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Enhancing Tensile Strength and Thermal Resistance of PLA-Carbon Fiber Composites Synthesis on Conventional and 3D Printing Methods

Ragu S.[1*], Sankar Ganesh R.[2], Karthikeyan S.[3], Ragul Sharma B.[3], Arun A.[3], Sanjay K.[3]

[1]*Assistant Professor, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore 641032, INDIA*

[2]*Associate Professor, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore 641032, INDIA*

[3]*UG Student, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore 641032, INDIA*

Abstract

This study investigates the tensile characteristics and thermal conductivity of PLA-carbon fiber (CF) regular composites and 3D printed PLA-CF composites, focusing on the impact of varying carbon fiber weight fractions. The carbon fiber reinforcement percentages range from 5 wt.% to 30 wt.%, allowing for a thorough comparison of mechanical and thermal properties. The analysis reveals a consistent improvement in tensile strength for both composite types, with PLA-CF regular composites achieving a peak 192% improvement at 25 wt.% and 3D printed PLA-CF composites showing a 209% improvement at 20 wt.%. The enhancement is attributed to effective fiber-matrix interactions and load transfer mechanisms. However, beyond the optimal weight fractions, tensile strength decreased slightly due to fiber agglomeration, poor dispersion, and void formation.FESEM morphology analysis provided critical insights into the failure mechanisms, indicating smooth fracture surfaces at lower fiber contents (5 wt.% to 15 wt.%), followed by enhanced fiber bridging and pull-out at peak fiber loadings. At higher fiber contents, fiber misalignment and void formation were observed, leading to reduced tensile strength.In terms of thermal performance, PLA-CF regular composites exhibited a 74% reduction in thermal conductivity, while 3D printed PLA-CF composites demonstrated an even greater 92% reduction, highlighting their superior thermal resistance. The reduction in thermal conductivity is attributed to fiber agglomeration and the FDM process used in 3D printing, which introduces interfacial thermal resistances. These findings underscore the importance of optimizing both fiber loading and manufacturing techniques to enhance the mechanical and thermal properties of PLA-CF composites, particularly for applications demanding high strength and thermal stability.

Keywords: *PLA-carbon fiber composites, Tensile strength, Thermal conductivity, Fiber-matrix interaction, 3D printed composites*

1. Introduction

3D printing technology has transformed the development of polymer composite materials for engineering applications. It facilitates the precise fabrication of complex geometries through material layering. In polymer composites, the process allows for the incorporation of reinforcements such as carbon fibers, graphene, or nanoparticles, enhancing mechanical properties like strength, stiffness, and thermal resistance. The ability to customize material compositions and fiber orientations improves the performance of printed components, making them suitable for industries such as aerospace, automotive, biomedical, and electronics. This technology minimizes material waste and reduces manufacturing lead times, enabling rapid prototyping and design optimization. Functional gradients within components are achieved by selectively integrating different materials, offering engineers the capability to produce lightweight, high-performance parts tailored to specific application requirements. Advances in multi-material printing continue to push the boundaries of polymer composites, establishing 3D printing as an essential tool for future engineering developments.

Recent innovations in polymer-reinforced 3D printing filaments have expanded the scope of additive manufacturing by enabling the creation of high-strength, lightweight materials. These filaments combine thermoplastic polymers such as PLA, ABS, or nylon with reinforcements like carbon fibers, glass fibers, or nanomaterials. The result is enhanced mechanical performance, including greater tensile strength, rigidity, and impact resistance.Incorporating continuous fibers into the polymer matrix has further pushed the limits of this technology, allowing for improved load-bearing capabilities. This approach embeds long fibers, which increases structural integrity while maintaining low weight. Additionally, the development of hybrid filaments, blending different reinforcement materials, allows for fine-tuning mechanical properties to meet specific engineering challenges.Improvements in fiber alignment and distribution within the matrix have led to more uniform material properties throughout the printed part. This technology facilitates the production of highly customized components that meet performance standards for demanding environments, such as heat resistance and durability under stress. As research progresses, polymer-reinforced filaments are moving beyond rapid prototyping, supporting the production of robust, functional end-use parts with optimized strength-to-weight ratios, suitable for sectors requiring high-performance materials.

Carbon-based fibers used in 3D printing filaments, such as carbon fiber, carbon nanotubes, and graphene, offer enhanced mechanical and thermal properties for high-performance manufacturing. Carbon fiber filaments, created by infusing short or continuous carbon fibers into a polymer matrix like nylon or PLA, deliver exceptional strength-to-weight ratios, stiffness, and thermal stability, making them ideal for lightweight structural parts.Carbon nanotube-reinforced filaments exhibit excellent electrical conductivity, high tensile strength, and improved thermal properties, suitable for electronics and high-stress components. Graphene-based filaments, with their superior electrical and thermal conductivity, improve mechanical durability and offer flexibility, enabling their use in advanced electronic devices and flexible structures.These carbon-based reinforcements create filaments that can handle demanding conditions while remaining lightweight, and ongoing research is optimizing fiber dispersion and bonding within polymers to further improve overall performance in diverse engineering environments.

