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Evaluation of High-Performance FFF Filaments for Structural Components in Electric Bicycle Motors

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Abstract. 3D printing, also known as additive manufacturing (AM), has become an inexpensive way of making prototypes and functional parts through various methods of printing. Fused filament fabrication (FFF) is one of the methods of AM that allows for less complex procedures to produce a part while providing lower operational costs than other forms of AM, such as selective laser melting (SLM) and stereolithography (SLA). Therefore, FFF has become a desirable method of production for various engineering applications requiring fast-paced design change and flexible capabilities. This study focused on the evaluation of high-performance filaments for use in structural components of electric bicycle (E-Bike) motor systems requiring mechanical strength and reliability in terms of exposure to the environment. Using mechanical tests, thermal evaluations, and chemical compatibility studies, five different commercially available materials (PLA, ASA, PC, PET-CF, and PPS-CF) were tested both electrically and through finite element analysis simulating working conditions. The objective of this research study was to determine if low-cost filaments manufactured through the FFF process could provide acceptable levels of performance with regards to long-term structural, thermal, and chemical properties associated with E-Bike applications. It was concluded that PLA is only useable for dimension verification, while both ASA and PC provided moderate improvement; therefore, fiber-reinforced composite materials, particularly PPS-CF, were the superior alternative for providing higher strength, stiffness, heat deflection, and chemical resistance. It was concluded that PPS-CF provided the most reliable selection to be used in long-term load-bearing motor components supporting the notion that FFF can be effectively used to manufacture high-performance, durable, cost-effective functional parts.

Keywords: Fused Filament Fabrication (FFF), Additive Manufacturing (AM), High-performance filaments, Electric bicycle motor components

1. Introduction

Additive manufacturing, more commonly referred to as “3D printing,” is a technology that offers considerable flexibility in terms of design freedom, shorter lead times for prototypes, and lower cost for small batch production, and is therefore very attractive for potential users [1]. Fused filament fabrication (FFF) is an additive manufacturing process that provides a more readily available and lower cost option as compared to the other methods of additive manufacturing, namely selective laser melting (SLM) and stereolithography (SLA) [2-4]. FFF is more accessible to the average person to operate than SLA or SLM because there are fewer barriers to implement it into your operation; also,

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while SLA has additional costs associated with post curing and using liquid materials, SLM has additional costs associated with both including and using protective atmospheres, explosions, and combustion of the powders used during the process [3,4]. The low cost of operating a FFF printer allows for prototyping at a lower cost, in addition to being able to also produce functional components; and it is important to note that there are fewer barriers to entry for using FFF as compared to traditional subtractive methods such as CNC machining, which require large donations of equipment and enough staff to physically run the machines to their full potential [5]. Compared to traditional subtractive processes (e.g., CNC machining of sheet metal), FFF offers many unique features that allow for increased geometric design flexibility, reduced wastage relative to the amount of finished product produced, and far faster iterations to achieve a functional design [1,5]. Using the current trend toward rapid development to establish the above assessment, there are many examples of companies using FFF in their production process. For instance, Contemporary Amperex Technology Co., Limited (CATL) used 3D printing technology in the production of battery fixtures, which resulted in a significant reduction in manufacturing costs and turnaround times when compared to traditional manufacturing methods [6].

While FFF technology has significant advantages over the traditional subtractive processes of manufacturing, FFF has some environmental and engineering challenges to be addressed with respect to the production of functional components [7,8]; specifically, very little has been done in regard to the potential use of FFF in high-performance applications, such as electric bicycle DC motor assemblies. Electric bicycle motor components experience both user-dependent loads and mechanical loads, therefore in order for them to operate properly, they must operate reliably under complex conditions of use; specifically, they must maintain functionality without failure under mechanical stress, maintain stability while being used under elevated temperature conditions, and also resist engagement with ambient contaminants such as dirt from the roadways, water contamination, and lubrication materials such as oils [7,8].

Motivated by the desire to provide a solution to the problems outlined above, the overall goal of the current research project is to design, fabricate, and test a motor component for an electric bicycle that has been produced using FFF that takes into account the Design for Additive Manufacturing (DfAM) principles [9]. More specifically, the objectives of this work are: (1) to evaluate various FFF materials based on their mechanical, thermal, and chemical properties, in order to make a systematic comparison of each; (2) to predict the performance of each material when subjected to realistic loads via finite element modelling and subsequent static structural analyses [10,11]; and (3) to determine whether or not PPS-CF has been developed as a high-performance filament that will perform as expected mechanically, thermally, and environmentally when used in an electric bicycle motor application while providing the advantages of FFF [12].

