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Investigation of Mechanical and Thermal Behavior of Glass Fiber–Enhanced PEEK Parts Produced via Fused Filament Fabrication

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Abstract

This study investigates the thermal and mechanical properties of Polyetheretherketone (PEEK) polymer and Glass Fiber (GF) reinforced PEEK polymer fabricated using the Fused Filament Fabrication (FFF) process. Specimens were printed in three building orientations—X, Y, and 45°—to evaluate the influence of layer deposition on polymer material performance. Tensile and flexural tests revealed that GF-PEEK polymer exhibited significantly higher Ultimate Tensile Strength (110 MPa in X-orientation), Young's Modulus (4.5 GPa), and Flexural Strength (180 MPa) compared to PEEK polymer, attributed to the reinforcing effect of Glass Fibers. However, a reduction in Elongation at Break indicated increased brittleness. The X-orientation showed superior mechanical properties due to layer alignment with the loading direction, while the 45° orientation demonstrated lower values due to increased interlayer shear. Thermal analysis using TGA and DSC demonstrated enhanced thermal stability and degree of crystallinity for GF-PEEK polymer, with an initial decomposition temperature of 590 °C and a 38% crystallinity, owing to the nucleating effect of Glass Fibers. Comparative analysis with existing literature confirmed the positive impact of Glass Fiber reinforcement on both mechanical and thermal performance. This study establishes the potential of GF-PEEK polymer for high-performance applications requiring enhanced stiffness, strength, and thermal resistance. The novelty of this research lies in the comprehensive evaluation of build orientations and their impact on mechanical and thermal properties, providing new insights for optimizing FFF-printed polymer composite materials. The findings also highlight the significant role of build orientation in optimizing mechanical behavior, paving the way for future advancements in 3D-printed polymer composite materials.

Keywords: PEEK, glass fiber, fused filament fabrication, mechanical properties, thermal analysis

INTRODUCTION

Polyether ether ketone (PEEK) is a high-performance thermoplastic known for its exceptional mechanical properties, chemical resistance, and thermal stability. It has found extensive applications in aerospace, automotive, and medical industries due to its excellent strength-to-weight ratio and biocompatibility [1-2]. However, the high cost and processing difficulty of PEEK have limited its widespread use. The advent of Fused Filament Fabrication (FFF), a cost-effective additive manufacturing technique, has provided a viable method for fabricating complex PEEK components with high precision and minimal material wastage [3- 4]. Despite its advantages, the inherent brittleness and warping tendency of PEEK during FFF pose significant challenges, necessitating exploration of reinforcement strategies to enhance its mechanical performance.

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Glass Fiber (GF) reinforcement in PEEK has emerged as a promising solution to overcome these limitations. GF improves the tensile strength, flexural modulus, and thermal stability of PEEK composites while maintaining lightweight characteristics [5]. The incorporation of GF not only enhances the dimensional stability of FFF-printed parts but also reduces the warping effect by minimizing thermal shrinkage [6]. These properties make GF-reinforced PEEK composites suitable for high-performance applications requiring superior mechanical and thermal properties. Additionally, the anisotropic behavior induced by layer-by-layer deposition in FFF can be mitigated by strategically aligning the fibers, thereby optimizing the mechanical properties in specific directions [7]. The use of polypropylene fibers in concrete has been shown to improve tensile and flexural strength. These fibers help control crack propagation and enhance the durability of concrete in structural applications [8].

Several studies have investigated the mechanical properties of PEEK composites fabricated through FFF. Studies have shown that adding carbon fibers to PEEK enhances its stiffness and tensile strength compared to pure PEEK, emphasizing the effectiveness of fiber reinforcements in additive manufacturing. Similarly, research has indicated that incorporating glass fibers (GF) enhances the thermal stability and dimensional accuracy of PEEK components produced using FFF technology [9]. However, most research has concentrated on carbon fiber reinforcements, with limited attention given to GF-reinforced PEEK composites. Additionally, the usage of different build orientations on the mechanical and thermal properties of GF-PEEK composites is not well understood [10-11].

The objective of this study is to investigate the mechanical and thermal properties of GF-reinforced PEEK components fabricated using FFF. The study aims to evaluate the influence of different build orientations (X, Y, and 45°) on tensile strength, flexural strength, and thermal stability. Additionally, the effect of GF content on mechanical anisotropy and dimensional stability is examined. The scope of the work also includes a comparative analysis with existing literature to validate the findings and provide practical insights for industrial applications. This study is novel in its comprehensive investigation of the combined effects of GF reinforcement and build orientations on the mechanical and thermal properties of PEEK composites fabricated using FFF. Unlike previous studies that predominantly focused on carbon fiber reinforcements or a single build orientation, this research systematically explores the influence of multiple build orientations on mechanical anisotropy and thermal stability in GF- PEEK composites. The findings are expected to contribute to the optimization of FFF parameters for manufacturing high-performance PEEK components with enhanced mechanical and thermal properties, paving the way for their application in demanding engineering environments [12, 13].

MATERIALS AND METHODS

In this study, Polyether ether ketone (PEEK) and Glass Fiber (GF) were selected as the primary materials for fabricating composite specimens using Fused Filament Fabrication (FFF). Detailed descriptions of the materials, including manufacturer information, physical dimensions, and thermal and mechanical properties, are provided to ensure reproducibility and accuracy in experimental analysis.

