment) on the mechanical properties of CFRPLA. Post treatments were chemical treatment (acetone of 100% concentration), and heat treatment process (heated 80, 100, 120, 140 and 160°C).
Starting tensile strength of CFRPLA was 70 MPa. The chemical treatment method gave a better result (80 MPa tensile strength) than the heat treatment method (74 MPa tensile).</td></tr>
<tr><td>Calles et al. (2021) [37]</td><td>15% CF</td><td>3D BIBO 2 Touch Dual Extruders</td><td><i>Infill density</i> 60, 80, 100%
<i>Infill pattern</i> grid, octa and triangular
<i>Layer height</i> 0.2 mm
<i>Printing speed</i> 60 mm/s
<i>Bed temperature</i> 60ºC
<i>Printing temperature</i> of 250ºC for CFRPLA</td><td>Tensile strength</td></tr>
<tr><td colspan="5">The influence of the printing parameters on the tensile strength of PLA and CFRPLA was analyzed.
The use of short carbon fiber reinforcements in PLA did not improve the mechanical strength of the tested samples.</td></tr>
<tr><td>Reverte et al. (2020) [40]</td><td>/</td><td>Ultimaker 2+ desktop 3D printer</td><td><i>Printing temperature</i> 210ºC
<i>Print speed</i> 50 mm/s
<i>Layer height</i> 0.16 mm
<i>Infill pattern</i> concentric
<i>Infill density</i> 100%
<i>Orientation</i> flat on the edge and up right</td><td>Tensile strength
Flexural strength
Stiffness
Interlaminar Shear Strength</td></tr>
<tr><td colspan="5">Effect of CF reinforcement and build orientation on the mechanical properties of CFRPLA and PLA samples. Mechanical properties depended significantly on the build orientation. On-edge and flat orientations showed the highest values for tensile strengths, flexural strengths, and stiffness</td></tr>
</table>

and up-right orientation showed the lowest. The tensile strength and tensile modulus of the flat CFRPLA composite increased by 47.1% and 179.9%, respectively.				
Magri et al (2019) [42]	15% CF	INTAMSYS (Intelligent additive manufacturing systems) FunMAT HT	***Nozzle temperature*** 190, 200, 210, 220, 230, 240ºC ***Bed temperature*** 40ºC ***Layer height*** 0.10 mm ***Print speed*** 20 mm/s ***Infill density*** 100 % ***Nozzle(printing) temperature*** 230ºC	Tensile strength Young modulus
Influence of printing temperature and infill line orientations on CFRPLA parts. Six combinations of infill line directions were selected. For each combination, 5 samples were prepared. Infill line orientations and the annealing conditions can have a significant influence on the properties of the printed specimens. For PLA and CFRPLA, the optimal nozzle temperature was 230ºC. A large increase in tensile strength and Young's modulus was achieved in the base orientation for the orientation of the combination [0/15/ 15], both for PLA and CFRPLA. PLA tensile strength - 43.83 MPa. CFRPLA tensile strength - 36.38 MPa. The tensile strength of CFRPLA was the lowest for 0º /90º. Tensile strength for 0° - 30.11 MPa, and for 90° - 28.25 MPa.				

4.2 Literature review on continuous CFRPLA

The research on continuous CFRPLA can be categorized into two groups: research of new technologies for the production and 3D printing of CFRPLA [15, 16, 18, 33, 35, 36, 43-47], and research that studies the influence of printing parameters on some mechanical properties [13-19]. Researchers in the first group aimed to validate their 3D printing techniques by analyzing some mechanical properties of printed CFRPLA samples.

The most frequently analyzed properties (from both groups) are shown in Fig. 6. It can be noticed that most of the research is based on the examination of flexural and tensile properties, followed by morphological analysis (morphological analysis regards the analysis of voids, micro cracks, fusion quality between PLA and fibers, and other imperfections occurred during the creation of composite materials).

