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RESEARCH

Enhancing Engineering Applications with Glass Fiber-Reinforced Polymer Composites: A Comprehensive Assessment of Manufacturing Techniques and Performance Properties

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A B S T R A C T

Glass fiber-reinforced polymer (GFRP) composites have gained widespread attention due to their superior mechanical and tribological properties, making them highly suitable for engineering applications such as bearings, gears, brakes, and seals. The primary objective of this research is to assess and compare the performance of GFRP composites fabricated using different reinforcement materials and manufacturing techniques. This study employs a comprehensive methodology combining experimental analysis and literature review to evaluate the mechanical strength, wear behavior, and surface characteristics of GFRP composites under various conditions. Key manufacturing processes such as hand lay-up, resin transfer molding, compression molding, injection molding, filament winding, and pultrusion are reviewed and compared in terms of performance output and feasibility. The findings reveal that increasing the glass fiber content significantly enhances mechanical strength, thermal stability, and wear resistance. Moreover, composites fabricated through precision-controlled techniques like resin transfer molding and injection molding exhibit improved surface finish and dimensional accuracy. The study concludes that the choice of manufacturing technique and material composition plays a critical role in optimizing composite performance. These insights provide a valuable foundation for selecting suitable composites in high-performance industrial applications and suggest future directions for enhancing material-environment compatibility.

1. INTRODUCTION

Polymer composites have witnessed a surge in popularity recently, driven by their distinctive attributes including a high strength-to-weight ratio, remarkable toughness, and resistance to corrosion. The incorporation of fibers and solid lubricants into polymer matrix composites offers the potential to augment their mechanical, thermal, and tribological characteristics. These materials find extensive utility across diverse industries such as aerospace, automotive, marine, and civil engineering, largely owing to their lightweight nature, superior strength, and outstanding durability.

Typically, these composites are fortified with fibers to bolster their mechanical properties, with glass fibers emerging as a prevalent choice due to their cost-effectiveness, impressive strength, and stiffness. Within this literature review, we will delve into the various compositions of glass fibers utilized for reinforcing polymer composites and explore their impacts on the mechanical properties of these composite materials. Predominantly, E-glass, S-glass, and C-glass stand out as the most common types of glass fibers employed in composites. E-glass, prized for its cost-efficiency and superb mechanical attributes, enjoys widespread use in composites, whereas S-glass and C-glass, endowed with even higher mechanical properties albeit at greater expense, see less frequent application in composite materials [1].

2. PREPARATION METHODS FOR POLYMER COMPOSITES

2.1. Hand lay-up method

The hand lay-up method is a traditional and relatively simple approach for producing polymer composites. In this method, the process begins with manually placing reinforcement fibers or fabrics, often in the form of mats or roving, into an open mold. These fibers are then thoroughly saturated with a liquid resin, typically a thermosetting one. After the reinforcement is evenly distributed and the mold is filled, it is left to cure at room temperature or under controlled curing conditions. The hand lay-up method is cost-effective and has a low initial investment, making it accessible for small to medium-sized productions. Suitable for Small to Medium Parts: It is particularly well-suited for producing small to medium-sized parts or prototypes [2].

2.2. Resin transfer molding (RTM)

Resin transfer molding is a closed-molding process designed to produce high-quality composite parts. It involves a more controlled approach compared to the hand lay-up method. In RTM, a pre-arranged reinforcement structure (usually fiber mats or fabrics) is placed inside a closed mold. A thermosetting resin, which may contain additives like curing agents, is then injected into the mold. The mold is typically heated and pressurized to facilitate resin flow, impregnate the fibers, and induce curing. It gives high-quality surface finish. RTM yields products with excellent surface finish and dimensional accuracy. Good for medium to large parts, it is suitable for medium to large-sized parts, low porosity. RTM can produce parts with low porosity, enhancing their mechanical properties [2,3].

2.3. Filament winding

Filament winding is a continuous manufacturing technique characterized by the systematic wrapping of continuous fiber roving around a rotating mandrel in a precise pattern. These roving's are subsequently impregnated with a resin and subjected to curing, resulting in the creation of cylindrical components boasting exceptional strength. This method is particularly well-suited for the production of large, hollow parts characterized by superior strength and stiffness. It gives: high strength: filament winding yields parts with outstanding strength, making it suitable for applications demanding structural integrity, hollow parts: It excels in creating hollow components, which are vital in various industries, including aerospace and marine, stiffness. The process delivers parts with impressive stiffness, making them suitable for load-bearing structures [3].

2.4. Pultrusion

Pultrusion is a continuous manufacturing method involving the continuous pulling of fibers through a resin bath and subsequently through a heated die, leading to resin curing. This process produces components endowed with exceptional strength, stiffness, and dimensional stability. It is particularly well-suited for crafting lengthy, straight, and intricate profiles with consistent cross-sections. It gives: High strength and stiffness. Pultrusion delivers parts with outstanding strength and stiffness, making it suitable for demanding structural applications, dimensional stability, Parts produced through pultrusion maintain their dimensions over time, ensuring consistent performance, complex profiles: It excels in creating complex profiles with constant cross-sections, which are often required in construction and infrastructure projects [3,4].

2.5. Compression molding

Compression molding is a widely adopted manufacturing method for polymer composites. It involves placing pre-cut reinforcement fibers or fabrics into a mold, which is then closed, usually with a hydraulic press. The mold is subjected to heat and pressure, causing the thermosetting resin to cure and bond the fibers together. It gives High strength, compression molding produces parts with high strength and stiffness, good surface finish: It offers good surface finish and low porosity, durability, parts made using this method are durable and resistant to environmental factors [3,4].

