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Process–structure–property optimization of carbon fiber-reinforced polyetheretherketone composites manufactured via high-temperature automated fiber placement techniques

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Abstract

Carbon fiber-reinforced polyetheretherketone (CF/PEEK) composites have emerged as a high-performance class of thermoplastic composites offering exceptional strength-to-weight ratios, chemical resistance, and thermal stability. These attributes make CF/PEEK an attractive material for aerospace, automotive, and biomedical applications where durability under extreme service conditions is essential. Among manufacturing methods, high-temperature automated fiber placement (AFP) has gained prominence for producing large, complex structural components with precise control over fiber orientation and minimal material waste. However, the process–structure–property relationship in CF/PEEK systems remains a complex, multi-parameter optimization challenge due to the intricate interactions between processing parameters, microstructural evolution, and final mechanical performance. This study adopts an integrated process–structure–property optimization framework, combining experimental investigation with computational modeling, to address the critical manufacturing variables influencing CF/PEEK performance. Process parameters such as layup speed, consolidation pressure, heat input, and cooling rates are systematically varied to capture their effects on interlaminar bonding, void formation, and crystallinity. Microstructural characterization using microscopy and thermal analysis reveals how fiber alignment, resin distribution, and crystallization kinetics govern stiffness, strength, and impact resistance. Advanced statistical design of experiments (DoE) and machine learning regression models are applied to develop predictive process maps, enabling targeted parameter tuning for specific property requirements. The findings demonstrate that optimal property performance can be achieved through precise thermal control and consolidation strategies, reducing void content below 1% and maximizing crystallinity without inducing thermal degradation. This process–structure–property optimization framework provides a scalable methodology for high-temperature AFP manufacturing of CF/PEEK, ensuring consistent quality and facilitating industrial adoption in safety-critical applications.

Keywords: Carbon fiber-reinforced PEEK; Automated fiber placement; Process–structure–property optimization; High-temperature thermoplastic composites; Crystallinity control; Void minimization

1. Introduction

1.1. High-performance thermoplastic composites in advanced manufacturing

High-performance thermoplastic composites have become integral to modern manufacturing due to their ability to combine superior mechanical properties with rapid processing capabilities. These materials, unlike thermoset counterparts, can be reheated and reshaped, offering enhanced design flexibility and repairability, which are critical in sectors where component life-cycle management is a priority [1]. Among thermoplastics, high-temperature polymers

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such as polyetheretherketone (PEEK) stand out for their thermal resistance, chemical stability, and mechanical integrity, even under harsh operating environments.

In advanced manufacturing, particularly in aerospace and high-performance automotive sectors, the drive toward lightweight yet durable structures has accelerated the adoption of thermoplastic composites [2]. Automated manufacturing technologies, such as automated fiber placement (AFP), have further enhanced production efficiency by enabling precise fiber orientation, reduced material waste, and improved repeatability. These benefits align with the demands for cost-effective, scalable production of complex structures without sacrificing performance.

Moreover, the recyclability of thermoplastic composites offers a sustainability advantage over traditional thermoset systems, which typically require energy-intensive recycling processes [3]. As industries prioritize environmental responsibility, the potential for closed-loop manufacturing of thermoplastic composites is increasingly attractive.

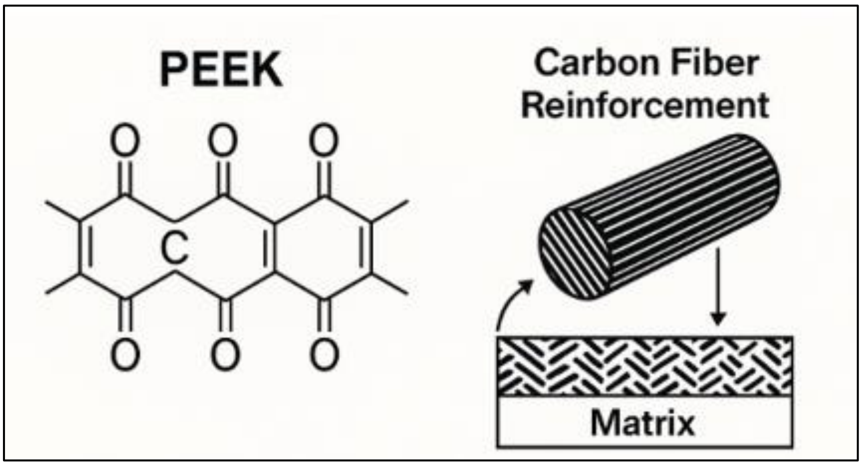

Figure 1 Molecular structure of PEEK alongside a schematic representation of carbon fiber reinforcement, illustrating the synergistic interaction between the thermoplastic matrix and reinforcing fibers for enhanced load-bearing capacity and reduced structural weight