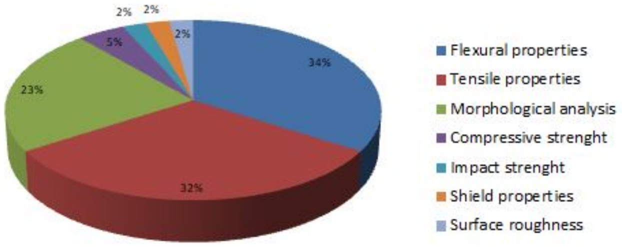

Fig. 6 Most often studied parameters of CFRPLA

All reviewed literature on the topic of continuous CFRPLA is listed in Table 2. The percentage of carbon fiber in CFRPLA (% of CF) is also displayed, as it is one of the most important characteristics of these composites. The tensile and flexural strengths that the authors of the papers managed to achieve with the composites used are also shown, because of the frequency with which they appear in many studies. Based on Table 2, it can be noticed that the percentage of CF can vary greatly. Even for similar or the same percentages, very different tensile and flexural strengths can be achieved. For example, Li et al. [48] achieved a tensile strength of 106.3 MPa with 15% CF, but Luo et al. [16] achieved only 75.51 MPa with the same percentage of carbon fiber. On the other hand, Tian et al. [45] got to a tensile strength of 256 MPa (which is 2.5x and 3.4x higher than Luo et al. [16] and Li et al. [48], respectively), but only used 8.9% of CF in the CFRPLA composite. This can be explained by acknowledging that the quality of CFRPLA printed samples is dependent not only on the percentage of CF, but also on other factors, such as the technology with which they have been produced, printing parameters used, the type of carbon fiber used, the orientation of carbon fibers, the manufacturer of the material, etc.

Table 2 Summary of the results of tensile and flexural strength analysis of the papers that deal with continuous CFRPLA

Paper	% of CF	Tensile strength (MPa)	Flexural strength (MPa)
[13] Babu et al. (2021)	/	25.42	60
[33] Chaudhry et al. (2019)	1.7	112	164
[35] Heidari-Rarani et al. (2019)	28.2	61.4	152.1
[14] Hu et al. (2018)	25	/	610
[48] Li et al. {2019}	1, 3, 5, 7, 10, 15	43.8, 62.1, 73.5, 82.6, 93.7, 106.3	/
[36] Li et al. (2016)	34	91	156
[15] Liu et al. (2018)	42.15, 43.32, 47.76, 51.92	/	/
[43] Luan et al. (2019)	/	/	/
[16] Luo et al. (2019)	0, 5, 10, 15, 20, 25, 30, 35, 40	36.89, 51.22, 65.54, 75.51, 80.38, 94.44, 107.02, 116.06, 143.11	/
[28] Matsuzaki et al. (2016)	6.6	185.2	133
[44] Qiao et al. (2019)	5	164	174.4
[49] Shang et al. (2020)	15	35.8	/
[45] Tian et al. (2016)	8.9	256	263
[17] Tian et al. (2016)	27	/	335
[46] Yao et al. (2017)	/	32.57	68.21
[18] Yin et al. (2019)	9.62	111	152.9
[50] Zeng et al. (2021)	/	/	/

[47] Zhang et al. (2020)	10.30	644.8	401.29
[51] Zhang et al. (2021)	5.9	190.1	142.7
[27] Namiki et al. (2014)	1	90	/
[10] Li et al. (2022)	/	/	/
[52] Valvez et al. (2020	/	/	/
[53] Maqsood et al. (2021)	18.2	245.4	168.88
[19] Dou et al. (2020)	22.7	243.53	/
[54] Li et al. (2021)	29.47	/	294.48
[55] Rimašauskas et al. (2019)	10	165	/
[56] Shen et al. (2019)	7.26	118.05	/

When analyzing the first group of research (development of novel preparation and 3D printing techniques of continuous CFRPLA), the majority stick to the techniques previously explained, but there are other approaches. For example, Zhang et al. (2020) [47] presented a novel 3D printing model, by using a pressure roller to pressurize and heat the model. Tensile strength was increased to 644.8 MPa and bending strength to 401.24 MPa, from starting points of 109.9 MPa and 163.13 MPa, respectively. Li et al. [36] managed to use three-dimensional rapid prototyping for continuous CFRPLA printing. They achieved a tensile strength of 91 MPa and a flexural strength of 156 MPa, which is a 225% and 194.3% improvement from the original PLA material. Heidari-Rarani et al. [35] designed an innovative extruder for FFF 3D printing that is also used to produce continuous CFRPLA. This extruder can be mounted on available FFF 3D printers without the need for a new chassis. Through validation experiments, the authors showed that their design printed continuous CFRPLA that achieved 36.8 % better tensile strength than pure PLA, as well as 109% better maximum bending strength. Chaudhry et al. [33] drilled a 1 mm hole on the side of a nozzle, at a 45° angle, through which a carbon fiber thread was inserted. This solved many previously uncovered challenges they had regarding printing the continuous CFRPLA. The authors achieved 112 MPa tensile strength and 164 MPa flexural strength in their continuous CFRPLA printed specimens.

