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Review Article

A review on integration of carbon fiber and polymer matrix composites in 3D printing technology

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ABSTRACT

Three-dimensional (3D) printing applications obtained by combining the lightness, high strength, and durability of carbon fiber with polymer matrix composites provide various industrial advantages. These advantages offer new design and production opportunities for automotive, aviation, space, medical devices, and many other industrial fields. This review article discusses material innovations in 3D printing technology with a focus on the integration of carbon fiber and polymer matrix composites. After examining the current state and future potential of 3D printing technology, the properties and advantages of carbon fiber and polymer matrix composites and the difficulties encountered with their integration into the 3D printing process were examined. In conclusion, this review article comprehensively discusses the current status, advantages, challenges, and future directions on the integration of carbon fiber and polymer matrix composites in 3D printing technology. This article can be an important resource for industry professionals and researchers in materials science and engineering.

1. Introduction

In recent years, additive manufacturing (AM) technologies have been playing an important role in the rapid and cost-effective production of components, especially those with complex geometries [1,2]. Innovations in this field support a wide spectrum of uses, especially from prototype production to end-use parts and offer alternative solutions to traditional production methods [3,4]. AM methods such as Fused Deposition Modeling (FDM) can be used on a wide range of materials, from plastics to metals and ceramics, thus offering new opportunities for industrial designers and engineers [5,6].

However, there are some limitations in the use of these methods. Traditional 3D printing materials generally have limited mechanical properties. This situation creates serious limitations, especially in industrial and structural applications that require high strength, hardness, and wear resistance [7,8]. For example, plastic-based filaments used in typical FDM printing fail rapidly under high loads or harsh environmental conditions [9,10]. In order to expand the application areas of such materials by increasing their strength performance, composite materials need to be further researched and adapted to 3D printing technology [11,12].

Composite materials are hybrid materials created by combining one or more different materials. This combination generally enables the materials to exhibit superior properties than those they have alone [13,14]. The use of composites in 3D printing technologies offers a wider range of industrial applications by increasing the strength, stiffness, and thermal resistance of materials [15-25]. Composite filaments, especially those containing reinforcements such as carbon fiber, glass fiber, and metallic fillers, are considered to be in the category of materials closest to the potential to provide the durability required for structural components [26,27].

In this context, the use of composite materials stands out as an important strategy to expand the application areas of 3D printing technology and increase the mechanical performance of materials [28,29]. Thus, 3D printing can be used more effectively in many fields, from automotive to aviation, from medical devices to structural engineering, and the acceptance rate of these technologies will increase.

This study focused on the production of composite filaments containing various reinforcement materials

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(carbon fiber, glass fiber, metal oxides, etc.) and their usability in 3D printing processes. Studies on improving the mechanical properties of composite filaments, such as tensile strength, modulus of elasticity, and creep resistance, are mentioned. In addition, filament production techniques, optimization of 3D printing parameters, and the suitability of materials for industrial applications were also examined. The development and characterization of composite filaments have been supported by various analytical methods. These include Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), Dispersive X-ray Spectroscopy (EDS), and various mechanical tests. These methods examine in detail the internal structure of composites and the distribution of reinforcement materials in the matrix and determine the effects of the materials on mechanical properties. In conclusion, this study demonstrates the potential of composite materials in 3D printing processes and aims to increase the suitability of these materials for industrial applications. Thus, the production of more durable, functional, and economical 3D-printed parts will become possible. These developments continue to push the boundaries of 3D printing applications by bringing together innovations in materials science, engineering, and manufacturing technologies.

The aim of this study is to examine the integration of carbon fiber and polymer matrix composites in 3D printing technology and to show how the desired mechanical properties and lightness of these materials can be transferred to 3D printing applications. This has the potential to revolutionize the production of high-performance and durable components and can lead to important applications in various industries (aerospace, automotive, and sports equipment). In addition, the study addresses technical challenges and solutions related to the use of carbon fiber and polymer composites in 3D printing, providing a resource to guide research and development activities in this area. Thus, it supports innovations in materials science and manufacturing technologies by providing new knowledge and ideas for the development and expansion of 3D printing technologies.

2. Literature Surway

In their study, Çanti et al. [30] carried out the production and characterization of composite filaments for 3D printing technology. The aim of the research is to increase the mechanical properties of filament materials used for 3D printers and thus provide a wider range of usage in industrial applications. In the study, Acrylonitrile Butadiene Styrene (ABS) was used as the main matrix material, and composite filaments were produced by adding various micro and nano-sized particles (MWCNTs, SiO_2, ZrB_2, Al) to this matrix. The production process was carried out using a twin screw extruder, as shown schematically in Figure 1, and the resulting filaments were characterized by methods such as DSC, SEM, EDS, tensile test, and surface roughness tests. Research results showed that micro and nanoparticles added to the ABS matrix significantly improved the Breaking Stress (UTS) and tensile strain of the composites. In particular, ZrB_2 and Al particles reinforced with microparticles significantly improved the mechanical strength of the material, increasing the tensile strain by 17.8% and 40%, respectively. Additionally, filaments reinforced with nanoparticles showed good performance overall, although they experienced local condensation and internal void problems. These findings show that composite filaments can be used in commercial FDM devices and that these new-generation materials can enable the production of more durable and functional 3D-printed parts thanks to their improved mechanical properties. As a result, this study can be considered as a step towards increasing the performance of the materials used in 3D printing technology and making them more suitable for industrial applications.

In the studies of Sezer et al. [31], the usability of carbon fiber-reinforced ABS composite filaments in the 3D printing process was investigated. For use in FDM 3D printers, carbon fibers were mixed with ABS granules using a twin-screw extruder and then formed into filaments with a single-screw extruder (Figure 2). In the research, the effects on the mechanical properties of the filaments obtained by adding 6 mm long carbon fibers to the ABS matrix were examined. Moreover, the printing pattern was found to have a significant effect on the mechanical properties. The filaments were used to produce standard ASTM D412 A tensile test patterns containing various weight percentages of carbon fiber. Tensile test results showed that as the carbon fiber ratio increased, the breaking strength of the parts increased, but ductility and toughness decreased. As a result, it has been found that extrusion temperature and speed have a significant impact on filament quality, and carbon fiber reinforcement, especially at low rates, significantly improves the mechanical properties of ABS. However, it has been observed that high carbon fiber ratios have negative effects on mechanical properties by increasing porosity. This study makes a significant contribution to the development of 3D printing materials and reveals the potential advantages of using FDM technology in industrial applications.

In the studies of Çelik and Gür [32], the effects of the parameters used in the production of ABS and carbon fiber-reinforced ABS composites with a 3D printer on the mechanical properties were examined.

