Research Article

Journal of Environmental Nanotechnology

Thermal and Mechanical Characterization of Alumina Reinforced Polylactic Acid Polymer Composite

Anandha Moorthy Appusamy, Sivakumar Karuppan, Madheswaran Subramaniyan* and Senthil Kumar Laxmanan

Department of Mechanical Engineering, Bannari Amman Institute of Technology, Erode, TN, India

Received: 28.03.2025 Accepted: 23.06.2025 Published: 30.03.2026

*madhesbannariamman@gmail.com

ABSTRACT

The introduction of additive manufacturing in the industry represents a significant technological advancement. Material innovations and updated printing methods have paved the way for enhancing the strength of fused deposition modeling (FDM) parts. While fully polylactic acid (PLA)-printed FDM parts exhibit minimal strength, sandwiched samples demonstrate significantly higher strength. Among the sandwiched samples (0%, 20%, 40%, 60%, 80%, and 100%), the 80% sandwich configuration achieved a tensile strength of 34.7 MPa, which is 18.3% higher than that of pure polylactic acid (PLA). This improvement is attributed to the alternating layers of PLA and reinforced composite material. In terms of flexural strength, the 40% sandwich reinforcement showed a 2.42% increase compared to pure PLA, indicating an optimal reinforcement level for flexural applications. Additionally, the impact strength of the 20% sandwich configuration improved by 20% over neat PLA. These enhancements result from the strategic placement of reinforced layers between PLA layers, where the reinforcing particles penetrate the base material and create strong bonding with the PLA matrix. These findings highlight that incorporating reinforced sandwich layers between PLA significantly improves the mechanical properties of FDM-printed parts while reducing the overall requirement for composite material. This approach offers a cost-effective and efficient method for achieving superior strength in additive manufacturing.

Keywords: Fused Deposition Modelling (FDM); Sandwich printing; Composite material; Polylactic acid; Alumina.

1. INTRODUCTION

Among the various additive manufacturing techniques, fused deposition modeling (FDM) stands out as an affordable and user-friendly technology for producing complex three-dimensional (3D) objects. FDM employs thermoplastic materials as feedstock, building the desired 3D model by depositing successive layers of cross-sectional laminas. Polylactic acid (PLA) is a commonly used feedstock material due to its biodegradability and ease of printing. Additionally, PLA's low melting point reduces warping, making it suitable for a wide range of applications. However, the mechanical properties of PLA limit the strength of printed parts, creating an opportunity to introduce composite materials to achieve the desired properties for specific applications. The incorporation of composite materials significantly enhances the mechanical properties of FDM-printed parts, offering improved strength, thermal resistance, stiffness, and more. Reinforcements such as carbon fibers, glass fibers, metal particles, and non-metal particles are used to achieve properties like high mechanical strength, durability, lightweight construction, and suitability for demanding environments. These advancements make FDM-printed composites highly valuable in industries such as aerospace, automotive, and biomedical engineering, where performance and reliability are critical.

The most commonly used materials for FDM printing include polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and acrylonitrile butadiene styrene (ABS), all of which are widely available on the market (Kristiawan *et al.* 2021; Moradi *et al.* 2021; Chokshi *et al.* 2022; Dave *et al.* 2022; Soares *et al.* 2018). Initially, single materials were predominantly used for fabricating objects in FDM printing (Durgashyam *et al.* 2019; Kumar *et al.* 2020; Teraiya *et al.* 2020; Dawoud *et al.* 2016; Ouazzani *et al.* 2023; Yankin *et al.* 2023). These single-material parts offer predictable strength, straightforward machine parameter settings without extensive experimentation, and cost-effectiveness. However, they are limited in terms of mechanical and other properties, such as wear resistance and strength-to-weight ratios. Achieving the desired performance characteristics with a single material is often challenging. To overcome these limitations, researchers have shifted their focus to developing composite materials. The recent studies on PLA-hybrid composites have improved mechanical and thermal properties because of interfacial bonding and reduced void formation. (Ramanandha and Venkatachalapathi. 2025). By blending different materials, composites combine the best properties of each component, enhancing strength, flexibility, durability, and more. These advanced materials provide improved strength, stiffness, heat resistance, and tailored mechanical properties, significantly extending the

lifecycle of printed products and expanding their potential applications. Additive manufacturing is a layer-by-layer fabrication process that inherently exhibits anisotropy in printed parts. Objects can be produced as either hollow or solid structures. Initially, researchers focused on improving the strength of printed parts by optimizing machine process parameters such as layer thickness, infill density, object orientation, printing temperature, and more (Sheoran and Kumar, 2020; Yang *et al.* 2019; Yadav *et al.* 2020; Mohamed *et al.* 2016). These optimizations led to significant improvements in part strength.

Subsequently, advancements shifted toward the development of composite materials, particularly those incorporating natural fibers such as jute, bamboo, banana, and hemp. Natural fibers offer numerous advantages, including biodegradability, eco-friendliness, cost-effectiveness, high stiffness-to-weight ratios, reduced environmental hazards, energy-efficient production, good acoustic properties, and a positive carbon footprint. However, several drawbacks were observed in parts printed with natural fiber composites, such as poor interfacial bonding, high moisture absorption, inconsistent fiber quality, thermal degradation, difficulty in fiber dispersion, limited processability, and lower mechanical strength (Dudek, 2013; Lee *et al.* 2021; Rajendran *et al.* 2021; Rajeshkumar *et al.* 2021; Le Duigou *et al.* 2019, Liu *et al.* 2023).

