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Optimization of Innovative Hybrid Polylactic Acid+ and Glass Fiber Composites: Mechanical, Physical, and Thermal Evaluation of Woven Glass Fiber Reinforcement in Fused Filament Fabrication 3D Printing

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Abstract: The growing demand for complex structures, energy absorption, and mechanically strong materials has led to the exploration of innovative composites. This study focuses on the manufacture, characterization, and evaluation of PLA+ reinforced with woven glass fiber. Using Fused Filament Fabrication (FFF) 3D Printer technology, the effects of adding woven glass fiber were examined through a tensile test with Digital Image Correlation (DIC)-induced, flexural, Charpy impact resistance, Shore D hardness, Differential Scanning Calorimetry (DSC) thermal tester, and SEM morphological tests. Results showed that adding four layers of glass fiber significantly improved mechanical properties: tensile strength increased by 85% to 95.44 MPa, flexural strength by 13% to 91.51 MPa, and impact resistance by 450% to 15.12 kJ/m^2. However, a reduction in hardness and thermal resistance was noted due to chemical interactions. These findings suggest potential applications of PLA+ composites in high-strength products for vehicle bumpers in the automotive industry and shin pads in the sports industry.

Keywords: composite; woven glass fiber; FFF; PLA+; reinforcement

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1. Introduction

Thermoplastic materials fabricated using Additive Manufacturing (AM) have been widely employed in the automotive and aerospace industries, primarily for prototyping [1,2]. The strength and toughness of thermoplastic materials are undoubtedly crucial factors in their application. Thermoplastics offer distinct advantages over other materials, such as thermosets, as they are easily recyclable and highly resistant to corrosion [3,4]. These characteristics make them particularly advantageous for automotive and aerospace applications. In the automotive field, such as in electric cars, thermoplastics are used as base materials for components like car walls [5]. Beyond the automotive and aerospace sectors, fields such as sports and medicine also frequently use thermoplastic polymer materials [6,7]. Composites must meet high feasibility standards, demonstrating optimal energy absorption capabilities while maintaining the established mechanical strength requirements to enhance product performance. Numerous studies have focused on improving energy absorption properties, particularly in polymer studies [8–10]. Polymers are considered to

have significant potential for further development because they are lighter, less expensive, and easier to shape than metals and ceramics, although they typically have lower mechanical strength [11]. One method for producing polymers involves transforming them into filaments, which are then printed using a 3D printing technique known as Fused Filament Fabrication (FFF). Compared to other manufacturing methods, FFF is more efficient at creating complex objects [12,13]. To enhance mechanical strength, polymers can be combined with other materials, such as glass fiber. The process of enhancing mechanical strength is approached by creating a composite using Polylactic Acid (PLA+) as the matrix and glass fiber as the reinforcement [14,15]. This combination improves the mechanical strength of PLA+ by leveraging the superior mechanical properties of glass fiber.

In this context, PLA+ was chosen as one of the most commonly used materials for product printing using AM [16,17]. The selection of PLA+ as the matrix material was based on its superior impact resistance compared to conventional PLA, making it suitable for applications requiring improved mechanical performance [18]. The mechanical properties of PLA have been tested and compared with several other polymers, such as Polyvinyl Chloride (PVC), Polystyrene (PS), Polypropylene (PP), and Nylon, which have tensile strength values of 49 MPa, 35.4 MPa, 49 MPa, and 71 MPa, respectively. Meanwhile, the flexural strength values are 70 MPa, 90 MPa, 80 MPa, 49 MPa, and 95 MPa, respectively [19]. It was found that PLA has the highest tensile strength among these polymers. However, some disadvantages of PLA+ include low toughness [20,21]. Strengthening methods are needed to increase the toughness of PLA+. The enhancement of polymer materials has been extensively studied in both academic and industrial fields. PLA+ can be improved by incorporating other materials, such as fibers, fillers, or nanomaterials, into the matrix [15,22,23].

Compared to metals, composites exhibit more complex mechanical properties, as their strength depends on factors such as fiber breakage within the composite, delamination, matrix cracking, and fiber detachment from the matrix [24–26]. Additionally, the energy absorption characteristics of composites are influenced by factors such as the type of reinforcement, fiber orientation, loading conditions, and geometric structure. Previous studies have used PLA+ as the matrix with carbon fiber as reinforcement, demonstrating that the addition of fibers can enhance the mechanical properties of PLA+ [15]. Another study investigated the inclusion of pine wood powder as reinforcement, showing that it also improves the mechanical properties of PLA+ [27]. Similarly, research on PLA combined with carbon fiber found that adding carbon fiber significantly enhances its mechanical properties [28–30]. Other studies incorporated glass fiber into PLA, which was also shown to enhance its mechanical properties [31,32]. Additionally, bio-fibers such as jute and nettle have been successfully used to reinforce PLA, further improving its mechanical performance [33,34]. Glass fiber has mechanical strength, but also a favorable balance of properties. While its overall strength is lower than other reinforcements fiber such as carbon fiber, it offers a high specific strength and is significantly more cost-effective [35]. These characteristics make glass fiber a practical and efficient reinforcement material for PLA+ composites.

This study explores the fabrication of composites using FFF technology, with PLA+ as the matrix and woven glass fiber as reinforcement. The novelty lies in the integration of woven glass fiber during the FFF process, offering a practical approach to significantly enhance PLA+'s mechanical properties, particularly tensile and impact resistance. By combining PLA+ with the superior mechanical attributes of glass fiber, this study aims to address the growing demand for complex structures with an ability to absorb the impact and made from strong materials. The findings of this research are particularly relevant for addressing key industrial challenges such as improving mechanical performance, cost-effectiveness, and sustainability in composite manufacturing. By enhancing the mechanical properties

of PLA+ with glass fiber reinforcement, this study has the potential to contribute to the development of more durable, efficient, and environmentally friendly composite materials. Mechanical tests, including tensile (ASTM D3039) [36], flexural (ASTM D790) [37], Charpy impact (ASTM E23) [38], and hardness (ASTM D2240) tests [39], along with thermal analysis namely Differential Scanning Calorimetry (DSC) and failure mechanism evaluation (SEM-EDX), were conducted.

2. Materials and Methods

2.1. Materials

This study utilized PLA+ material fabricated by Esun as the matrix and woven glass fiber as the reinforcement, with variations of 1, 2, 3 and 4 layers. Each variation of the test had a minimum of 5 test samples to minimize measurement errors and obtain more valid data. The composite fabrication process was carried out using an Anycubic Kobra Max FFF machine (Anycubic, Shenzhen, China). The Kobra Max was chosen due to its use of a distance sensor to adjust the gap between the nozzle and print bed. This feature is crucial in this study to accommodate the thickness of the woven glass fiber added during the manufacturing process.