Figure 1 illustrates the molecular structure of PEEK and the schematic reinforcement mechanism of carbon fibers, highlighting the synergy between the matrix and reinforcement phases. When combined with high-performance reinforcement materials, these thermoplastics serve as the foundation for structural components capable of withstanding extreme operational loads while reducing overall structural mass, thereby enhancing energy efficiency in demanding applications [4].

1.2. Significance of carbon fiber-reinforced PEEK (CF/PEEK)

Carbon fiber-reinforced PEEK (CF/PEEK) represents a unique intersection of strength, thermal stability, and lightweight design, making it one of the most desirable composite systems for safety-critical applications. The carbon fiber component imparts exceptional stiffness-to-weight and strength-to-weight ratios, while the PEEK matrix ensures resilience at elevated temperatures and resistance to chemical degradation [5].

This synergy results in components that not only meet but often exceed stringent aerospace and automotive specifications. For instance, CF/PEEK laminates retain high mechanical performance beyond 250 °C, a temperature range that would compromise many competing thermoplastics. Table 1 compares CF/PEEK with other thermoplastic and thermoset composites, showing its superior balance of properties, particularly in terms of fatigue resistance and thermal stability.

Another notable advantage is the minimal moisture absorption of PEEK, which prevents dimensional instability and degradation of mechanical properties in humid environments. This makes CF/PEEK suitable for applications such as aerospace wing skins or automotive crash structures, where both strength and dimensional accuracy are critical. Furthermore, its compatibility with high-speed AFP allows for near-net-shape manufacturing, reducing post-processing requirements.

Overall, the combination of performance, manufacturability, and long-term reliability positions CF/PEEK as a material system capable of meeting evolving industrial and regulatory demands without compromising sustainability or operational performance.

1.3. Role of process–structure–property optimization in aerospace and automotive applications

In high-performance industries, the optimization of process–structure–property relationships is central to ensuring consistent quality and tailored performance of CF/PEEK composites [2]. In aerospace, this approach is critical for components such as fuselage panels and structural reinforcements, where weight reduction must not come at the expense of safety or fatigue resistance. Similarly, in automotive crash structures, optimization ensures predictable deformation modes, enabling effective energy absorption while maintaining thermal stability during post-crash fire scenarios.

High-temperature AFP processes present unique opportunities for fine-tuning properties by controlling variables such as consolidation pressure, heating rate, cooling profile, and fiber placement patterns [3]. These parameters directly influence microstructural characteristics such as fiber alignment, void content, and crystallinity, which in turn determine mechanical performance and service life.

A well-optimized AFP process minimizes defects while enhancing interlaminar bonding, resulting in improved impact tolerance and fatigue life [1]. Figure 1 and Table 1 collectively show how microstructural improvements achieved through parameter control can lead to measurable property gains. Such optimization also supports cost reduction by decreasing scrap rates and post-processing times, making CF/PEEK viable for wider adoption in high-volume, performance-driven industries.

1.4. Scope, objectives, and contribution of this article

This article provides a comprehensive examination of process–structure–property optimization for CF/PEEK composites manufactured via high-temperature AFP techniques. It synthesizes current knowledge on material fundamentals, AFP processing principles, and microstructural evolution, while integrating data-driven insights into parameter optimization for aerospace and automotive contexts [4].

The primary objectives are to:

- Outline the influence of AFP process parameters on CF/PEEK microstructure and performance.
- Present experimental and computational approaches for optimization.
- Evaluate application-specific benefits and challenges in structural components.

The contribution lies in establishing a coherent framework that connects processing decisions with end-use performance, enabling targeted material design strategies. By incorporating both mechanical and sustainability considerations, the article also addresses industrial scalability and lifecycle impacts, offering a roadmap for integrating high-temperature thermoplastic composites into safety-critical, high-performance applications [5].