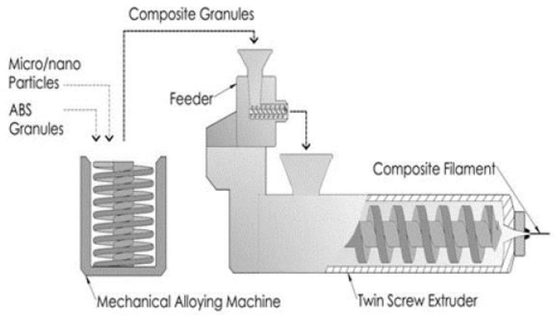

Figure 1. The production steps of nano-micro polymer composite filaments [30]

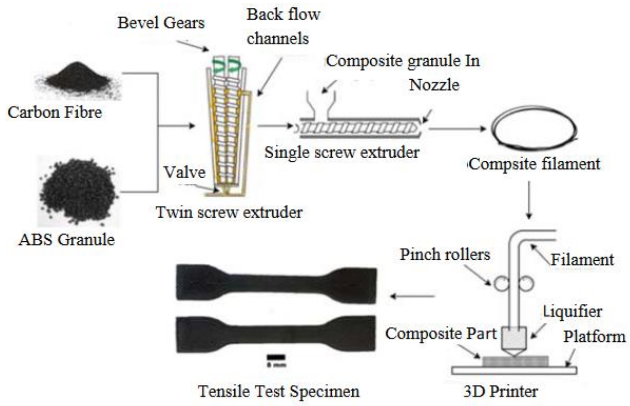

Figure 2. Composite filament preparation and 3D printing [31]

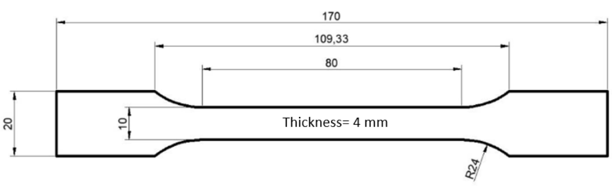

Figure 3. Tensile test sample dimensions in ISO-527-2-type-1A standard [32]

The work includes the production and testing of tensile test samples in accordance with the ISO 527-2 Type-1A standard (Figure 3) using various printing directions and filling angles. The results showed that regular ABS exhibited better mechanical properties than carbon fiber-reinforced ABS. Tensile test results revealed that printing parameters, especially the way the samples were placed on the production table and the internal structure filling angles, had a significant effect on the mechanical properties. Significant differences in mechanical properties were observed between samples with different printing directions and internal structure filling angles. The study emphasizes that optimizing 3D printing parameters is important, especially in terms of strengthening interlayer connections and reducing material defects. These optimizations can increase the suitability of 3D-printed parts for industrial applications and enable the production of parts with a wide range of uses.

In the studies of Urtekin et al. [33], the mechanical properties of polyester resin matrix and unidirectional carbon fiber reinforced composite materials produced by the hand-laying method at room temperature were examined. The study was carried out by placing unidirectional carbon fibers in one to three layers into a polyester matrix and then applying various mechanical tests (tensile, bending, and low-speed impact tests). According to the tensile test results, two-layer composites reached the highest tensile strength values. In bending tests, three-layer composite materials have the highest elasticity values when the fiber direction angle is 0°. In impact tests, single-layer composites showed the highest deformation values. These results show that the number of layers has a significant effect on the mechanical properties of composite materials. The higher tensile strength of two-layer composites emphasizes the effect of layers on mechanical performance. In addition, the high elasticity values of three-layer composites in bending tests indicate the potential use of these structures in applications requiring high flexibility. As a result, this study reveals in detail how the methods and materials used in the production of unidirectional carbon fiber-reinforced polyester composite materials with different numbers of layers affect the mechanical properties of the final product. This information can be taken into account when designing and manufacturing composite materials, especially in sectors such as aerospace, automotive, and defense industries.

In the work of Güneş and Çayıroğlu [34], the mechanical behavior of 3D printed parts with continuous steel wire reinforcement was examined (Figure 4). In the research, production with steel wire-reinforced polymer nylon material provided an approximately 5.58 times higher strength increase compared to unreinforced polymer nylon material. This result shows that continuous steel wire reinforcement can significantly increase the strength of 3D-printed parts. Additionally, the effects of steel wire reinforcement and different printing patterns on strength were also investigated. The strength performances of the parts produced using different printing patterns were compared, and the patterns with the highest strength values were determined. This study provides important information about innovations and potential applications in steel wire-reinforced 3D printing technology. In particular, the potential of using this technology in the production of parts requiring high strength in industrial applications and engineering fields is emphasized.

In the studies of Nergün et al. [35], the infrared heating method was used to increase the mechanical properties of continuous carbon fiber-reinforced thermoplastic composites (CFRTP). Thermoplastic filaments were produced using polyamide and continuous carbon fibers, and the aim was to increase the mechanical properties with an infrared heat source during the printing process, as seen in Figure 5.

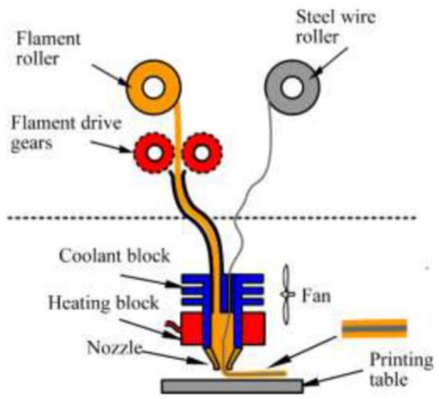

Figure 4. The extruder mechanism developed for composite printing [34]

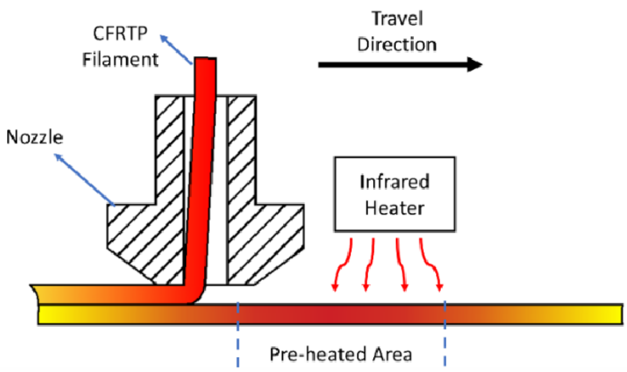

Figure 5. Schematic image of the infrared heater [35]

In experiments using three-point bending tests, significant increases in bending modulus and bending strength were observed when infrared heaters were used at low printing speeds. The highest flexural strength was measured as ~420 MPa, and the highest flexural modulus was measured as ~52 GPa. These results show that infrared heating is an effective method to improve the mechanical properties of CFRTP composites. By using infrared heating at low printing speeds, it was possible to increase interlayer bonding and thus improve mechanical properties. These findings increase the potential for CFRTP use, especially in industries such as aerospace, automotive, and medical.