2.2. Methods

2.2.1. Specimen Manufacturing Procedure

The manufacturing process of the PLA+ specimens reinforced with woven glass fiber was conducted using an Anycubic Kobra Max FFF Machine (Anycubic, Shenzhen, China), and the specimens were designed using Autodesk Inventor. The slicer software used was Ultimaker Cura (version 5.8.1). The printing parameters employed in this study are presented in Table 1. The addition of woven glass fiber was manually performed during the manufacturing process, with each layer of fiber pre-cut and carefully positioned. The manufacturing process for adding layers is as follows:

(a) Initial Layer:

The initial layer or base composite PLA+ reinforced with woven glass fiber is printed on the bed at temperature of 60 °C. This base layer serves as the initial foundation that adheres to the bed, facilitating the addition of glass fiber.

(b) Glass Fiber Addition:

Woven glass fiber was added to the PLA+ filament in four variations: 1, 2, 3, and 4 layers. During printing, the nozzle was raised using the pause function, and the glass fiber was placed on the sample. Layers were added with intervals to enhance bonding and stress distribution, ensuring that the glass fiber was aligned properly for optimal performance. Figure 1 illustrates the geometry of the woven glass fiber.

Table 1. Parameters of 3D printing.

Variable	Value	Unit
Layer Height	0.2	mm
Layer Width	0.4	mm
Wall Thickness	1.2	mm
Nozzle Temperature	208	°C
Bed Temperature	60	°C
Print Speed	60	mm/s
Infill	100	%
Top/Bottom Line Direction	45/−45	°

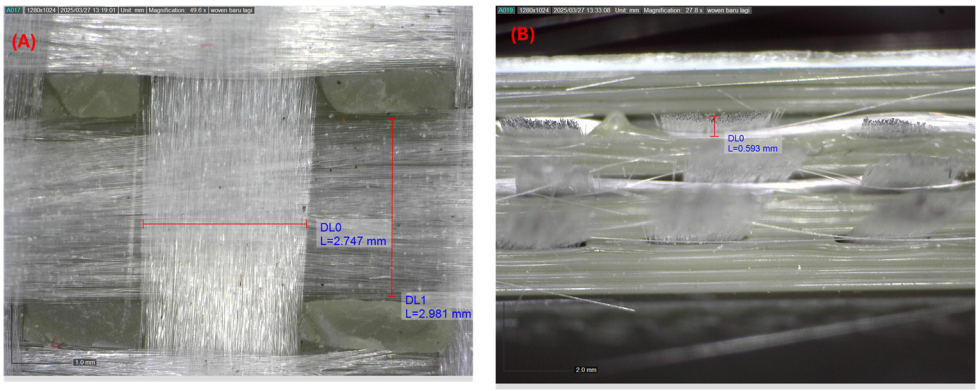


Figure 1. Geometric of woven glass fiber using Dino-lite digital microscope (Dino-Lite, Taipei, Taiwan), (**A**) width of woven glass fiber, (**B**) thickness of woven glass fiber.

(c) Next Layer:

After the woven glass fiber was placed, the printing process was continued by pressing the resume menu, as illustrated in Figure 2A–C. The sensor on the Kobra Max 3D printer (Anycubic, Shenzhen, China) played a crucial role in controlling the nozzle height, thereby facilitating the optimal distance between the glass fiber and the PLA+ filament. This ensures that the PLA+ material can penetrate the gaps within the glass fiber and merge with the base layer, creating a bond between the glass fiber and the PLA+.

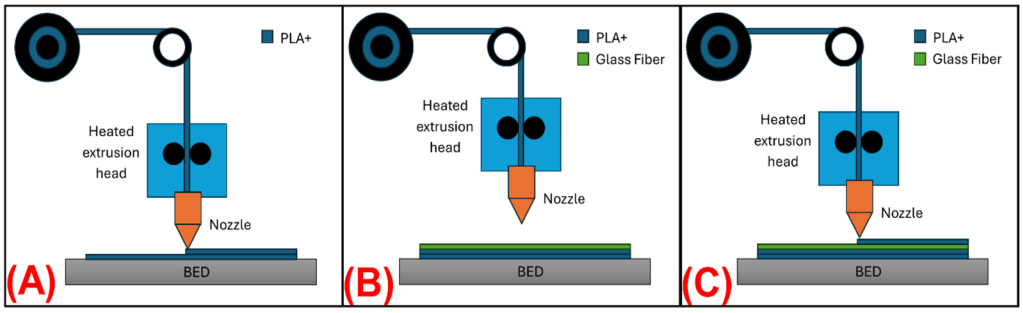


Figure 2. Schematic of the PLA+ and glass fiber composite manufacturing process: (**A**) molding of the initial layer, (**B**) addition of woven glass fiber on top of the initial layer, and (**C**) molding of the next layer on top of the woven glass fiber.

(d) Layer Variation:

To evaluate the effect of woven glass fiber reinforcement in PLA+, specimens were prepared with different fiber layer variations and the specimen thickness measured:

0 layers: PLA+ only. (t = 3 mm)
1 layer: Glass fiber added at 50% of the printing process (t = 3.15 mm).
2 layers: Glass fiber added at 33% and 66% (t = 3.3 mm).
3 layers: Glass fiber added at 25%, 50%, and 75% (t = 3.45 mm).
4 layers: Glass fiber added at 20%, 40%, 60%, and 80% (t = 3.6 mm).

The addition of a glass fiber layer increases the thickness of the specimen by 0.15 mm for each layer used as reinforcement. The glass fiber was placed precisely, ensuring alignment, consistent force, and even intervals to achieve proper bonding and stress distribution with the PLA+ matrix. For impact test specimens, the placement percentages were specifically calculated below the notch to improve accuracy.

2.2.2. Mechanical Testing

Mechanical testing was conducted to evaluate the properties of composites fabricated using an FFF 3D printer with PLA+ as the matrix and glass fiber as reinforcement. All tests were performed following ASTM standards to ensure accuracy and reliability, as shown in Figure 3A–D. The testing methods included the following.

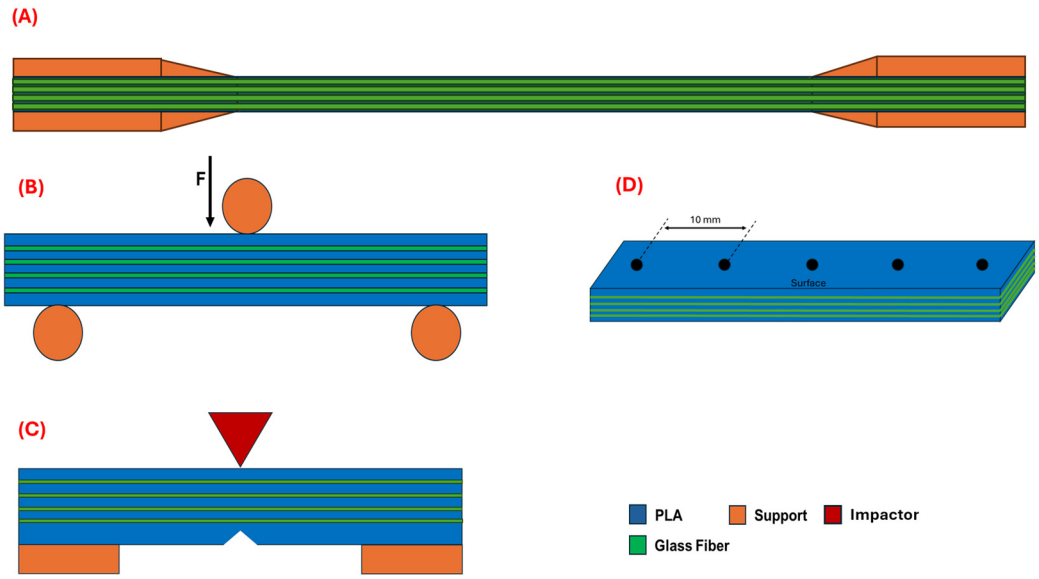


Figure 3. Specimen mechanical test with 4 layer additions of glass fiber. (**A**) Tensile test, (**B**) flexural test, (**C**) impact Charpy test, (**D**) hardness test.