Considering the works from the second group (influence of printing parameters on mechanical properties), it can be concluded that the most frequently investigated printing parameters are layer height/thickness, infill density, fill pattern, printing temperature, printing speed and % of CF in CFRPLA.

Babu et al. [13] concluded that *tensile and flexural strength increase as layer thickness/height increases*. According to them, when the layers are higher/thicker, there is more material in one layer. Consequently, more material needs more time to cool down. When the next layer prints, layers with a higher layer height will have higher temperatures in comparison to layers with smaller layer heights. This results in better adhesion of two consecutive printed layers when the layer thickness is higher. However, this conclusion is contradictory to the other research (Hu et al. [14], Tian et al. [17], Dou et al. [19]). In their experiments, the values of *the flexural and tensile strength showed a tendency to increase* *with a reduction in layer thickness/height.* With a smaller layer height, there is less area between the printing nozzle and printing bed, which means that the material must be extruded in a tighter space. Due to this, there is more contact pressure between the nozzle and the extruded material. This pressure results in better bonding of extruded lines of the material, which improves mechanical properties (Tian et al. [17]). There is also a smaller air gap between consecutive layers and the percentage of CF in CFRPLA is much higher with decreasing layer thickness/height, which also contributes to better mechanical properties (Hu et al. [14]).

With an increase in infill percentage, the tensile and flexural strength increase (Babu et al. [13]). This is because, by reducing the infill percentage, more voids are created in the material, which become stress concentration areas. In these areas, the cracks in the material start and spread under increasing loads (Babu et al. [13]). In addition, more infill percentage provides a better bending strength.

Regarding the infill pattern, the h*exagonal pattern showed the best results regarding tensile strength* (Babu et al. [13]). The honeycomb structure of this pattern turned out to be strong, occupied a large space, and did not buckle easily when bending. On the other hand, Luo et al. [16] used the *spiral offset pattern* as the best suited pattern for printing continuous CFRPLA. As it has only one jump point (the point where the extrusion of the filament is stopped, the nozzle goes to the slightly higher Z axis value, moves to the correct position, goes down along the Z axis and resumes the extrusion of the filament) in the nozzle path during printing. In addition, the filling direction is along the central axis of the specimen, which is better for the tensile properties of the specimen.

With an increase in the printing temperature, the flexural and tensile strength increases. Tian et al. [17], Dou et al. [19], and Hu et al. [14] concluded that the printing temperature has a minor effect on the flexural strength. This can also be caused by a very small temperature measurement range (200, 215, 230°C). Tian et al. [17] concluded that the flexural strength shows good values at temperatures up to 240°C. At higher temperatures, the surface accuracy is lost during printing, because then the PLA is almost in a liquid state, so it flows out of the printing nozzle. Additionally, printing should not be done at temperatures below 180°C, as it is very difficult to extrude the composite when printing below 180°C due to its low flow rate.

With an increase in printing speed, the flexural strength decreases slightly (Hu et al. [14]). As the filament spends less time in the heated extruder head, the adhesion between PLA and CF is worse. The influence of printing speed on flexural strength is not significant, but it exists. Hu et al. [14] and Tian et al. [17] explained that the influence of printing speed on flexural strength is insignificant because, while reducing the impregnation period and the pressure on filament during printing (both of which should result in the worst flexural strength), it increases the overall fiber percentage in CFRPLA, which results in better flexural strength. When these two contradictory properties are combined, they result in an almost neutral influence of printing speed on flexural strength. Dou et al. [19] came to a similar conclusion that the printing speed very slightly affects the tensile strength, due to the less compressive forces in the printer nozzle that are caused by the lower extrusion speed due to the lower printing speed.

Other literature regarding continuous CFRPLA is displayed in Table 3, along with machines used, percentage of CF in CFRPLA, input parameters (regard printing parameters used in the research), output parameters (regard measured properties of 3D printed specimens), results and category which they are a part of.