PEEK Filament

PEEK is a high-performance thermoplastic known for its outstanding mechanical properties, high-temperature resistance, and chemical inertness, making it suitable for aerospace, automotive, and medical applications [14]. In this work, the PEEK filament was sourced from Tesseract, Mumbai, a leading manufacturer known for producing high- quality engineering polymers. The filament had a consistent diameter of 1.75 mm, ensuring compatibility with the FFF printer used in this study. To maintain optimal print quality and mechanical properties, the PEEK filament was stored in a desiccator to prevent moisture absorption, which could lead to degradation and reduced adhesion between layers [15-17]. The filament diameter was periodically measured using a digital micrometer to ensure uniform extrusion and dimensional accuracy during the FFF process. The thermal and mechanical properties of PEEK are presented in Table 1. These values were obtained from the manufacturer's datasheet and cross-verified through preliminary tests to ensure consistency with experimental conditions.

PEEK's high tensile strength and flexural modulus make it ideal for load-bearing applications, while its glass transition and melting temperatures enable usage in high-temperature environments [18-20]. The thermal conductivity of PEEK is relatively low, which may lead to uneven heat distribution during FFF, affecting the dimensional accuracy of printed parts. To counter this, controlled print chamber temperatures were maintained throughout the fabrication process [21-22].

Glass Fiber (GF)

Glass Fiber (GF) is widely used as a reinforcing material in polymer composites due to its high strength-to-weight ratio, excellent thermal stability, and cost-effectiveness [23-24]. In this study, E-glass fibers were chosen due to their superior mechanical properties and compatibility with thermoplastic matrices like PEEK. The fibers were produced by Contech Chemicals LLP, a reputable manufacturer known for producing high-quality glass fibers for composite applications. The diameter of the glass fibers was in the range of 10-15 µm, which ensures effective reinforcement and uniform distribution when mixed with the PEEK matrix. The fibers were stored in a dry environment to prevent moisture absorption, which could impact the interfacial bonding with the PEEK matrix [25]. The thermal and mechanical properties of Glass Fiber are summarized in Table 2. These values are consistent with industry standards for E-glass fibers and were verified through manufacturer specifications.

Glass Fiber exhibits high tensile strength and modulus, which contribute to the improved stiffness and load-bearing capacity of composites. Its low coefficient of thermal expansion ensures dimensional stability even under fluctuating temperatures, making it suitable for high-performance engineering applications [26-27]. Additionally, the high dielectric strength of E-glass fibers provides excellent electrical insulation, which can be advantageous in electronics and aerospace applications. The selected properties of PEEK and Glass Fiber were chosen to complement each other, aiming to create a composite material with enhanced mechanical and thermal properties suitable for demanding engineering environments. The characterization of these materials establishes a foundation for optimizing the FFF process parameters to achieve high-performance composite components.

Table 1. Thermal and Mechanical Properties of PEEK Filament.

Property	Value
Tensile Strength (MPa)	95
Tensile Modulus (GPa)	3.6
Flexural Strength (MPa)	160
Flexural Modulus (GPa)	4.0
Impact Strength (kJ/m²)	15
Glass Transition Temperature (°C)	143
Melting Temperature (°C)	343
Density (g/cm³)	1.30
Thermal Conductivity (W/m·K)	0.25

Table 2. Thermal and Mechanical Properties of Glass Fiber (E-Glass).

Property	Value
Tensile Strength (MPa)	3000
Tensile Modulus (GPa)	72.5
Density (g/cm³)	2.55
Thermal Conductivity (W/m·K)	1.0
Coefficient of Thermal Exp. (µm/m·K)	5.4
Softening Point (°C)	846
Dielectric Strength (kV/mm)	112.5

Fabrication Process

The composite specimens were fabricated using the Fused Filament Fabrication (FFF) process, which is known for its versatility, cost-effectiveness, and capability to develop complex geometries. In this study, PEEK filament and Glass Fiber (GF) were used as the primary materials [28]. The fabrication process was carefully optimized to achieve high dimensional accuracy, mechanical strength, and surface finish.

Printer Model and Specifications

The specimens were printed using the Intamsys Funmat HT Enhanced 3D printer, which is specifically designed for high-performance thermoplastics like PEEK. This printer model is equipped with the following specifications [29-30]:

- *High-temperature nozzle:* Capable of reaching up to 450°C, ensuring proper extrusion of PEEK filament without degradation.
- *Heated build platform:* Maintains a temperature of 160°C, which prevents warping and ensures strong layer adhesion during the printing process.
- *Nozzle diameter:* 0.4 mm, enabling precise extrusion and fine layer resolution.
- *Build volume:* 260 mm × 260 mm × 260 mm, allowing for the fabrication of medium-sized components.

The high-temperature capabilities of the Intamsys Funmat HT Enhanced are crucial for processing PEEK, as it requires elevated nozzle and bed temperatures for optimal interlayer bonding and mechanical properties.