(a) Tensile Test

The tensile test followed ASTM D3039 [36], designed for polymer composites. Five variations (0, 1, 2, 3, and 4 layers of glass fiber) were tested, with five specimens per variation. Specimens measured 20 mm × 200 mm, and testing was conducted at 2 mm/min for accurate strain transfer; we used Universal Testing Machine (UTM) from the Carson Brand with load capacity 50 kN (Carson, Taipei, Taiwan). Digital Image Correlation (DIC) was used during the tensile test to observe strain distribution in the PLA+ composite reinforced with woven glass fiber. This also helped to identify initial cracks by tracking pattern movements on the specimen's surface [40]. Before testing, the specimen was prepared with a white base coat and black spray paint to create a speckle pattern for DIC analysis. A digital camera CANON EOS 750 D with EF-S-18-55 mm lens was used for recording, and the data were analyzed using MATLAB R2024a version with the Ncorr toolbox [41,42].

(b) Flexural Test

The flexural test followed the ASTM D790 [37] standard, using a three-point bending method to evaluate the flexural stress and strain of PLA+ composites reinforced with woven glass fiber. Five variations (0, 1, 2, 3, and 4 layers) were tested, with five specimens per variation for reliable data. Specimens measured 12.5 mm × 100 mm, with thicknesses of 3–3.5 mm depending on the number of layers. The 100 mm length complied with the standard, which requires a minimum gauge length of 16 times the specimen thickness. The testing speed was set at 2 mm/min; for the flexural test, UTM from Carson brand with load capacity 50 kN was used.

(c) Impact Charpy Test

The impact test used the Charpy method following ASTM E23 [38], chosen for its suitability for thick specimens and compatibility with woven glass fiber reinforcement.

Specimens measured 10 mm × 55 mm with a 10 mm thickness, and glass fiber was added below the notch for accurate results. Five variations (0, 1, 2, 3, and 4 layers of glass fiber) were tested, with five specimens per variation. The hammer weighed 1 kg, with an arm length of 83 cm, and the test was conducted at an angle of 156°. The Charpy impact testing machine from Frank brand was used.

(d) Durometer Hardness Test

The hardness test followed the Shore D method as per ASTM D2240 [39], commonly used for polymers and elastomers. The test measured the hardness of PLA+ composites reinforced with woven glass fiber. Five variations (0, 1, 2, 3, and 4 layers) were tested, with five specimens per variation to ensure accuracy. Durometer Shore D HTTK-37D (Teckoplus, Hongkong, China) with range 0–100 HD was used in this test.

2.2.3. Characterization

Density, thermal, and morphology analyses were conducted to evaluate PLA+ composites reinforced with woven glass fiber. The density test measured five variations with specimens 20 mm × 20 mm and 3 mm thick. Thermal analysis, using Differential Scanning Calorimetry (DSC) A60 Plus (Shimadzu, Kyoto, Japan) instrument, assessed PLA+, glass fiber, and reinforced PLA+ by heating samples from 40 °C to 600 °C at 20 °C/min under a nitrogen atmosphere with flow rate 30 mL/min, identifying the glass transition, cold crystallization, melting point, and endothermic reactions. Morphological analysis, performed with a Scanning Electron Microscope (SEM) Phenom ProX (Thermo Fisher Scientific Inc., Waltham, MA, USA) and Dino-Lite microscope (Dino Lite, Taipei, Taiwan), examined failure patterns in flexural tests across all variations and assessed impact damage in a single sample. For SEM, BSD Detector brand was used with a magnification of 750× to 5000×; for the Dino-Lite microscope, a magnification of 40–60× was used.

3. Results

3.1. Tensile Test

The tensile test results are shown in Figure 4A–C. From Figure 4A, it can be seen that all samples exhibited plasticity after reaching a yield stress of 10 MPa and 0.5% strain, indicating that adding woven glass fiber to the PLA+ composite does not significantly affect the yield region. However, Figure 4B shows that adding glass fiber improves tensile strength consistently with an increasing number of layers. The fiber orientation of woven glass fiber has a significant impact; this is evident from the fact that, during the complete fracture of the PLA+ material, the woven glass fiber aligned with the direction of the applied force did not experience complete failure. This indicates that the woven glass fiber, when oriented in the same direction as the tensile load, is capable of withstanding greater loads compared to the PLA+ matrix. The lowest tensile strength was 31.82 MPa for no layers, while the highest was 59.44 MPa for four layers, representing an 85% improvement. This value is higher compared to PLA reinforced with ramie fibers. The printing angle also influenced tensile strength, with PLA+ printed at a 45° angle showing lower tensile stress (30 MPa) due to load distribution. This value is higher compared to PLA reinforced with ramie fibers [43]. The addition of one, two, and three layers of glass fiber resulted in tensile strength increases of 10% (36 MPa), 20% (40 MPa), and 60% (50 MPa), respectively. The increase in the value of tensile strength is due to the woven glass fiber, which helps to distribute the force evenly across the specimen area [12,15]. The elastic modulus remained nearly constant at approximately 2 GPa across all variations, indicating that the addition of the woven glass fiber mainly enhances tensile strength by distributing the load evenly, without significantly affecting stiffness.