These limitations prompted further research into artificial fiber and particle-reinforced composites. While these materials significantly improved the strength of FDM-printed parts and required minimal adjustments to machine parameters compared to pure materials, they introduced new challenges. Reinforcement fibers often caused brittleness, reduced compatibility with the matrix material, agglomeration, and uneven distribution due to high density and fiber-to-fiber or particle-to-particle contact during printing. Additionally, composite filaments, particularly short fiber composites (SFC), exhibited poor interlayer adhesion, and particle-reinforced composites suffered from agglomeration, leading to increased porosity between layers. These issues ultimately reduced the overall strength of the printed parts.

To address these challenges, a novel sandwich method was developed for part fabrication. This approach combines the benefits of pure and composite materials while mitigating their individual drawbacks. The mechanical and biological properties of parts fabricated using this method were thoroughly analysed (Wickramasinghe *et al.* 2020; Bryll *et al.* 2006; Pervaiz *et al.* 2021, Osman *et al.* 2018, Velu *et al*. 2019).

To address these challenges, researchers have turned their attention to developing composite materials, which are engineered by combining different components to enhance properties such as durability, flexibility, and strength. Composites offer improved heat resistance, tailored mechanical strength, stiffness, hardness, wear resistance, and extended functional lifespans for products. However, despite their versatility, composite filaments used in 3D printing often face issues such as poor interlayer adhesion and particle agglomeration, particularly in reinforced composites. These problems arise due to the use of short fibers and uneven distribution of particles, which increase porosity between layers and ultimately reduce the overall strength of 3D-printed parts. To overcome these limitations, researchers are exploring several strategies, including optimizing fiber length and orientation to enhance interlayer adhesion and minimize porosity, as longer fibers can bridge layers more effectively, improving structural integrity (Lee *et al.* 2021; Rajendran *et al.* 2021; Rajeshkumar *et al.* 2021; Le Duigou *et al.* 2019). Additionally, surface modification of fibers through chemical treatments or coatings can strengthen their bond with the matrix material, reducing agglomeration and improving layer adhesion. Advanced 3D printing techniques, such as Fused Deposition Modeling (FDM), with optimized parameters like temperature, printing speed, and layer height, can further enhance layer bonding and reduce defects. Furthermore, the development of hybrid composites, which combine different types of fibers such as carbon and glass fibers, offers a balanced approach to improving both strength and interlayer adhesion in 3D-printed parts.

To address the challenges associated with FDM printing, a novel sandwich method was employed to fabricate the FDM parts. In this study, a PLA/aluminum oxide composite material was developed in-house, and samples were printed using the sandwich method, which involves alternating layers of complete and composite materials. The mechanical properties of the printed parts, including tensile strength, compression resistance, impact strength, and hardness were evaluated. The upcoming section will discuss the materials used, their preparation, and the filament fabrication process

2.MATERIALS AND METHODS

2.1 Materials

The graphical workflow is illustrated in Figure 1.1. The process begins with material selection. Polylactic acid (PLA) is a widely preferred material for fused deposition modeling (FDM) due to its low cost, ease of use, and environmental sustainability. However, to enhance the mechanical properties and expand the application scope of printed parts, researchers have explored the use of composite materials. By incorporating alumina (aluminum oxide, procured from NICE chemicals a purity of 99.5%, and a density of 3.95 g/cm^3) into PLA, the resulting composites exhibit unique characteristics that make them suitable for specific

applications. For this study, PLA granules (1.24 g/cc) were procured from All Plast, Coimbatore, India, and utilized for filament preparation.

Aluminum oxide (Al_2O_3), commonly known as alumina (400 mesh: 37-40 microns), was procured from Nice Chemicals, Coimbatore. Renowned for its exceptional strength and thermal stability, alumina enhances PLA composites, making them suitable for applications requiring high-temperature performance, such as functional prototypes and structural components. The compatibility of these composite materials with FDM printing technology significantly broadens their utility, enabling the production of complex geometries and customized parts with superior properties. The integration of PLA and alumina composites paves the way for innovative advancements across various industries, including healthcare, where they serve as specialized materials with enhanced characteristics.

2.1.1 Melt Flow Index Analysis

The melt flow index (MFI) tester evaluates the extrusion rate of thermoplastic materials under specific temperature and flow conditions. This standardized assessment of polymer flow characteristics is essential for determining their suitability for FDM extrusion processes. The results are measured in grams over a 10-minute interval. For composite materials, particularly those based on thermoplastics, MFI testing is crucial to analyze their flow behavior during processing. This analysis helps determine the flowability and printability of materials for FDM printing. Additionally, MFI testing plays a key role in quality control by ensuring the consistency of the material's composition and processing behavior, which is critical for maintaining the mechanical properties and performance of the final composite product. In this study, MFI testing was conducted on the PLA/Al_2O_3 composite to evaluate its flow characteristics.