2.6. Injection molding

Injection molding is a high-volume, automated manufacturing process commonly used for thermoplastic polymer composites. It begins with the melting of a thermoplastic resin, which is then injected into a closed mold under high pressure. The mold is cooled, and the final part is ejected. It gives offers excellent dimensional accuracy and surface finish (high precision), complex shapes, and it is suitable for producing complex and intricate part designs. High volume, this method is ideal for high-volume production [4,5].

Each of these preparation methods offers distinct advantages and is chosen based on factors such as the desired product attributes, part size, complexity, and budget constraints. Manufacturers often select the most appropriate method to achieve the best balance between cost, quality, and production requirements [6,7].

The composites were selected based on specific performance needs. Glass fibers were chosen for their high strength, stiffness, and cost-effectiveness, while thermosetting resins like epoxy, PEEK, and PTFE provided the necessary thermal stability and mechanical strength. Fillers such as carbon fiber, graphite, MoS_2, PTFE, and bronze were included to enhance wear resistance, reduce friction, and improve lubrication. These selections aimed to optimize the tribological performance of the composites for applications like bushings, seals, and sliding elements.

Conventional materials used in wear-intensive applications often lack sufficient durability and friction resistance. While glass "fiber-reinforced polymers (GFRPs)" show promise, there is still no clear standard for their optimal composition and fabrication. This study addresses the need for a detailed evaluation of GFRPs, focusing on how different fillers and manufacturing methods impact their mechanical and tribological performance in engineering uses.

The article aims to evaluate the mechanical and Tribological properties of glass fiber-reinforced polymer composites produced using various manufacturing techniques and enhanced with different fillers like graphite, PTFE, and MoS_2 etc. It focuses on identifying optimal composite formulations for improving performance in engineering applications such as seals, bearings, and gears etc.. Summary of all manufacturing methods and their applications are given in Annexure I (page no. 15).

3. EFFECT OF VARIOUS COMPOSITION OF GF ON THE PROPERTIES OF POLYMER COMPOSITES

Li et al. [8] conducted a study on the impact of load and sliding time on pure PEEK and PEEK reinforced with 30% short glass fibers. They used a ball-on-disc machine and observed that the glass fiber-reinforced PEEK composite exhibited significantly improved mechanical strength (a 64%–66% increase; see Table 2), a higher thermal decomposition temperature (a 75% increase), and enhanced wear resistance compared to pure PEEK. The coefficient of friction and wear loss increased with higher loads and longer sliding times, highlighting the durability of the glass fiber-reinforced PEEK composite for wear-intensive application [8].

Table 1. The mechanical properties of pure PEEK and glass fiber reinforced PEEK [4].

Number of Samples	Pure PEEK	Glass Fiber /PEEK
Tensile strength (MPa)	90.3	148.2
Tensile modulus (GPa)	2.8	4.9
Flexural strength (MPa)	139.1	230.7
Flexural modulus (GPa)	3.7	8.9

Zhu et al. [9] investigated the potential of PEEK composites for use in self-lubricating bushings in articulating revolute pin joints. Their study compared unfilled and glass fiber-reinforced PEEK with PEEK composites filled with graphite, PTFE, and carbon fibers.

They observed that the composites with solid lubricants had significantly higher load-bearing capacity and improved resistance to subsurface failures. In particular, Bush C, which contained 10% carbon fiber, 10% graphite, and 10% PTFE, showed a notably lower wear coefficient (0.13 × 10^-6 mm^3/Nm) compared to Bush A, had a higher wear coefficient (4.33 × 10^-6 mm^3/Nm).which only had 30% carbon fiber.

Additionally, the graphite and PTFE blend effectively reduced shear forces and internal temperature, enhancing material performance during articulation [9].

Study conducted by Hamilton et al. [10] for improving the wear resistance of polyether ether ketone (PEEK) by reinforcing it with carbon and glass fibers at varying weight percentages. PEEK pins with a diameter of 6.5 mm were injection molded and reinforced with 0 wt.%, 20 wt.% carbon, 30 wt.% carbon, and 30 wt.% glass fiber. These samples were tested using a pin-on-disc tribometer against steel discs to evaluate their specific wear rates.

The tests were performed under controlled conditions, considering load variations from 10 N to 30 N, sliding velocities between 1.2 m/s and 1.4 m/s, and counter-surface hardness ranging from 211 HV to 630 HV.

This experimental setup aimed to mimic the operating conditions found in oil and gas industry valves, particularly between polymer anti-extrusion rings and steel sealing interfaces. The use of reinforced PEEK was intended to extend the service life of these components by minimizing direct metal-to-metal contact and reducing wear. One of the key findings was the development of compressive residual stresses in carbon fiber-reinforced PEEK, which increased proportionally with the applied load. These stresses were found to enhance the material's wear performance and durability, making it a promising candidate for high-load sealing applications loads [10].

Chen et al [11] conducted an experimental investigation to examine the dynamic compressive behavior of polyetheretherketone (PEEK) composites reinforced with short fibers. The study focused on key factors such as strain rate, fiber reinforcement, and the manufacturing method. They employed a Hopkinson compression bar system to test specimens, subjecting them to varying strain rates ranging from 800/s to 2500/s. The deformation and failure processes were meticulously recorded using an ultra-high-speed camera system. Additionally, scanning electron microscopy was utilized to examine fracture surfaces and analyse the mechanisms of failure. Four different specimens of PEEK composites were employed in the study, and for three loading rates of 2500/s, 1500/s, and 800/s, three striker bars of lengths 400 mm, 450 mm, and 700 mm were employed, respectively. The key findings of their research were as follows: Failure Mechanism: The primary cause of failure in short fiber-reinforced PEEK composites was identified as interface deboning. This finding sheds light on a crucial aspect of the material's behavior under dynamic compressive loads. Fabrication Method Impact: The study revealed that extruded short fiber-reinforced -PEEK composites displayed more uniform fiber distributions when compared to their injection-molded counterparts. This variation in fiber distribution significantly influenced strain rate-sensitivity and fracture toughness. Fracture Toughness: Notably, the injection-molded specimens exhibited higher fracture toughness compared to the extrusion specimens (Fig.1 a and b). This suggests that the manufacturing method has a substantial impact on the material's ability to resist fracture under dynamic compression.