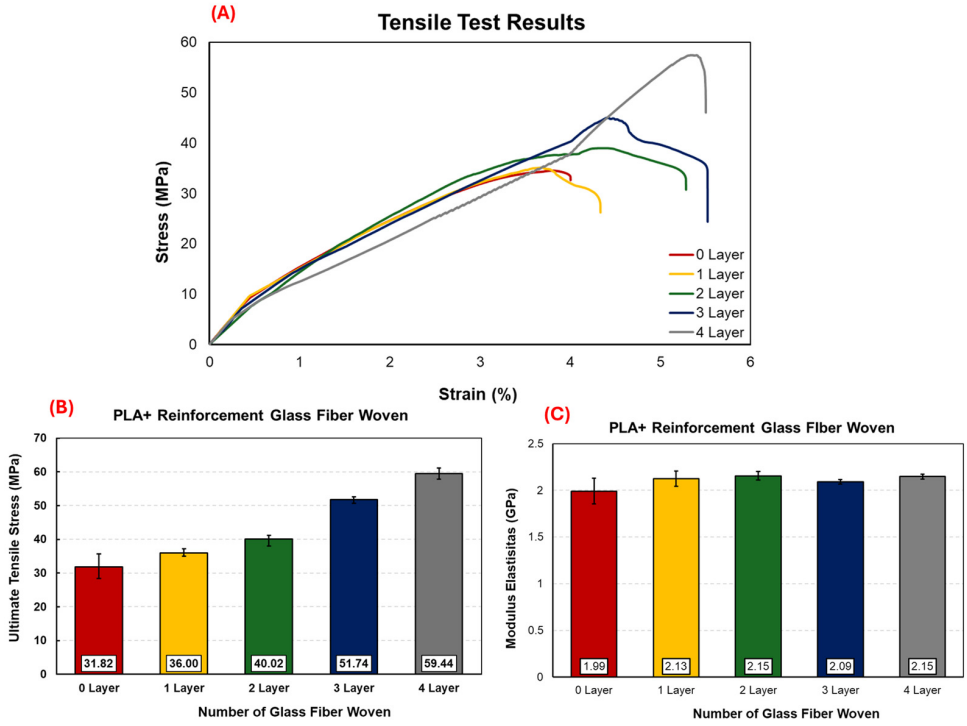


Figure 4. Tensile test data: (**A**) tensile test graph for each variation, (**B**) ultimate tensile stress graph, (**C**) tensile test elastic modulus graph.

All results of the Digital Image Correlation (DIC) analysis are shown in Figure 4. The DIC analysis at εyy, performed using Ncorr, highlights the failure occurring in PLA+ composites reinforced with woven glass fiber. Two types of images are presented for each variation: the failure image from the experiment and the failure image from the DIC analysis. As seen in Figure 5, the experimental failure and the red areas in the DIC analysis closely align, as the red areas indicate regions of high strain. The analysis not only shows the strain distribution but also helps identify the failure modes, such as delamination, interlaminar rupture, or fiber–matrix slippage, which are critical for understanding the material's behavior under stress. For the no-layer sample, the red area is concentrated in the center, showing that the highest strain occurs in the middle region. This indicates potential failure due to interlaminar rupture. In contrast, for the 1–4 layer samples, the failure pattern is more distributed due to the even strain distribution provided by the addition of the glass fiber. This suggests that glass fiber reinforcement helps reduce the likelihood of delamination and fiber–matrix slippage, leading to improved mechanical properties, such as strength, in PLA+ composites reinforced with glass fiber under tensile loading.

3.2. Flexural Test

As illustrated in Figure 6A, the addition of woven glass fiber to PLA+ composites produced using 3D print FFF improves flexural strength. However, the addition of woven glass fiber does not result in a significant change in the flexural modulus, indicating that it does not significantly affect the stiffness of PLA+. Figure 6B,C show that the PLA+ specimen (0 layer) had a flexural modulus of 2.86 GPa and a maximum flexural stress of 89.90 MPa but exhibited brittleness after surpassing its elastic limit. Adding one layer of glass fiber increased the maximum flexural stress to 93.11 MPa and the flexural modulus to 2.92 GPa, while also enhancing resistance to plastic deformation. With two layers, the maximum flexural stress reached 88.32 MPa, and the flexural modulus was 2.87 GPa. For the three-layer specimen, the maximum flexural stress increased to 90.31 MPa, but the elastic modulus decreased slightly to 2.85 GPa.

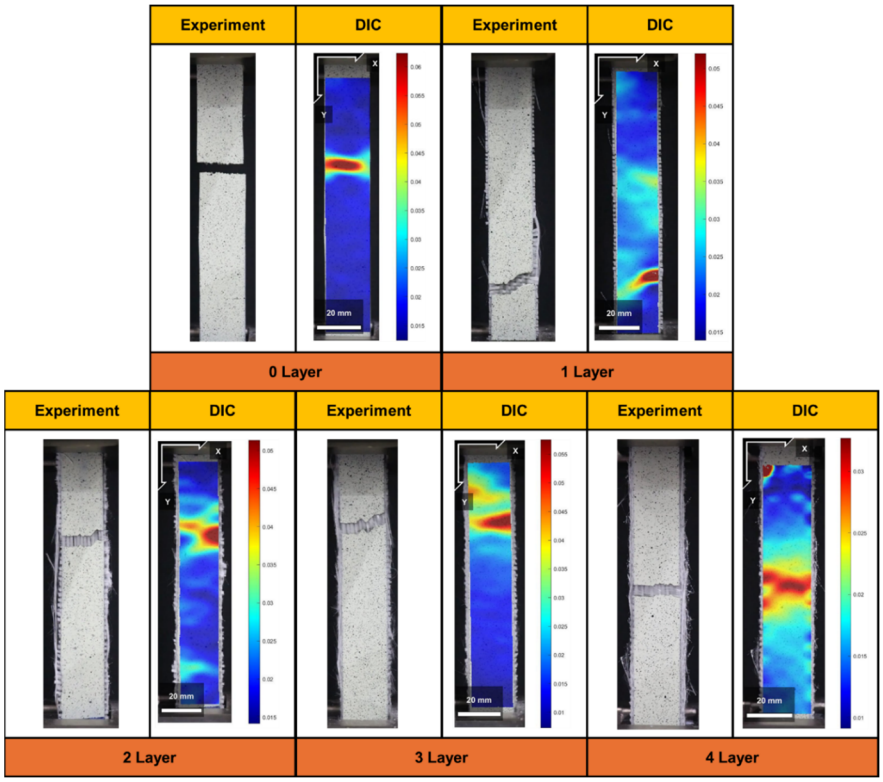


Figure 5. The results of the analysis using DIC during the tensile test.