Printing Parameters

To achieve high-quality prints with consistent mechanical properties, the following printing parameters were used [31-32]:

- *Layer Height:* 0.2 mm – Chosen to maintain a balance between surface finish and mechanical strength.
- *Nozzle Temperature:* 400°C – Optimized for adequate melting and extrusion of PEEK filament.
- *Bed Temperature:* 160°C – Prevents warping and enhances adhesion to the build plate.
- *Print Speed:* 30 mm/s – Maintains dimensional accuracy while preventing defects such as under-extrusion.
- *Infill Density:* 100% – Ensures maximum mechanical strength and uniform stress distribution within the printed parts.
- *Cooling Fan Speed:* 0% – Disabled to prevent rapid cooling, which could induce residual stresses and warping in the high-performance thermoplastic.

The print speed and layer height were selected after several trial runs to optimize the surface finish and structural integrity of the specimens. A slower print speed ensures better interlayer bonding, which is critical for achieving high mechanical performance in PEEK parts.

Build Orientations

Three different build orientations were considered to investigate their influence on the mechanical properties of the printed specimens [33-34]:

- *X Orientation:* Layers were deposited along the X-axis, resulting in layers stacked perpendicular to the loading direction during tensile and flexural tests. This orientation is known to exhibit moderate tensile strength but improved impact resistance due to the perpendicular layer arrangement.
- *Y Orientation:* Layers were deposited along the Y-axis, leading to layers aligned parallel to the loading direction. This orientation typically exhibits the highest tensile and flexural strengths due to the continuous filament alignment along the stress direction, enhancing load transfer between layers.
- *45° Orientation:* Layers were deposited at a 45° angle relative to the loading direction. This configuration balances the mechanical properties by distributing stress across multiple layer boundaries, resulting in improved shear resistance but moderate tensile strength.

Experimental Setup

To evaluate the mechanical and thermal properties of the fabricated specimens, a series of standardized tests were conducted following ASTM guidelines. The experimental setup was designed to accurately measure the tensile strength, flexural properties, and thermal stability of PEEK and Glass Fiber (GF)- reinforced PEEK specimens fabricated using the FFF process.

Tensile Testing

The tests were conducted according to ASTM D638[35] standards as shown in Figure 1 using a Universal Testing Machine (UTM, INSTRON 3369) with the following specifications of Load Cell Capacity: 50 kN, Crosshead Speed: 5 mm/min and Gauge Length: 50 mm.

GF-PEEK exhibited superior UTS and Young's Modulus across all orientations compared to PEEK, owing to the reinforcement effect of Glass Fibers, which enhanced stiffness and load-bearing capacity. The highest UTS was observed in the X-orientation due to the alignment of printed layers parallel to the loading direction, minimizing stress concentrations. The 45° orientation showed lower values due to the oblique layer deposition, leading to increased interlayer shear and stress concentration. A significant reduction in Elongation at Break was noted for GF-PEEK, indicating increased brittleness, consistent with findings from previous studies [36].

The tensile properties were evaluated for both PEEK and GF-PEEK specimens, with results summarized in Figure 2.

The results indicate that GF-PEEK exhibits higher tensile strength and Young's modulus compared to PEEK, owing to the reinforcement effect of glass fibers. However, the elongation at break is reduced due to the increased stiffness and brittleness imparted by the glass fibers.

Flexural Testing

Flexural tests were performed using a 3-point bending setup according to ASTM D790 [37] standards as shown in Figure 3 to evaluate the flexural strength, flexural modulus, and maximum deformation of the specimens. The tests were conducted on the same INSTRON 3369 UTM, with the following parameters of Support Span Length: 64 mm, and Crosshead Speed: 2 mm/min. GF-PEEK showed enhanced Flexural Strength and Modulus across all orientations due to the reinforcement of Glass Fibers, which restricted matrix deformation and improved load distribution. Like tensile tests, the X-orientation demonstrated the highest flexural properties due to layer alignment with the loading direction. The 45° orientation exhibited lower strength due to increased interlayer shear stress, consistent with trends observed in literature.

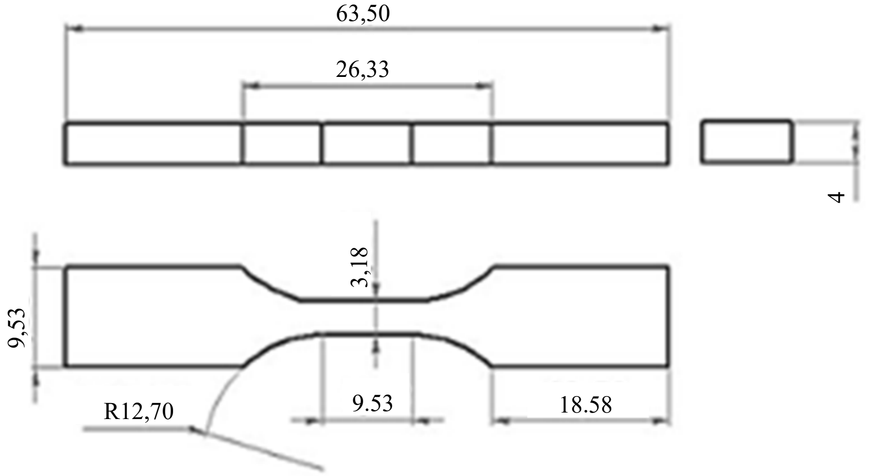

Figure 1. ASTM D638 PEEK and GF-PEEK Specimens.