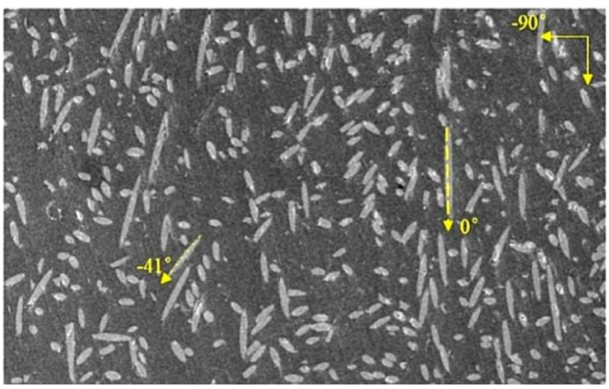

Fig. 1a. SEM micrograph (100 μm scale) showing the fiber distribution in short glass fiber-reinforced PEEK fabricated by injection molding [11].

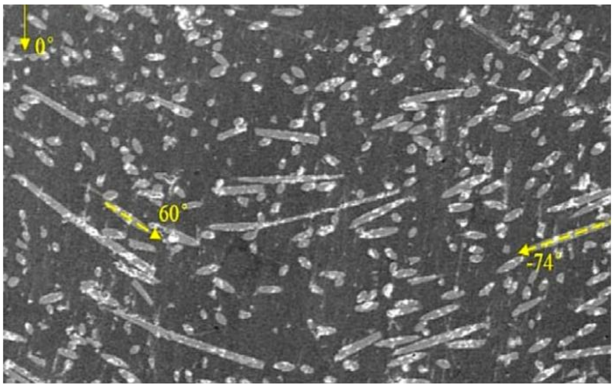

Fig. 1b. SEM micrograph (100 μm scale) showing the fiber distribution in short glass fiber-reinforced PEEK fabricated by extrusion [11].

Their findings provided insights into the failure mechanisms of these composites and highlighted the significance of uniform fiber distribution and manufacturing processes in determining fracture toughness and strain rate-sensitivity [11].

Nallusamy [12] explored the effect of adding Titanium Dioxide (TiO_2) nanoparticles and E-glass fibers to epoxy composites. The study showed that incorporating 3 wt% TiO_2 significantly enhanced flexural strength, reaching 203.36 MPa. XRD and SEM analyze confirmed uniform nanoparticle dispersion and strong fiber-matrix bonding. The composites were produced using the hand lay-up method, enabling controlled variation of TiO_2 content and detailed evaluation of mechanical performance [12].

In the research led by Huang et al. [13] the focus was on designing and manufacturing a material intended for use as seals in high-temperature applications. Specifically, they utilized specimens of Glass Fiber-Reinforced Polytetrafluoroethylene for testing on a linear reciprocating tribo-machine. The study aimed to investigate the material's behaviour under various test parameters, including applied normal force (28.8 N), contact pressure (1.6 MPa), sliding speeds (300 rpm), and stroke length (50 mm). The temperature range for the tests encompassed a wide spectrum, ranging from 500°C to 2000°C.Run-in Stage: Initially, during the run-in stage of testing, the PTFE and steel surfaces were in direct contact, leading to a high wear rate. This is a common phenomenon during the initial stages of tribological testing when surfaces adapt to each other. Their findings are Transition to Steady Wear. As the top layer of PTFE was worn away, the embedded glass fibers gradually became exposed and assumed the role of primary load-bearing constituents. Consequently, there was a significant reduction in the wear rate during this transition. The exposed glass fibers play a crucial role in the material's wear resistance, Effect of Temperature: The study revealed that the behaviour glass fiber-PTFE was influenced by temperature, at temperatures below the glass transition temperature. The glass fibers were strongly bonded with the matrix, potentially due to restricted movement of the rigid amorphous segments within the PTFE matrix. This resulted in a distinct wear behaviour characterized by third-body abrasion, flake delamination of the PTFE matrix, scratching, reformation of a transfer film on the counter-face, and filling of large PTFE grooves. Stable Wear Behaviour: In the stable region, these various wear behaviours continued to stable wear behaviour: In the stable region, these various wear behaviours continued to occur simultaneously, contributing to dynamic steady wear. Consequently, the wear rate at higher temperatures, such as 200°C, exhibited slight fluctuations occur simultaneously, contributing to dynamic steady wear. Consequently, the wear rate at higher temperatures, such as 200°C, exhibited slight fluctuations as shown in Fig. 2 [13].

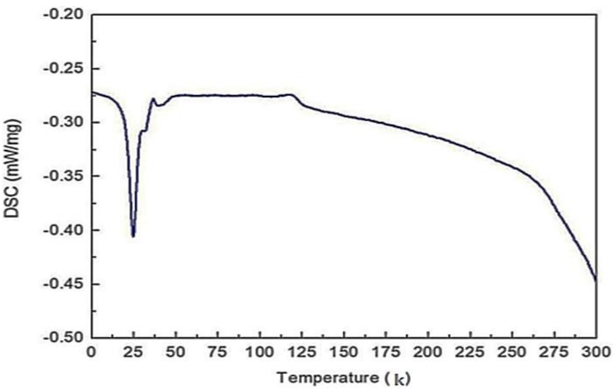

Fig. 2. The differential scanning calorimetric thermo gram of the glass fiber reinforced PTFE [13].