In the study of Kurban et al. [36], the use of carbon-based filament yarns in different forms in the design of textile-reinforced concrete structures was examined. The study includes textile components used in the form of raw yarn and hybrid yarn coated with various polymers. Particular emphasis was placed on the knitting technique, which is one of the many hybrid yarn production methods used in the textile industry. In the research, samples were produced by placing two different textile surfaces produced using three different yarn structures into concrete in three different positions. Compared to the use of raw filament, a 23% increase in bending strength was observed with the use of hybrid yarn and a 167% increase in bending strength with the use of epoxy-coated filament. This study provides important information for more effective reinforcement of carbon fiber-reinforced concrete structures and provides methods on how to improve the mechanical properties of textile-reinforced concrete using epoxy coating or hybrid yarn technologies. These findings have important implications, especially for structural applications requiring high strength, and have the potential for the development of textile-reinforced concrete technologies.

In Tanabi's study [37], the temperature effect on the mechanical properties of composite materials produced through 3D printing was examined. The research covers short glass fiber reinforced polyamide 6 (GFPA6) composites and unreinforced ABS polymer at various temperatures (from -20 °C to 60 °C). The experiments were carried out on samples produced according to the ASTM D638 standard, and the samples were subjected to tensile loading at various temperatures. As a result of the tensile tests, it was determined that the GFPA6 material showed up to 56% higher hardness and up to 59% higher strength than ABS, as seen in Figure 6. It has been observed that as the temperature increases, both materials undergo significant deformation, and their tensile strength decreases. Additionally, by microscopic analysis of the fracture surfaces, fiber extrusion was determined to be the dominant fracture mechanism for GFPA6 and filament fracture for ABS. Research results indicate the potential for the use of these materials in various industries, such as aerospace and automotive, and contribute to the understanding of their structural performance, especially under different temperature conditions.

In the research of Seçgin et al. [38], optimization of the surface roughness of parts produced using carbon fiber filament with 3D printers was discussed. In the research, the effects of different printing parameters (nozzle temperature, layer thickness, filling ratio) on surface roughness were examined. Signal/Noise ratio analysis was performed using the Taguchi methodology, and the parameters that provided the best surface quality were determined. According to the results of the analysis, the optimum levels for nozzle temperature, layer thickness, and filling ratio were determined to be 240°C, 0.1 mm, and 20%, respectively. The study provides valuable information on how material surface quality can be improved in 3D printing processes and highlights the importance of optimizing printing parameters when using special filaments such as carbon fiber. These findings may be particularly useful in industrial applications and production requiring high quality.

In Yıldız's study [39], the creep behavior of carbon fiber-reinforced polylactic acid (PLA) samples produced using 3D printing technology was examined. Samples were prepared by adding carbon fiber to PLA polymer at

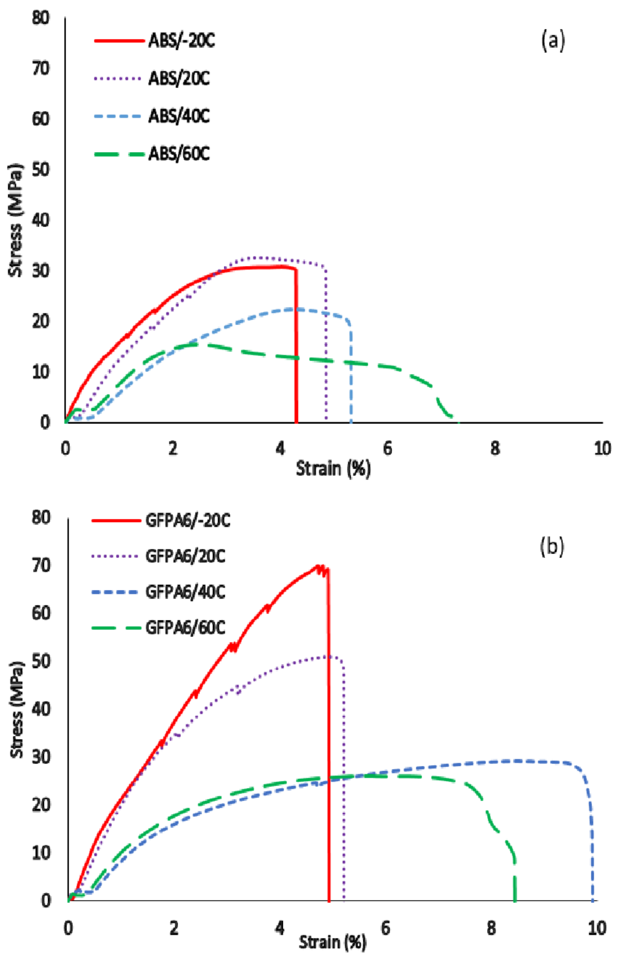

Figure 6. Stress vs strain diagram of a) ABS and b) GFPA6 [37]

different rates (0%, 15%, 20%), and experiments were carried out at various filling rates (70%, 80%, 90%, 100%). Creep tests were carried out specifically at 37 °C and under loads ranging from 20-80 Newtons. Study results indicate lower "exponentially related creep" rates in 15% and 20% carbon fiber reinforced samples compared to unreinforced samples. This shows that 15% of CF-reinforced composites are more stable and perform well. Additionally, the fracture areas of the samples were examined in detail with SEM analysis, and changes in the material structure and damage mechanisms were observed. These findings indicate that the addition of carbon fiber to the PLA matrix improves the mechanical properties of the material by affecting the creep resistance, thereby increasing the suitability of these composites for industrial applications.

In the study of Taleb [40], the production and mechanical tests of continuous wire-reinforced PLA matrix filament for 3D printers were carried out. It is aimed to increase the mechanical properties of the filaments used in 3D printers and thus improve the durability of the printed parts. In the study, continuous wire-reinforced composite PLA filament was produced using a single screw extruder and a designed mold. Tensile test samples were printed using the produced filament, and their mechanical strength was determined. Experimental results revealed that samples printed with composite filament showed significantly higher strengths compared to samples printed with pure PLA filament. This shows that continuous wire reinforcement can significantly improve the mechanical performance of PLA matrix composites. The results indicate that such composite filaments can expand the scope of 3D printing applications, especially by using them in the production of structural components.

In the work of Çelik et al. [41], a composite filament extruder machine was developed for 3D printers. The aim is to evaluate whether these filaments meet industrial requirements by preparing functional composite test samples. The study focuses on various composite materials and covers the design and manufacturing of an extrusion system to ensure the processability of these materials in the filament geometric structure by the molten filament fabrication method. Thanks to technological developments, AM techniques have become popular and have an important place in industrial production. These innovations have encouraged various studies to expand the use of AM, especially in order to save time and cost in production processes. The study focused on the processability of materials such as polymer-matrix composite and carbon fiber by extrusion method, their mechanical properties, and their suitability for the AM process. As a result, by producing composite filaments with the designed extruder machine, it has been shown that these filaments can be used for 3D printers and comply with industrial standards.