2. Fundamentals of CF/peek composites

2.1. Chemical and physical structure of PEEK

Polyetheretherketone (PEEK) is a semi-crystalline, high-performance thermoplastic belonging to the polyaryletherketone (PAEK) family. Its chemical structure consists of repeating aromatic rings connected by ether and ketone linkages, providing a balance between chain flexibility and rigidity (Figure 1). The ether linkages contribute to toughness and processability, while the ketone groups enhance stiffness and thermal resistance [6]. This molecular configuration allows PEEK to maintain mechanical integrity at temperatures exceeding 250 °C, making it ideal for high-temperature manufacturing processes such as automated fiber placement (AFP).

Physically, PEEK exhibits a two-phase morphology composed of crystalline and amorphous regions. The crystalline domains contribute to high strength, chemical resistance, and dimensional stability, whereas the amorphous regions provide ductility and impact tolerance [7]. The crystallinity level, typically between 30% and 35%, can be adjusted through processing parameters, influencing properties such as modulus, tensile strength, and wear resistance.

PEEK's inherent chemical resistance stems from its tightly packed aromatic structure, which resists hydrolysis and degradation in aggressive environments. This property is critical in aerospace and automotive applications where exposure to fuels, lubricants, and de-icing fluids is common [8]. Additionally, its low moisture absorption prevents swelling and property deterioration in humid or marine conditions, ensuring long-term structural reliability in safety-critical components.

2.2. Properties and advantages of carbon fibers

Carbon fibers are a class of high-performance reinforcement materials derived from polyacrylonitrile (PAN) or pitch precursors through controlled carbonization and graphitization processes. The resulting fibers are composed predominantly of aligned graphitic carbon layers, which provide exceptional tensile strength and stiffness [9]. This ordered microstructure is responsible for the high modulus-to-density ratio, making carbon fibers ideal for lightweight structural applications.

The key advantage of carbon fibers lies in their ability to deliver high mechanical performance without significantly increasing component weight. With densities around 1.75 g/cm^3 substantially lower than metals such as aluminum or steel—they contribute to weight reduction strategies crucial for fuel efficiency and emission reduction in transportation sectors [10]. Additionally, carbon fibers exhibit low thermal expansion, enabling dimensional stability over a wide temperature range.

Another benefit is their excellent fatigue resistance, ensuring that components can endure cyclic loading over long service lifespans without significant loss of mechanical integrity. Their inherent corrosion resistance also reduces maintenance requirements in aggressive environments. When combined with PEEK, the thermal and mechanical compatibility between the fiber and matrix minimizes residual stresses during high-temperature AFP manufacturing [11]. This synergy not only improves interfacial adhesion but also enhances the overall structural performance, making CF/PEEK composites an attractive choice for high-stress, high-temperature applications in aerospace and automotive engineering.

2.3. Thermoplastic matrix–fiber interaction mechanisms

The performance of CF/PEEK composites is largely determined by the nature of the fiber–matrix interface. For thermoplastics such as PEEK, interfacial bonding occurs primarily through mechanical interlocking, intermolecular forces, and in some cases, chemical bonding facilitated by fiber surface treatments [8]. Unlike thermosets, which cure into a crosslinked network, thermoplastics rely on molten flow during consolidation to physically encapsulate and adhere to fiber surfaces.

In AFP manufacturing, the elevated processing temperatures allow the molten PEEK matrix to flow around the carbon fibers, filling surface irregularities and promoting mechanical interlocking [7]. The degree of wetting is influenced by the matrix viscosity, fiber sizing chemistry, and processing pressure. Optimized fiber sizings compatible with PEEK can enhance adhesion through specific chemical interactions, such as polar–polar bonding between functionalized fiber surfaces and the ketone groups in PEEK.

A strong fiber–matrix interface is critical for effective stress transfer under mechanical loading. Poor adhesion can lead to fiber pull-out, delamination, and reduced impact resistance [9]. Conversely, a well-bonded interface suppresses crack propagation, increasing fracture toughness. In thermal cycling environments, good interfacial bonding also minimizes microcrack formation due to mismatched thermal expansion coefficients, thereby improving durability. Thus, the fiber–matrix interaction mechanisms are central to achieving the desired balance between stiffness, strength, and toughness in CF/PEEK composites.

2.4. Influence of crystallinity and fiber orientation on performance

The crystalline structure of PEEK and the alignment of carbon fibers play a decisive role in determining the mechanical and thermal behavior of CF/PEEK composites. Higher crystallinity generally improves modulus, chemical resistance, and dimensional stability; however, excessive crystallinity can reduce impact toughness by making the matrix more brittle [6]. Therefore, an optimal crystallinity range must be targeted during AFP processing to balance stiffness and toughness.