Carbon fiber-reinforced filaments have been widely researched for their superior mechanical and thermal properties, making them suitable for high-performance applications. Theincorporating carbon fibers into PLA significantly enhances both tensile and flexural strength, alongside improving thermal stability [1]. The increased strength, stiffness, and thermal resistance of thermoplastic composites reinforced with carbon fibers [2]. Ning et al., highlighted that short carbon fiber-reinforced thermoplastics achieve better tensile strength and stiffness, largely influenced by fiber content and orientation [3]. The continuous carbon fiber reinforcement dramatically improves tensile strength and flexural modulus, suitable for lightweight, high-stress components [4]. The proper fiber orientation in continuous fiber-reinforced PLA leads to enhanced mechanical properties, especially tensile and flexural strength [5]. The successfully fabricated continuous fiber composites with increased impact resistance, presenting carbon fiber reinforcement as an ideal solution for lightweight, high-strength parts [6]. Author reported that carbon fiber-reinforced thermoplastics offer enhanced strength, particularly useful for biomedical applications that demand robust, biocompatible materials [7]. It was discovered that carbon fiber-reinforced nylon improves both tensile and flexural properties, with superior thermal stability [8].

The significant influence of fiber orientation on tensile strength in 3D-printed continuous fiber-reinforced thermoplastics [9]. In-nozzle impregnation technology, which achieves uniform fiber-matrix distribution, enhancing the strength-to-weight ratio of printed parts [10]. The combined additive manufacturing with thermoforming to produce continuous carbon fiber composites, which resulted in improved mechanical performance, particularly in tensile and flexural strength [11]. Enhanced thermal conductivity and mechanical strength in carbon fiber-reinforced thermoplastics, making them suitable for high-temperature applications [12]. The bio-based thermoplastics, revealing that carbon fiber reinforcement significantly improves tensile and flexural properties, offering potential for sustainable materials [13]. The evaluated the wear and thermal properties of carbon fiber-reinforced thermoplastics, finding improvements in hardness, tensile strength, and heat resistance [14]. The importance of fiber alignment in carbon fiber-reinforced thermoplastics, highlighting its impact on anisotropic behavior and overall mechanical performance [15].

2.Materials and methods

2.1 Polylactic Acid (PLA)

Polylactic Acid (PLA) is a biodegradable thermoplastic derived from renewable resources such as cornstarch or sugarcane, making it an environmentally friendly alternative to traditional petroleum-based plastics. It exhibits excellent clarity and a glossy finish, which enhances its aesthetic appeal in various applications, including packaging, disposable cutlery, and 3D printing. PLA has a density of approximately 1.24 g/cm³, contributing to its lightweight characteristics. In terms of physical properties, PLA demonstrates good tensile strength, typically ranging from 50 to 70 MPa, and a tensile modulus of about 3-4 GPa, allowing for effective load-bearing applications. The elongation at break is around 6-15%, indicating its relatively brittle nature compared to other thermoplastics. Thermally, PLA has a glass transition temperature (Tg) of approximately 60°C and a melting temperature (Tm) of about 180-190°C, which defines its processing conditions. Its thermal stability makes it suitable for applications requiring moderate heat resistance. The degradation of PLA occurs under composting conditions at temperatures above 60°C, leading to its decomposition into lactic acid, which can further be utilized in various biological processes. These properties contribute to PLA's growing popularity in sustainable materials development and 3D printing technologies.

2.2 Carbon fibers (CF)

Carbon fibers are high-performance materials composed primarily of carbon atoms, known for their exceptional strength-to-weight ratio and stiffness. These fibers are produced through the carbonization of precursor materials, such as polyacrylonitrile (PAN), pitch, or rayon, which are heated to high temperatures (above 1000°C) in an inert atmosphere. Carbon fibers typically exhibit a density of around 1.7 g/cm³, significantly lower than metals, making them an attractive choice for lightweight structural applications. In terms of physical properties, carbon fibers possess remarkable tensile strength, ranging from 2000 to 6000 MPa, and a tensile modulus between 200 and 500 GPa, allowing them to withstand high stresses without deformation. Their elongation at break is usually low, around 1-2%, indicating their brittle nature. Thermally, carbon fibers have excellent thermal stability, with a thermal conductivity of approximately 20-200 W/m·K, depending on the fiber type and orientation. They exhibit a high thermal decomposition temperature, typically above 300°C, making them suitable for high-temperature applications. Additionally, carbon fibers are chemically inert and resistant to many corrosive environments, further enhancing their applicability in aerospace, automotive, and sports equipment industries. These properties make carbon fibers a popular choice for composite materials, where they are often combined with polymers to create lightweight, strong, and durable components.