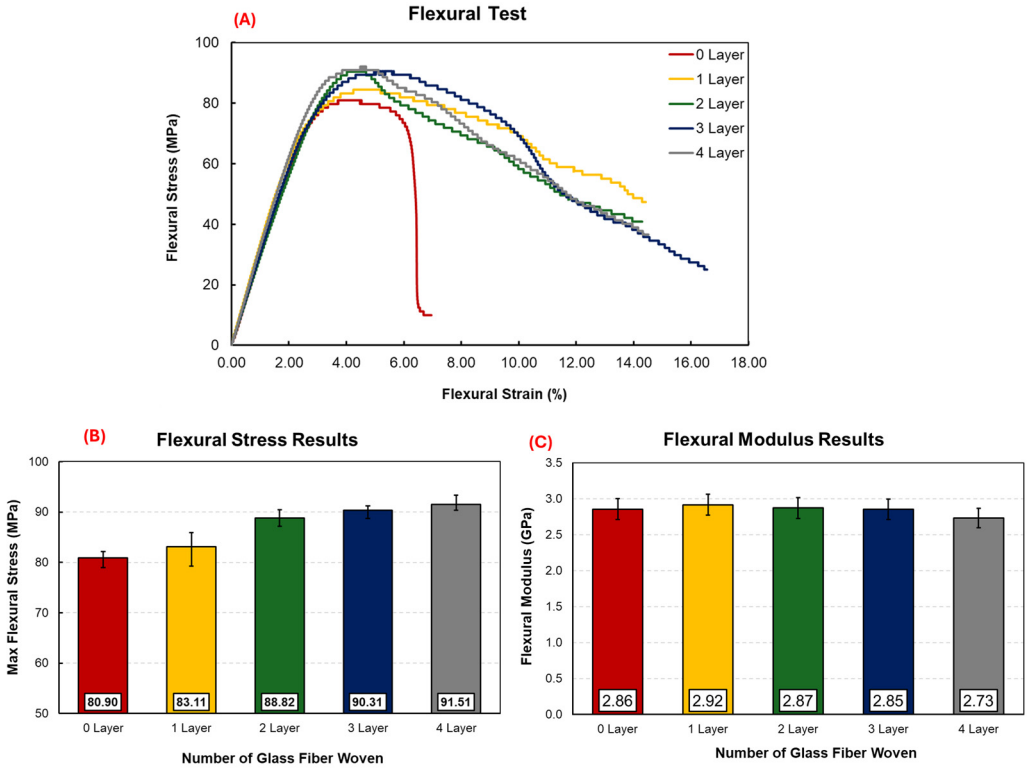


Figure 6. Flexural test results: (**A**) flexural test results graph, (**B**) flexural stress graph, (**C**) flexural modulus graph.

A further decrease in flexural modulus was observed in the four-layer specimen, which had a modulus of 2.73 GPa. This decrease could be attributed to the number of layers, which causes a reduction in the thickness of the PLA+ matrix. As a result, the specimen became more flexible because the glass fibers did not fully support the tensile

and compressive loads experienced by the specimen during the flexural test. However, the four-layer specimen exhibited the highest maximum flexural stress at 91.51 MPa. This behavior can be attributed to the addition of woven glass fiber improving stress distribution at the bottom of the specimen, as the glass fiber holds the tensile load in the flexural bottom area [44]. The increase in flexural strength with the addition of four layers of glass fiber does not fully align with theoretical predictions. It was expected that with two glass fiber layers supporting the tensile load at the bottom of the specimen, a significant improvement in flexural strength would occur. However, the test results show only a 13% increase. The flexural test concludes that adding glass fiber enhances the bending load resistance of PLA+. However, adding more than two layers of glass fiber led to a decrease in the flexural modulus, suggesting a potential reduction in stiffness.

Visual observations using a Dino-Lite microscope, as shown in Figure 7, reveal differences in the failure patterns of composites reinforced with woven glass fiber layers. The specimen with no layers, or without glass fiber, shows a failure pattern characterized by cracking at the bottom, the point of maximum stress. The addition of one layer of glass fiber does not result in significant changes, as the glass fiber is located at the neutral axis (the axis that does not experience compressive or tensile loads), leading to a failure pattern still marked by cracking at the bottom. The impact of glass fiber becomes evident with the addition of two to four layers, as this provides more even stress distribution, resulting in fracture patterns without cracking [45]. This aligns with the test results, where specimens with three and four layers exhibited lower modulus of elasticity compared to the no-layer specimen, which showed failure through cracking.

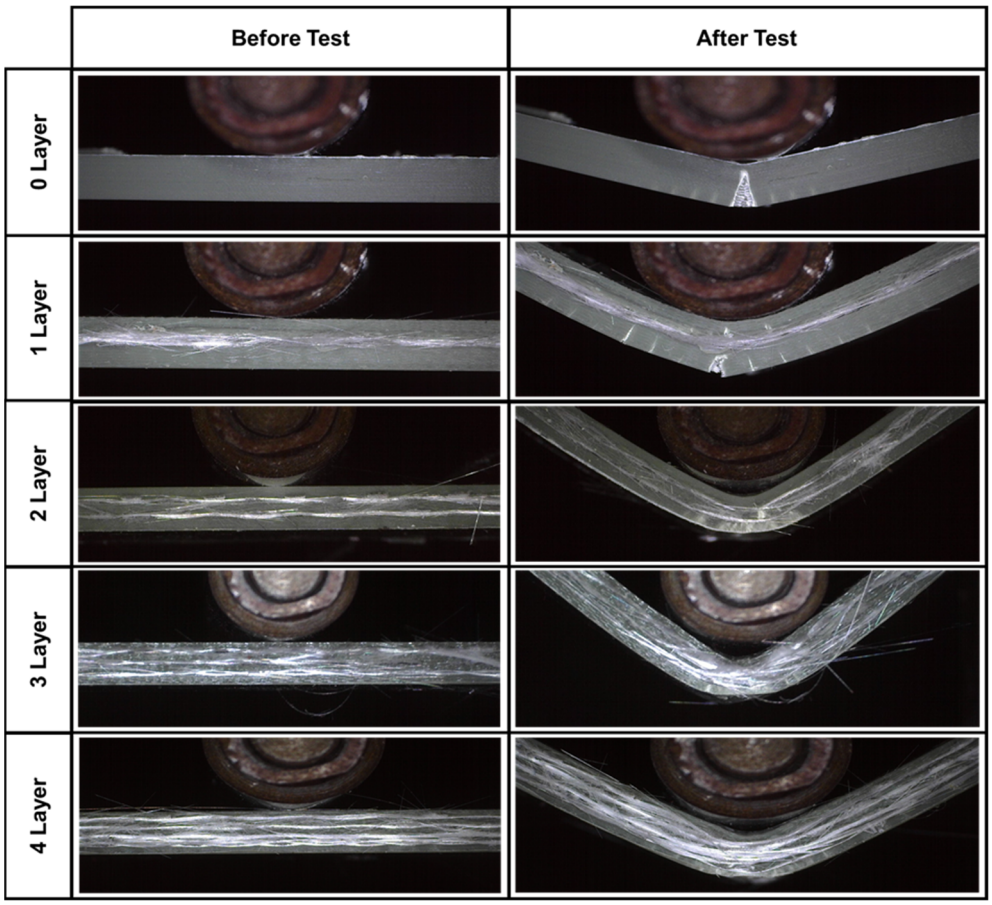


Figure 7. The results of the bending process of PLA+ composites reinforced with woven glass fiber.