By using the electric bicycle component as an example, this study will highlight the possibilities for a low-cost option of FFF-3D printing for producing high-performance products by analyzing potential materials used, how to select the appropriate design methodology, and demonstrating practically the feasibility of FFF-3D printing.

2. Method

2.1. Materials comparison and selection

This study evaluated six different 3D printing filament materials to determine their suitability for fabricating the electric bicycle motor structure using Fused Filament Fabrication (FFF) technology. The six materials were PLA, ASA, PC, PET-CF, PPA-GF, and PPS-CF, each exhibiting distinct mechanical, thermal, and chemical characteristics tailored to specific engineering requirements [13-20]. A comparative overview of tensile strength, flexural modulus, and heat deflection temperature

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is summarized in Figure 1, while the overall normalized performance distribution is shown in Figure 2.

The sources for the materials were: Bambulab for PLA, ASA, PC and PET-CF filament [14], Raise3D for the PPA-GF filament, and Nanjing Advanced Thermoplastic Composites Co., LTD for the PPS-CF filament [21,22].

PLA was used for the initial dimensional verification phases and to perform prototype testing. PLA is low-cost, easy to print, and offers sufficient dimensional accuracy for rapid model iteration [8]. Because PLA demonstrated excellent dimensional verification, it was suitable for refining the models until sufficient accuracy was obtained and was particularly important for the electric bicycle study when the models had been considered acceptable for prototyping. For functional components intended to function under actual loads/interaction with the environment, PLA is not an appropriate material choice due to its low heat resistance, inferior mechanical strength, and low durability [8].

ASA is longer lasting outdoors with better UV and weather resistance than PLA, and it has more impact strength than PLA and is therefore suitable for semi-structural outdoor applications, but its tensile and flexural properties were still lower than high-performance composites, and a moderate heat resistance [9].

PC (polycarbonate) has impressive tensile strength, decent heat resistance, and it is known for outstanding impact toughness; overall polycarbonate is a respected engineering plastic [10]. However, PC typically requires high printing temperatures and stringent processing conditions—particularly for fabricating high-quality components, and although PC can outperform composites in certain aspects such as temperature and rigidity; it offers less performance than fiber-reinforced composites in a system under certain conditions [7].

The PET-CF (carbon fiber reinforced PET) combines very good tensile strength (131 MPa), pretty good flexural modulus (5320 MPa), and good impact resistance (36 kJ/m²) in a filament [11]. The water absorption is low and also a contributor to the dimensional stability. For components where there is a need for high strength with reasonable processing difficulty, PET-CF is a suitable to adequately good choice, but there are still limits for long-term stability when subjecting the composite to high-temperature conditions or chemicals to the filament density [7,14].

The PPA-GF (glass fiber reinforced polyphthalamide) filament has good tensile strength (89 MPa), flexural strength (143 MPa), with high rigidity (4850 MPa), and excellent heat resistance with a heat deflection temperature up to 147 °C. The most likely application for PPA-GF would be engineering parts that demand robustness and provide an incredible material performance advantage over BA. Compared to PPS-CF, PPA-GF demonstrates limited long-term durability when subjected to high temperatures or chemically aggressive environments [7,16].

PPS-CF (carbon fiber reinforced polyphenylene sulfide) is from Nanjing Advanced Thermoplastic Composites Co., LTD, and it demonstrated leading mechanical properties (tensile strength 115 MPa, flexural strength 200 MPa, flexural modulus 13 GPa), leading heat resistance (service temperature >200 °C), leading chemical resistance (non-porous, and chemically inert), inherent flame-characteristics (V-0 rating), and very low-water absorption contributes to dimensional stability and long-term reliability in unpredictable or hostile environments [15-19]. Taking into account the actual work grabbing exposure temperatures, continuous vibration, potential exposure to water or lubricants, and harsh mechanical reliability conditions that all electric bicycle motor components must endure, PPS-CF was finally chosen for the scope of this study. Its comprehensive performance in strength, heat resistance, and chemical stability renders it an optimal candidate for critical engineering components requiring long-term safety and durability [15-19].

Figures 1-2 (radar and bar charts) summarize the key physical and mechanical properties for all materials, and the sources for each filament are also noted above [15-19]. This comparison provides an excellent foundation for the experimental and simulation work that will follow on PPS-CF.