2.3 Synthesis of PLA – CF filament

The synthesis of Polylactic Acid (PLA) carbon fiber filament is a multi-step process designed to effectively combine carbon fibers with PLA, significantly enhancing the mechanical and thermal properties of the final product. The process begins with the selection of high-quality PLA, which typically has a molecular weight ranging from 100,000 to 200,000 g/mol. This range ensures suitable viscosity and flow characteristics during the extrusion process, enabling efficient processing without compromising the material's integrity. Next, carbon fibers are selected based on their exceptional properties, which include tensile strengths reaching up to 6000 MPa and moduli ranging from 200 to 500 GPa. These fibers are generally cut into lengths of 1 to 5 mm, optimizing their dispersion within the PLA matrix and maximizing their reinforcing effect. The proportion of carbon fibers added to the PLA is carefully controlled, with typical loadings ranging from 5% to 30% by weight; a loading of around 15% is commonly used to strike a balance between improved mechanical performance and processability. The actual compounding of the PLA and carbon fibers is conducted using a twin-screw extruder, which operates at temperatures between 160°C and 190°C. This temperature range is crucial for ensuring that the PLA maintains its flow properties while facilitating the dispersion of the carbon fibers throughout the polymer matrix. During this phase, the shear forces generated by the extruder help achieve a uniform mixture, which is critical for ensuring consistent properties in the final filament.

Once compounded, the mixture is extruded through a die at temperatures of approximately 180°C to 210°C to produce the filament. The control of the extrusion temperature is essential, as it affects the filament's final properties, including its diameter, which is typically maintained within 1.75 mm or 2.85 mm to suit standard 3D printing equipment. After extrusion, the filament undergoes cooling, which can be achieved using a water bath or air cooling system. This cooling step solidifies the material, and the rate of cooling can influence the crystallinity and mechanical properties of the filament. Following cooling, the filament is spooled onto reels for storage and later use in 3D printing. Throughout the entire synthesis process, rigorous quality control measures are implemented. These include monitoring the diameter consistency of the filament, which is generally maintained within ±0.05 mm, and conducting mechanical tests to evaluate properties such as tensile strength and modulus. The resulting PLA carbon fiber filament showcases significantly improved mechanical properties compared to standard PLA, with tensile strengths reaching up to 100 MPa and tensile moduli exceeding 6 GPa. Additionally, the thermal properties are enhanced, with a glass transition temperature (Tg) around 60°C and a melting temperature (Tm) of approximately 180°C. This comprehensive synthesis process culminates in a high-performance filament that leverages the biodegradable nature of PLA while benefiting from the outstanding strength and stiffness of carbon fibers.

2.4 Synthesis of PLA – CF

The synthesis of Polylactic Acid (PLA) carbon fiber composites using an injection molding machine involves combining carbon fibers with PLA to enhance the material’s mechanical and thermal properties. The process begins by selecting PLA with a molecular weight of 100,000 to 200,000 g/mol to ensure optimal flow during processing. Carbon fibers, known for their high tensile strengths (up to 6000 MPa) and moduli (200-500 GPa), are added to the PLA matrix, typically in weight fractions between 5% and 30%. A twin-screw extruder operates at 160°C to 190°C to uniformly disperse the carbon fibers throughout the PLA. The compounded material is then pelletized and introduced into the injection molding machine, where it is melted at temperatures ranging from 180°C to 210°C. The molten composite is injected into a mold under high pressure, usually between 50 and 150 MPa, and the mold is kept at temperatures of 30°C to 60°C to ensure proper cooling and crystallization. Controlling the injection speed and pressure is crucial to preventing fiber breakage, as carbon fibers are sensitive to high shear forces. Cycle times range from 30 to 90 seconds, depending on part complexity and thickness. Once the part has cooled and solidified, it is ejected from the mold. The resulting PLA carbon fiber parts exhibit tensile strengths up to 100 MPa and improved thermal properties, with a glass transition temperature around 60°C and melting point at 180°C. These composites offer better dimensional stability and resistance to deformation, ensuring high-quality performance across various uses.

2.5 Composites sample preparation

The preparation of PLA-carbon fiber composites involves incorporating carbon fibers into the PLA matrix at varying weight percentages (5% to 30%) in 5% increments. The process begins with compounding the PLA and carbon fibers using a twin-screw extruder at temperatures between 160°C and 190°C to ensure uniform fiber dispersion. The compounded mixture is then pelletized and either processed through traditional injection molding or 3D printing. In injection molding, the pellets are melted at 180°C to 210°C and injected into molds, while for 3D printing, the mixture is extruded into filament and printed using fused deposition modeling (FDM) techniques. Tensile test samples are prepared in a dog bone shape following ASTM D638 standards, with five samples made for each weight percentage. These samples are tested for tensile strength, modulus, and elongation at break using a universal testing machine. For thermal conductivity testing, rectangular samples measuring 30 x 30 x 10 mm are prepared from each formulation and analyzed using thermal conductivity equipment. The study includes five samples per weight percentage for both tensile and thermal tests, ensuring accuracy and statistical reliability. Comparing injection molding and 3D printing methods allows for an understanding of how different fabrication processes impact the mechanical and thermal properties of PLA-carbon fiber composites.