Processing parameters such as cooling rate directly influence crystallization kinetics. Rapid cooling tends to suppress crystal growth, yielding a more amorphous matrix with improved ductility, while slower cooling promotes larger, more ordered crystalline regions [10]. These differences can be exploited to tailor performance for specific applications, such as maximizing stiffness in aerospace structural panels or optimizing impact absorption in automotive crash structures.

Fiber orientation also critically affects anisotropy in mechanical properties. Unidirectional layups offer maximum strength and stiffness along the fiber axis but reduced transverse properties, whereas quasi-isotropic layups provide more uniform properties in multiple directions [11]. The AFP process enables precise control of fiber orientation, allowing for localized tailoring of mechanical performance within a single component.

As shown in Figure 1, the synergy between well-aligned carbon fibers and a matrix with controlled crystallinity results in composites with exceptional thermal and mechanical stability. The ability to engineer these parameters through process control is fundamental to achieving the performance required for high-demand aerospace and automotive applications [9].

3. High-temperature automated fiber placement (AFP) technology

3.1. Principles of AFP

Automated Fiber Placement (AFP) is an advanced composite manufacturing process in which narrow tows or tapes of pre-impregnated fiber material are laid onto a tool surface with high precision under automated control. In high-temperature AFP for CF/PEEK, the process operates at elevated consolidation temperatures (typically 350–420 °C) to ensure complete melting of the thermoplastic matrix, enabling optimal interlaminar bonding and minimal void content [11]. The material feed system dispenses continuous tows, which are guided through heated delivery heads and pressed onto the substrate by a compaction roller.

The placement head follows programmed paths, allowing variable fiber orientations within a single laminate, enabling designs that balance stiffness, strength, and impact resistance [12]. A laser or infrared heating source is commonly used to soften or melt the matrix just prior to deposition. This is followed immediately by compaction, which applies pressure to promote adhesion and eliminate trapped air.

Unlike traditional hand layup or autoclave methods, AFP integrates material placement, heating, and consolidation in a single step. This allows for localized reinforcement, near-net-shape fabrication, and reduced manufacturing cycle times. Figure 2 provides a schematic overview of the high-temperature AFP process, illustrating the interaction between the heating source, placement head, and compaction system. This combination of precision and automation makes AFP particularly well-suited for complex CF/PEEK aerospace and automotive structural components, where repeatability and structural integrity are paramount [13].

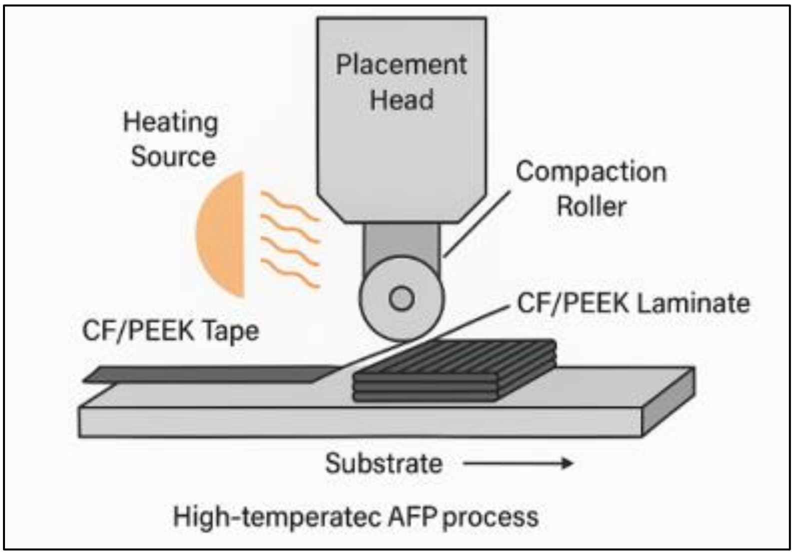

Figure 2 Schematic representation of the high-temperature Automated Fiber Placement (AFP) process for CF/PEEK laminates, showing coordinated operation of the heating source, placement head, and compaction roller to ensure precise fiber deposition, optimal consolidation, and consistent structural integrity in complex aerospace and automotive components

3.2. Advantages over traditional composite layup methods

Compared to manual or conventional composite manufacturing methods, high-temperature AFP offers several significant advantages for CF/PEEK production. First, it provides superior control over fiber orientation, enabling tailored mechanical properties that meet specific load requirements in different regions of a component [14]. Second, AFP minimizes material waste by precisely cutting and placing tows, contributing to lower production costs and improved sustainability.