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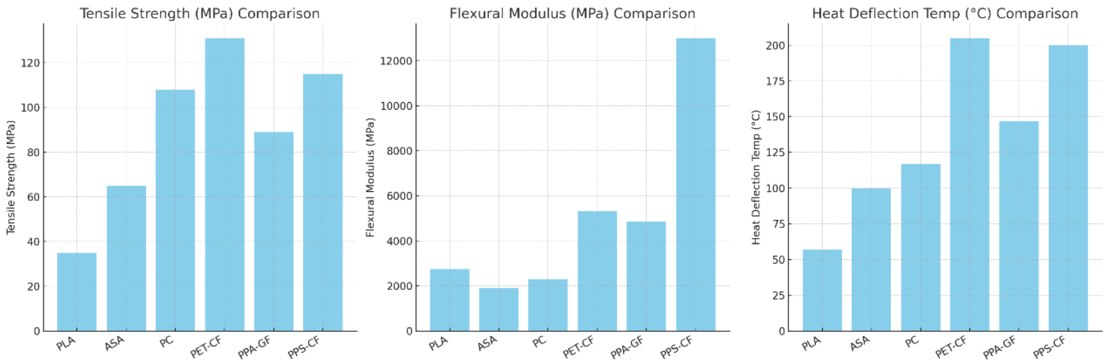

Figure 1. Comparative mechanical and thermal properties of FFF materials

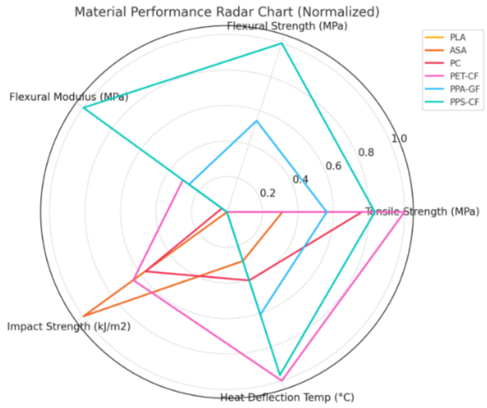

Figure 2. Material performance radar chart (normalized)

2.2. Experiment

In this study, five different commercially available FFF materials were compared - PLA, ASA, PC, PET-CF (Bambulab), and PPS-CF (Bambulab). The objective was to assess their suitability for structural components subjected to mechanical and thermal loads in e-bike applications [7-12]. PLA was included only to test for dimensional accuracy and rapid prototyping because of its low mechanical and thermal resistance [8]; the other four materials (ASA, PC, PET-CF and PPS-CF) were investigated for their potential to be used long term in functional applications [9-13]. All materials were procured from reputable suppliers to guarantee quality consistency and minimize batch-to-batch variability of filaments; PLA, ASA, PC, and PET-CF were purchased directly from Bambulab to ensure the printer and filament parameters were aligned; PPS-CF was purchased specifically from the Bambulab high-performance filament category due to the increased reinforcement they use with the same filament compatibility on the same printer [11,12].

All specimens were produced on a Bambulab H2D 3D printer, and both the printer and software functionality include an actively regulated chamber, automatic calibration features, and hardened steel nozzles for use with abrasive composite filaments [11]. Printing parameters were aligned as closely as possible with ISO specimen preparation standards [16]. All of the specimens were printed on a common layer height of 0.2 mm to balance surface finish with mechanical properties since those changes can be markedly noticeable at a reduced height. The nozzles were individually calibrated based on the manufacturer specifications: PLA (210-220 °C); ASA (250-260 °C); PC (260-280 °C); PET-CF (265-275 °C); and, PPS-CF (290-310 °C). The bed temperature was adjusted to a range of 60-110 °C, depending on material adhesion, and the prints were completed within a closed building chamber to provide thermal stability and to limit warpage [16,17]. For structural comparative purposes, the infill density was set to 100%, with a rectilinear infill to ensure isotropic load distribution in the test specimens [17]. The influence of post-processing was excluded from mechanical testing; all specimens were tested in their as-printed state, except for the removal of minimal support structures.