Tatsumi et al. [14] conducted a study to investigate the wear behavior of pure PEEK, PEEK +30% Glass Fiber, and PEEK +30% Carbon Fiber under both dry and oil-lubricated conditions. They employed various viscosity grades of PAO (Polyalphaolefin) oil, including PAO2, PAO4, and PAO10, as lubricants. The tests were carried out using a Mini Traction Machine (MTM) at a speed of 0.5 m/s and an applied load of 50 N, simulating gear application at ambient temperature over duration of 60 minutes.

The research findings were primarily focused on two key factors, Transfer Films: One aspect of the analysis cantered on the formation of transfer films of PEEK composites on the steel counterparts. These transfer films play a crucial role in reducing friction and wear and Hardness Modification: The study also considered the modification of surface hardness in the composite materials as a result of the testing conditions. Their observation were, Oil-Lubrication Effects: Oil-lubrication was found to effectively reduce friction in PEEK +30% Carbon Fiber composite. This suggests that the presence of carbon fibers had a beneficial impact on the material's response to lubrication. Transfer Films: Thick transfer films were observed for both pure PEEK and PEEK +30% Glass Fiber even under oil-lubricated conditions. However, in the case of PEEK +30% Carbon Fiber. transfer films did not form, regardless of whether the testing was conducted in dry or oil-lubricated conditions, Composite Behavior: In the PEEK +30% Carbon Fiber composite, fractured fibers were exposed on the wear tracks after testing, indicating a different wear behavior compared to the other composites. In contrast, the wear tracks on PEEK +30% Glass Fiber showed well-embedded matrix and less damage to the fibers [14].

Table 2. PAO base oil properties [14].

Parameters	Temperature (°C)	PAO2	PAO4	PAO10
Density, g/cm^3	15	0.798	0.819	0.836
Kinematic viscosity, cSt	25	8	31	136
	40	5	17.5	65.1
	100	1.7	3.9	9.8
Pressure-viscosity coefficient, GPa^{-1}	25	15	19	22

According to Radcliffe [15] research focuses on reciprocating compressor seals, particularly piston rod packing crucial for pollution control. Traditional metallic rings gave way to polymers like PTFE. Radcliffe suggests various fillers, including Carbon Fiber, Glass Fiber, MoS2, bronze, and ceramics, to enhance material hardness and wear resistance significantly. The study aims to reduce friction and wear for better compressor performance [15]. Samancioglu [16] prepared compressor piston sealing, materials for rider bands, piston rings, and packing are suggested to be made from PTFE (Teflon) with various fillers, including Glass fiber (5-15% for hardness), Carbon (10-35% for deformation strength), Graphite (5-15% for excellent wear properties), Bronze (40-60% for high thermal conductivity), and MoS2 (5% for reduced friction). These materials are compression-molded and are suitable for non-lubricated, low-friction operation. Careful formulation and filler selection enhance their self-lubricating properties, extending their lifetimes, especially in dry gas environments up to 250°F, beyond which they soften and wear more. These materials should not be used under intermittent oil supply conditions to avoid high ring wear. For higher pressure and temperature applications, filled PEEK composites, PI Polyimide Resin (known for chemical resistance and temperature resistance), and PPS (suitable for elevated temperatures and pressures) are recommended as high-performance polymer alloys [16].

Davim et al. [17] conducted a study to evaluate the impact of 30 wt% carbon or glass fiber reinforcement in PEEK on friction and wear behaviour when sliding against a steel surface under extended dry sliding conditions. The experiments were performed using a pin-on-disc machine under specific test conditions: a contact pressure (pv) of 2 MPa, which encompassed different combinations of pressure (p) and sliding velocity (v), including p = 8 MPa and v = 0.25 m/s, and p = 2.68 MPa and v = 0.75 m/s. The tests were conducted at room temperature over a sliding distance of 15 km. They found that the PEEK reinforced with 30 wt % carbon fibers exhibited a lower friction coefficient compared to pure PEEK. On the other hand, PEEK reinforced with 30 wt % glass fibers showed a higher friction coefficient throughout the test. Also Both PEEK-Carbon Fiber 30% and PEEK-Glass Fiber30% demonstrated excellent wear resistance in comparison to pure PEEK. However, PEEK with 30 wt % carbon fibers exhibited the most favourable tribological behavior [17]. PEEK is a high-performance polymer known for its excellent properties but plagued by a high coefficient of friction and stick-slip behavior in its pure form. Their study focused on PEEK composites reinforced with short Glass Fiber, Carbon Fiber, and solid lubricants like PTFE and graphite. The goal was to enhance the PV limit, crucial for severe operating conditions. Using a pin-on-disc machine, pins slid over mild steel discs at speeds of 2 m/s and 3 m/s for an hour, varying loads until pin failure. Criteria for test parameter selection and PV limit were suggested. Results showed that pure PEEK had a high, fluctuating coefficient of friction, a high wear rate (2 x 10^-14 m^3/Nm), and a low P-V limit (150 Nm/s). PEEK with 30% Carbon Fiber exhibited good strength but poor tribological performance. However, PEEK with 25% glass fiber and 15% PTFE and graphite demonstrated excellent wear resistance, a low friction coefficient, and the highest PV limit value, making it suitable for bearings in harsh operating conditions [18].