Usun et al. [42] studies focus on the CFRTP 3D printing process and investigate its potential to be used as an alternative production method, especially in sectors such as aviation, automotive, prototyping, medical applications, and space industry. Using the FDM method, the effects of printing parameters (such as nozzle temperature, printing speed, layer thickness, and heated bed temperatures) on the mechanical performance of CFRTPs were examined. CFRTP filaments were obtained using PLA and carbon fiber, based on the melt impregnation technique, and three-point bending test samples were printed using these filaments. Test results showed 23% fiber proportion with flexural strength ranging from 108 to 224 MPa and flexural modulus ranging from 9.67 to 17.69 GPa. In conclusion, this study shows that the use of CFRTPs in 3D printing processes can be effective, especially in applications requiring high mechanical properties, and its use can become widespread in various industrial sectors.

In the studies of Yeşil and Asi [43], the water absorption properties of glass and carbon fiber-reinforced polyester and vinyl ester pultruded hybrid composite profiles were examined. The main aim of the study is to determine the water absorption properties of composites produced using various fiber contents and resin types to predict their long-term performance. The extrusion process is the process of producing composite materials with constant cross-section. In this process, fibers are immersed in a pool of resin and pulled through a heated die with the cross-sectional geometry of the specific profile, allowing the composite materials to cure. In the research, four different I-section beam configurations were produced using glass fiber, carbon fiber, glass fiber continuous strand mat, and carbon woven roving mat, and polyester and vinyl ester resins were preferred as a matrix. Water absorption tests were carried out by immersing the composite samples in water according to the ASTM D 570 standard. Fiber contents were determined by the calcination method according to TS 1177 EN ISO 1172 standard. The results obtained were analyzed using the data obtained from the experiments. Glass-carbon fiber-reinforced polyester matrix composite materials tend to absorb more water than other samples, and glass-fiber-reinforced polyester matrix composite materials have the lowest water absorption percentage. This is due to the void content of the polyester matrix. It has been observed that the percentage of water absorption increases as the carbon fiber ratio increases. This situation was caused by voids formed due to poor penetration of polyester resin into carbon fibers. Glass-carbon fiber reinforced vinyl ester matrix composite materials have the lowest water absorption percentage values. Because vinyl ester has better penetration capacity than polyester, and the void content of vinyl ester composites is lower than polyester composites. For this reason, vinyl ester resin composites are preferred, especially in marine applications. These findings show that water absorption can significantly affect the long-term behavior of composite materials and that fiber content and matrix type play a determining role in these properties. Such information is critical in determining the design and application areas of composite materials.

In the study by Yaman et al. detailed in the reference [44], carbon fibers are explored for their distinct applications and manufacturing techniques stemming from a variety of precursor materials including polyacrylonitrile (PAN), rayon, and various other organic and inorganic precursors. The results and properties of the carbon fibers significantly depend on the choice of raw materials and the processing conditions applied. Different carbon fibers exhibit varying degrees of modulus and strength, which categorizes them into types like ultra-high modulus, high modulus, intermediate modulus, and low modulus, each having specific applications ranging from aerospace to medical technologies. Significant numerical results include the production efficiency and the fiber modulus and strength. For instance, PAN-based carbon fibers, which make up about 90% of the carbon fiber market, have a yield of around 40-45% from the precursor, with the fibers undergoing intense processing conditions including stabilization, carbonization, and graphitization. These fibers achieve a modulus in the range of 300-500 GPa and tensile strength around 3 GPa.

In the studies of Yaman et al. [45], the physical and chemical properties of carbon fibers, their production methods, and their use in various industrial applications were discussed. In summary, the high strength, low weight, and high electrical and thermal conductivity properties of carbon fibers are emphasized. Additionally, the production processes of carbon fibers from various raw materials (PAN, rayon, tar, pitch) and the effects of these processes on fiber properties are detailed. The application areas of carbon fibers cover a wide range. It has been stated that it is used effectively in areas such as aviation, space, automotive, sports equipment, construction, and medicine. In addition, it has been emphasized that carbon fibers are a preferred material in a wide variety of industrial applications thanks to their properties such as high fatigue resistance, corrosion resistance, and chemical inertness. The study also provides information on innovations in carbon fiber production technologies and how these innovations affect the cost, and it is predicted that carbon fibers may have wider usage areas in the future. This information reveals the future potential of carbon fibers.

In the study of Kaygısız et al. [46], they examine the mechanical properties of materials printed on a 3D printer using carbon fiber-reinforced filaments. The research indicates that fiber-reinforced composite materials have a wide range of uses due to their properties, such as high strength, hardness, and conductivity. These materials are especially used in areas such as aircraft structural elements, wind turbine blades, automotive exterior panels, and computer enclosures. In the study, carbon fiber-filled nylon filament (ePA-CF) and PLA+ filament materials produced by ESUN were used. These filaments were printed with a 3D printer, and the mechanical properties of the samples were comparatively examined. It has been observed that the tensile strength of the material increases significantly, especially when carbon fiber-reinforced nylon filament ePA-CF is used. The results of the research point to important opportunities for 3D printing technologies to be used more effectively, especially in industrial applications and in the production of products requiring high performance.

In the studies of Öztürk et al. [47], the production of continuous fiber-reinforced composite filaments and the printability of these filaments on a 3D printer were examined. In particular, 3D printer technology has been used for the production of complex parts and offers lower cost, faster, and easier production advantages compared to traditional production methods. However, the parts produced with 3D printer technology cannot be used as final products due to their low strength properties, requiring improvement of the material. In the study, high-strength continuous fiber-reinforced composite filament was produced with an extruder device using carbon fiber yarn and PLA. The mold was designed and produced by coating the continuous fiber with thermoplastic material. By using the FDM method, these filaments were produced and are suitable for use in 3D printers, and parts were printed in the specified dimensions. As a result, the production of continuous fiber-reinforced composite filaments was successful, but some technical difficulties and problems with material properties were identified. This study provides important information for increasing material strength in the production of complex parts with 3D printer technology and forms the basis for future research in this field.

In the studies of Hu et al. [48], the production of continuous carbon fiber (CCF) reinforced prepreg filament and the use of 3D printing were discussed. An innovative method for printing continuous carbon fiber composite parts using FDM technology is proposed. Within the scope of the research, first, CCF prepreg filament was produced, and then the extruder heads of 3D printers were modified to print this filament. The mechanical properties of the produced composite parts were examined using a three-point bending test and Surface Response Methodology. The results showed significant improvements in the flexural strength and modulus of composites produced using certain printing parameters. Layer thickness was determined as the parameter that makes the biggest contribution to the final bending strength. These findings increase the potential of 3D printing, especially in industries such as aerospace and automotive that require materials that are lightweight and have high mechanical performance. Additionally, the study developed a detailed mathematical model for the production of CCF-reinforced composite parts by 3D printing and proved this model with validation tests.