Mechanical testing adhered to ISO specifications [16-18]. The tensile specimens conformed to ISO 527 Type 1B geometry with a gauge length of 50 mm. Flexural properties were identified under ISO 178 via a three-point bending fixture with a span-to-thickness ratio of 16:1. Impact resistances were identified under ISO 179 by using un-notched Charpy samples to indicate resistances to sudden shocks [17]. Mechanical tests were conducted on an Instron 5969 universal testing machine with a 10 kN load cell (calibration accuracy: ±0.5%), with five or more specimens per condition to ensure statistical relevance [18]. The Heat Deflection Temperature (HDT) at 0.45 MPa was identified with a TA Instruments TMA Q400 comprised analysis, with heating rate of 2 °C/min upon reaching the deflection of > 0.25 mm. The retrieved values were then compared to baseline referenced literature values for each polymer system, permitting an understanding of deviation and statistically confirming consistency in having performed experiments [10,12].

Mechanical testing followed ISO requirements, which were performed with test samples of ISO 527 Type 1B geometry, having a gage length of 50 mm for tensile testing and undergo flexural property testing using three-point bending per ISO 178 with a span to thickness ratio of 16:1; and for measuring the impact resistance of the test samples (Charpy test) according to ISO 179 from un-notched samples subjected to an impact event. All mechanical testing was conducted utilizing the Universal Testing Machine (Instron 5969) using a load cell with a 10 kN capacity (calibrated to within ±0.5%); each condition tested had five or more test samples to provide a statistically valid result. The resistance of a sample to failure under heat and deflection (Heat Deflection Temperature (HDT)), measured under a load of 0.45 MPa, was determined using TMA Q400 from TA Instruments heated at a rate of 2 °C/min to deflection of > 0.25 mm. The measured values were compared to published literature values on HDT for each of the polymer systems, thereby allowing for determination of deviations as well as verification of experimental method consistency [10,12].

Experimental modality with finite element simulation was used to augment the physical tests and predict realistic in-use performance [19]. As summarised above, CAD models of the ISO test specimens were produced in SolidWorks and were meshed with tetrahedral elements with an average size of 0.5 mm. The boundary conditions were imposed similarly to how the experimental conditions were set up, e.g., fixed grip for tensile specimens and three-point load for the flexural models [21]. For e-bike service simulations, a simplified geometry of the mounting bracket was utilized with representative loads (1.5–2.0 kN, corresponding to rider and cargo weight transfer). In the coupled thermo-mechanical simulations, thermal loads of 25 °C (ambient), 60 °C (moderate exposure summer), and 90 °C (worst-case exposure near the motor housing) were imposed with added thermal loads [21,22].

Material input parameters were a combinations of the experimental averages and literature values ranging from tensile strength σ_t of 50-120 MPa, flexural strength σflex of up to 200 MPa, flexural modulus Eflex of 2000 - 13000 MPa, impact toughness of 20 - 36 kJ/m², and HDT values from 57°C (PLA) to over 220 °C (PPS-CF) [7-12]. To evaluate high temperature stability, degradation factors were estimated from reported retained curves for modulus and strength where PLA shows total loss (70-80% loss at 90 °C), ASA and PC show moderate retention (55-80% variable depending on the property examined), while PET-CF and PPS-CF retained over 85% of their strength and stiffness making these materials a more reliable candidate for use in applications with continuous thermal cycling [12,13,19].

This integrated approach ensures that comparison of candidate material properties considers both inherent mechanical properties and more realistic service conditions that the structural components

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of an e-bike will occult [19,20]. By integrating standard experiments and multiphysics simulations, this study establishes a more robust framework for selecting optimal FFF filaments for load-bearing, thermally stressed applications [20-22].

3. Result

A comparative dataset also revealed a number of clear trends with the performance of the evaluated filaments Figure 3. PLA provided moderate tensile (50 - 65 MPa) and flexural (70 - 100 MPa) strength with the lowest heat deflection temperature (55 - 60 °C) and quickly degraded when immersed in detergent, affirmed previous literature confirming it is a decent prototyping material, but not a functional structural material [7,8,14]. ASA demonstrated improved performance against weather and chemicals, but was limited in flexural performance ~50 - 80 MPa, which limits overall structural performance for cosmetic or semi-structural components that act under moderate (maximum transient load) [9]. PC had the best toughness (impact 30 - 40 kJ/m²) and thermal stability (110 - 120 °C) but was shown to not have the same stiffness as fiber-reinforced alternatives [10]. While PC outperformed neat polymers, it exhibited inferior performance compared to PET-CF and PPS-CF filaments; the flexural modulus >5 GPa and HDT of ~205 °C of the PET-CF filament was substantial, meaning a better rigidity and heat performance than neat and polymer blends overall [11]. And, with moderate chemical stability, supports profiles as a stretch and automate order flexibility, lastly, PPS-CF had the best performance of potential candidates, consistently achieving tensile strength of 100 - 120 MPa, flexural modulus > 7 GPa, while retaining over 90% of its mechanical performance from detergent degradation at 60 °C for over 30 min and clearly illustrating its structural performance, in addition to chemical resistance as a benefit [12-15].

