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REVIEW PAPER

A Review of FDM Process Parameters, Mechanical Properties, Tribological Behavior, and Numerical Modeling of Carbon Fiber Reinforced PLA for Bearing Applications

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Abstract

Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is widely used to produce polymeric and composite components due to its low cost, design flexibility, and relatively low material waste. Carbon fiber-reinforced polylactic acid (CF-PLA) has attracted attention for lightweight engineering applications because carbon fibers can enhance stiffness and strength while retaining the processing advantages of thermoplastic FDM. However, the performance of printed CF-PLA is strongly affected by process parameters, fiber orientation, porosity, interlayer bonding, and surface characteristics. This review synthesizes published research on the effects of nozzle temperature, printing speed, layer height, infill density, raster angle, build orientation, and carbon-fiber content on the mechanical and tribological behavior of FDM-printed CF-PLA and related composites. Particular attention is given to tensile, flexural, impact, compressive, friction, and wear behavior, as well as the potential use of CF-PLA in bush bearings and robotic systems. Numerical and finite-element modeling approaches for predicting thermal and mechanical behavior are also discussed. The literature indicates that carbon-fiber reinforcement can improve stiffness and load-bearing capability, but its benefits depend strongly on fiber distribution, orientation, interfacial bonding, and manufacturing quality.

1. Introduction

Additive manufacturing (AM) has progressed from a rapid-prototyping technology to a manufacturing route for functional engineering components. Unlike conventional subtractive manufacturing, AM builds components layer by layer, enabling complex geometries, lightweight structures, customization, and reduced material waste. Among AM processes, Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF), is particularly accessible because it uses relatively inexpensive equipment and commercially available thermoplastic filaments.

Polylactic acid (PLA) is one of the most widely used FDM materials because of its ease of printing, dimensional stability, and relatively low processing temperature. Nevertheless, neat PLA has limitations in applications involving high mechanical loads, elevated temperatures, impact, or prolonged sliding contact. Fiber reinforcement has therefore been investigated to improve the stiffness and strength of FDM-printed polymers. Carbon fiber reinforced PLA (CF-PLA) is of particular interest because carbon fibers provide high specific stiffness and can improve dimensional stability while retaining the low density associated with polymer-based components [1–4].

The performance of an FDM-printed component depends not only on the bulk material but also on manufacturing parameters and the resulting internal architecture. Nozzle temperature affects melt flow and interlayer diffusion; printing speed influences deposition and thermal history; and layer height, infill density, raster angle, and build orientation affect porosity, anisotropy, and load transfer [2–6]. Carbon-fiber content and

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orientation introduce additional variables because reinforcement can be preferentially aligned during extrusion.

These factors become particularly important when CF-PLA is considered for sliding components such as bush bearings. Bearing materials must withstand contact pressure and repeated sliding while maintaining acceptable friction, wear resistance, dimensional stability, and thermal performance [7-10]. Robotic systems are a potentially attractive application because lightweight bearing components may reduce moving mass and facilitate rapid customization. However, the literature has investigated the mechanical properties of CF-PLA more extensively than its tribological behavior in actual bearing applications [11-14].

The objective of this review is to critically synthesize research on FDM-printed CF-PLA and related polymer composites, with emphasis on process parameters, mechanical properties, tribological behavior, bearing and robotic applications, and numerical modeling. The review identifies consistent trends, limitations in the current evidence, and research gaps that require integrated experimental and computational investigation.

Figure 1 depicts the working principle of Fused Deposition Modeling (FDM) for fabricating CF-PLA components. The schematic illustrates filament feeding, controlled heating, extrusion through the nozzle, and layer-wise deposition onto the build platform. Coordinated X–Y movement and vertical Z-axis motion enable progressive material placement and formation of the final three-dimensional component.