2.6 Tensile testing

Tensile testing of polymer composites is performed using an Instron universal testing machine to evaluate key mechanical properties such as tensile strength, modulus, and elongation at break. The composite specimens are prepared in a dog bone shape according to the ASTM D638 standard, with a gauge length typically set between 50 to 115 mm depending on the sample size. The loading rate is maintained at a constant speed of 1 to 5 mm/min, ensuring consistent strain application. The polymer composite samples are clamped securely in the machine's grips, and tensile force is applied until the specimen fractures. The machine records the stress-strain behavior throughout the test, allowing for the determination of tensile properties. The Instron system provides precise control and real-time data acquisition, with the load cell calibrated for polymer composites testing to handle forces depending on the material's strength. The results, including tensile strength (measured in MPa), modulus, and percentage elongation, are used to compare the mechanical performance of different composite formulations.

2.7 Thermal conductivity

The Laser Flash Method (LFA) is a widely used technique for measuring the thermal conductivity of composite materials, especially for high-performance applications. The procedure begins with the preparation of a solid, flat sample, typically in a disc or rectangular shape, with dimensions ranging around 10 to 30 mm in diameter or side length and 1 to 10 mm in thickness, depending on the equipment's specifications. The sample is placed in a temperature-controlled chamber within the Laser Flash Apparatus. During the test, a short laser pulse is applied to one side of the sample. This pulse heats the surface, and the resulting temperature rise on the opposite side of the sample is monitored using an infrared detector. The time taken for the heat to propagate through the material is recorded, which is referred to as thermal diffusivity.The Laser Flash Method is advantageous because it is non-contact, quick, and capable of testing materials at various temperatures, ranging from room temperature to high temperatures (up to 2000°C), depending on the apparatus. It provides accurate thermal conductivity values in W/m·K and is ideal for anisotropic composite materials where heat conduction varies in different directions.

$$k=\alpha \cdot \rho \cdot Cp \qquad (1)$$

Where,

α = *Thermal diffusivity (measured in mm²/s)*
ρ = *Density of the composite material (kg/m³)*
Cp =Specific heat capacity (J/kg·K)

3.Result and discussion

3.1 Tensile characteristics

The tensile tests were conducted on both PLA-carbon fiber (CF) regular composites and 3D printed PLA-CF composites, with the results compared to evaluate the impact of varying carbon fiber weight fractions on tensile strength as shown in Figure 1. The weight percentages of carbon fiber reinforcement ranged from 5 wt.% to 30 wt.%, with increments of 5 wt.%, allowing for a comprehensive analysis of the relationship between fiber loading and mechanical performance. The PLA-CF regular composites, a consistent improvement in tensile strength was observed as the carbon fiber content increased, up to 25 wt.%. At 25 wt.%, the composite demonstrated peak tensile strength, showing a 192% enhancement compared to pure PLA. This notable increase can be attributed to the effective load transfer between the PLA matrix and the reinforcing carbon fibers, which significantly boosts the composite's ability to resist tensile forces. Additionally, starting from 5 wt.% of carbon fiber, the tensile strength increased progressively by 39%, 64%, 92%, and 129% at 10 wt.%, 15 wt.%, and 20 wt.%, respectively. However, when the carbon fiber content reached 30 wt.%, a 88% improvement in tensile strength was observed compared to pure PLA, but the strength was slightly reduced compared to the 25 wt.% composite. This drop may be attributed to issues such as fiber agglomeration or suboptimal fiber-matrix bonding at higher fiber loadings, which can lead to stress concentrations and premature failure under load.