3.3. Impact Test

The results of the Charpy impact test, as shown in Figure 8A–C, demonstrate a consistent and significant improvement in impact resistance for PLA+ composites reinforced with woven glass fiber layers. The material without woven glass fiber (0 layer) exhibited a Charpy impact resistance value of 2.70 kJ/m^2. A significant increase was observed with the addition of one layer of glass fiber, improving the toughness of PLA+ by 150% to 6.96 kJ/m^2. The toughness continued to improve with additional layers, reaching 8.82 kJ/m^2 with two layers, 10.95 kJ/m^2 with three layers, and a maximum of 15.12 kJ/m^2 with four layers, representing a 450% increase. This improvement is attributed to the woven glass fiber's ability to absorb and distribute impact energy across the specimen [46,47]. During the impact loading, cracks initiate from the notch tip and propagate towards the woven glass fiber layer. As the crack front reaches the fiber layer, crack propagation decelerates, indicating a shift in the failure mechanism toward interfacial debonding between the glass fiber and the PLA+ matrix. This behavior suggests that a significant portion of the impact energy has dissipated through mechanisms such as matrix cracking, fiber–matrix debonding and delamination. The presence of woven glass fiber likely contributes to energy absorption by impeding crack growth and promoting crack deflection or friction at the interface. When compared to PETG, a material used for shin pads [48], PLA+ composite reinforced with woven glass fiber demonstrated significantly better impact performance in terms of impact toughness. This is due to the fact that the PLA+ composite reinforced with woven glass fiber achieved a Charpy impact resistance up to 15.12 kJ/m^2, whereas conventional PETG such as the Ultimaker brand offered 7.9 $\pm$ 0.6 kJ/m^2 [49]. Therefore, PLA+ composites reinforced with woven glass fiber possess excellent energy absorption capabilities, making them suitable for applications requiring good energy absorption, such as shin pads (sport shin guards).

The post-impact visualization can be shown in Figure 8B,C, and was analyzed using SEM. Figure 8B highlights the bonding between the PLA+ matrix and the woven glass fiber reinforcement. The Charpy impact test caused most of the glass fibers to detach due to the inability of the PLA+ matrix and woven glass fiber to withstand the shock load together. The rapid application of impact load induced high shear stress, weakening the adhesion between the matrix and the reinforcement. Figure 8C reveals cracks in the PLA+ matrix caused by failure under the impact load. These cracks in the matrix, combined with the detachment of fibers, suggest a failure mode that aligns with typical interfacial strength models for composite materials [50]. The brittle nature of PLA+, combined with high stress concentration, resulted in matrix cracking during the test.

3.4. Hardness Test

The hardness test results using the Shore D method on PLA+ composites reinforced with woven glass fiber, as shown in Figure 9A, indicate a decrease in hardness. The highest Shore D hardness value was observed in the specimen without reinforcement (0 layers) at 72.2 ShD. With the addition of one layer of glass fiber, there was no significant change, with a hardness value of 72 ShD. A slight decrease was noted with the addition of two layers of glass fiber, resulting in a hardness value of 71.7 ShD. A significant decrease occurred with three layers of glass fiber, where the hardness dropped to 68.3 ShD. The lowest hardness value, 66.6 ShD, was observed in the specimen with four layers of woven glass fiber. This decrease in hardness is attributed to the non-homogeneous distribution of the woven glass fiber within the PLA+ composite, reducing its effectiveness in resisting the penetration of the indenter. While the addition of glass fiber improved tensile, bending, and other mechanical properties, it did not enhance resistance to indentation. Consequently, reinforcing PLA+ composites with woven glass fiber proved effective for stress distribution under static loads but less so for resisting indentation.

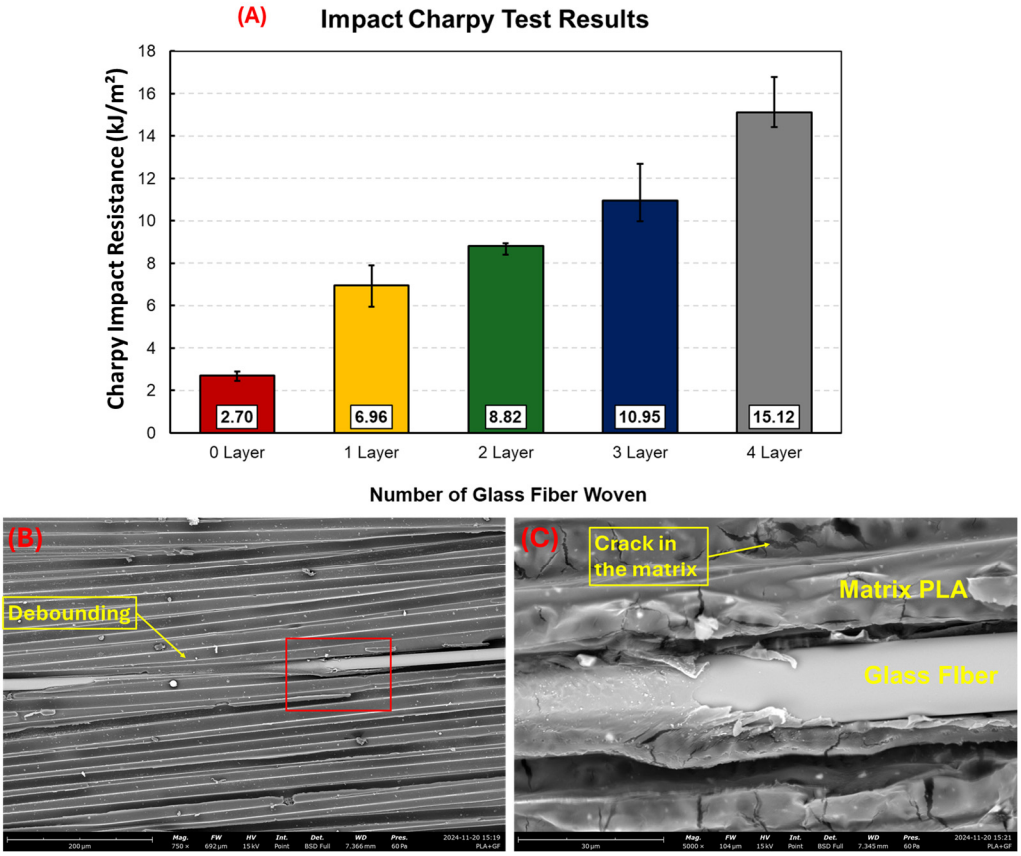


Figure 8. The results of the impact test on PLA+ composites reinforced with woven glass fiber and morphology analysis using SEM: (**A**) graph impact resistance, (**B**) morphology at magnification 750× magnification, (**C**) morphology at 500× magnification.

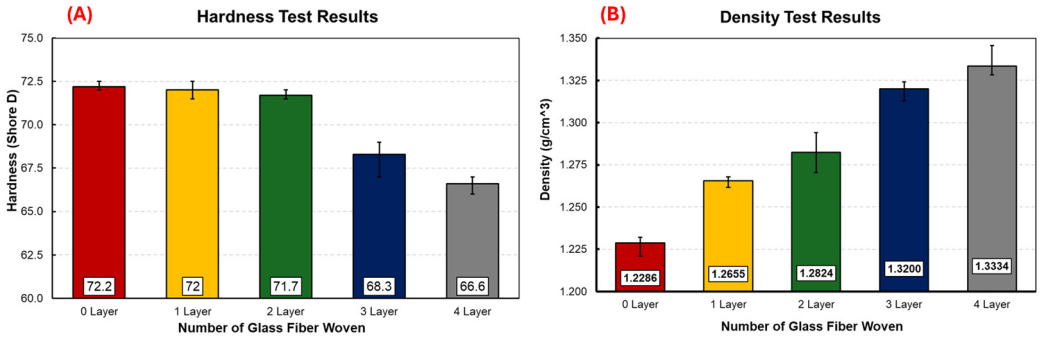


Figure 9. The hardness and density test results on PLA+ composites reinforced with woven glass fiber. (**A**) Hardness test, (**B**) density test.