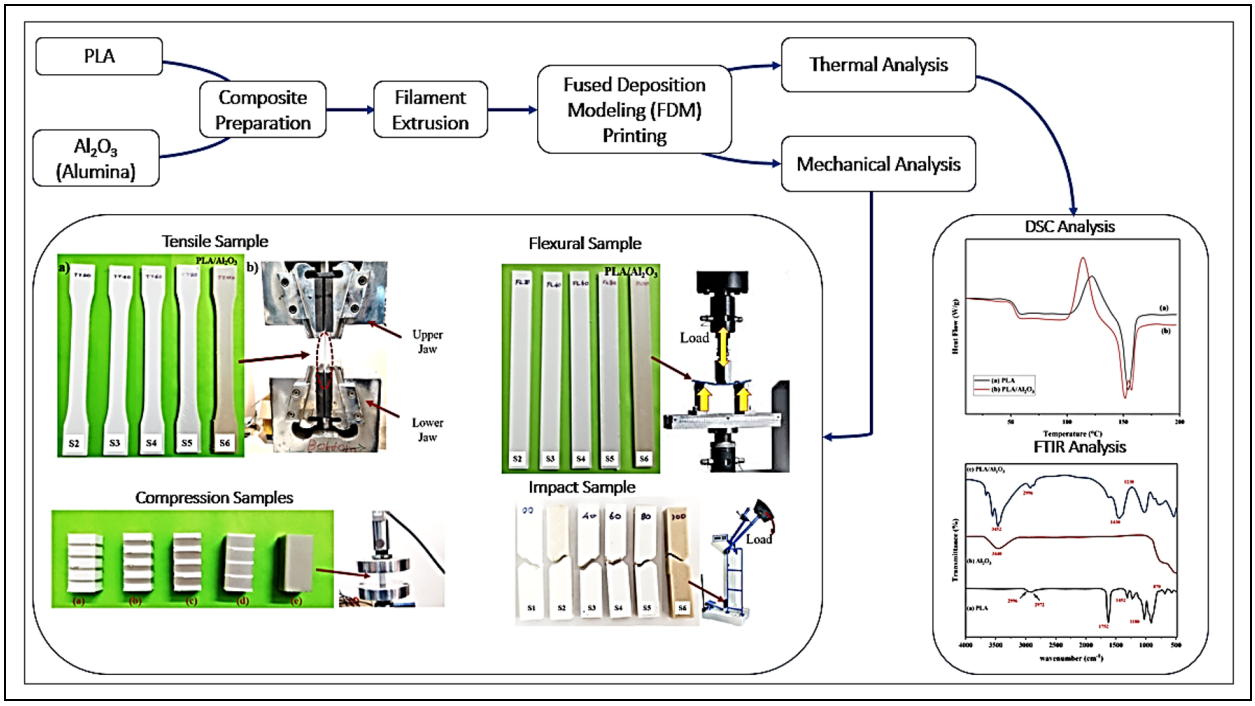


Fig. 1: Graphical flow of investigation

2.2 Filament Preparation

The composite material was prepared in-house using filament extruder. A Single Screw Filament Extruder (SSE) is used to prepare the filaments. The MFI-investigated composite material was fed into the extruder to prepare the feedstock material. The extruder parameters were optimized by the repeatability for the consistent filament extrusion, and the filament was produced. The extruder contains a single screw encased within an 80-mm-diameter barrel. The optimized key input parameters, such as barrel temperature (160°C+3°C), take-off speed (165 mm/s), and roller unit extruder distance (2.4 m), are controlled to assure the manufacture of uniform-diameter feedstock wire. Maintaining temperatures below the recommended range leads to un-melted pellets and extrusion interruptions, which reduce ingredient bonding. Furthermore, the inclusion of surfactants (wax) improves material flow, resulting in smoother filament surfaces and consistent diameters compared to formulations without surfactants.

2.3 Sample Preparation

A Flashforge Creator3 Pro Fused Deposition Modeling (FDM) printer equipped with a twin extruder

system was employed for this study. The printer offers a build volume of 300 x 250 x 200 mm and utilizes a 400-micron nozzle to achieve a layer thickness of 200 microns with a 100% infill density. All samples were printed under consistent process parameters and environmental conditions to ensure uniformity. The samples were fabricated by sequentially depositing alternating layers of pure PLA and reinforced PLA. In the dual extruder setup, one extruder was dedicated to pure PLA, while the other was used for reinforced PLA material. This configuration enabled the creation of sandwich-structured samples through the alternate deposition of layers from the left and right extruders. The stacking sequence consisted of five layers of pure PLA and four layers of PLA/Alumina, with the volume fraction of the reinforced PLA ranging from 20% to 80%. Samples designed for tensile, compression, flexural, and impact tests were printed using this method to evaluate their mechanical properties.

2.4 Mechanical Testing

2.4.1 Tensile Testing

Tensile samples were fabricated in compliance with ASTM D638 standards. All samples were printed under identical machine parameters, including a 0° orientation, 100% infill density, and a 60°C bed temperature. Tensile testing was conducted using a Universal Testing Machine (Model: FIE-UNITEK-9400, India). During the test, the samples were securely gripped between one movable and one fixed jaw. A gradual load was applied until the sample either fractured or reached a strain rate of 10%.

2.4.2 Compression Testing

Compression samples were prepared according to ASTM D695 standards, with cross-sectional dimensions of 12.7 mm x 12.7 mm and a height of 25.4 mm. The same Universal Testing Machine (Model: FIE-UNITEK-9400, India) was utilized for compression testing. A consistent testing speed of 2 mm/min was maintained throughout the investigation to ensure accurate and reliable results.

2.4.3 Flexural Testing

For the flexural analysis of polymers and polymer composites, samples were designed and printed in accordance with ASTM D790 standards. The dimensions of the flexural samples were 127 mm in length, 13 mm in width, and 3.2 mm in thickness. The flexural test was performed using a 3-point bending method in compression mode. This test evaluated the flexural strength and flexural modulus of the printed samples.

2.4.4 Impact Testing

To assess the shock-loading properties of the printed samples, impact testing was conducted following ASTM D6110 standards. The impact samples featured a cross-sectional area of 100 mm^2 and a length of 55 mm. A V-notch was machined into each sample at a 45° angle with a depth of 2 mm to facilitate the impact investigation.