Table 3 Literature regarding continuous CFRPLA composites

Paper	Material	Machine	Input parameters	Output parameters
Overview and results				
Babu et al. (2021) [13]	/	Raise 3D V2 N2	***Layer heights/thickness*** 0.08, 0.25, 0.64 mm ***Infill densities*** 20, 40, 60, 80% ***Layer patterns*** rectangular, triangular, hexagonal	Tensile properties Flexural properties Interlaminar shear strength Surface roughness
Parameter influence The combination of layer height of 0.64 mm and infill density of 60% produced best results.				
Chaudhry et al. (2019) [33]	/	ANET A-8M (modified extrusion head)	***Number of reinforced layers*** ***Material impact*** ***Interlayer gap***	Tensile properties Flexural properties
New technology, parameter influence The carbon fiber thread was passed through a 1 mm hole at a 45° angle, which resolved problems with CFRPLA printing.				
Heidari-Rarani et al. (2019) [35]	28.2 % CF	Custom 3D printer	/	Tensile properties Flexural properties Morphological analysis
New technology Tensile modulus of elasticity increased 208% Ultimate tensile strength increased 36% Failure strain decreased 62% Bending modulus improved 367% Maximum bending strength improved 109%				
Hu et al. (2018) [14]	/	Mendel (modified extrusion head)	***Printing temperature*** 200, 215, 230°C ***Printing speed*** 60, 90, 120 mm/min ***Layer thickness*** 0.6, 0.9, 1.2 mm	Flexural properties Morphological analysis
Parameter influence The printing temperature has a minor influence on the flexural strength. Decrease in printing speed = small increase in flexural strength. Higher temperature and lower printing speed = better bonding between PLA and CF. Smaller layer thickness = higher flexural strength				
Li et al. (2019) [47]	Different CF %	Custom 3D printer (same as ref [45], [16])	***Percentage of CF*** 1, 3, 5, 7, 10, 15%	Tensile properties
Parameter influence Influence of CF percentage in CFRPLA. PLA tensile strength = 38.2 MPa CFRPLA (1%) tensile strength = 43.8 MPa CFRPLA (3%) tensile strength = 62.1 MPa CFRPLA (5%) tensile strength = 73.5 MPa CFRPLA (7%) tensile strength = 82.6 MPa CFRPLA (10%) tensile strength = 93.7 MPa				

CFRPLA (15%) tensile strength = 106.3 MPa				
Li et al. (2016) [36]	34% CF	Custom 3D printer	/	Tensile properties Flexural properties Dynamic mechanical analyzer Morphology analysis
New technology Comparison of new material created with their printer and other CFRPLA was performed, and 13.6 % improvement in tensile strength, 164% improvement in flexural strength was observed.				
Liu et al. (2018) [15]	Different CF %	Custom 3D printer	***Relative density*** 0.92, 2.17, 4.05, 6.84% ***CF volume content*** 42.15, 43.32, 47.76, 51.92% ***Truss angle*** (30, 35, 40, 45, 50, 55°	Compressive strength Flexural properties Morphology analysis
New technology, parameter influence The free-hanging 3D printing method achieved an average structural error of 1.89% (which was improved from the original results of 19.64%). Compression strength improved by 224% compared to pure thermoplastic parts.				
Luan et al. (2019) [43]	/	Custom 3D printer	/	Deformation
New technology The authors developed a dual-material 3D printing process for CFRPLA printing and integrated monitoring functionalities so that the applied load position can be located, the deformation distribution can be recognized and the damage detected.				
Luo et al. (2019) [16]	Different CF %	Custom 3D printer	***Fill pattern*** mesh, line, and spiral offset filling pattern ***CF volume content*** 0, 5, 10, 15, 20, 25, 30, 35, 40% ***Amount of CF layers*** 0, 5, 10, 15, 20, 25, 30, 35, 40 ***Positioning of the inserted layers*** 10, 10-11, 9-11, 8-12, 7-13, 7-14	Tensile properties Flexural properties Morphology analysis
New technology, parameter influence Technology allows for selective enhancement of different layers of 3D printing parts. With 40 % of CF in CFRPLA, tensile strength was increased by 287.9%.				
Matsuzaki et al. (2016) [28]	6.6 % CF	Blade-1 (modified)	/	Tensile properties Young's modulus Morphology analysis
New technology Nozzle design, which combines CF and PLA inside it. Tensile strength of CFRPLA specimen was 435% improved compared to PLA specimens.				
Qiao et al. (2019) [44]	5% CF	Custom 3D printer	***Amplitude*** 0, 30, 40, 50, 60 µm ***Resin solution concentration*** 0, 5, 10, 15%	Tensile properties Flexural properties Morphology analysis