Bijwe et al. [19] examined the influence of lubricant additive (PTFE) and reinforcement additives (Carbon Fiber, Glass Fiber, bronze powder) on the tribological behavior of PEEK-based composites in sea water lubrication. They found that PTFE reduced friction and improved wear resistance, particularly at a 20% volume fraction. The addition of Carbon Fiber further enhanced wear resistance, especially under high loads and speeds, showing a synergistic effect with PTFE.

In contrast, Glass fiber and bronze powder had an antagonistic effect, diminishing wear resistance when combined with PTFE. This study highlights the complex interactions between additives in optimizing tribological performance [19]. Chu et al. [20] investigated the properties of polyetheretherketone (PEEK) matrix composites reinforced with 30% chopped glass fibers. These composites were prepared via injection molding, and their tensile, flexural, and impact characteristics were analysed. The study found that while the coefficient of thermal expansion of neat PEEK remained constant, Fig. 3 shows the addition of glass fibers significantly reduced the coefficient of thermal expansion (CTE), For instance, at 77 K, the CTE of neat PEEK was 46.5 x 10^-6 K^-1, whereas for GFS/PEEK at 295 K, it was reduced to 14.4 x 10^-6 K^-1. Unfilled PEEK shows greater thermal expansion with rising temperature, while glass fiber reinforcement limits this effect. This indicates improved dimensional stability in the reinforced composite [20].

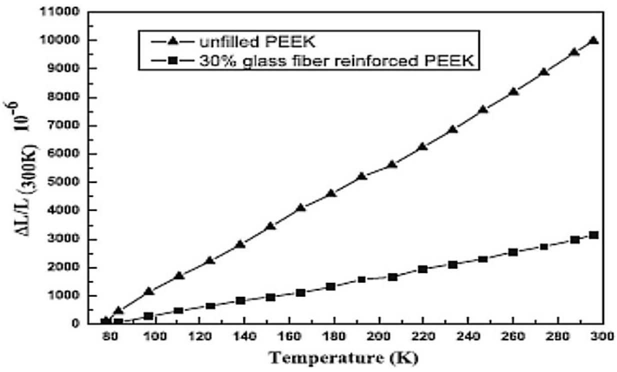

Fig. 3. Temperature vs thermal expansion [20].

Avanzini et al [21] Conducted a study to evaluate the wear and rolling contact fatigue of different PEEK materials, including unfilled PEEK and PEEK reinforced with various short fibres. These reinforcements included 10% carbon fibre, graphite, and PTFE-filled matrix, as well as PEEK filled with 30% carbon micro-fibres and a 30% glass fibre-filled matrix. The tests were conducted on a rolling contact fatigue bench under dry conditions. A noteworthy finding from their research was that the specimens reinforced with 30% glass fibres exhibited unexpectedly high fatigue resistance. This suggests that the incorporation of 30% glass fibres into the PEEK matrix had a positive impact on the material's ability to withstand rolling contact fatigue, a result that might not have been initially anticipated [21]. Li et al. [22] investigated the tribological performance of pure PEEK and PEEK reinforced with 30 wt %Glass Fibber Reinforcement under various conditions. Figure 4 shows the variation in specific wear rate of pure PEEK and GF+PEEK composites with various applied load in N, tested at a reciprocating frequency of 2 Hz under dry and water-lubricated experimental conditions.

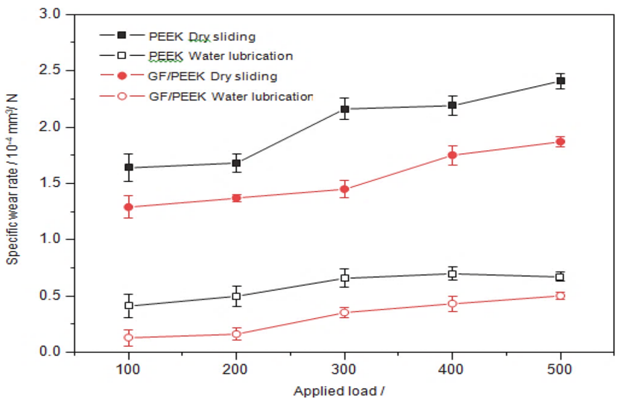

Fig. 4. Specific wear rate of pure PEEK and GF/PEEK composites as a function of applied load under dry and water-lubricated conditions (reciprocating frequency: 2 Hz; duration: 60 min) [22].

During the experiment author has observed the GF+PEEK composite has significantly more wear resistance than pure PEEK polymer material in the load range of 100N –500 N. This improvement is attributed to the reinforcing effect of glass fibers, which improve the composite's load-bearing capacity. Under dry sliding, the specific wear rate of GF+PEEK gradually increased from approximately 1.3×10^{-4} to 1.9×10^{-4} $mm^3/N{\cdot}m$ with increasing load.

Figure 5 [22] presents the SEM micrographs of the GF+PEEK composite worn surfaces under dry sliding and water-lubricated conditions. Under dry sliding (Figure 5a), the surface exhibited pronounced grooves oriented along the sliding direction and it shows severe plastic deformation and scuffing. In water-lubricated conditions (Figure 5b) appeared significantly smoother and shown that both plastic deformation and scuffing were substantially reduced, reflecting the improved wear resistance of the GF+PEEK composite in the presence of lubrication [22].

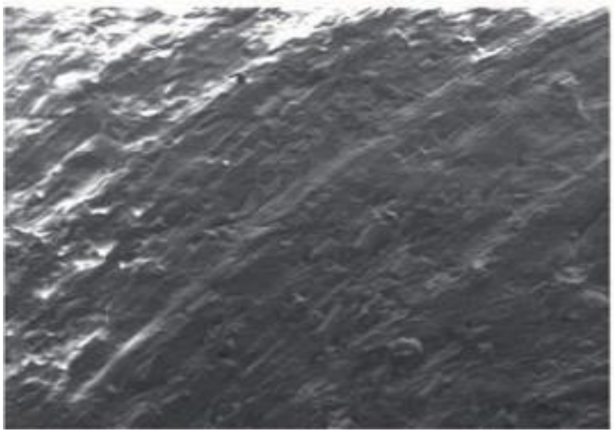

Fig. 5a. SEM views of worn GF/PEEK composite surfaces under dry sliding [22].