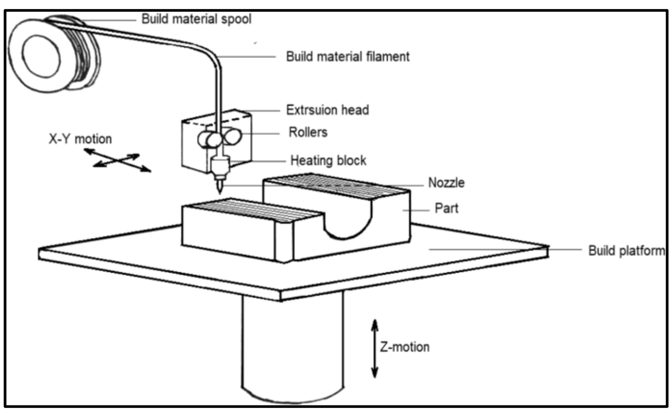

Figure 1: Schematic representation of the Fused Deposition Modeling (FDM) process for the fabrication of CF-PLA components. Adapted and redrawn based on the FDM process described by Cano-Vicent et al. [15].

2. Literature Review

2.1 FDM Process and CF-PLA Material

In FDM, a thermoplastic filament is heated and extruded through a nozzle before being deposited according to a sliced toolpath. Successive layers of roads cool and fuse to form the component. Because deposition follows a prescribed path and bonding occurs between adjacent roads and layers, FDM components are generally anisotropic and may contain internal voids. Consequently, the strength of a printed component is governed by both the intrinsic material properties and the quality of the deposited architecture [3,5,6].

PLA is attractive for FDM because it generally exhibits good printability and low warpage. The addition of carbon fibers can increase stiffness and, under suitable processing conditions, improve strength and dimensional stability. However, the effectiveness of reinforcement depends on fiber content, length, distribution, orientation, and fiber-matrix adhesion. Poor dispersion, agglomeration, and voids can reduce the expected benefits of reinforcement [1–4].

2.2 Influence of FDM Process Parameters

Nozzle temperature is closely related to melt viscosity and interlayer bonding. Insufficient temperature can limit polymer diffusion across interfaces, whereas excessive temperature may cause thermal degradation or dimensional instability. The optimum temperature is therefore material- and machine-dependent and should be considered together with printing speed and layer height [2,5].

Printing speed affects deposition rate and the thermal history of the material. Excessively high speeds can lead to inconsistent extrusion and insufficient bonding, while lower speeds may improve deposition quality at the expense of productivity. Layer height similarly affects surface quality, interlayer contact, printing time, and internal geometry. These parameters are particularly relevant to tribological components because deposited surface morphology influences initial contact and wear [5–8].

Infill density and raster angle control the internal load path. Higher infill generally increases structural integrity and reduces internal voids, but also increases mass and manufacturing time. Raster orientation can produce strong anisotropy because load transfer is more efficient along deposited roads than across weak inter-road or interlayer interfaces. Carbon fibers may further reinforce the preferred deposition direction, making build orientation and fiber orientation important design variables [2–6].

2.3 Mechanical Properties of FDM-Printed CF-PLA

Published studies generally report that carbon-fiber reinforcement increases stiffness and can improve tensile performance when fibers are adequately distributed and aligned with the loading direction [1–4]. However, the improvement is not necessarily proportional to fiber content. Excessive reinforcement may promote agglomeration, reduce matrix continuity, and increase defect sensitivity. Consequently, optimum fiber content depends on the filament formulation and processing conditions.

FDM components also exhibit strong directional dependence. Tensile specimens loaded parallel to the principal deposition or reinforcement direction generally perform better than specimens loaded across interfaces. Failure may occur through matrix cracking, fiber breakage, fiber pull-out, void growth, or interlayer delamination. These mechanisms demonstrate that a mechanical property measured in one orientation cannot automatically be generalized to all service conditions [3–6].

Flexural and impact behavior similarly depend on reinforcement architecture and printing orientation. Carbon fibers can increase flexural stiffness but may also reduce ductility. The balance between matrix toughness, fiber reinforcement, and the presence of weak interfaces influences impact response. For bearing applications, compressive and cyclic properties are also important because the bearing surface is subjected to contact pressure and repeated loading.