			Treatment speed 5, 15, 25, 35 mm/s	
New technology, parameter influence Ultrasound assisted 3D printer was developed for printing CFRPLA. Ultrasounds were used for better bonding of materials. Tensile strength of CFRPLA improved 34%. Flexural strength of CFRPLA improved 29%. Increase of ultrasonic amplitude can improve surface roughness.				
Shang et al. (2020) [49]	15% CF	Fibertech	***Amplitude*** 0, 4, 5, 6, 7, 8 A/mm ***Frequency*** 0, 0.2, 0.25, 0.3, 0.35, 0.4 ω/Hz	Tensile properties
New technology, parameter influence The sinusoidal path extrusion method for 3D printing was developed. Investigation of the amplitude and frequency on the tensile properties was analyzed. With increasing amplitude and frequency, the tensile strength increased by 95.4%. With increasing amplitude and frequency, the tensile modulus increased by 57.3%.				
Tian et al. (2016) [45]	8.9% CF	Custom 3D printer	/	Tensile properties Flexural properties Impact strength Morphology analysis
New technology The production of fully recyclable CFRPLA material was proposed. The properties of recycled material were tested. The remanufactured CFRPLA specimens exhibited a 25% higher bending strength than the original ones. With 8.9% CF, the recycled specimen had a flexural strength of 263 MPa.				
Tian et al. (2016) [17]	27% CF	Custom 3D printer	***Temperature of liquefier*** 180, 190, 200, 210, 220, 230, 240 °C ***Layer thickness*** 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 mm ***Feed rate of filament*** 60, 80, 100, 120, 140, 160 mm/min ***Hatch spacing*** 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8 mm ***Transverse movement speed*** 100, 200, 300, 400, 500, 600 mm/min	Flexural properties
Parameter influence The influence of the printing parameters on the flexural properties was analyzed, and explanations for the obtained results were given. Recommended temperature range 200-230°C. T<180°C – it was difficult to extrude CFRPLA T>240°C – PLA was almost liquid, and had too much flow Recommended layer thickness range 0.4-0.6 mm Hatch spacing range 1.8-0.4 mm				
Yao et al. (2017) [46]	/	Kossel Rostock Delta D-force	***Filament density*** 20, 40, 60, 100 %	Tensile properties Flexural properties

			Different types of CF 3k, 6k, 12k	
New technology CF was not only used for structural reinforcement, but as a strain sensor as well. Changes of electrical resistance of the fibers, due to deformation, is used as a self-monitoring technique. This is useful for smart structures.				
Yin et al. (2019) [18]	Different CF %	COMBOT-I	***Number of layers*** 2-12 ***Hatch spacing*** 1.6 – 0.8 mm ***Filling angle*** 90° - 0°	Tensile properties, Flexural properties, Shielding properties
New technology Composites whose shielding effectiveness can be controlled were presented as well as the methodology on how was done. Shielding effectiveness was controlled through printing parameters.				
Zhang et al. (2020) [47]	10.30% CF	Custom 3D printer	/	Tensile Properties Flexural properties
New technology The 3D printer with pressure roller was presented, and the influence of the pressure roller on the properties of the printed parts was investigated. The tensile strength and bending strength of the specimens were increased to 644.8 MPa and 401.24 MPa by increasing the pressure, compared to the tensile strength and bending strength of the specimens without a pressure of 109.9 MPa and 163.13 MPa.				
Zhang et al. (2021)[51]	5.9% CF	/	/	Tensile properties Compressive properties, In-plane shear, Interlaminar shear Morphology analysis
An algorithm model for describing the 3D deformation and progressive failure process of composites was presented and validated. The relative error of the model was 8.23%.				
Namiki et al. (2014) [27]	1% CF	Custom 3D printer	/	Tensile properties Morphology analysis
Comparison of the properties of PLA and CFRPLA was performed. The tensile strength of CFRPLA was 90 MPa, compared to 57.1 MPa of PLA.				
Maqsood et al. (2021) [53]	18.2% CF	Modified MeCreator 2 (Geeetech) 3D printer, Prusa i3 MK3S 3D printer	/	Tensile properties Flexural properties Morphology analysis
Comparison of mechanical properties of PLA, PLA with short CF, PLA with continuous CF and short reinforced PLA with continuous CF. Continuous CFRPLA showed the best tensile and flexural properties compared to other composites.				
Dou et al. (2020) [19]	22.7% CF	Modified desktop-level RepRap Kossel 3D printer	***Layer height*** 0.2, 0.25, 0.3, 0.35, 0.4 mm ***Extrusion width*** 0.86, 1.02, 1.18, 1.34, 1.5 mm ***Printing temperature*** 190, 200, 210, 220, 230°C	Tensile properties Morphology analysis