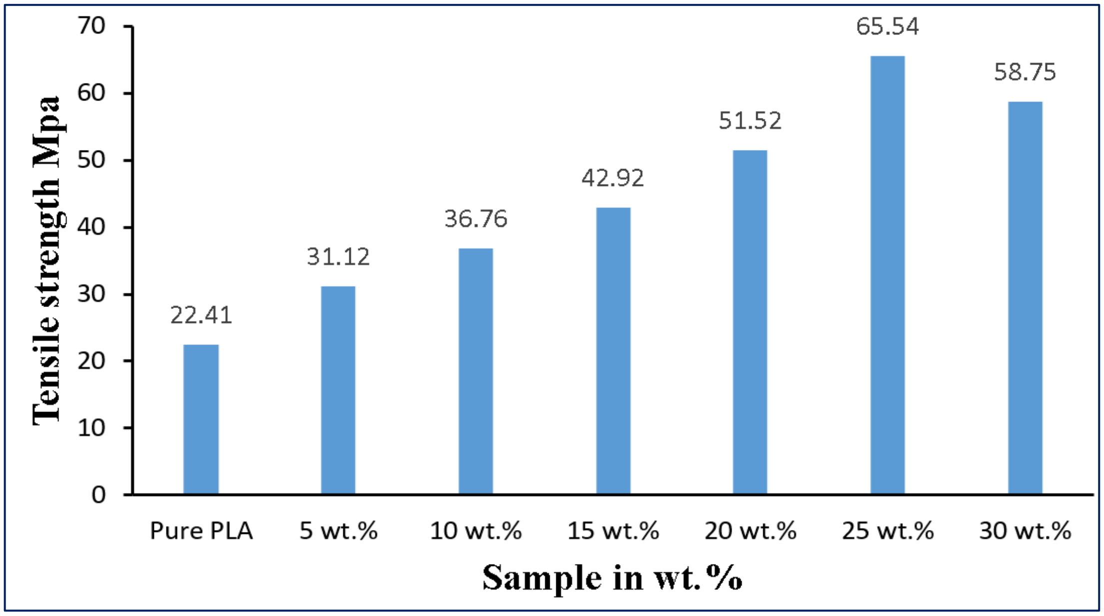

Figure 1: Tensile strength of regular PLA – Carbon fiber (CF) reinforced composites

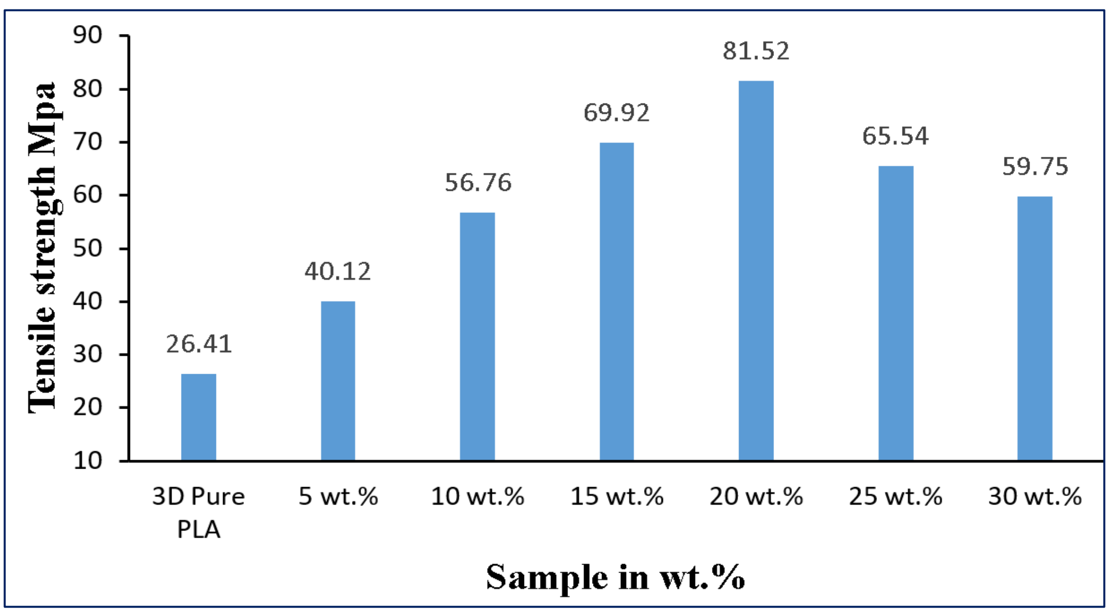

Figure 2: Tensile strength of 3D printed PLA – Carbon fiber (CF) reinforced composites

The 3D printed PLA-CF composites, tensile strength results exhibited a similar trend but with even more pronounced improvements. The 20 wt.% PLA-CF 3D printed composite exhibited an 209% increase in tensile strength compared to pure PLA, showing that 3D printing methods can effectively capitalize on the reinforcing properties of carbon fibers. This can be linked to the controlled layer-by-layer deposition process in 3D printing, which may contribute to better alignment of the fibers along the load direction, thereby enhancing mechanical properties. The 5 wt.% carbon fiber content in 3D printed composites showed a significant 52% increase in tensile strength, while further increments to 10 wt.% and 15 wt.% resulted in tensile strength improvements of 115% and 165%, respectively.However, similar to the regular composites, a slight reduction in tensile strength was observed at 25 wt.% and 30 wt.% in the 3D printed samples, where the tensile strength improvements dropped to 148% and 126%, respectively. This reduction, compared to the 20 wt.% composite, can again be linked to potential fiber misalignment, void formation, or overcrowding of fibers at higher weight fractions, which may hinder optimal stress transfer from the PLA matrix to the carbon fibers. Despite the reduction when compared to 20 wt.%, the tensile strength at 25 wt.% and 30 wt.% remained significantly higher than that of pure PLA, indicating the continued reinforcing effects of the carbon fibers, albeit less effectively utilized at higher loadings.