2.5 Characterization

2.5.1 FESEM Analysis

Field Emission Scanning Electron microscopy examination is critical in evaluating composite polymer parts made using FDM-3D printing. This microscopic examination will provide a clear fracture analysis that can be comprehended using the information contained within the printing. This will show bonding information, infill porosity, particle dispersion, and so on. The FESEM (Model: Carl Zeiss-Sigma 300, Make: German) was used to analyse samples at different magnifications and sputter-coat them for better visibility.

2.5.2 Thermal Analysis

The thermal properties of composite materials are critically evaluated using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). These techniques are essential for assessing the thermal behavior of composites, providing valuable insights into their stability under varying temperature conditions, phase transitions, polymer chain degradation, and chemical reactions that may impact long-term performance and durability. Differential Scanning Calorimetry (DSC) measures the heat flow associated with phase transitions in materials. It accurately determines key thermal properties such as the glass transition temperature (Tg), melting temperature (Tm), and specific heat capacity. This information is crucial for understanding material behavior, reaction kinetics, and thermal stability. DSC is widely used in research, development, and quality control across industries such as polymers, pharmaceuticals, and food science. Thermogravimetric Analysis (TGA) provides detailed data on the temperature at which materials undergo weight loss or decomposition. This technique is instrumental in material selection, process optimization, and quality control. TGA is particularly valuable in industries like plastics, rubber, and aerospace, where thermal properties directly influence material performance, lifespan, and compliance with safety standards. Additionally, TGA aids in evaluating polymer additives, fillers, and blends, facilitating the development of advanced materials with tailored properties for specific applications. Together, DSC and TGA serve as vital tools for quality control, ensuring consistency in material characteristics and identifying potential manufacturing defects. They play a pivotal role in

advancing material science and engineering, enabling the design of innovative materials with optimized thermal properties for diverse industrial applications.

2.5.3 Fourier Transform Infrared Spectroscopy Analysis

Fourier Transform Infrared Spectroscopy (FTIR) is a critical analytical tool for examining polymer composites. It provides valuable insights into the chemical composition, interfacial bonding, and stability of these materials. By detecting functional groups present in both the polymer matrix and any additives or fillers, FTIR analysis enables researchers and engineers to verify the material's chemical consistency and ensure its properties meet desired specifications. During FTIR analysis, infrared light passes through an interferometer and is directed toward the sample. This process generates an interferogram, a raw signal that represents light intensity as a function of the mirror's position. To interpret this data, the interferogram undergoes a Fourier Transform (FT), converting it into a more familiar IR spectrum plot of intensity versus wavenumber. This spectrum reveals detailed information about the material's molecular structure and chemical interactions.

X-Ray Diffraction (XRD) is another essential technique for the comprehensive characterization of polymer composites. XRD provides critical insights into the structural properties of these materials, including crystallinity, filler dispersion, and structural changes that may occur during manufacturing or under service conditions. This information is vital for optimizing material performance and ensuring quality assurance. XRD is a rapid and efficient method for analysing the crystal structure, composition, and behaviour of polymer composites. It helps identify the degree of crystallinity and provides details about the unit cell dimensions and lattice parameters. By monitoring structural changes, XRD aids in the development and optimization of advanced polymer composites for various applications.

3. RESULT AND DISCUSSION

3.1 Thermal Behaviour

3.1.1 Thermogravimetric Investigation

Thermogravimetric Analysis (TGA) is an essential technique for quantifying the weight changes in polymeric materials as a function of temperature. The TGA results, as depicted in Figure 1.2, provide critical insights into the thermal stability and degradation behavior of the materials under investigation. These findings are instrumental in predicting optimal processing conditions and understanding material performance. Polylactic Acid (PLA) undergoes natural degradation when exposed to environmental factors such as sunlight (UV radiation) and moisture. To evaluate its thermal properties, TGA was conducted in a nitrogen atmosphere, with temperatures ranging from ambient temperature to 800 °C. The TGA results (Figure 1.2) reveal the following: Curve (a): Represents pure PLA, which undergoes complete degradation at 400 °C. Curve (b): Illustrates the thermal behavior of PLA/Alumina composites, showing improved thermal stability compared to pure PLA. Curve (c): Depicts the thermal profile of pure alumina, along with its corresponding mass loss. These results highlight the influence of alumina reinforcement on the thermal stability of PLA, demonstrating its potential to enhance the material's resistance to degradation at elevated temperatures.