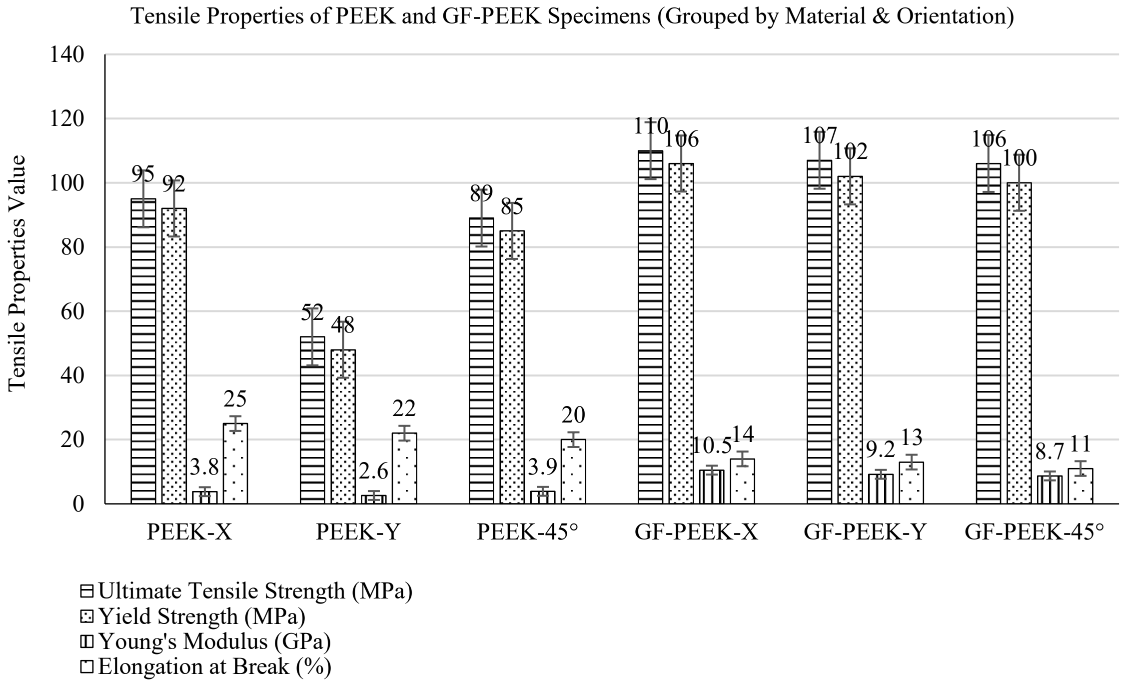

Figure 2. Tensile Properties of PEEK and GF- PEEK Specimens.

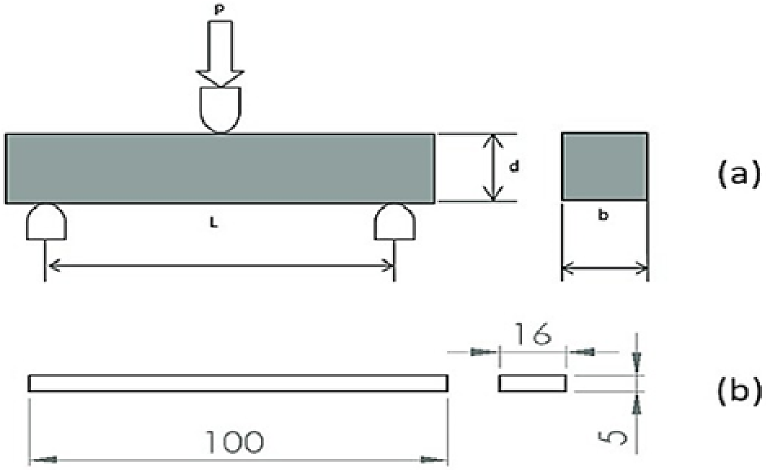

Figure 3. ASTM D790 PEEK and GF-PEEK Specimens.

GF-PEEK showed enhanced Flexural Strength and Modulus across all orientations due to the reinforcement of Glass Fibers, which restricted matrix deformation and improved load distribution. Like tensile tests, the X-orientation demonstrated the highest flexural properties due to layer alignment with the loading direction. The 45° orientation exhibited lower strength due to increased interlayer shear stress, consistent with trends observed in literature. The flexural properties for PEEK and GF-PEEK specimens are presented in Figure 4.

The GF-PEEK specimens exhibited superior flexural strength and modulus due to the glass fibers reinforcement, which enhances stiffness and load- bearing capacity. However, maximum deformation decreased, indicating increased brittleness.

2.4.1. Thermal Analysis

Thermal properties were evaluated using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to assess the thermal stability and melting behavior of the materials.

2.4.1.1. Thermogravimetric Analysis

Thermogravimetric Analysis (TGA) [38] was conducted using TA Instruments Q50 in a nitrogen atmosphere with the following test conditions of Temperature Range: 30°C to 700°C, Heating Rate: 10°C/min and Sample Weight: 10 mg. The thermal degradation behavior of PEEK and GF-PEEK is shown in Figure 5.

The GF-PEEK showed improved thermal stability with a slightly higher initial decomposition temperature and residual mass, attributed to the thermal resistance of glass fibers.