2.4 Tribological Behaviour

Tribological performance is governed by the interaction between material composition, surface roughness, normal load, sliding speed, temperature, and counterface condition. FDM surfaces contain layer lines and directional roughness, which can influence asperity contact, transfer-film formation, and wear debris generation [7–10].

Carbon fibers may improve wear resistance by increasing surface stiffness and reducing deformation, but the effect is not universally beneficial. Poorly bonded fibers can be pulled out during sliding and may contribute to abrasive action. Wear mechanisms may include adhesive wear, abrasive wear, fatigue or delamination wear, and fiber pull-out. The dominant mechanism is expected to change with load, speed, temperature, and surface condition.

Compared with mechanical characterization, systematic tribological studies of CF-PLA remain comparatively limited. Differences in test configuration, counterface, load, sliding speed, specimen orientation, and surface finish also make direct comparison between studies difficult. Standardized testing and reporting are therefore necessary to establish reliable relationships between FDM parameters and wear performance [7–10].

2.5 CF-PLA for Bush Bearings and Robotic Applications

Bush bearings are sliding-contact components that require a balance of compressive strength, low friction, wear resistance, dimensional stability, and thermal stability. FDM-printed CF-PLA is attractive because it offers low density, rapid manufacturing, and geometric flexibility. These advantages may be particularly useful in robotic systems, where reduced moving mass and rapid replacement of customized components can be valuable.

However, the suitability of CF-PLA for a practical bearing cannot be established from tensile strength alone. Long-duration sliding tests, cyclic loading, thermal effects, shaft-counterface interactions, and dimensional changes must be evaluated. Evidence from general polymer-composite tribology can inform material selection. However, it should not be interpreted as direct proof of suitability for bearing unless the specific CF-PLA formulation and service conditions have been experimentally validated [7–10].

2.6 Numerical Modeling and Finite Element Analysis

Numerical modeling can complement experimental testing by predicting temperature fields, residual stresses, deformation, and stress distributions. In FDM, thermal history is important because it affects interlayer diffusion and residual stress. Mechanical models must also account for anisotropy arising from the deposition path and, for CF-PLA, the preferential orientation of fibers [5,6,11].

Finite element analysis can be used to estimate the response of printed components under tensile, compressive, contact, and structural loading. However, accurate prediction requires material models that account for orthotropic or anisotropic behavior, porosity, interlayer bonding, and temperature dependence. Experimental calibration and validation are therefore essential. For bearing applications, future modeling could combine structural FEA with contact mechanics and experimentally derived wear laws to predict stress distribution and wear progression.

2.7 Comparative Synthesis and Research Gaps

The reviewed literature indicates a consistent trend: mechanical performance of CF-PLA has received substantial attention, while tribological performance and application-level validation remain less developed. Studies generally agree that fiber orientation, raster direction, and interlayer bonding strongly affect anisotropy. However, optimum process parameters are not universal because they depend on material formulation, printer configuration, nozzle geometry, and test orientation.

A second gap concerns the lack of integrated studies linking FDM process parameters to the full sequence of material structure, mechanical response, surface condition, friction, and wear. A third gap is the limited evidence for the long-term performance of CF-PLA bush bearings under realistic robotic duty cycles. Finally, validated numerical models that couple anisotropic mechanical behavior with contact and wear are still needed.

These gaps suggest that future work should move beyond single-response optimization. A multi-objective framework should consider mechanical strength, wear rate, coefficient of friction, mass, dimensional stability, and manufacturing time simultaneously. Design of Experiments (DOE), response-surface methods, and machine-learning approaches may help identify robust parameter windows, provided the underlying experimental data are sufficiently reliable.

3. Materials and Methods/ Review Procedure

This review was developed through a structured synthesis of literature identified in the original project report and the associated review manuscript, with emphasis on FDM/FFF manufacturing, PLA-based composites, carbon-fiber reinforcement, mechanical characterization, tribological behavior, process optimization, and numerical modeling. The review scope was organized into five themes: (i) material and reinforcement characteristics, (ii) FDM process parameters, (iii) mechanical properties, (iv) friction and wear, and (v) numerical modeling and application validation.