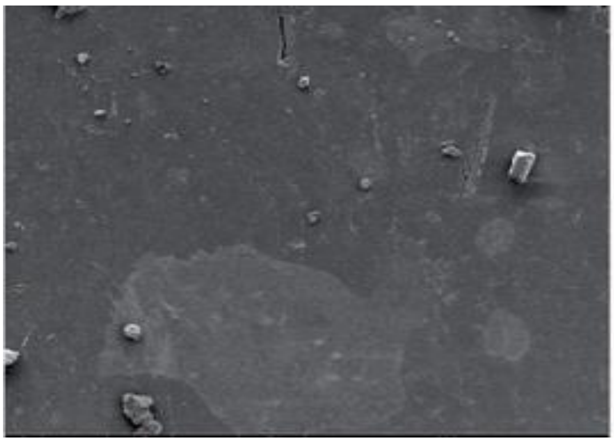

Fig. 5b. SEM views of worn GF/PEEK composite surfaces under water lubrication [22].

Kawakame et al, [23] conducted a study focusing on self-lubricating composites intended for electric motor seal applications. Their research identified that PTFE (Polytetrafluoroethylene) reinforced with 15% glass fibers and additives, such as 5% MOS2 (Molybdenum Disulphide), exhibited superior wear resistance properties. The wear rate curve for this composite material demonstrated a relatively linear behavior, measuring 4.75x10^-6 mm^3/Nm at a lower load of 20N. However, under a higher load of 29.5 N, the wear rate curve exhibited nonlinearity, suggesting a change in wear behavior [23]. As per the report by Lancaster et al. [24] were noted that the wear rate of PTFE (Polytetrafluoroethylene) can be substantially enhanced by incorporating inorganic and organic filler materials. Commonly employed fillers include glass fiber, carbon, bronze, and Kevlar. The choice of filler material is typically a trade-off between achieving desired frictions and wear properties for the polymer. Glass fiber is preferred filler for PTFE, typically used in volumes ranging from 15% to 25% to achieve the desired material characteristics [24]. In their study of Tanaka et al. [25] examined the impact of incorporating glass fibers and MoS2 (Molybdenum Disulphide) separately on friction and wear characteristics.

According to their findings, glass fibers in PTFE (Polytetrafluoroethylene) are effective in preventing significant fragmentation of PTFE, particularly under heavy loading conditions. Additionally, the addition of MoS2 to the glass fiber-filled composite was proposed to reduce abrasion, indicating potential improvements in wear resistance [25]. Khedkar et al. [26] investigated the sliding wear behavior of PTFE and PTFE composites with various filler materials.

Filler additions increased hardness and wear resistance in all composites, with the best wear resistance observed in composites containing carbon and graphite, glass fibers and MoS2, and PPDT fibers. SEM analysis revealed different modes of failure for each composite, such as three-body abrasion and fiber pull-out. The study suggested filler combinations like MoS2, bronze, and glass fiber for improving tribological properties in bearing materials [26]. Unal et al. [27] examined the impact of solid lubricant on PTFE (Polytetrafluoroethylene) reinforced with glass fibers. Here are they found PTFE reinforced with 17% glass fibers and 25% bronze exhibited excellent wear resistance, with a wear rate of

6.290 x 10^-6 mm^3/Nm and a low coefficient of friction (0.11).Further investigations included PTFE filled with varying bronze percentages: 25%, 40%, and 60% by weight. These compositions resulted in wear rates ranging from 1 to 100 x 10^-6 mm^3/Nm and friction coefficients between 0.12 and 0.22.The study concluded that filler materials were effective in preventing large-scale fragmentation of polymer composites, resulting in the formation of small, discontinuous fragments. However, under heavy loading conditions, these filler materials tended to fracture and cause abrasion to the contact surface [27].

Gong, et al. [28] conducted an investigation into three polymer seal materials: PTFE with 25% Bronze filler, PI with 20% Glass Fiber, 25% MoS2, and 5% graphite fillers, and PEEK with 25% MoS2 and 10% glass fiber fillers. The study involved testing these polymer composites using a specialized sealing ring test rig, with each composite's sealing ring configuration in contact with a steel counter surface. SEM (Scanning Electron Microscopy) analysis was employed to examine the filler properties and wear patterns of the composites.

The result in Fig. 6 revealed that as the speed increased under oil-lubricated conditions, the surface temperature and melting rate of the PTFE, PI, and PEEK composites also raised. The friction coefficient initially decreased with increasing speed, reaching a minimum, and then increased again as speed further increased. Notably, the coefficient of friction for the PTFE and PEEK sealing composites was lower compared to the PI sealing composite, primarily attributed to reduced leakage during testing. This research sheds light on the frictional behavior and performance of these polymer composites in sealing applications [28].