Gahletia et al. [49] work deals with the process of reinforcing micro carbon fiber filled filament in nylon with Kevlar, Fiberglass, and HSHT Fiberglass with various layer thicknesses, reinforcement types, and filling patterns. The study suggests that the optimal composition of these components can be used to produce strong, high-quality parts, especially for use in fields such as the aerospace and automotive industries. The research states that properties such as tensile strength, wear resistance, and surface roughness were examined during the production of these composites under varying process parameters. The study stated that these properties were tested in samples in accordance with various standards (ASTM et al. IV and ASTM G99). It is described that the response surface methodology and the central composite design approach are used as well, and the MOGA-ANN approach is used to optimize multiple response targets. The study results showed that maximum tensile strength, as well as minimum surface roughness and wear rate, were achieved by using a certain fiber layer thickness and filling pattern. These findings support the potential use of these material combinations in industrial applications and provide a basis for future research.

In the work of Xin et al. [50], the fusion bonding performances of composites reinforced with short and continuous carbon fibers were examined using fusion filament fabrication. The study used short beam shear and in-plane tensile shear tests to evaluate the effects of short fiber quantity on filament bonding properties. The results revealed that with the increase of short fiber content, there was first an increase and then a decreasing trend in the interlaminar shear strength (ILSS) and in-plane shear strength. In particular, samples containing 5% short fibers showed a significant increase in their load-carrying capacity and fusion bonding performance, outperforming the sample containing 0% fibers, with an increase of approximately 41% and 80% in ILSS and in-plane shear strength, respectively. When the damaged surfaces were examined, fiber extrusion and resin breakage were determined as the dominant bond failure models. It was found that the use of the appropriate amount of short fibers effectively improved the fusion bonding of S-CFRPCs. These results seem promising for the future design of strong and durable composite structures.

Almeshari et al. [51] examine the development process of polypropylene composite filaments reinforced with short carbon fibers for 3D printing. The research proposes a method in which short carbon fiber (SCF) content is mixed with polypropylene (PP) granules in different proportions (4% to 22% by weight) and processed in a twin-screw extruder and then made into filaments using a single-screw extruder. The produced filaments were evaluated in terms of their mechanical, physical, and morphological properties. The findings specifically indicate that the composite containing 22% SCF showed a 150% improvement in tensile strength and a 260% improvement in impact energy compared to pure PP. However, the values in the fracture time of the composites showed a linear decrease of up to 11% SCF content, after which there was a sharper decrease. Research suggests that SCF/PP composites are suitable for 3D printing applications and can be used especially in applications requiring high performance.

When the literature is evaluated, the prominent mechanical properties can be categorized when matrix material types and reinforcement elements are used, as in Table 1.

Table 1. Prominent mechanical properties according to material type and reinforcement elements

Material Type	Particle / Reinforcement Type	Reinforcement Features (Ratio, Morphology, Size, etc.)	Production Method Parameters	Featured Mechanical Properties	Summary	Ref.
ABS	MWCNTs, SiO_2, ZrB_2, Al	Micro and nano-sized particles, varying ratios	Twin screw extruder	Increase in tensile stress and strain	Use of composite filaments in industrial applications	[30]
ABS	Carbon fiber	6 mm long fibers, 10%-30% weight percentages	Twin-screw extruder, single-screw extruder	Increased mechanical strength, decreased flexibility	Mechanical effects of carbon fiber-reinforced ABS filaments	[31]
ABS	Carbon fiber	10%-20% weight percentages, fiber length not specified	3D printing with varying printing directions and filling angles	Effect of printing parameters on mechanical properties	Effect of printing direction and internal structure filling angles	[32]
Polyester resin	Carbon fiber	Unidirectional fibers, 1-3 layers	Hand-laying method	Differences in tensile and bending strength	Effect of the number of layers on mechanical properties	[33]
Polymer nylon	Steel wire	Continuous wire reinforcement, wire diameter not specified	3D printing with steel wire reinforcement	5.58 times increase in strength	Mechanical behavior of steel wire reinforced 3D printed parts	[34]
Polyamide	Carbon fiber	Continuous fibers, varying printing speeds, and infrared heating	Infrared heating during 3D printing	Increase in bending strength and modulus	Improvement of mechanical properties by infrared heating	[35]
Concrete	Carbon-based threads	Different yarn structures, hybrid yarn techniques	Textile reinforced concrete design	The large increase in bending strength	Design of textile-reinforced concrete structures	[36]
GFPA6, ABS	Glass fiber	Short fibers, 10%-30% weight percentages, temperature (-20°C to 60°C)	3D printing with varying temperatures	Increase in hardness and strength, temperature effects	The effect of temperature changes on composite materials	[37]
Carbon fiber	-	-	Varying 3D printing parameters: nozzle temperature (200°C-260°C), layer thickness (0.1-0.3 mm), filling ratio (10%-50%)	Optimization of surface roughness	Effects of 3D printing parameters on surface quality	[38]
PLA	Carbon fiber	0%, 15%, 20% weight percentages, filling rates (70%-100%)	3D printing with varying filling rates	Improvement in creeping behavior	The creep resistance of carbon fiber-reinforced PLA	[39]
PLA	Continuous wire	Continuous wire reinforcement, wire diameter not specified	Single screw extruder	Significant increase in endurance	Mechanical tests of continuous wire-reinforced PLA filaments	[40]
Various composites	-	-	Composite filament extruder machine development	-	Development of composite filament extruder machine	[41]
CFRTP	Carbon fiber	23% fiber proportion, varying printing parameters	FDM method: nozzle temperature (200°C-260°C), printing speed (30-90 mm/s), layer	Increase in bending strength and modulus	Potential for use of CFRTPs in 3D printing processes	[42]

			thickness (0.1-0.3 mm)			
Polyester, Vinylester	Glass and carbon fiber	Varying fiber contents (10%-30% weight percentages), different resin types	Pultrusion process	Water absorption properties, long-term performance	Water absorption properties of hybrid composite profiles	[43]
Poliakrilnitril	Carbon fiber	Diameter ~7-10 µm, High Orientation,	Oxidation, Carbonization, Graphitization	High Strength, High Modulus	Widely used, ~90% of carbon fiber production, good balance between strength and modulus	[44]
-	Carbon fibers	Varying production methods, different raw materials (PAN, rayon, tar, pitch)	Various production methods	High strength, low weight	Industrial use of carbon fibers and production methods	[45]
Nylon, PLA	Carbon fiber	10%-20% weight percentages, fiber length not specified	3D printing with carbon fiber filaments	Increase in tensile strength	Effects of carbon fiber reinforced filaments in 3D printing	[46]
PLA	Carbon fiber	Continuous fiber reinforcement, varying fiber lengths	Extruder device, FDM method	Strength increase, production difficulties	Production of continuous fiber-reinforced composite filaments	[47]
CCF	Carbon fiber	Continuous carbon fiber, prepreg filament	Modified extruder heads, FDM method	Improvements in bending strength and modulus	Production and use of continuous carbon fiber reinforced prepreg filament	[48]
Nylon (MCF filled)	Kevlar, Fiberglass, HSHT Fiberglass	Varying layer thicknesses, reinforcement types (Kevlar, Fiberglass, HSHT Fiberglass), filling patterns	Dual extrusion system, varying process parameters	Increased tensile strength, bending strength, and impact resistance	Production and performance analysis of micro carbon fiber filled nylon filaments reinforced with Kevlar, Fiberglass, and HSHT Fiberglass	[49]
Composite	Continuous carbon fiber	Varying short fiber content (5%-20% weight percentages)	Fusion filament fabrication	Fusion-bonding performance	Fusion-bonding performance of short and continuous carbon fiber reinforced composites	[50]
Polypropylene	Short carbon fiber	Different proportions (4%-22% by weight), fiber length not specified	Twin-screw extruder, single-screw extruder	High mechanical performance	Development of short carbon fiber reinforced polypropylene composite filaments	[51]