3.5. Density Test

The density test results, as illustrated in Figure 9B, showed that the addition of woven glass fiber to the PLA+ material manufactured using FFF 3D printing increased the composite's density. The specimen with no layers or without the addition of glass fiber had the lowest density, at 1.2286 g/cm^3. The increase in density was proportional to the number of glass fiber layers added. With the addition of one layer of glass fiber, the density increased to 1.2655 g/cm^3. The PLA+ composite with two layers of glass fiber had a density of 1.2824 g/cm^3, while the composite with three layers of glass fiber reached a density of 1.3200 g/cm^3. The highest density was observed in the PLA+ composite with four layers, at 1.3334 g/cm^3. Compared to the no-layer specimen, the four-layer specimen exhibited an increase of 8.5%. This increase occurred because the density of glass fiber

is higher than that of PLA+, which is 2.5 g/cm^3 [51]. Overall, while the increase was not particularly significant, it remains an important consideration, especially in product design applications.

3.6. Thermal Analysis

Figure 10 presents the outcomes of a thermal analysis conducted using DSC across a temperature range of 40 °C to 600 °C. The results demonstrated a decrease in the endothermic melting and decomposition peaks of PLA+ reinforced with woven glass fiber; however, no peak was detected for the glass fiber material, as its melting temperature of 800–1000 °C had not been reached [52]. PLA+ showed glass transition at 61.93 °C and heat flow at −0.4 mW/mg. Crystallization transpired at 101.1 °C, an endothermic melting point was observed at 171.58 °C, and material decomposition occurred at 373.68 °C. In contrast, woven glass fiber-reinforced PLA+ demonstrated diminished values across all parameters. The glass transition occurred at 58.21 °C with a heat flow of −0.28 mW/mg, while low-temperature crystallization happened at 99.24 °C. The endothermic melting of glass fiber-reinforced PLA+ occurred at 170.7 °C, while material degradation happened at 367.09 °C. The greatest significant reduction in heat flow during material decomposition was seen, with PLA+ recording −14.78 mW/mg and PLA+ reinforced by woven glass fiber at −8.37 mW/mg, reflecting a decrease of 40%. The addition of other materials to PLA disrupts the integrity of the PLA molecular chains, thereby restricting their mobility and lowering the crystallization point. This also leads to a decrease in the decomposition point [53]. The reductions observed in the DSC values between PLA+ and glass fiber-reinforced PLA+ are attributed to the interaction between the glass fiber and PLA+, which hinders the decomposition of PLA+. The addition of glass fiber improved the mechanical properties of PLA+, but it additionally changed its thermal characteristics. The reduced decomposition value of PLA+ reinforced by woven glass fiber indicates that the material is more susceptible to thermal degradation owing to chemical interactions between the glass fiber and PLA+.

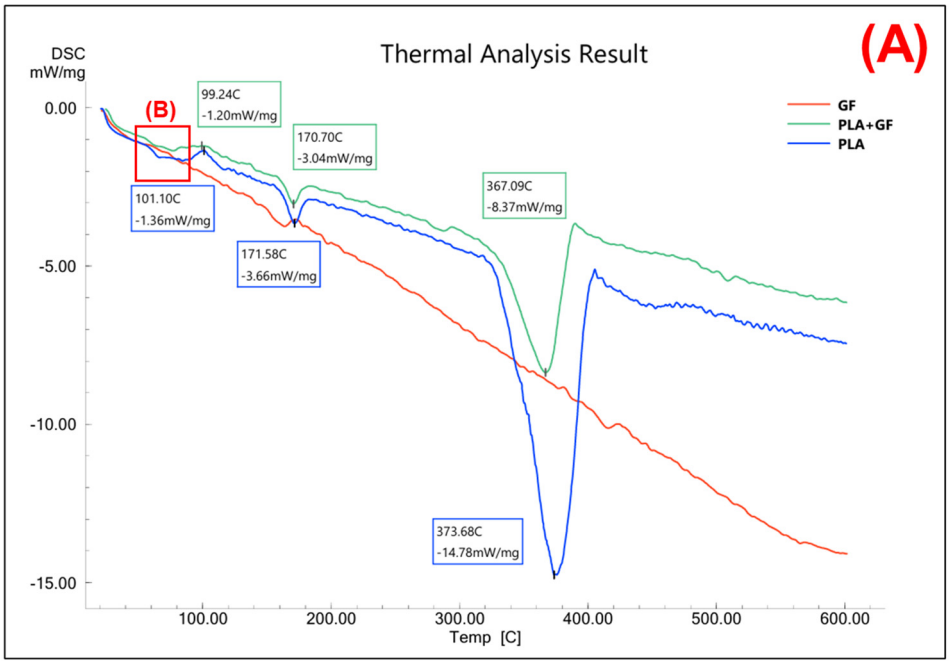


Figure 10. *Cont.*

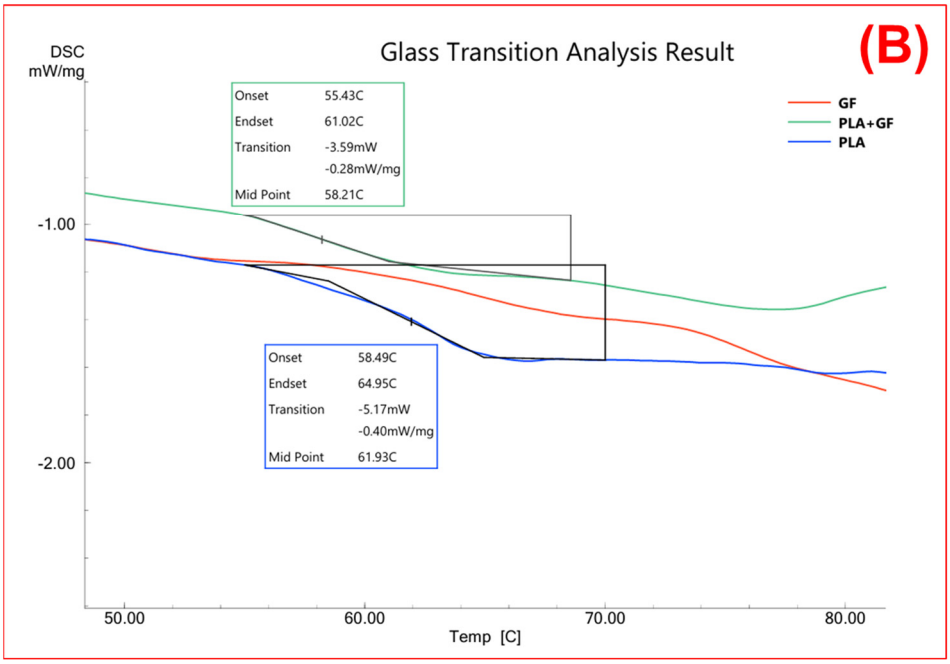


Figure 10. DSC test results: (**A**) thermal analysis graph from 40 to 600 °C; (**B**) graph of glass transition analysis from 50 to 80 °C.