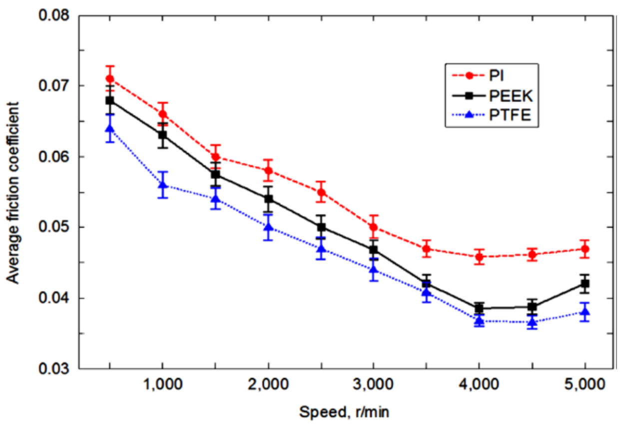

Fig. 6. Average friction coefficient and Speed [28].

Nallusamy et al [29] investigated the use of granite powder as filler in glass fiber-reinforced epoxy composites. The study found that adding 5 wt% granite powder significantly improved wear resistance and reduced material loss. Mechanical properties, including tensile, flexural, and impact strength, also increased with filler content up to 50%. Wear performance was evaluated using the pin-on-disc method. While the enhancements are notable, the study also acknowledges potential cost and environmental considerations [29]. Karthikeyan et al. [30] investigated the sliding wear behavior of Aluminium-6063 composites reinforced with varying amounts of silicon carbide (SiC). Using a pin-on-disc test, they found that wear loss increased with sliding velocity, while higher SiC content (5–9%) significantly reduced wear. SEM analysis revealed micro and transverse cracks, indicating complex wear mechanisms [30].

Vina et al. [31] conducted an experiment on the wear behavior of glass fiber fabric-reinforced polyetherimide (PEI) composites under dry sliding conditions at both ambient and elevated temperatures (200°C). They found that the incorporation of glass fiber into PEI resulted in a reduction in wear volume compared to plain PEI. With an increase in temperature, there was an overall increase in the wear volume of the glass-PEI composite. However, at 200°C, an interesting trend emerged where the wear volume decreased. The observed reduction in wear volume at 200°C was attributed to the fact that, at this temperature, the contact point of the composite pin approached temperatures closer to the glass transition temperature due to microstructural variations within the material. This study provided valuable insights into the wear behavior of glass fiber-reinforced PEI composites under varying temperature conditions, which can have implications for material selection and performance optimization in practical applications [31].

Pawar et al. [32] studied friction and wear properties of PTFE-PTFE (hybrid polymer) composite with different percentage of glass fiber rotating under dry and lubricated conditions by using a pin on disk Tribometer in the standard laboratories. From the study it is found that velocity of 0.5 m/s, 1 m/s and 2 m/s, applied of 15.75 N, 25.56 N and 35.37 N and rotating time of 30 min, 60 min and 90 min. PTFE with 25% GF is giving optimum wear rate and specific wear rate in both dry and wet sliding condition [32]. Abhang et al. [33] manufactured asymmetric gears of PLA materials by 3-D printing manufacturing techniques for improving load carrying capacity, as well as reduction of weight and vibration level during operating the drive for given period [33]. Iqbal. et al. [34] developed, a cement-gypsum board with natural fiber reinforcement abaca fiber. They have examined the impact of fiber content on the flexural strength and physical characteristics of cement-gypsum panels, cement-gypsum panels with varying amounts of abaca fiber content (0%, 1%, 2%, 3%, and 4%) etc.

The research explores the tribological performance of PEEK/PTFE composites enhanced with glass fibers and solid lubricants at ambient temperature. Results demonstrate improved wear resistance and lower friction, supporting their potential in high-performance, dry-contact applications. [34,35]. Sanjay et al. [36] have done research work on piston ring material with the Jatropha as lubricating oil to increase the efficiency and the life of the engine component in automotive area. The life span and working ability are governed by the friction and wear tribological characteristics of components of the engine in automotive industry. The life span of vehicle is calculated by the life of its sensitive part that is susceptible to wear out. In tribological system "piston -ring-liner" observed 45–55% of frictional mechanical losses. To control the friction and wear losses, lubrication is necessary. Lubricant is the main part to maintain reliable functions of the machine or engine; it provides smooth operations and chances of failure are under control [36]. Abhang et al. [37] studied a critical review of wear and frictional characteristics of hybrid polymer composite materials under rotating pin-on-disc tribometer and reciprocating wear testing machine [37].

Iqbal et al. [38] investigates in their study of the tribological properties of PEEK, PTFE reinforced with new additives. Tribological tests are conducted at different temperatures on tribometer under dry sliding conditions and different environmental temperatures to elevated temperature. The hybrid composite exhibited lower friction and lower wear rate than those of without hybrid composite materials at both low and elevated temperatures. The combined effect of solid-state lubrication of hybrid PTFE composite was found satisfactory at higher temperature. Formation of transfer films on the steel surface was also analysed at various environmental temperatures [38, 39]. Matsagar et al. [40] developed Ni-Cr based self-lubricating composite bearings materials for automotive application [40]. Udaya Kumar et al [41] explore the effect of hybrid reinforcement on mechanical properties and dry sliding wear behavior of "vinyl ester" (VE) composites". They have developed new composites incorporated with surface treated reinforcing materials of Carbon Fiber, and used significantly in automotive sliding and bearing components [41].

Sivasankaran et al. [42] have done the research on application of fly ash and nano-silica in concrete to increase the strength properties of concrete mixed with Nano -silica and fly ash. The results of Nano-silica improve overall strength characteristics. Different experimental analysis was carried out to obtain the results such as compression strength, ultimate divide tensile strength and elastic modulus of the enriched concrete mixture. From the observed results it was found that, compression strength was increased by adding 1% nano silica and 25% of fly ash and also increased the ultimate tensile strength by 28%. Balasaheb [43] experimental work conducted on polyetheretherketone as a base polymer material, and PTFE used as a solid lubricant. These polymer materials reinforced with glass fibres and additives like MoS2, Bronze. The effects of time, load, sliding velocity and filler content in PEEK/PTFE are experimentally examined. Results showing PEEK polymer improves tribological properties. It is observed that in PEEK/PTFE addition of glass fibers with MoS2 shows the higher wear resistance as compared to other fillers. Also while increasing the percentage of bronze in polymer composite resist the wear rate.