3. Discussion and Estimation

This review article examines in depth the use of composite filaments in 3D printing technology, revealing the potential of these materials in industrial applications. The results of the studies show that various reinforcements are effective in improving the mechanical properties of composite filaments. These improvements have the potential to reduce costs and speed up production processes by diversifying material selection, especially in applications requiring high performance. The discussion is categorized under the following subheadings.

3.1 Effects on Mechanical Properties

With the addition of reinforcement materials, significant improvements were achieved, especially in tensile strength and bending strength. However, reducing effects of these reinforcements on other mechanical properties, such as material flexibility and ductility, have also been observed. For example, while carbon fiber reinforcement increased the strength of ABS and PLA matrices, it reduced the machinability and flexibility of the materials. This highlights that material choices must be carefully evaluated against application specifications. In Table 2, the effects of matrix materials and reinforcement elements on mechanical properties according to their type are evaluated.

3.2 Effects of Environmental and Operational Conditions

Studies in the literature have also tested the durability of composite materials against environmental and operational factors. In particular, temperature changes and water absorption have emerged as determining factors in material performance. The low water absorption of vinyl ester and carbon fiber reinforced composites provides advantages in applications that come into contact with water, such as marine. Against temperature changes, materials such as GFPA6 have shown that they are suitable for use in the automotive and aerospace sectors by offering high-temperature resistance. In Table 3, the affected properties of the composite material components are categorized according to their operational properties.

3.3 Sustainable Production Technologies

3D printing technology offers great opportunities for customized production and waste minimization. However, innovative methods need to be developed to reduce the environmental impact of this technology and increase energy efficiency. Future research may develop more efficient 3D printing techniques and printing processes that optimize energy use.

3.4 Long-term Performance and Reliability Tests

Detailed studies designed to evaluate the long-term performance and reliability of composite filaments can be conducted. This is especially critical for industries such as aerospace and automotive that require structural integrity and durability. Aging processes of materials, long-term fatigue tests, and exposure to environmental factors can be examined.

3.5 Innovative Design and Manufacturing Approaches

The discovery of new material combinations and hybrid structures could revolutionize 3D printing technology. Future research may focus on multi-material printing techniques and hybrid printing systems, which may allow the production of more complex and functional parts. Additionally, Artificial Intelligence (AI)-)-AI-supported design optimization and simulation-based engineering applications can contribute to further improvement of materials and manufacturing processes. In Table 4, the aims of the research themes and suggestions/approaches are categorized.

Table 2. Effect of matrix material and reinforcement elements on mechanical properties according to their type

Material Type	Conditions	Affected Features	Effect Type	Explanation	Ref.
GFPA6, ABS	Temperature changes (-20 °C to 60 °C)	Strength, deformation	Strength decreases, deformation increases	High temperatures weaken the structure of the material and increase deformation.	[37]
Vinylester, Polyester	water absorption	Water absorption rate	Decrease or increase	Vinylester shows lower water absorption because it is more resistant to water. Polyester shows higher absorption.	[43]
Glass and carbon fiber reinforced polyester/vinyl ester	Water absorption and continuous exposure	long term performance	Performance decreases	Water absorption can reduce the structural integrity and mechanical properties of the material over time.	[44]
PLA	Temperature (37 °C) and load (20-80 Newtons)	Creep resistance	Improvement	The creep resistance of PLA at high temperatures increases with carbon fiber reinforcement.	[39]
Various composites	High carbon fiber ratio and porosity	Mechanical properties	Decrease in features	A high carbon fiber ratio may have a negative impact on mechanical properties by increasing porosity.	[31,50]

Table 3. Properties of the material type affected by operational properties

Material Type	Conditions	Affected Features	Effect Type	Explanation	Ref.
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Table 4. Purposes of research themes and suggestions

Research Theme	Purpose	Suggestions and Approaches
Expanded Range of Materials	Examining the 3D printing performance of different materials	Testing new or little-used ingredients, adding customized supplements.
Environmental Durability and Recycling	Reducing the environmental impact of materials	Working on biodegradable and fully recyclable materials.
Sustainable Production Technologies	Increasing the energy efficiency of production processes	Developing new printing techniques that optimize energy use.
Long-Term Performance and Reliability Tests	Assessing the durability and structural integrity of materials	Conducting aging tests, fatigue tests, and environmental exposure tests.
Innovative Design and Manufacturing Approaches	Improving production processes and material functionality	Using multi-material and hybrid printing systems, applying AI-supported design optimization.

4. Potential Future Applications

The integration of 3D printing technology and composite materials has the potential to revolutionize various industries by enabling customized production, high-performance materials, smart structures, environmentally friendly manufacturing, and rapid prototyping. In the medical and healthcare sectors, 3D printing can produce tailored prosthetics, orthotics, and implants that precisely fit individual anatomies. High-performance materials, such as those used in the aerospace and automotive industries, will benefit from lighter, stronger, and more durable composites, enhancing fuel efficiency and reducing carbon emissions. The development of smart materials integrated with sensors will allow for the creation of intelligent structures capable of monitoring their condition and responding to environmental changes. Furthermore, 3D printing offers more sustainable production methods by reducing waste and improving energy efficiency, providing economic and environmental benefits. The rapid and cost-effective production of complex geometric structures through 3D printing accelerates innovation in engineering and design. These advancements, at the intersection of materials science, engineering, and manufacturing technologies, hold promise for substantial improvements in efficiency, performance, and sustainability across various sectors.

5. Conclusions

This review study focuses on the production of various composite filaments and their use with 3D printing technology. Research has involved the reinforcement of ABS, PLA, polyamide, polyester resin, and various other polymers with different reinforcement materials such as carbon fiber, glass fiber, metal particles, and continuous wire. The findings can be listed as follows;

- It has been shown that reinforcement elements significantly improve the mechanical properties of co-composite materials. In particular, the improvements observed in critical mechanical properties such as tensile strength, bending strength, and creep resistance enable a wider range of industrial applications for these materials.
- GFPA6 and glass fiber-reinforced polyamide samples, which exhibit superior performance against temperature effects, offer potential application opportunities, especially in the aviation and automotive industries. In terms of water absorption properties, vinyl ester matrix composites stand out as ideal options, especially for marine applications.
- Studies have shown that optimization of 3D printing parameters can significantly affect material surface quality and mechanical integration. This provides strategic information on customizing and processing filaments, especially for industrial applications requiring high performance.