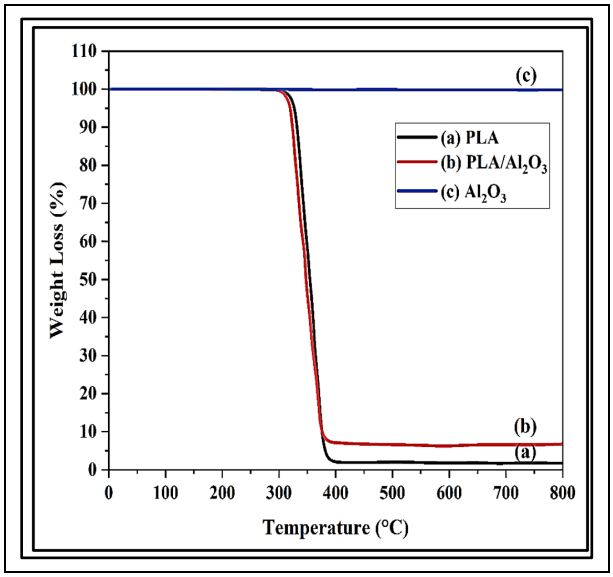


Fig. 2: (a) TGA of PLA, (b) PLA/ Al_2O_3 and (c) Al_2O_3

At 270°C, the polymer substrate undergoes homolysis, leading to the breakdown of its molecular structure. The formation of acetaldehyde is observed at 230°C, with its concentration decreasing significantly by 440°C. This reduction is attributed to the decomposition of acetaldehyde through a complex chain reaction, ultimately resulting in the production of carbon monoxide and methane at elevated temperatures. The findings demonstrate that the reinforced PLA/Al_2O_3 composites (comprising 93% PLA and 7% Al_2O_3) exhibit enhanced effectiveness. Additionally, the reinforcement of alumina was found to lower the degradation temperature of PLA. A noticeable temperature shift was observed with the incorporation of alumina: the onset temperature decreased from 327°C to 307°C, while the offset temperature increased from 360°C to 376°C. These results highlight the influence of alumina on the thermal stability and degradation behaviour of PLA.

3.1.2 Differential Scanning Calorimetry Investigation

The heat transfer rates of both pure and composite materials were analyzed using differential

scanning calorimetry (DSC), and the results are presented in Figure 3. The analysis revealed that pure PLA exhibits a glass transition temperature (Tg) of 54.8°C, a cold crystallization temperature (Tcc) of 122°C, and a melting temperature of 154.5°C. The study further indicates that the exothermic cold crystallization process initiates at 109°C. Notably, the incorporation of alumina into the PLA matrix resulted in a reduction of both the glass transition temperature and the cold crystallization temperature. Additionally, the DSC curve (b) reveals multiple melting peaks, characterized by higher and lower melting points, which can be attributed to the melting restrictions imposed by the interaction between PLA and alumina.

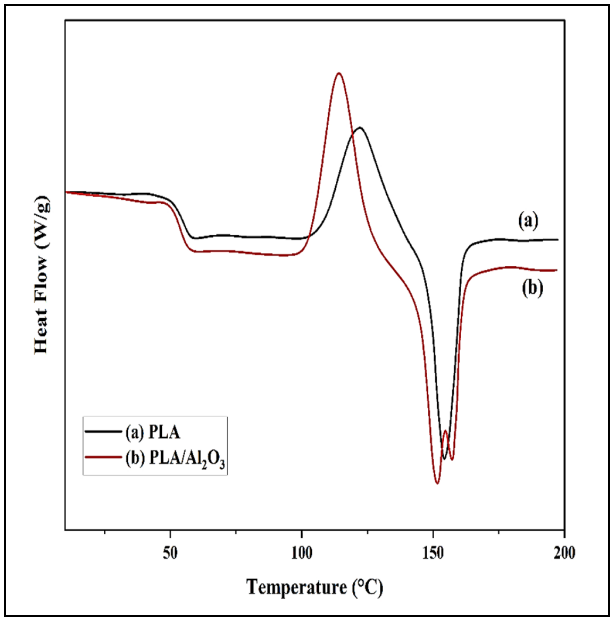


Fig. 3: DSC analysis of PLA (a) and PLA/ Al_2O_3 (b)

3.1.3 Fourier Transform Infrared Spectroscopy Analysis

The composites were analyzed using Fourier transform infrared (FTIR) spectroscopy with a Vertex 70 spectrometer from Bruker-Alpha. The analysis was conducted in the wavenumber range of 500 cm^{-1} to 4000 cm^{-1}, operating in transmission mode with 120 scans per sample and a resolution of 2 cm^{-1}. The FTIR spectra of PLA and the composite materials are illustrated in Figure 4. For pure PLA, characteristic peaks were observed at 1752 cm^{-1}, 1180 cm^{-1}, and 1081 cm^{-1}, corresponding to the C=O carbonyl stretching and C-O-C ester group vibrations. The results confirmed the absence of additional elemental peaks, with only polylactide and aluminum being detected. A novel phase was identified in the spectra of the new composites. The presence of alumina was confirmed by a peak at 3452 cm^{-1}, which also appeared in the composite spectra, indicating successful reinforcement. Additionally, the appearance of O-H groups was evidenced by supplementary peaks in the composite material.