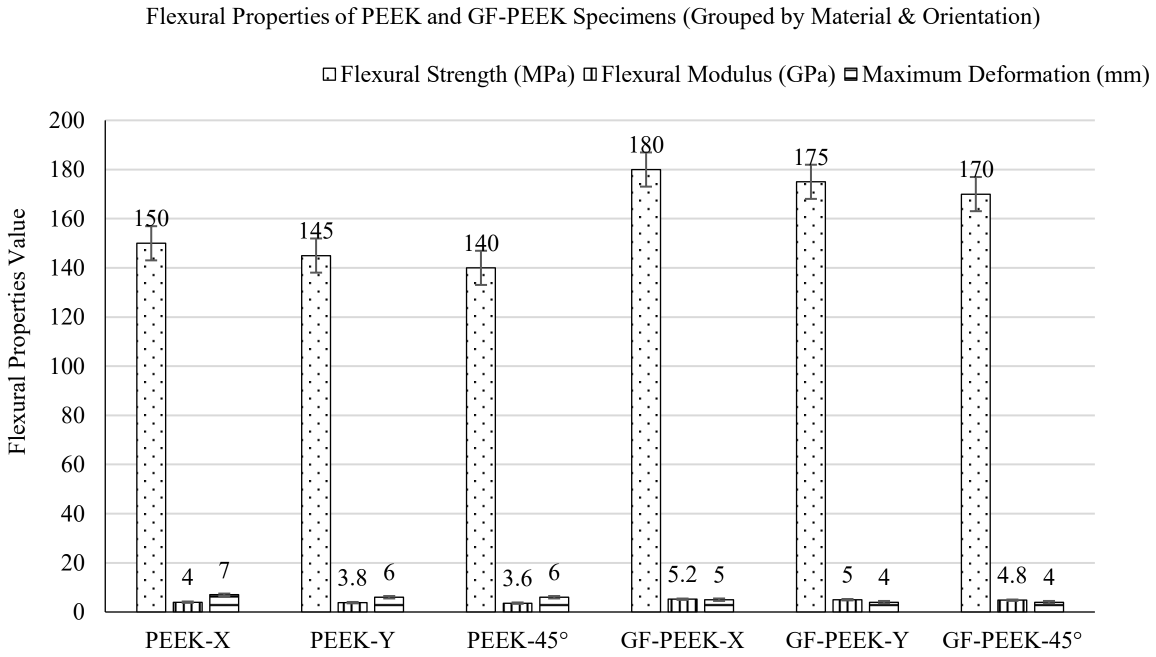

Figure 4. Flexural Properties of PEEK and GF- PEEK Specimens.

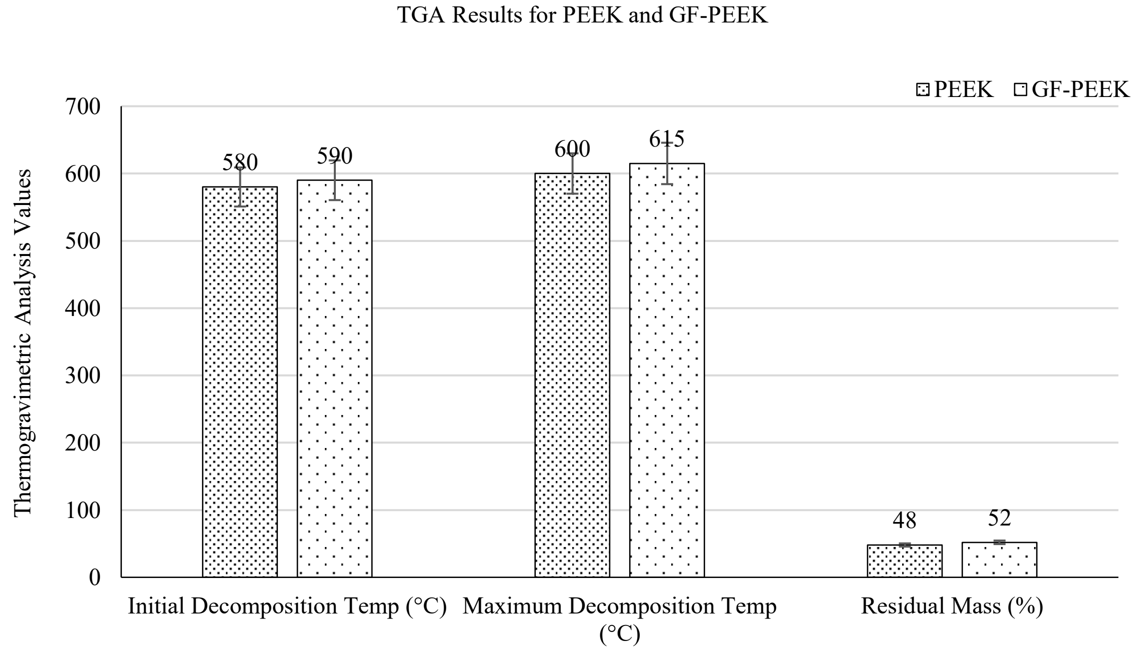

Figure 5. TGA Results for PEEK and GF-PEEK.