Relevant studies were compared according to fiber content, printing orientation, layer height, nozzle temperature, infill, raster angle, test method, applied load, sliding speed, and principal response. Because published studies use different materials, machines, specimen geometries, and test conditions, a quantitative meta-analysis was not attempted. Instead, the evidence was synthesized to identify consistent trends, contradictory findings, and areas where evidence remains insufficient. Short- and continuous-fiber systems were considered separately, where their reinforcement architectures materially affected interpretation.

Table 1: Synthesis of major research themes and findings in FDM-printed CF-PLA studies.

Research theme	Key variables	Primary response	Overall synthesis
Material reinforcement	CF content, fiber distribution, interface	Strength, stiffness	Reinforcement can improve stiffness; excessive content and defects can reduce benefits.
FDM parameters	Temperature, speed, layer height	Strength, surface quality	Optimum settings are material- and machine-dependent.
Build strategy	Raster angle, orientation, infill	Anisotropy, load transfer	Orientation strongly affects directional performance.
Tribology	Load, speed, roughness, counterface	Friction, wear	Performance is highly condition-dependent and less systematically studied.
Bearing application	Contact pressure, cyclic operation	Durability, dimensional stability	Application-level validation remains limited.
Numerical modelling	Thermal history, anisotropy, contact	Stress, deformation, temperature	Models require experimental calibration and validation.

Table 1 synthesizes major research themes in FDM-printed CF-PLA, covering material reinforcement, processing parameters, build strategy, tribological behavior, bearing applications, and numerical modeling. It highlights the principal variables and responses while emphasizing reinforcement effects, parameter sensitivity, anisotropy, application-level limitations, and the need for experimentally validated predictive models.

4. Result and Discussion

The synthesis indicates that no single FDM parameter can be optimized independently for all performance measures. For example, a parameter combination that improves tensile strength may not minimize surface roughness or wear. Similarly, high infill density may improve load-bearing capacity but increase component mass, which can be undesirable in robotic systems. This supports multi-objective optimization rather than optimization based on a single mechanical response.

From a bearing perspective, surface characteristics deserve greater attention. The FDM deposition strategy creates directional topography that may influence the real contact area and film transfer. Therefore, the effect of printing orientation should be investigated not only through tensile testing but also through friction and wear testing. Post-processing may reduce roughness, but it can also change dimensions and alter the surface region in which fibers are preferentially distributed.

Numerical modeling provides a route to reduce the number of experimental trials, but only when the model captures the dominant physics. A homogenized isotropic model may be insufficient for CF-PLA because the printed component can exhibit orthotropic behavior. For bearing applications, a useful modeling framework should incorporate anisotropic mechanical properties, contact pressure, temperature rise, and experimentally measured wear behavior. Such a model could support component-level design and predict service performance more effectively than a purely mechanical tensile model.

5. Conclusions

This review examined the current understanding of FDM-printed carbon-fiber-reinforced PLA, with emphasis on process parameters, mechanical performance, tribology, bearing applications, and numerical modeling. The literature demonstrates that carbon fibers can improve stiffness and, under suitable conditions, strength; however, the magnitude of improvement depends on fiber content, orientation, dispersion, interfacial bonding, and the quality of the FDM process.

FDM parameters such as nozzle temperature, printing speed, layer height, infill density, raster angle, and build orientation strongly influence anisotropy, surface quality, and mechanical performance. Tribological behavior is additionally controlled by surface roughness, load, sliding speed, temperature, and counterface conditions. Compared with mechanical characterization, the tribological behavior of CF-PLA—particularly in realistic bush-bearing and robotic applications—remains insufficiently investigated.

The principal research opportunity is therefore to develop an integrated framework connecting process parameters, printed microstructure, mechanical response, surface characteristics, friction, and wear. Future studies should combine DOE-based optimization, standardized tribological testing, long-duration cyclic evaluation, and validated numerical modeling. Such work could enable the development of lightweight, durable, and application-specific FDM-printed bush bearings for robotic and other engineering systems. The principal limitations of the present review are the heterogeneity of published testing conditions and the incomplete availability of directly comparable bearing-level data.

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