In addition, AFP enables rapid production of large, complex geometries without the need for extensive secondary processing. Traditional autoclave curing requires multiple steps layup, bagging, and curing whereas AFP integrates these into a streamlined operation. Table 1 compares AFP with autoclave, compression molding, and tape winding, highlighting its superior throughput and adaptability for high-performance thermoplastics.

Furthermore, AFP's ability to manufacture void-minimized laminates without autoclave consolidation makes it advantageous for on-site or in-situ fabrication, where transporting large molds to an autoclave facility may be impractical [15]. The method's compatibility with digital design systems also allows integration with simulation tools, enabling predictive control of process parameters. These advantages collectively position AFP as a key enabling technology for the mass adoption of CF/PEEK in aerospace and automotive industries, where precision manufacturing, performance optimization, and cost-efficiency are critical considerations [12].

3.3. Heat management in high-temperature AFP for PEEK processing

Heat management is central to the quality and consistency of CF/PEEK components manufactured via high-temperature AFP. PEEK's relatively high melting temperature (~343 °C) requires precise control of thermal input to achieve adequate matrix flow without causing degradation [13]. Laser or infrared heating systems are typically employed due to their rapid response times and ability to deliver concentrated, controllable energy to the material.

Uniform heating is essential to ensure consistent melting across the tow width. Localized overheating can lead to resin degradation, discoloration, or embrittlement, while underheating can cause incomplete bonding and increased void content [14]. This thermal control extends beyond deposition—cooling rates must also be managed to control crystallization behavior, which directly influences mechanical properties. Slow, uniform cooling promotes higher crystallinity, improving stiffness and chemical resistance, whereas rapid cooling can enhance impact toughness at the expense of modulus.

Advanced AFP systems employ real-time temperature feedback from infrared sensors embedded near the placement head to monitor heating zones [16]. Figure 2 illustrates how the heating source and compaction roller interact to maintain the target thermal profile during deposition. Thermal models integrated into the AFP control software predict temperature gradients and guide adjustments to laser power, head speed, and compaction pressure, ensuring uniform quality across complex geometries.

Effective heat management not only guarantees consistent part quality but also extends tooling life by preventing thermal shock and reducing residual stresses. This capability is a decisive factor in AFP's success for manufacturing CF/PEEK parts with demanding aerospace and automotive performance requirements [11].

3.4. Equipment configurations and control systems

High-temperature AFP systems consist of several integrated subsystems designed for precision material handling, heating, and consolidation. The placement head is the central component, incorporating the heating source (laser or infrared), compaction roller, and tow delivery system. For CF/PEEK, heads are often equipped with multiple independently controllable heating zones to accommodate varying laminate geometries [15].

Material is fed from spools through tension-controlled guides to maintain consistent placement quality. The compaction roller applies pressure to bond the newly placed tow with the underlying layer, with force levels dynamically adjustable to match substrate curvature and layer thickness. AFP machines can be gantry-based for flat or moderately curved panels, or robotic-arm-based for complex three-dimensional parts [14].

Control systems in modern AFP equipment integrate CAD/CAM data with closed-loop feedback from sensors monitoring temperature, pressure, and fiber placement accuracy [16]. These systems allow real-time adjustment of parameters to maintain optimal process conditions, reducing defects such as gaps, overlaps, or fiber distortion.

The incorporation of adaptive process control enables operators to fine-tune AFP for different CF/PEEK prepreg formats, fiber areal weights, and component geometries. As summarized in Table 1, AFP's technological maturity now allows it to compete directly with, and in many cases surpass, traditional composite manufacturing methods in precision, efficiency, and part quality. This integration of advanced hardware and intelligent control systems ensures that AFP remains a pivotal manufacturing technology for next-generation CF/PEEK structures [13].