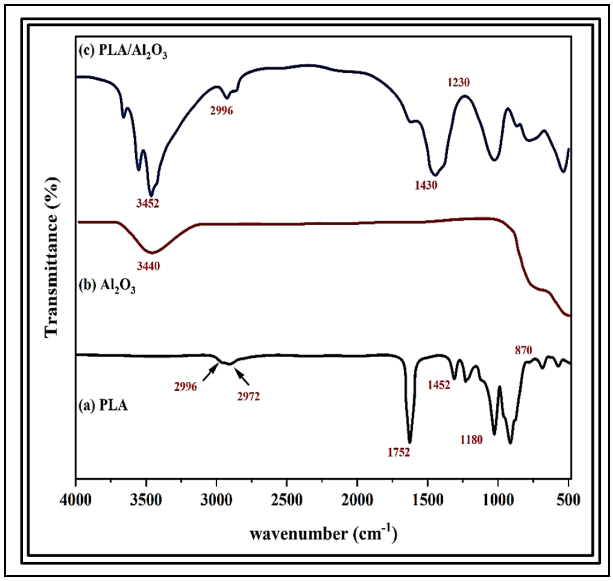


Fig. 4: (a) FTIR of PLA, (b) alumina and (c) Al_2O_3/PLA mixture

3.2 Sandwiches Mechanical Investigation

3.2.1 Tensile Strength Investigation

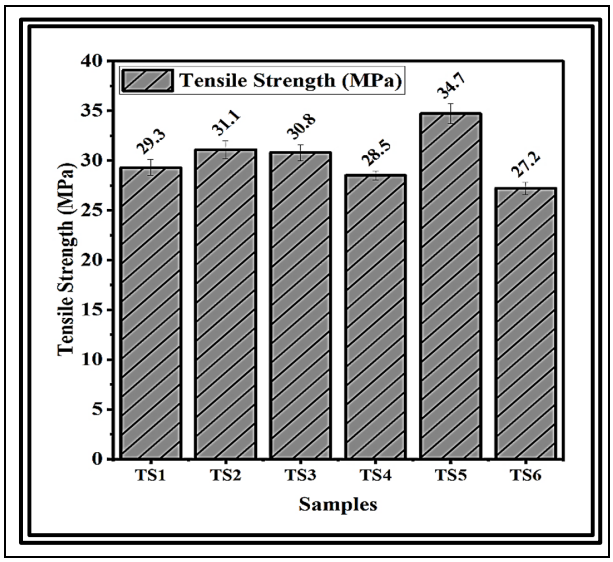


Fig. 5: Tensile strength

The observed results, as illustrated in Figure 5, reveal that pure PLA (S_1) exhibits a tensile strength of 29.3 MPa. In contrast, the PLA/Alumina sandwich composite (S_5) demonstrates a tensile strength of 34.7 MPa, which is 19% higher than that of pure PLA and 28% higher than that of the fully reinforced composite (S_6). The enhanced mechanical performance can be attributed to the improved bonding achieved through the introduction of sandwich structures, which effectively reduce voids between the layers. This reduction in voids promotes stronger interlayer junctions and facilitates better load distribution across the layers. During mechanical loading, failure cracks are arrested at these

junctions, enabling the material to withstand higher loads (Zhang *et al.* 2008).

3.2.2 Compression Strength Investigation

The figure 6 displays the compression results, the results indicate that the compressive strength of the samples varies significantly with the percentage of Al_2O_3 reinforcement. While the pure PLA sample (CS1) demonstrated the highest compressive strength (39 MPa), the sandwiched samples exhibited a non-linear trend in strength as the reinforcement percentage increased. Notably, CS_3 (40% reinforcement) showed a strength close to that of pure PLA, suggesting an optimal balance between reinforcement and mechanical performance. However, higher reinforcement percentages (e.g., 60% and 80%) led to a reduction in compressive strength, likely due to increased interfacial stress and potential defects at the layer junctions. The fully reinforced sample (CS_6) displayed moderate strength, indicating that complete reinforcement may not always yield the best mechanical properties. These findings highlight the importance of optimizing the reinforcement ratio to achieve desired mechanical performance in layered composites.

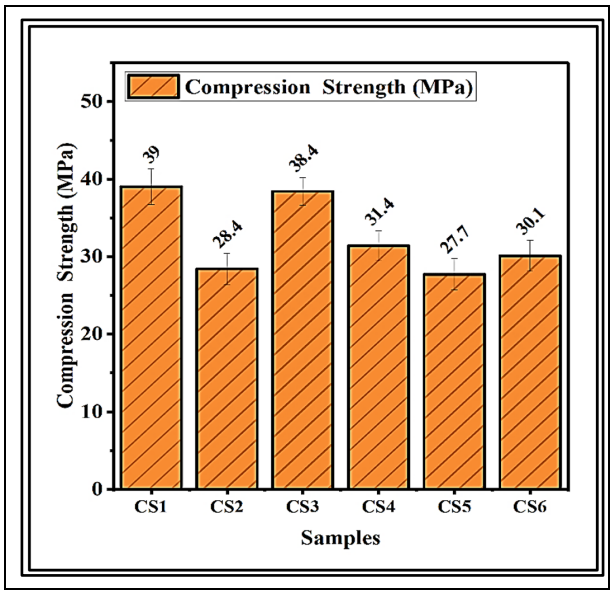


Fig. 6: (a) Compression strength and (b) modulus of PLA/Al_2O_3 composites

3.2.3 Flexural Strength Investigation

The flexural strength of the samples, as illustrated in Figure 7, reveals a 2.42% improvement for the 40% Al_2O_3 sandwiched composite (FS_3) compared to pure PLA (FS_1). However, no significant improvement was observed in the other sandwiched or fully reinforced samples. During flexural loading, the direction of the applied stress changes, initiating fractures that propagate across neighbouring layers. In the sandwiched composites, these fractures are arrested at the layer junctions, leading to a slight increase in strength. Notably, the sandwiched composites demonstrated a 27.6% higher flexural strength compared to the fully reinforced sample (FS_6). This difference can be attributed to the presence of voids and delamination in the fully reinforced samples, which compromise their structural integrity. The results highlight that while the 40% sandwiched composite (FS_4) achieved the highest flexural strength (67.8 MPa), higher reinforcement percentages (e.g., 80% in FS_5 and fully reinforced FS_6) led to reduced performance due to increased interfacial defects and stress concentrations. These findings emphasize the importance of optimizing the reinforcement ratio to enhance interfacial bonding and minimize defects in layered composites.