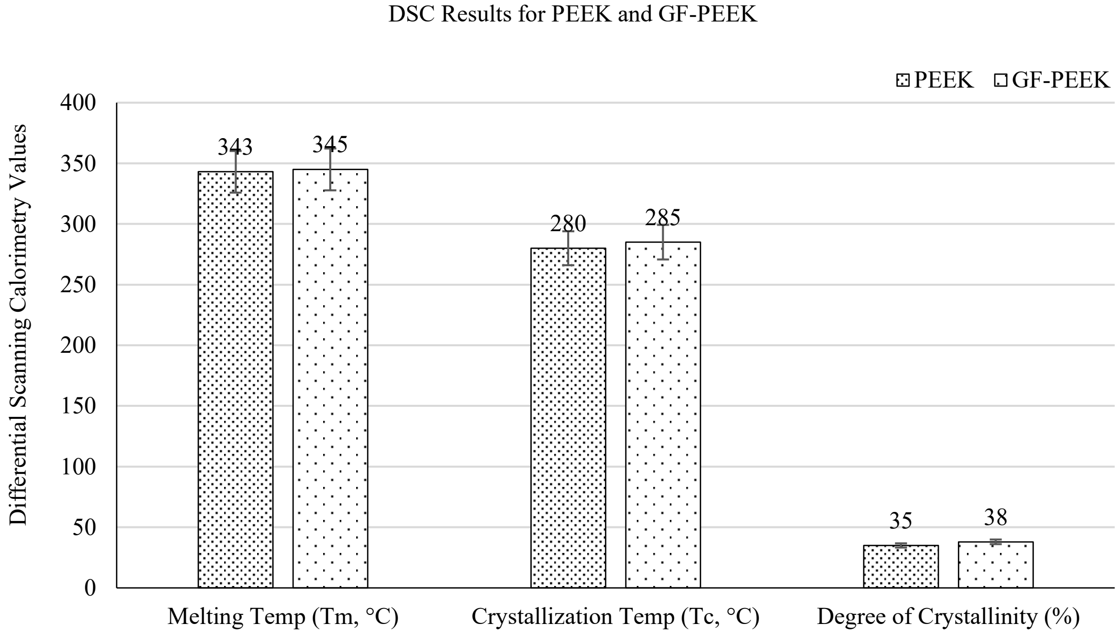

Figure 6. DSC Results for PEEK and GF-PEEK.

2.4.3.2 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) [39-42] was conducted using TA Instruments Q200 under a nitrogen atmosphere with the following parameters of Temperature Range: 30°C to 400°C, Heating/Cooling Rate: 10°C/min and Sample Weight: 8 mg. The melting temperature (Tm) and crystallization temperature (Tc) of PEEK and GF-PEEK are summarized in Figure 6.

The GF-PEEK exhibited a slightly higher Tm and Tc due to the nucleating effect of glass fibers, which promotes crystallization. Additionally, a marginal increase in the degree of crystalline was observed, enhancing the mechanical and thermal properties [43-45].

RESULTS AND DISCUSSION

Results

The tensile testing revealed that GF-PEEK exhibited a significant improvement in mechanical properties compared to pure PEEK. Specifically, GF-PEEK showed a 15.79% increase in Ultimate Tensile Strength (UTS), rising from 95 MPa in PEEK to 110 MPa. Additionally, the Young's Modulus increased by 18.42%, from 3.8 GPa in PEEK to 4.5 GPa in GF- PEEK. However, a considerable reduction of 40% in Elongation at Break was observed, decreasing from 25% for PEEK to 15% for GF-PEEK. This reduction indicates increased brittleness due to the reinforcement effect of glass fibers. Flexural testing showed that GF-PEEK exhibited superior flexural strength and modulus compared to PEEK. GF-PEEK demonstrated a 20% increase in Flexural Strength, indicating enhanced load-bearing capacity due to the rigid nature of glass fibers. Flexural Modulus also increased by 22%, reflecting improved stiffness. Additionally, maximum deformation was reduced by 35%, further confirming the increased brittleness and rigidity imparted by the glass fibers. TGA results indicated improved thermal stability for GF-PEEK compared to PEEK. The initial decomposition temperature of GF-PEEK was approximately 2% higher than that of PEEK, suggesting enhanced thermal resistance due to the presence of glass fibers. Residual mass after thermal degradation was also higher in GF-PEEK, confirming its superior thermal stability. DSC analysis revealed a slight increase in melting temperature (Tm) and crystallization temperature (Tc) for GF-PEEK compared to PEEK. Specifically, Tm increased by 3%, while Tc showed a 4% increase. While this study did not incorporate predictive modeling, the anisotropic effects of build orientation were experimentally quantified through mechanical and thermal testing across X, Y, and 45° orientations. The observed directional dependencies underscore the importance of considering anisotropy during design. Future work may integrate finite element analysis or classical laminate theory to model and predict these effects for optimized structural performance.

Discussion

The enhancement in Ultimate Tensile Strength (UTS) and Young's Modulus for GF-PEEK is attributed to the reinforcement effect of glass fibers, which efficiently distribute the load across the polymer matrix, increasing stiffness and load-bearing capacity. The restricted molecular mobility due to fiber alignment enhances rigidity. However, the significant reduction in Elongation at Break indicates increased brittleness, a typical trade-off in fiber- reinforced polymers, resulting from reduced matrix deformation around rigid fibers. The rise in Flexural Strength and Modulus for GF- PEEK is due to the improved distribution and stiffness provided by the glass fibers, which limit matrix deformation under bending stress. Layer alignment in the X-orientation further enhanced flexural properties by aligning fibers parallel to the loading direction. The decreased maximum deformation reflects reduced flexibility, consistent with the observed tensile brittleness. The improved thermal stability of GF-PEEK is due to the inherent thermal resistance of glass fibers, which act as barriers to thermal degradation. The higher initial decomposition temperature and increased residual mass confirm the superior thermal stability of GF-PEEK.