	Printing speed 50, 100, 200, 300, 400 mm/min
Parameter influence The tensile properties of the printed parts gradually decrease with the increase in the layer height and the extrusion width. With the increase in the printing temperature, the tensile properties increase. With increasing printing speed, tensile properties decrease. The pull-out of the continuous fibers is the main failure of 3D printed continuous CFRPLA parts.	

5. CONCLUSION

The use of carbon fiber reinforced PLA (CFRPLA) composites in 3D printing has made a significant contribution to improving the quality of printed parts, but it has also opened new questions and dilemmas that require even more detailed research in this area. There are many factors that to a greater or lesser extent affect the final quality of printed parts of CFRPLA composites. They include both printing parameters and other factors such as fiber length, fiber properties, fiber orientation, CF content, fiber production process, post-processing of printed samples, etc. Certainly, some factors have been shown to have a significant impact on the performance of printed samples, and they are particularly underlined and analyzed in more detail in this paper.

What can first be noticed is that there is much more research related to 3D printed continuous composites than short CFRPLA composites. Building orientation, infill percentage, infill pattern, temperature, and printing speed are the most often analyzed process parameters when it comes to CFRPLA with short carbon fibers, and their influence can be seen in detail in the literature review related to short carbon fibers. The far larger number of works related to continuous CFRPLA compared to short CFRPLA may be explained by the fact that the reinforcements obtained with continuous CFRPLA are much larger than the reinforcements obtained with short CFRPLA, which makes continuous CFRPLA more interesting.

Based on the reviewed research for the 3D printing of continuous CFRPLA composites, it can be concluded that it is important to establish sufficient temperature and pressure, as well as enough time for material impregnation. These three factors are key to producing a reliable composite material. Temperature can be influenced directly, through the printing temperature parameter, that every slicer program has. However, with pressure, the situation is a bit more complicated. Pressure depends on the printing speed, layer height, and other printing parameters, and is more difficult to control. Therefore, many studies deal with the effects that different printing parameters have on the mechanical properties of 3D printed continuous CFRPLA. The other area on which a lot of researchers are focused is new technology creation, in terms of modifying printer heads and nozzles, adding different equipment to existing 3D printers or building new ones. This way, maybe new 3D printing technologies for printing continuous CFRPLA parts can enhance the mechanical properties of those parts, and one would not only be limited to parameter optimization to create materials and parts with satisfactory mechanical properties.

Poor bonding of PLA with carbon fibers, which can affect surface adhesion and mechanical properties of printed parts, has been the subject of research in many studies [31, 36, 57]. Although there have been attempts to overcome this in some studies such as [53, 19, 44], a generally accepted solution to this problem has not yet been found.

From the reviewed literature, some research gaps have been identified, and these gaps are as follows:

- There are not many studies that compare the surface quality of printed samples of PLA and CFRPLA as well as the influence of different factors on the same.
- As the properties of the final samples depend even on the material manufacturer, the color of the filament, and the type of printer, many comparative studies with the same 3D printer and group of tested parameters and materials are needed to draw a general conclusion regarding the influence of individual factors and results.
- Not many experiments have been conducted on this topic regarding the influence that annealing or chemical treatments have on the mechanical properties of the samples, however, annealing has not shown significant effects, while chemical treatment has yielded slightly better results.
- How to connect the influence of a group of parameters and their mutual relation to the properties of CFRPLA parts.

Many questions remain open, and we await the results of some new research. Certainly, one of the important tasks of research in this area is to find a method that will, on a case-by-case basis, propose optimal parameters that will give the best quality of printed parts. Also important is the research in the field of materials and finding ways to improve the quality of existing CFRPLA and other composites as input materials in the FFF process.

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