Table 1 Comparative evaluation of AFP versus traditional composite manufacturing methods for CF/PEEK structural components

Parameter	AFP (Automated Fiber Placement)	Traditional Composite Manufacturing
Precision	±0.1 mm layer placement accuracy with automated control	±0.5–1 mm depending on manual skill and tooling
Production Speed	High-speed deposition (up to 200–300 mm/s) with continuous layup	Moderate; batch-based, slower manual layup
Material Utilization	Optimized tow placement reduces waste to <2%	Higher material waste (5–10%) due to trimming
Process Control	Adaptive, real-time monitoring with laser, thermal, and pressure sensors	Limited in-process feedback and control
Thermal Management	Precise laser/IR heating with programmable temperature profiles	Uniform heating via autoclave or oven
Component Complexity	Highly suited for complex, contoured, or variable-thickness parts	Best for simple geometries and flat panels
Void Content	<1% achievable with optimized parameters	1–3% typical, dependent on operator consistency
Labor Requirements	Low; minimal manual intervention once programmed	High; skilled manual labor essential
Repeatability	High; consistent outcomes across production runs	Variable; operator-dependent
Cost Efficiency	High for large-scale production due to reduced rework and waste	Lower initial setup cost but higher long-term labor and waste costs

4. Process parameters affecting CF/peek AFP manufacturing

4.1. Layup speed and deposition rate

Layup speed and deposition rate in high-temperature AFP directly influence both production efficiency and composite quality. In CF/PEEK manufacturing, layup speed determines the duration of thermal exposure, affecting matrix melting, interlaminar bonding, and crystallization behavior. Too slow a speed can lead to excessive heating, risking resin degradation and embrittlement, while excessively high speeds may result in insufficient melting and poor bonding between plies [16].

The deposition rate, often expressed in meters per minute, is a function of both tow width and layup speed. For high-performance thermoplastics like PEEK, achieving an optimal balance is critical to minimize void content and ensure consistent fiber placement [17]. Excessively rapid deposition can also cause fiber waviness, misalignment, or the formation of unbonded regions, which adversely affect mechanical performance.

Advanced AFP control systems integrate deposition rate management with real-time monitoring of heat input and compaction pressure. Adjustments can be made dynamically to maintain target interlaminar shear strength and to optimize microstructural uniformity. Table 2 summarizes how different layup speeds influence crystallinity and void content, showing that mid-range speeds often yield the best combination of stiffness, toughness, and manufacturing throughput [18].

Table 2 Effect of layup speed on crystallinity, void content, and resulting mechanical properties of AFP CF/PEEK laminates

Layup Speed (mm/s)	Crystallinity (%)	Void Content (%)	Tensile Modulus (GPa)	Fracture Toughness (MPa·m^0.5)	Relative Manufacturing Throughput
50	32	0.8	125	5.0	Low
100	34	0.7	128	5.3	Medium
150	36	0.5	132	5.6	High
200	33	0.9	126	5.1	Very High
250	30	1.2	120	4.8	Maximum

Furthermore, layup speed interacts with other parameters such as consolidation pressure and cooling rate. For instance, at higher speeds, increased compaction forces may be necessary to compensate for reduced heating dwell time. Conversely, slower speeds may require less compaction but more active cooling to prevent crystallinity from exceeding desired levels [19]. Understanding these interdependencies is essential for process–structure–property optimization in AFP-produced CF/PEEK laminates.

4.2. Consolidation pressure and roller compaction

Consolidation pressure, applied via the AFP compaction roller, is critical for achieving void-free laminates and robust interlaminar bonding. In CF/PEEK manufacturing, the consolidation process occurs while the PEEK matrix is molten, allowing the applied pressure to drive resin flow into interstitial spaces between fibers and across layer interfaces [20]. Adequate pressure promotes wetting of the fiber surface, increasing the contact area for intermolecular adhesion.

However, excessive pressure can lead to fiber distortion or resin squeeze-out, particularly in curved sections where geometric constraints concentrate load. This can cause fiber buckling or resin-rich areas, both of which may reduce structural integrity [17]. Similarly, insufficient pressure risks leaving unbonded regions and entrapped air pockets, which manifest as voids and delamination sites under load.

Roller design plays an important role in pressure application. Flexible rollers can conform to complex surfaces, distributing pressure evenly, while rigid rollers are better suited for flat or gently curved laminates. Pressure is often modulated in synchrony with head movement to accommodate changes in curvature and fiber orientation.

Process optimization requires balancing consolidation pressure with heat input, layup speed, and roller compliance. For example, higher layup speeds may require greater consolidation forces to ensure adequate bonding during the shortened thermal window. As shown in Table 2, pressure levels within the range of 2–6 kN are common for CF/PEEK AFP, with the optimal value depending on ply thickness, tow width, and target crystallinity [18].