The behaviour of the PPS-CF is clearly no performance expectations, important for electric bicycle applications additions as they would be subject to many cleaning, thermal cycling, and continuous load; making PPS-CF ideal as a structural polymer material [13-15].

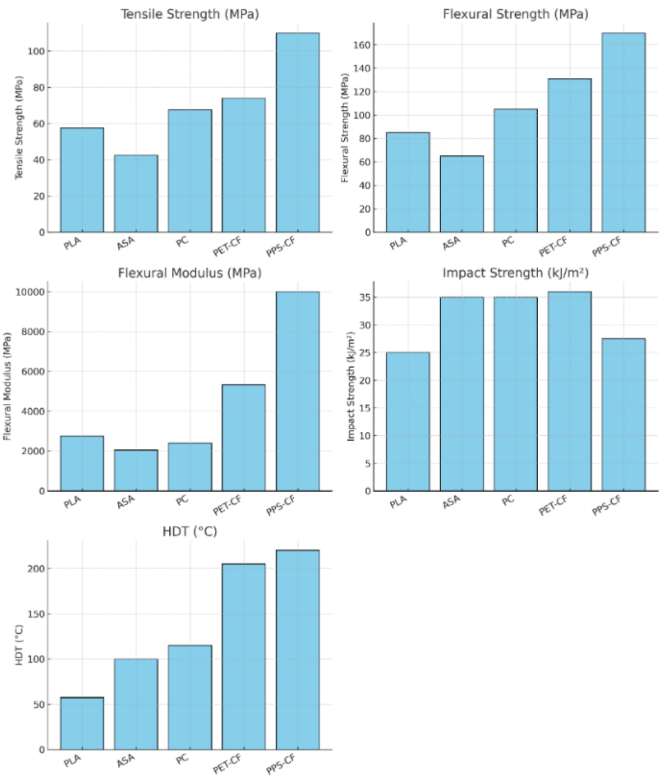

Figure 3. Mechanical and thermal property comparison of FFF materials

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4. Conclusion

A systematic evaluation was conducted to assess the feasibility of using Fused Filament Fabrication (FFF) to create structural components for electric bicycle motors. An extensive comparison of five materials (PLA, ASA, PC, PET-CF and PPS-CF) was conducted, which included mechanical testing, thermal characterization, chemical resistance testing and finite element simulations under realistic service conditions. The results of the study demonstrated different material dependent trends; PLA demonstrated good dimensional accuracy but was thermally and mechanically weak, making it only appropriate for prototype parts; ASA and PC showed medium outdoor durability and impact performance but demonstrated low mechanical stiffness when subjected to sustained loads; PET-CF had high rigidity (Eflex ≈ 5.3 GPa) and high heat deflection (≈205°C), and was therefore deemed a suitable option for medium range structural parts; and finally, PPS-CF was the clear winner with 100-120 MPa of tensile strength, >7.0 GPa of flexural modulus, and superior heat & chemical resistance when exposed to detergents. The results suggest that PPS-CF is the most suitable and durable filament for long-term load bearing applications in e-bike motors, which suggests that low-cost FFF technology has the potential to transition from prototype to high-performance engineering manufacturing applications.

Although these accomplishments have been made, there are still several limitations to consider. This study was limited to the laboratory-controlled environment and to simulation testing without any large-scale empirical testing of the FFF parts within an assembled e-bike system. Chemical resistance testing was also limited to detergent materials and did not include other environmental exposure testing such as UV aging, fatigue cycling, and humidity degradation. Furthermore, the findings are limited in their generalizability because of limitations in the literature and data set considered in the study.

Future work should therefore include additional empirical testing, including in situ mechanical testing of parts under real-world riding conditions, as well as expanding the scope of work to incorporate the study of hybrid materials, machine-learning guided optimization for DfAM (Design for Additive Manufacturing), and multi-scale modeling to provide a more in-depth understanding of the structure–property relationships. Finally, by incorporating a more extensive body of existing literature and multiple industrial case studies, it is possible to increase the replicability and relevance of these findings in order to facilitate the broader industrial acceptance of FFF-based composites for functional and high-performance components.

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