The study highlights that carbon fiber reinforcement plays a critical role in enhancing the tensile strength of both regular PLA composites and 3D printed composites. However, there appears to be an optimal fiber loading, particularly around 20 wt.% to 25 wt.%, where the tensile strength reaches its peak. Beyond this threshold, fiber dispersion, bonding efficiency, and manufacturing method play a crucial role in determining the mechanical properties, as observed from the slight reductions in tensile strength at higher fiber loadings. The data from both regular and 3D printed composites provide valuable insights into the structural integrity and performance of PLA-based materials reinforced with carbon fibers, particularly for applications where mechanical strength is a priority. By comparing the two methods, it is evident that 3D printing provides slightly enhanced tensile properties at similar fiber loadings, potentially due to the inherent benefits of controlled fiber deposition in additive manufacturing.This investigations underlines the importance of selecting the appropriate fiber loading and manufacturing technique to optimize the mechanical performance of PLA composites, especially for applications requiring high strength and reliability.

3.2 Composites fractured surface morphology analysis

The FESEM morphology analysis of the tensile test fractured surfaces provides crucial insights into the underlying failure mechanisms, correlating directly with the observed tensile strength improvements in both PLA-CF regular composites and 3D printed PLA-CF composites as shown in Figure 3 and 4. In the PLA-CF regular composites, significant improvements in tensile strength were observed up to 25 wt.% carbon fiber content, as confirmed by the FESEM analysis. At lower fiber contents (5 wt.% to 15 wt.%), the fractured surfaces exhibit smooth regions with some fiber pull-out, indicating limited fiber-matrix interaction and suggesting that failure was primarily matrix-dominated. As the fiber content increases to 25 wt.%, the fracture surfaces reveal more pronounced fiber bridging, fiber pull-out, and fiber breakage, signifying stronger interfacial adhesion between the PLA matrix and carbon fibers. The presence of shorter pull-out lengths and some broken fibers at this weight percentage indicates effective stress transfer from the matrix to the reinforcing fibers, contributing to the peak tensile strength at 25 wt.%. However, at 30 wt.%, FESEM images reveal fiber agglomeration and the presence of voids, leading to premature failure and a reduction in tensile strength, likely due to stress concentration points formed by poorly dispersed fibers.

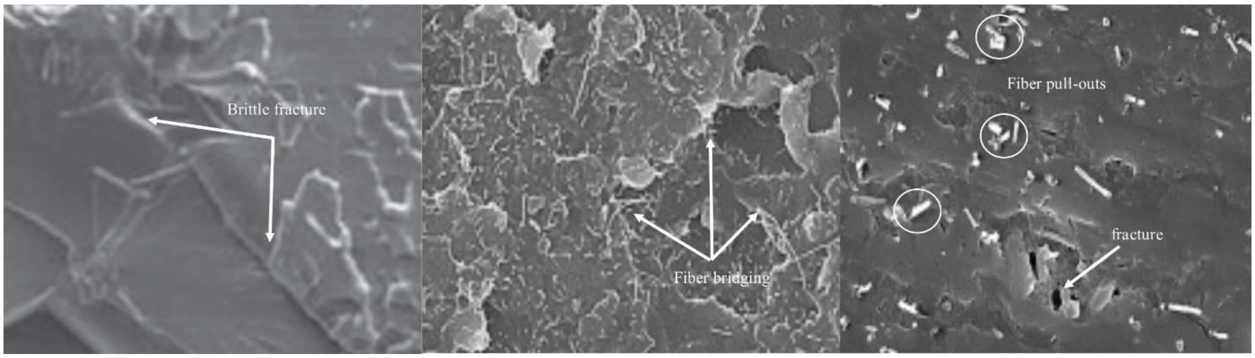

Figure 3: Fracture surface morphology analysis of pure PLA, PLA – 25wt.% and PLA – 30wt.%