As a result, these studies provide a guide to what role composite filaments and 3D printing technology can play in industrial applications and what methods can be followed to maximize the performance of these materials. Future studies can build on these findings and focus on the development of 3D printing materials that are more durable, functional, and resistant to environmental factors. This is especially critical for the discovery of economical and efficient production methodologies that can replace high-cost materials.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original and was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

A. Kaptan and F. Kartal jointly supervised and improved the study, co-wrote the text, and proofread the manuscript.

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References

1. Heidari-Rarani, M., Rafiee-Afarani, M., & Zahedi, A. M. *Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites.* Composites Part B: Engineering, 2019. 175, 107147: p. 1–8.
2. Sharma, B., Bhavsar, P., Moscoso-Kingsley, W., & Madhavan, V. *Detecting first layer bond quality during FDM 3D printing using a discrete wavelet energy approach.* Procedia Manufacturing, 2020. 48: pp. 718–724.
3. Bhagia, S., et al. *A critical review of FDM 3D printing of PLA biocomposites filled with biomass resources, characterization, biodegradability, upcycling, and opportunities for biorefineries.* RSC Advances, 2020. **10**(37): p. 21698–21723.
4. Hwang, S., Reyes, E. I., Moon, K., Rumpf, R. C., & Kim, N. S. *Thermo-mechanical characterization of metal/polymer composite filaments and printing parameter study for fused deposition modeling in the 3D printing process.* Journal of Electronic Materials, 2015. 44: p. 771–777.
5. Kristian, R. B., Imaduddin, F., Ariawan, D., Ubaidillah, & Arifin, Z. *A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters.* Open Engineering, 2021. **11**(1): p. 639–649.
6. Tamir, T. S., Xiong, G., Fang, Q., Dong, X., Shen, Z., & Wang, F. Y. *A feedback-based print quality improving strategy for FDM 3D printing: an optimal design approach.* The International Journal of Advanced Manufacturing Technology, 2022. **120**(3): p. 2777-2791.
7. Tura, A. D., Lemu, H. G., Melaku, L. E., & Mamo, H. B. *Impact of FDM 3D printing parameters on compressive strength and printing weight of PLA components.* In International Workshop of Advanced Manufacturing and Automation, 2022, October. p. 495–504.
8. Alhazmi, M. W., Backar, A. H., & Backar, A. H. *Influence of infill density and orientation on the mechanical response of PLA+ specimens produced using FDM 3D printing.* Int. J. Adv. Sci. Technol, 2020. **29**(6): p. 3362–3371.
9. Rownaghi, A., Lawson, S., Li, X., Thakkar, H., & Rezaei, F. *Recent advances in 3D printing of structured materials for adsorption and catalysis applications.* Chemical Reviews, 2021. **121**(10): p. 6246–6291.
10. Kokkinis, D., Schaffner, M., & Studart, A. R. *Multimaterial magnetically assisted 3D printing of composite materials.* Nature Communications, 2015. **6**(1), 8643: p. 1–10.
11. Alhnan, M. A., et al. *A lower temperature FDM 3D printing for the manufacture of patient-specific immediate release tablets.* Pharmaceutical Research, 2016. 33: p. 2704–2712.
12. Bose, S., Roy, M., & Bandyopadhyay, A. *Recent advances in bone tissue engineering scaffolds.* Trends in Biotechnology, 2012. **30**(10): p. 546–554.
13. Ahmed, T. N., Belduque, M. C., & Tate, J. S. *Time dependence of magnetic moment of strontium-ferrite powder measured with a biaxial vibrating sample magnetometer (VSM)*. AIP Advances, 2021. **11**(1), 015048: p. 1–5.
14. Goyanes, A., Wang, J., Buanz, A., Martínez-Pacheco, R., Telford, R., & Gaisford, S. *3D printing of medicines: engineering novel oral devices with unique design and drug release characteristics.* Molecular Pharmaceutics, 2015. **12**(11): p. 4077–4084.