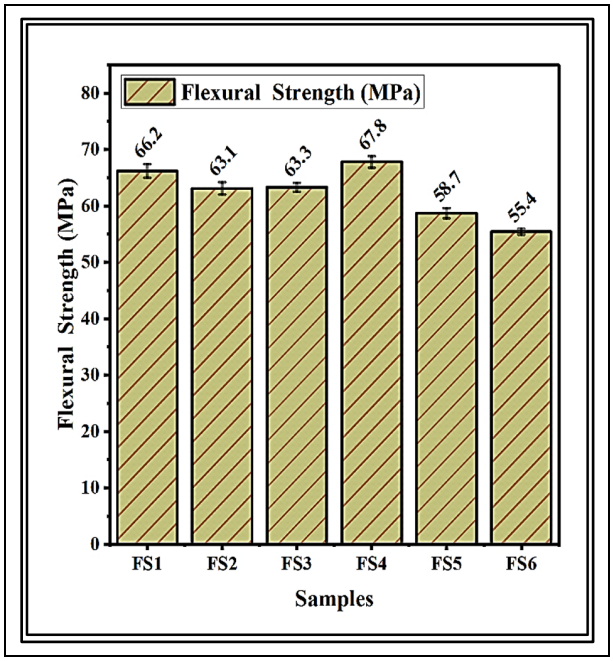


Fig. 7: Flexural strength

3.2.4 Impact Investigation

The additively printed samples exhibit anisotropic properties, particularly in the vertical direction, which necessitates an investigation into their shock-loading capacity. The results of the impact strength tests for various sandwich configurations are presented in Figure 8. The pure PLA samples demonstrated an impact strength of 2500 Joule, while the 20% sandwich structure showed a 20% improvement in strength. Interestingly, no significant difference in impact strength was observed between the pure PLA samples and the fully reinforced samples. Among the tested configurations, only the 20% sandwich structure exhibited a notable improvement, suggesting that 20% reinforcement represents the optimal configuration for enhancing impact strength. The reduced performance of the fully reinforced samples can be attributed to the presence of voids, the V-notch effect, and excessive fiber-to-fiber contact, which likely

compromised their structural integrity and prevented them from outperforming the pure PLA samples.

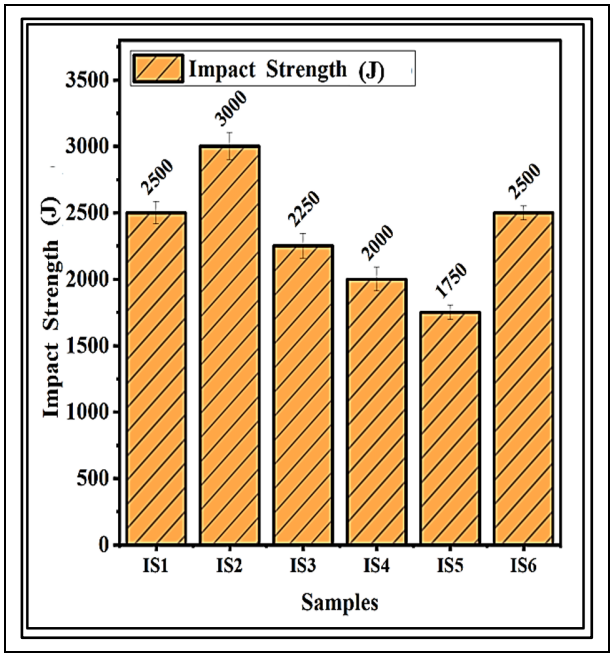


Fig. 8: Impact strength of PLA/Al_2O_3 samples S_1, S_2, S_3, S_4, S_5 and S_6

3.2.5 Hardness Investigation

Scratch and penetration resistance are critical factors for materials, as they directly influence suitability, performance, structural integrity, and potential applications. The hardness values of the PLA/Al_2O_3 composites are illustrated in Figure 9. The results clearly demonstrate that incorporating reinforced layers enhances the material's hardness. The hardness of the composites increased from 72.6 ± 1.25 SHN for S1 (pure PLA) to 86.2 ± 1.5 SHN for S5, representing an 18.7% improvement compared to pure PLA. These findings highlight that the inclusion of higher-modulus fillers within the composite layers significantly enhances the material's hardness, making it more suitable for applications requiring superior mechanical resistance.

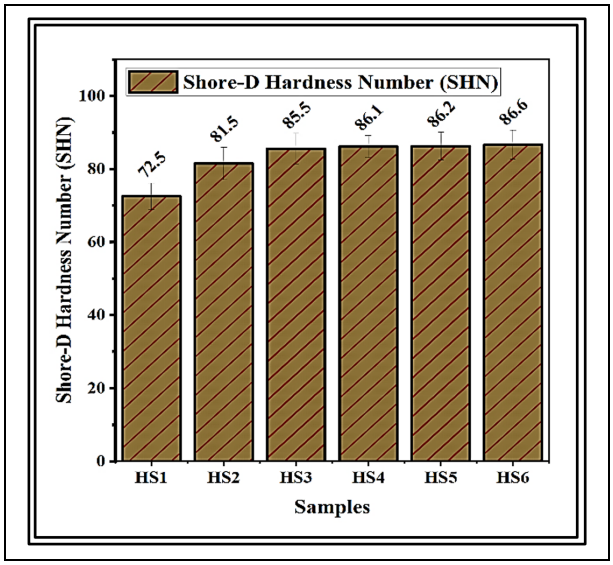


Fig. 9: Shore-D of S_1, S_2, S_3, S_4, S_5 and S_6 PLA/Al_2O_3

3.2.6 Field Emission Microscopic Investigation

The surface morphology of the PLA/Al_2O_3-reinforced layers were analysed using field emission scanning electron microscopy (FESEM), and the resulting images are presented in Figure 10. The FESEM analysis reveals that the Al_2O_3 particles are uniformly distributed within the PLA matrix, a result attributed to the twin-time extrusion process used during the preparation of the feedstock material. This dual extrusion process ensured thorough mixing of the Al_2O_3 particles with the PLA base material, promoting homogeneity and enhancing the interfacial bonding between the layers. Additionally, the sandwiching technique facilitated strong adhesion between the outer layers and the pure PLA core, further improving the structural integrity of the composite. The uniform distribution of Al_2O_3 particles, combined with the effective bonding achieved through sandwiching, contributed to the enhanced mechanical strength observed in the sandwiched components. These findings underscore the importance of optimized processing techniques in achieving superior material properties for advanced applications.