4. Discussion

4.1. The Effect of Adding Woven Glass Fiber on Material Properties

The addition of woven glass fiber significantly improved the mechanical properties of PLA+ composites, enhancing their resistance to static loads, including in tensile, flexural, and impact performance. The reinforcement made PLA+ more ductile, as evident in the tensile and flexural graphs. PLA+ composites reinforced with woven glass fiber exhibited prolonged strain during the tensile test compared to PLA+ without reinforcement, which failed through brittle breaking with a maximum tensile strength of 31.82 MPa. In contrast, the reinforced composites did not fracture due to the glass fiber's ability to distribute stress more uniformly. The tensile strength increased with additional layers of glass fiber, reaching a maximum of 59.44 MPa with four layers, representing an 85% improvement.

Similarly, flexural strength improved, with the highest value of 91.51 MPa observed in the composite with four layers of glass fiber. However, the addition of glass fiber reduced indentation resistance, as shown in the hardness test. PLA+ without reinforcement had the highest Shore D hardness value of 72.2, while the value decreased to 66.6 ShD in the composite with four layers of glass fiber.

The inclusion of woven glass fiber also affected the material's thermal properties. A decrease in decomposition temperatures was observed, indicating that chemical interactions between the glass fiber and PLA+ increased the material's susceptibility to thermal decomposition. Despite these thermal changes, the mechanical improvements, particularly in tensile, flexural, and impact performance, make PLA+ composites reinforced with woven glass fiber suitable for applications requiring enhanced mechanical strength.

4.2. The Effect of Orientation and the Number of Woven Glass Fiber Layers

The direction of the fiber significantly influenced the test results in this study. Figure 11A,B demonstrates that aligning fibers with the applied force direction optimally distributes the load. Proper stress distribution is essential for maintaining structural integrity, particularly in composite materials [54,55]. Composites with effective load distribution generally exhibit enhanced mechanical properties. Therefore, a careful evaluation

of glass fiber alignment during the composite fabrication process using FFF 3D printing is strongly recommended. The Anycubic Kobra Max 3D printer played a critical role in this research. To accommodate the thickness of the glass fiber, the nozzle-to-bed distance was adjusted by 0.05 to 0.1 mm, optimizing the production of specimens aligned with the force direction. The printer allowed these adjustments to be made either during pauses or throughout the production process, ensuring precise alignment and high-quality specimens.

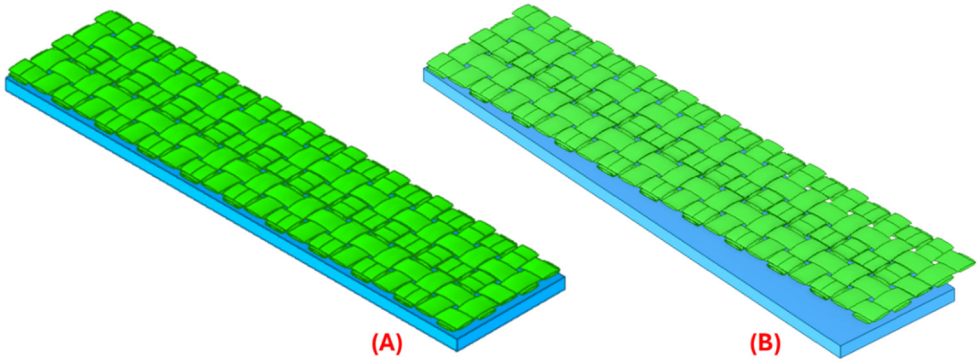


Figure 11. The orientation of the glass fiber within the PLA+ matrix; (**A**) aligned straight in the same direction as the applied force, (**B**) slightly shifted due to contact with the 3D printer nozzle.

4.3. Application and Implications

Based on the tests conducted, it was found that the addition of glass fiber can enhance the energy absorption of PLA+, and therefore that PLA+ composites reinforced with woven glass fiber possess the potential for application in many different fields, For instance, in energy absorption applications, in addition to face sheets in composite sandwich structures [56,57] and materials for sports applications using FDM technology, such as shin pads, outer shells of knee pads, and helmets [58–60], these materials could also be used for roofs in the automotive industry [61]. This study's implications involve increasing the use of FFF 3D printing in composite manufacturing. This progress can stimulate innovation and technological advancement across multiple industrial sectors. Furthermore, by understanding the mechanical properties of fibers and the parameters of FFF 3D printing, we can engineer materials with customized mechanical qualities to meet specific requirements [62].

5. Conclusions

The conclusions formulated in this study are as follows:

- From the results of the tensile test combined with DIC analysis, the addition of woven glass fiber during the manufacturing process made the material stronger in withstanding tensile loads. PLA+ composites with the addition of four layers of glass fiber were 85% stronger compared to standard PLA+. DIC analysis showed that the glass fiber helped distribute the load, preventing stress concentration in one area.
- From the results of the bending tests, the addition of woven glass fiber during the manufacturing process made the material stronger in withstanding bending loads. PLA+ composites with the addition of four layers of glass fiber were 13% stronger compared to standard PLA+. The addition of glass fiber also caused a change in the failure mode experienced by the specimens.
- From the impact test results, the addition of woven glass fiber during the manufacturing process made the material tougher when absorbing energy from impact loads. PLA+ composites with the addition of four layers of glass fiber were 450% tougher compared to standard PLA+. Glass fiber facilitated load distribution, enhancing energy absorption, making the material suitable for shin pads and vehicle bumpers

- The hardness test results indicate that the incorporation of woven glass fiber during production diminished the material's resistance to indentation in hardness testing. PLA+ composites with four layers of glass fiber had an indentation resistance of just 66.6 ShD, which is inferior to the typical PLA+ measurement of 72.2 ShD.
- The DSC thermal study revealed that the addition of woven glass fiber during production increases the material's likelihood of breaking down at high temperatures due to the chemical reaction between the glass fiber and PLA+. PLA+ exhibited −14.78 mW/mg during material decomposition, whereas PLA+ reinforced with woven glass fiber demonstrated −8.37 mW/mg, indicating a 40% reduction.
- The addition of woven glass fiber during the 3D printing FFF process using PLA+ filament improved the mechanical properties of PLA+ in resisting static loads. This was proven by the results of tensile, bending, and impact tests. However, PLA+ composites reinforced with glass fiber had a drawback in resisting indentation, as evidenced by the decreased hardness values during hardness testing. The DSC thermal study reveals that the addition of woven glass fiber to the manufacturing process increased the material's likelihood of breaking down at high temperatures due to a chemical reaction between the glass fiber and PLA+. PLA+ exhibited −14.78 mW/mg during material decomposition, whereas PLA+ reinforced with woven glass fiber demonstrated −8.37 mW/mg, indicating a 40% reduction.

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