15. Kodali, D., Umerah, C. O., Idrees, M. O., Jeelani, S., & Rangari, V. K. *Fabrication and characterization of polycarbonate-silica filaments for 3D printing applications.* Journal of Composite Materials, 2021. **55**(30): p. 4575–4584.
16. Yohannan, A., Vincent, S., Divakaran, N., Pottikadavath Venugopal, A. K., Patra, S., Ashish, K., & Mohanty, S. *Experimental and simulation studies of hybrid MWCNT/montmorillonite reinforced FDM based PLA filaments with multifunctional properties enhancement.* Polymer Composites, 2024. **45**(1): p. 507–522.
17. Parmaksız, F., Anaç, N., Koçar, O., & Erdogan, B. *Investigation of mechanical properties and thermal conductivity coefficients of 3D printer materials.* International Advanced Researches and Engineering Journal, 2023. **7**(3): p.146–156.
18. Gupta, A., Fidan, I., Hasanov, S., & Nasirov, A. *Processing, mechanical characterization, and micrography of 3D-printed short carbon fiber reinforced polycarbonate polymer matrix composite material.* The International Journal of Advanced Manufacturing Technology, 2020. 107: p. 3185–3205.
19. Saroia, J., Wang, Y., Wei, Q., Lei, M., Li, X., Guo, Y., & Zhang, K. *A review on 3D printed matrix polymer composites: its potential and future challenges.* The international journal of advanced manufacturing technology, 2020. 106: p.1695-1721.
20. Luan, C., Yao, X., Zhang, C., Wang, B., & Fu, J. *Large-scale deformation and damage detection of 3D printed continuous carbon fiber reinforced polymer-matrix composite structures.* Composite Structures, 2019. 212: p. 552–560.
21. Tian, X., Todoroki, A., Liu, T., Wu, L., Hou, Z., Ueda, M., ... & Lu, B. *3D printing of continuous fiber reinforced polymer composites: development, application, and perspective.* Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers, 2022. **1**(1), 100016: p. 1–20.
22. Perna, A. S., Viscusi, A., Gatta, R. D., & Astarita, A. *Integrating 3D printing of polymer matrix composites and metal additive layer manufacturing: surface metallization of 3D printed composite panels through cold spray deposition of aluminum particles.* International Journal of Material Forming, 2022. **15**(2): p.15.
23. Zhu, W., Fu, H., Xu, Z., Liu, R., Jiang, P., Shao, X., ... & Yan, C. *Fabrication and characterization of carbon fiber reinforced SiC ceramic matrix composites based on 3D printing technology.* Journal of the European Ceramic Society, 2018. **38**(14): p. 4604–4613.
24. Parandoush, P., Zhou, C., & Lin, D. *3D printing of ultrahigh strength continuous carbon fiber composites.* Advanced Engineering Materials, 2019. **21**(2), 1800622.
25. Adumitroaie, A., Antonov, F., Khaziev, A., Azarov, A., Golubev, M., & Vasiliev, V. V. *Novel continuous fiber bi-matrix composite 3-D printing technology.* Materials, 2019. **12**(18), 3011.
26. Pakula, D., Brząkalski, D., Sztorch, B., Frydrych, M., Špitalský, Z., & Przekop, R. E. *Natural and synthetic polymer fillers for applications in 3D printing—FDM technology area.* Solids, 2022. **3**(3): p. 508–548.
27. Bandyopadhyay, A., & Bose, S. *Bone tissue engineering using 3D printing.* Materials Today, 2021. 16: p. 496–504.
28. Sikder, P., Challa, B. T., & Gummadi, S. K. *Bioactive amorphous magnesium phosphate-polyetheretherketone composite filaments for 3D printing.* Materialia, 2022. 22: pp. 865–883.
29. Wickramasinghe, S., Nguyen-Van, V., Ghazlan, A., Nguyen-Xuan, H., & Tran, P. *FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects, and treatments.* Polymers, 2020. **12**(7), 1529: p. 1–42.
30. Çanti, E., Aydın, M., & Yıldırım, F. *Production and characterization of composite filaments for 3D printing.* Politeknik Dergisi, 2018. **21**(2): p. 397–402.
31. Sezer, H., Eren, O., Börklü, H., & Özdemir, V. *Additive manufacturing of carbon fiber reinforced plastic composites by fused deposition modeling: Effect of fiber content and process parameters on mechanical properties.* Journal of the Faculty of Engineering and Architecture of Gazi University, 2019. **34**(2): p. 663–674.
32. Çelik, S., & Yılmaz, G. Ü. R. *3 boyutlu yazıcı ile üretilen ABS ve karbon fiber takviyeli ABS kompozitlerde üretim parametrelerinin mekanik özelliklere etkisi.* Balıkesir Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 2021. **23**(1): p. 200-209.
33. Urtekin, L., Gunes, D., Yılan, F., & Çanlı, M. *The effect of layers on the unidirectional carbon fibers of the reinforced polyester resin matrix composite material.* Gazi University Journal Of Science Part C: Design and Technology, 2022. **10**(3): p. 495-503.
34. Güneş, M., & Çayıroğlu, İ. *Mechanical behavior of 3D printed parts with continuous steel wire reinforcement.* El-Cezeri, 2022. **9**(1): p. 276-289.
35. Nergün, M., Nafız, Ö., Vatandaş, B. B., Altuğ, Uşun, A. & Gümrük, R. *Obtaining high mechanical properties polyamide-continuous carbon fiber reinforced thermoplastic composites with infrared heating.* Avrupa Bilim ve Teknoloji Dergisi, 2022. (36): p. 222–226.
36. Kurban, M., Babaarslan, O., & Çağatay, İ. H. *Carbon-based filament yarns are used in different forms in the design of textile-reinforced concrete structures.* Textile and Apparel, 2022. **32**(2): p. 173–182.
37. Tanabi, H. *Investigation of the temperature effect on the mechanical properties of 3D printed composites.* International Advanced Researches and Engineering Journal, 2021. **5**(2): p. 188–193.
38. Seçgin, İ., Kahraman, H., Cesur, İ. *Karbon fiber filament kullanılan eklemeli imalat işleminde yüzey pürüzlülüğü optimizasyonu.* 1st International Conference on Recent Academic Studies. May 2-4, 2023. Konya, Turkey: p. 121-123.
39. Yıldız, A. *Investigation of the creep behavior of 3D printed carbon fiber reinforced PLA specimens,* Master Thesis, Karabuk University, Institute of Graduate Education, 2022.
40. Taleb, M. D. *Production and testing of continuous wire-reinforced PLA filament for the 3D printer,* 2023. Master Thesis, Karabuk University, Institute of Graduate Education, Turkey.
41. Çelik, B., Şener, B., Serin, G., & Unver, H. O. *Ergiyik filament fabrikasyonu, 3B yazıcılar için kompozit filament ekstrüder makinesi geliştirilmesi.* Makina Tasarım ve İmalat Dergisi, 2020. **17**(2): p. 65-75.
42. Uşun, A., Gümrük, R., Yıldız, N., & Vatandaş, B. B. *Examination of the influence of printing parameters for the continuous carbon fiber-reinforced thermoplastics based on fused deposition modeling.* The International Journal of Materials and Engineering Technology, 2022. **5**(2): p. 65–70.
43. Yeşil, Ö., & Asi, O. *Investigation of the water absorption properties of pultruded hybrid composite profiles.* Usak University Journal of Engineering Sciences, 2019. **2**(1): p.

48–56.

44. Yaman, N., Öktem, T., & Seventekin, N. *Karbon liflerinin üretimi.* Tekstil ve Konfeksiyon, 2006. **16**(3), p. 164-173.
45. Yaman, N., Öktem, T., & Seventekin, N. *Karbon liflerinin özellikleri ve kullanım olanakları.* Tekstil ve Konfeksiyon, 2007. **17**(2): p. 90-95.
46. Kaygısız, H., Pektürk, H. Y., & Topuz, P. *Karbon fiber takviyeli filamentler kullanarak 3 boyutlu yazıcıda basılan malzemelerin mekanik özelliklerinin incelenmesi.* International Symposium On 3D Printing Technologies 3-4 Apr 2017, 3D-PTS2017: p. 213-217.
47. Öztürk, F. H., Öz, Ö., Aydın, M., Kılıç, E., İsak, S. O., & Bektaş, U. *Sürekli fiber takviyeli kompozit filament üretimi ve yazdırılması.* In 4th International Congress on 3d Printing (additive manufacturing) Technologies and Digital Industry. 2019. Antalya: p. 592-596.
48. Hu, Q., Duan, Y., Zhang, H., Liu, D., Yan, B., & Peng, F. *Manufacturing and 3D printing of continuous carbon fiber prepreg filament.* Journal of Materials Science, 2018. 53: p. 1887-1898.
49. Gahletia, S., Kaushik, A., Garg, R. K., Chhabra, D., Kovács, A., Khargotra, R., & Singh, T. *Fabrication and analysis of micro carbon fiber filled nylon filament reinforced with Kevlar, Fiberglass, and HSHT Fiberglass using dual extrusion system.* Materials Today Communications, 2023. 35, 106075: p. 1–11.
50. Xin, Z., Ma, Y., Chen, Y., Wang, B., Xiao, H., & Duan, Y. *Fusion-bonding performance of short and continuous carbon fiber synergistic reinforced composites using fused filament fabrication.* Composites Part B: Engineering, 2023. 248, 110370.
51. Almeshari, B., Junaedi, H., Baig, M., & Almajid, A. *Development of 3D printing short carbon fiber reinforced polypropylene composite filaments.* Journal of Materials Research and Technology, 2023. 24: p. 16–26.