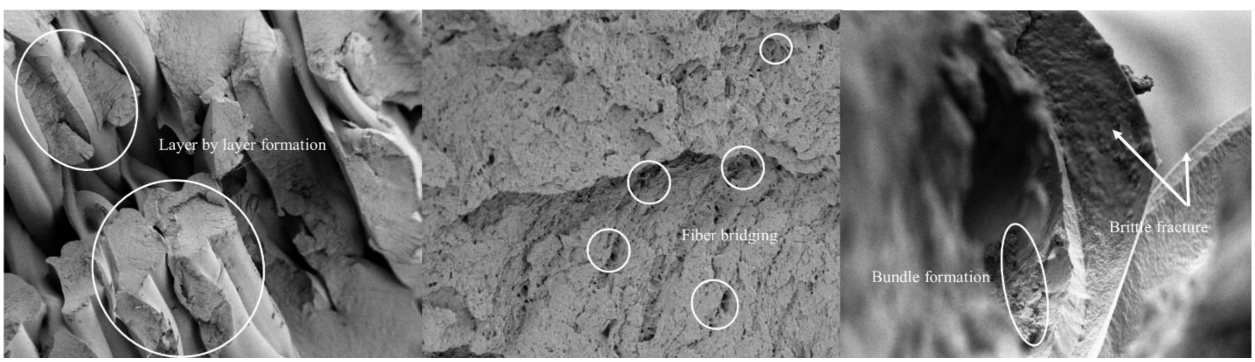

Figure 4: Fracture surface morphology analysis of 3D printed pure PLA, PLA – 20wt.% and PLA – 30wt.%

In the case of 3D printed PLA-CF composites, significant tensile strength improvement was noted up to 20 wt.%, with FESEM analysis further supporting these findings. At lower fiber loadings (5 wt.% to 15 wt.%), the fracture surfaces exhibit layered striations, a result of the fused deposition modeling (FDM) process, along with some fiber pull-out, indicating moderate fiber-matrix bonding. At 20 wt.%, the FESEM images show fibers more uniformly embedded in the PLA matrix, with minimal fiber pull-out and some evidence of fiber breakage, indicating stronger fiber-matrix interaction and efficient stress transfer, which explains the enhanced tensile strength at this fiber content. The layered striations are less pronounced, suggesting improved interlayer bonding at this loading. However, at higher fiber contents (25 wt.% and 30 wt.%), the fracture surfaces reveal interlayer delamination, void formation, and increased fiber pull-out, contributing to the reduction in tensile strength. These defects likely result from incomplete fusion between printed layers and the presence of fiber agglomerates, which disrupt the structural integrity of the composites at higher carbon fiber loadings.Thus, the FESEM analysis highlights how optimal fiber distribution, fiber-matrix bonding, and the manufacturing process significantly impact the mechanical properties of PLA-CF composites, with regular composites performing best at 25 wt.%, and 3D printed composites at 20 wt.%, before fiber dispersion and processing defects limit further tensile improvements.

3.3 Thermal conductivity

The thermal conductivity analysis of both PLA-CF regular composites and 3D printed PLA-CF composites with 30 wt.% carbon fiber reinforcement reveals a substantial reduction in heat transfer properties. The PLA-CF regular composites exhibited a 74% reduction in thermal conductivity, while the 3D printed PLA-CF composites demonstrated an even more pronounced 92% reduction. This significant decrease in thermal conductivity indicates the material's ability to act as an effective thermal insulator, enhancing its thermal resistance. The introduction of carbon fibers into the PLA matrix alters the composite's thermal conduction pathways, where the carbon fibers, though thermally conductive, are dispersed within a thermoplastic matrix that impedes heat flow. At 30 wt.%, the carbon fibers create thermal barriers, preventing efficient heat transfer due to fiber agglomeration and fiber-matrix interfacial resistance, which further reduces thermal conductivity.The 3D printed PLA-CF composites show greater thermal resistance, likely due to the layer-by-layer deposition in the Fused Deposition Modeling (FDM) process, which introduces additional interfacial thermal resistances between layers, disrupting the continuity of thermal conduction. These interfacial voids and the anisotropic nature of the printed layers enhance the material’s ability to resist heat flow, contributing to the higher thermal resistance. This behavior is highly advantageous in applications requiring materials with low thermal conductivity and good insulation properties, as the reduced thermal conductivity translates to improved thermal stability under varying thermal loads. The combination of carbon fiber reinforcement and the processing method plays a critical role in controlling the composite's thermal behavior, making PLA-CF composites particularly useful in environments where thermal management is essential.

4. Conclusion

The investigation of PLA-carbon fiber (CF) regular composites and 3D printed PLA-CF composites shows substantial enhancements in both tensile strength and thermal resistance due to carbon fiber reinforcement. Tensile strength improvements were observed up to 192% for regular composites at 25 wt.%, and 209% for 3D printed composites at 20 wt.%, compared to pure PLA, driven by efficient load transfer and strong fiber-matrix interactions, as verified by FESEM analysis. However, at 30 wt.%, both composites exhibited slight reductions in tensile strength (88% for regular composites and 126% for 3D printed samples) due to fiber agglomeration and void formation, which compromised the fiber dispersion and stress transfer. In terms of thermal properties, the regular composites demonstrated a 74% reduction in thermal conductivity, while the 3D printed composites showed an even more significant 92% reduction, attributed to the layer-by-layer FDM process, which created interfacial thermal resistances and disrupted heat transfer pathways. These findings emphasize the importance of optimizing fiber content and manufacturing techniques to maximize both mechanical and thermal performance, making PLA-CF composites ideal for applications requiring superior strength and thermal stability.