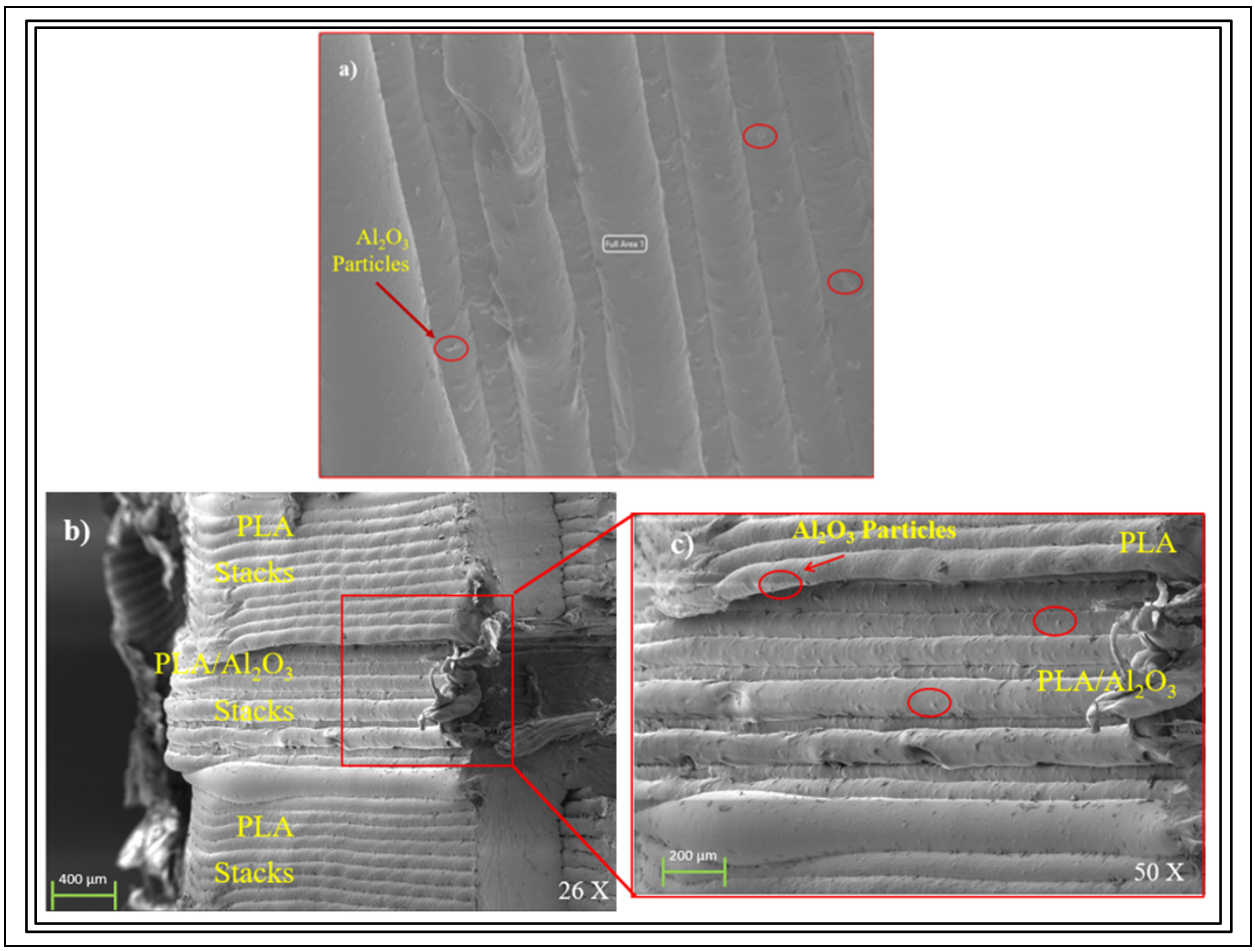


Fig. 10: FESEM analysis of Al_2O_3 reinforced PLA

4. CONCLUSION

This research demonstrates the effective enhancement of thermal, mechanical, and microstructural properties of FDM-printed PLA through the integration of a PLA/Al_2O_3 sandwich configuration. The composite material was fabricated using a single-screw filament extruder, with an optimal 7% Al_2O_3 reinforcement composition determined through melt flow index analysis. Despite the inherent limitations of FDM-printed components, such as reduced tensile and flexural strength due to reinforcement agglomeration, the innovative sandwich layering technique effectively addressed these challenges. By alternating layers of PLA and PLA-composite (ranging from 20% to 80% of the total layers) using a dual-nozzle FDM printer, significant performance improvements were achieved. Differential scanning calorimetry (DSC) revealed a reduction in the glass transition temperature and an increase in crystallinity, confirming the successful incorporation of Al_2O_3 within the PLA matrix. The sandwich configuration resulted in an 18.5% improvement in tensile strength compared to pure PLA and a 27.41% increase over fully reinforced samples. Additionally, flexural and impact strengths showed notable enhancements, while hardness improved by 18.7%. These findings indicate that the sandwich technique promotes better interfacial bonding, reduces reinforcement agglomeration, and ensures uniform distribution, leading to consistent improvements in thermal and mechanical properties. This approach offers a promising solution for enhancing the performance of FDM-printed materials, making them suitable for a wide range of applications.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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