Qahhar et al. [44] conducted experiment on the milling process of polyester matrix-based composites reinforced with abaca and glass fibers, produced through the press molding process. The milling process was utilized by a 10 mm diameter 4-flute carbide end mill cutter with a 45-degree helix angle. The study aimed to investigate the influence of cutting conditions (spindle speed, feed, and depth of cut) on vibration during the milling process of abaca-glass fiber composites. Machining processes on hybrid composite materials involve activities such as surface cutting, hole drilling and other cutting processes to achieve final shape and dimension of the composite product.

There were several unexpected situations during the process, such as ununiformed vibrations due to inconsistent of natural fiber structures and non-ideal cutting conditions lead to progressive tool wear and low quality of the cutting surface [44]. Iqbal et al. [45] studied the bending strength of the Fiber Metal Laminate with different fiber content. Five panels of abaca FRP were prepared using hand-lay-up methods. In this work the weight content of the fiber in the panels were taken 0%, 3.56%, 5.18%, 8.94% and 12.22% respectively. The aluminium alloy sheet was laminated to the composite panel using epoxy super glue. The result of the experiment showed that the content of abaca fibre significantly affects the bending strength of the fiber metal laminate. Feyzullahoğlu [46] investigated the effects of different filler materials on adhesive wear behaviour of glass fiber reinforcement. In this work polymetilmetacrilat, glass beads and glass sand were used as filling material in glass fiber reinforcement polymer composite samples. The adhesive wear behaviours of samples were carried out using ball on disc type tribometer. The friction force and coefficient of friction were measured during the experimental test. The volume loss and wear rate values of samples were determined according to experimental test. Results show that the wear resistance of glass Beads filled glass fiber reinforcement polymer composite samples was much more than non-filled and polymetilmetacrilat filled GFRP composite samples [46]. Abhang et al. [47,48,49] determined the tribological parameters of SAE-10W-30 with the addition of nano-hybrid composites. In this work author has designed the process variable levels for the four-ball tribometer for concentration in the percentage of weight of nano-hybrid composites and determine the wear scar diameter and friction coefficient of hybrid nano-composites. From the experiment observed that the addition of nano-composite in combination with SAE-10W-30 reduces the coefficient of friction by 40 %. The experimental work on hybrid nano-composites provides sustainable energy solutions and environmental conservation while simultaneously addressing current and future demands [47,48,49].

4. CONCLUSION

This study presents a comprehensive evaluation of glass fiber-reinforced polymer composites with a particular focus on their preparation methods, mechanical performance, and tribological behavior. The comparative analysis of various manufacturing techniques including hand lay-up, RTM, compression molding, injection molding, filament winding, and pultrusion highlights the trade-offs between process complexity, part quality, and production efficiency. Experimental findings confirm that increasing glass fiber content enhances mechanical properties such as tensile strength, flexural strength, and modulus. While also improving wear resistance under dry and lubricated conditions. The addition of solid lubricants like PTFE and graphite further optimizes frictional performance. Observations from different test methods and surface analysis techniques (e.g., SEM) validate the role of filler type, distribution, and processing technique in determining composite durability and functionality for advanced engineering applications.

Future research in this domain can focus on the development of sustainable and bio-based glass fiber-reinforced composites to address growing environmental concerns. The integration of hybrid reinforcements and multilayer structures could further enhance the mechanical and tribological performance of composites in extreme operating conditions. Additionally, advancements in artificial intelligence and machine learning may enable predictive modeling of wear behavior, aiding in the rapid optimization of material design. Investigating the performance of these composites under real-time industrial applications and complex loading environments will provide more practical insights and contribute to broader commercial adoption. The study is limited to standard laboratory conditions and does not consider environmental aging effects. Additionally, detailed analysis of fiber–matrix interfacial bonding was not conducted.

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Appendix I: Preparation methods for hybrid polymer composites and their applications.

Method	Description	Advantages	Process Challenges	Suitable Applications	References
Hand Lay-Up	Manual placement of glass fibers in open mold, followed by resin saturation and curing.	- Low cost - Simple - Ideal for prototyping	- Labor-intensive - Skill-dependent - Inconsistent quality	Small to medium-sized parts, prototypes	[1,2]
Resin Transfer Molding (RTM)	Closed-mold resin injection into preform under pressure and heat.	- High surface finish - Low porosity - Accurate dimensions	- High equipment cost - Skilled operation required	Medium to large precision parts	[2,3]
Compression Molding	Fibers and resin placed in heated mold, compressed and cured.	- High strength - Good surface finish - Durable	- Limited to simple shapes - Long cycle time	Structural components, auto parts	[3,4]
Injection Molding	Molten thermoplastic resin injected into mold at high pressure.	- High precision - Complex shapes - High output	- Expensive tooling - Thermoplastics only	Mass production of detailed parts	[1,4]
Filament Winding	Fibers wound on rotating mandrel, impregnated with resin and cured.	- Very strong - Hollow parts - Stiff	- Time-intensive - Requires precision - Special equipment	Pipes, tanks, pressure vessels	[2,5]
Pultrusion	Continuous pulling of resin-impregnated fibers through a heated die.	- High strength - Dimensional stability - Consistent profiles	- Limited to straight parts - Needs skilled monitoring	Profiles for construction, railings	[4,5]