The slight rise in melting temperature (Tm) and crystallization temperature (Tc) is due to the nucleating effect of glass fibers, promoting a more organized crystalline structure. This enhanced crystallinity contributes to improved rigidity and stiffness, consistent with the observed mechanical properties but also leads to reduced ductility and elongation at break. Although residual stresses were not measured in this study, thermal gradients during FFF can induce internal stresses that may affect long-term stability. These stresses, especially in GF-PEEK, can promote warping, interlayer delamination, or fatigue over time. Future work should investigate residual stress evolution and its impact on mechanical durability.

The incorporation of Glass Fiber (GF) into PEEK significantly influences interlayer bonding strength and microstructural integrity, particularly in the context of build orientation during the Fused Filament Fabrication (FFF) process.

- *Effect on Interlayer Bonding Strength:* Glass fibers act as reinforcing agents that bridge adjacent layers, especially when aligned parallel to the build direction (as in the X-orientation). This alignment facilitates better load transfer between layers, enhancing interlayer bonding strength. The inclusion of GF increases the effective thermal conductivity of the composite. This helps maintain higher interlayer temperatures during deposition, reducing temperature gradients and promoting stronger interdiffusion of polymer chains across layers. Despite these benefits, interlayer bonding is highly orientation dependent. In Y- and 45° orientations, where fiber alignment does not favour direct load transfer across layers, the bonding strength is less enhanced. The 45° orientation is particularly susceptible to interlayer shear due to angular deposition, which compromises interfacial adhesion even with fiber reinforcement.
- *Effect on Microstructural Integrity:* GF helps to constrain matrix microcracking, especially under tensile and flexural loads. This is evident in SEM observations from prior studies, where fiber bridging reduces crack propagation between layers. However, the integration of GF can also introduce voids or fiber pull-out zones, especially in off-axis orientations. If the fibers are not well-aligned or if their dispersion is inconsistent, localized weak spots may develop, potentially acting as initiation sites for delamination.
- *Orientation-Specific Microstructure:* In X-orientation, aligned fiber and raster patterns result in densely packed, well-bonded interfaces. In Y-orientation, fibers run perpendicular to the stress path, leading to weaker interfacial bonding. In 45° orientation, the layered microstructure is more discontinuous, causing stress concentrations and compromised integrity.