References

1. Zhang, Y., Liu, Q., Liu, Z., Wang, C., & Yu, Y. (2020). "Enhancement of mechanical properties in carbon fiber-reinforced PLA composites for 3D printing." Materials Science and Engineering: A, 791, 139708. http://doi.org/10.1016/j.msea.2020.139708
2. Ferreira, R.T.L., Amatte, I.C., Dutra, T.A., & Bürger, D. (2017). "Mechanical properties of carbon fiber-reinforced thermoplastic composites using 3D printing." Polymer Composites, 38(3), 455-463. http://doi.org/10.1002/pc.23636
3. Ning, F., Cong, W., Qiu, J., Wei, J., & Wang, S. (2015). "Additive manufacturing of carbon fiber-reinforced thermoplastic composites using fused deposition modeling." Composites Part B: Engineering, 80, 369-378.http://doi.org/10.1016/j.compositesb.2015.06.013.
4. Li, N., Li, Y., & Liu, S. (2016). "Rapid prototyping of continuous carbon fiber-reinforced polylactic acid composites by 3D printing." Journal of Materials Processing Technology, 238, 218-225.http://doi.org/10.1016/j.jmatprotec.2016.07.025
5. Tian, X., Liu, T., Yang, C., Wang, Q., & Li, D. (2016). "Interface and performance of 3D printed continuous carbon fiber-reinforced PLA composites." Composites Part A: Applied Science and Manufacturing, 88, 198-205. http://doi.org/10.1016/j.compositesa.2016.06.032
6. Dickson, A.N., Barry, J.N., McDonnell, K.A., & Dowling, D.P. (2017). "Fabrication of continuous carbon, glass and Kevlar fiber-reinforced polymer composites using additive manufacturing." Additive Manufacturing, 16, 146-152. http://doi.org/10.1016/j.addma.2017.06.004
7. Tsouknidas, A., Pantazopoulos, M., Katsoulis, I., Fasnakis, D., Maropoulos, S., & Michailidis, N. (2016). "3D printed carbon-fiber reinforced thermoplastic insulators for biomedical applications." Polymers, 8(3), 82. http://doi.org/10.3390/polym8030082.
8. Goh, G.D., Yap, Y.L., Tan, H.K.J., Sing, S.L., Yeong, W.Y., & Tan, M.J. (2018). "Characterization of mechanical properties and failure analysis of carbon fiber-reinforced nylon 3D printed composites." Materials & Design, 137, 79-89. http://doi.org/10.1016/j.matdes.2017.10.057
9. Chacón, J.M., Caminero, M.A., García-Plaza, E., & Núñez, P.J. (2019). "Additive manufacturing of continuous carbon fiber-reinforced thermoplastics: Processing and characterization." Additive Manufacturing, 25, 258-269. http://doi.org/10.1016/j.addma.2018.11.002

10. Matsuzaki, R., Ueda, M., Namiki, M., Jeong, T.K., Asahara, H., Horiguchi, K., & Nakamura, T. (2016). "Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation." Scientific Reports, 6, 23058.http://doi.org/10.1038/srep23058
11. Cicala, G., Latteri, A., Marchetti, M., Reina, G., & La Rosa, G. (2018). "Integration of FDM additive manufacturing with thermoforming for cost-effective continuous carbon fiber composites." Composites Part B: Engineering, 132, 152-160. http://doi.org/10.1016/j.compositesb.2017.09.022
12. Shiratori, H., Sakamoto, S., Sekine, H., Kudo, A., Suzuki, S., &Torizuka, S. (2019). "Mechanical and thermal properties of continuous carbon fiber-reinforced 3D printed thermoplastic composites." Polymers, 11(10), 1688. http://doi.org/10.3390/polym11101688
13. Gkartzou, E., Koumoulos, E.P., &Charitidis, C.A. (2017). "Production and 3D printing processing of bio-based thermoplastic filament reinforced with carbon fibers." Manufacturing Review, 4, 12. http://doi.org/10.1051/mfreview/2017010
14. Markandan, K., Khan, F.U., Jeevanandam, J., Mani, S., Yahya, M.Y., & Kun, Y.Z. (2022). "Mechanical, thermal, and wear characterization of 3D-printed carbon fiber-reinforced thermoplastics." Journal of Materials Engineering and Performance, 31, 7116-7127. http://doi.org/10.1007/s11665-022-07070-5
15. Blok, L.G., Longana, M.L., Yu, H., & Woods, B.K.S. (2018). "An investigation into 3D printing of fiber-reinforced thermoplastic composites." Additive Manufacturing, 22, 176-186. http://doi.org/10.1016/j.addma.2018.05.021