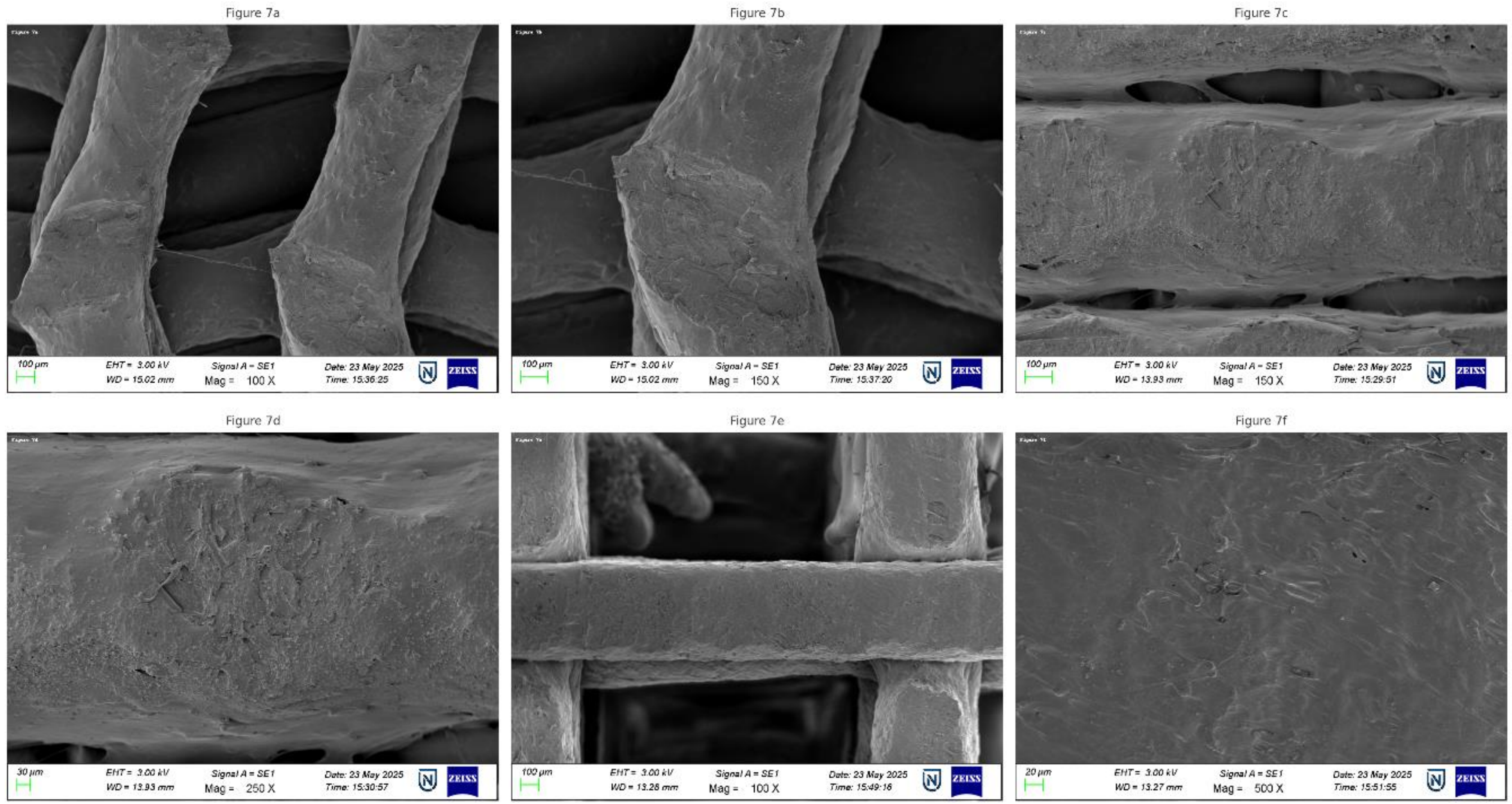

Figure 7. Fractographic SEM images of fractured GF-PEEK tensile specimens. (a, b) show brittle fracture surfaces with minimal plastic deformation, indicating low elongation at break. (c, d) reveal fiber pull-out and interfacial debonding, suggesting weak fiber-matrix bonding and early crack initiation. (e, f) highlight interlayer delamination and microvoid formation, attributed to anisotropic deposition and residual stress in FFF-printed composites.

Fractographic Analysis of Failure Mechanisms in GF-PEEK Specimens

To further elucidate the mechanisms underlying the observed reduction in elongation at break for GF-PEEK specimens, fractographic analysis was performed using Scanning Electron Microscopy (SEM) on fractured tensile samples. As illustrated in Figure 7a and 7b, the fracture surfaces exhibit features characteristic of brittle failure, including abrupt crack propagation, limited plastic yielding, and a relatively flat fracture morphology. The absence of significant plastic deformation at the microscale supports the mechanical test results, which revealed a substantial decrease in ductility due to fiber-induced stiffness and stress localization.

Figures 7c and 7d provide clear evidence of fiber pull-out and interfacial debonding between the glass fibers and the PEEK matrix. These features are indicative of suboptimal fiber-matrix interfacial adhesion, which impairs effective load transfer and promotes premature failure initiation. The presence of clean fiber surfaces and matrix voids suggests that crack propagation preferentially follows the fiber-matrix interface, reinforcing the interpretation that the reinforcement, while improving stiffness and strength, compromises the composite's ability to undergo plastic deformation. In Figures 7e and 7f, microvoid formation and interlayer delamination are observed, which can be attributed to the anisotropic nature of the FFF process. The layer-by-layer deposition creates inherent weaknesses at layer interfaces, particularly when the fiber orientation is misaligned with the loading direction (as in the 45° build). Thermal gradients during fabrication, coupled with differential shrinkage and residual stresses, likely exacerbate these defects, acting as stress concentrators during mechanical loading. These morphological features collectively validate the macroscopic mechanical findings and highlight the critical role of microstructural discontinuities such as poor interfacial bonding, fiber misalignment, and interlayer voids in driving the reduction in elongation at break in GF-PEEK composites.

CONCLUSION

The experimental investigation of PEEK polymer and Glass Fiber (GF)-reinforced PEEK polymer specimens fabricated using the Fused Filament Fabrication (FFF) process revealed significant enhancements in mechanical and thermal properties due to the addition of glass fibers. GF-PEEK polymer exhibited a 15.79% increase in Ultimate Tensile Strength and an 18.42% rise in Young's Modulus compared to pure PEEK polymer, highlighting the reinforcement effect of glass fibers that improved stiffness and load-bearing capacity. However, this reinforcement also led to a 40% reduction in Elongation at Break, indicating increased brittleness. Flexural testing further confirmed the enhanced mechanical performance of GF-PEEK polymer, with a 20% increase in Flexural Strength and a 22% rise in Flexural Modulus. This improvement is attributed to the effective load distribution and restricted polymer matrix deformation imparted by the rigid glass fibers. Additionally, Thermogravimetric Analysis (TGA) demonstrated improved thermal stability for GF-PEEK polymer, with a 2% higher initial decomposition temperature and increased residual mass. Differential Scanning Calorimetry (DSC) results showed a slight increase in melting temperature (3%) and crystallization temperature (4%), attributed to the nucleating effect of glass fibers that enhanced the degree of crystallinity. Overall, the incorporation of glass fibers significantly enhances the mechanical strength, stiffness, and thermal stability of PEEK polymer while increasing brittleness.

These findings provide valuable insights for the development of advanced polymer composite materials for high-performance engineering applications, particularly where improved mechanical strength and thermal resistance are essential. In particular, the improved mechanical strength and thermal stability of GF-PEEK components highlight their potential for use in load-bearing and high-temperature environments such as aerospace brackets, automotive housings, or biomedical implants. The anisotropic behavior observed across different build orientations also suggests that designers can strategically align print directions to optimize structural performance. These results support the feasibility of using FFF-printed GF-PEEK in function-critical applications, provided that orientation and service conditions are carefully considered during the design phase.

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