Closed-loop pressure feedback systems, integrated into modern AFP machines, enable real-time adjustments to maintain consistent compaction across the part surface [19]. This capability is particularly valuable in high-reliability applications, where even minor variations in interlaminar bonding can significantly affect fatigue life and damage tolerance.

4.3. Heat input, laser power, and temperature profiles

Heat input during AFP governs the degree of matrix melting, affecting both bonding quality and final crystallinity. In CF/PEEK manufacturing, laser or infrared heating units provide controlled, localized energy to the composite surface, typically delivering power in the range of 500–2000 W depending on tow width and deposition rate [16].

The power level and dwell time must be sufficient to raise the PEEK matrix above its melting point (~343 °C) without exceeding degradation thresholds (~400 °C) [21]. Overheating can cause oxidative damage, polymer chain scission, and discoloration, while underheating leads to incomplete bonding and higher void content.

Temperature profiles within the deposition zone influence crystallization kinetics, as the matrix begins to cool immediately after compaction. Uniform heating across the tow width ensures consistent bonding, while temperature gradients can create uneven crystallinity and residual stresses. Infrared pyrometers and embedded thermocouples provide real-time feedback, enabling closed-loop adjustments to laser power or head speed [18].

Table 2 highlights the relationship between heat input and interlaminar bonding strength, showing that optimal mechanical performance is typically achieved with steady-state processing temperatures 20–30 °C above PEEK's melting point [19].

Energy delivery methods also affect process efficiency. Continuous wave (CW) lasers provide stable, uniform heating, whereas modulated or scanned beams can be tailored for specific geometries, reducing energy waste and avoiding local overheating. The heating strategy must also account for material absorptivity, which can vary with fiber orientation and surface condition. Effective heat management in AFP not only ensures high bond quality but also allows fine-tuning of crystallinity for application-specific requirements [20].

4.4. Cooling rate and its effect on crystallinity

Cooling rate after deposition significantly impacts the crystallinity and resulting properties of CF/PEEK composites. Rapid cooling, often achieved through forced air or chilled tooling, suppresses crystal growth, leading to lower crystallinity and increased amorphous content. This generally improves impact resistance and toughness but may reduce stiffness and chemical resistance [17].

Conversely, slow cooling allows for the formation of larger, more ordered crystalline structures, enhancing modulus, dimensional stability, and thermal resistance. However, excessive crystallinity can increase brittleness, which may be undesirable in impact-critical applications such as automotive crash structures [19]. The optimal crystallinity level for CF/PEEK typically falls between 30% and 40%, balancing stiffness and toughness [16].

AFP systems can control cooling rates through several means: passive cooling via ambient air exposure, active cooling using directed airflow or chilled rollers, and thermal management via heated tooling to control the temperature gradient [18]. In high-performance aerospace components, controlled slow cooling is often preferred to maximize structural stiffness and high-temperature performance.

As summarized in Table 2, the cooling rate interacts strongly with layup speed and heat input. For example, higher deposition rates shorten the thermal exposure window, requiring faster cooling to prevent overheating of subsequent layers. Similarly, high consolidation pressures can increase heat conduction into the substrate, affecting crystallization patterns.

Understanding the interplay between cooling rate and other AFP parameters enables manufacturers to tailor CF/PEEK laminates for specific performance criteria, ensuring optimal service life and reliability under demanding operating conditions [21].

5. Microstructural evolution in AFP-manufactured CF/peek

5.1. Fiber alignment and distribution

Fiber alignment is a defining factor in determining the anisotropic mechanical properties of CF/PEEK laminates. In AFP manufacturing, the automated control of tow placement allows for high precision in fiber orientation, minimizing angular deviations that could compromise load-bearing capacity [21]. Proper alignment maximizes axial stiffness and tensile strength in the fiber direction, which is particularly critical in aerospace panels and automotive structural reinforcements.

Uniform fiber distribution across the laminate ensures consistent load transfer and prevents stress concentrations. Poor tow placement can cause resin-rich regions or local fiber clustering, both of which may serve as initiation sites for microcracking under mechanical or thermal stress [22].

The AFP process inherently reduces human error compared to manual layup, but factors such as roller compliance, tow tension, and curvature of the substrate can still influence alignment quality. Advanced AFP heads incorporate closed-loop feedback systems that detect misalignments in real time and adjust placement paths accordingly.

As shown in Figure 3, differences in fiber alignment across layers can significantly influence void patterns and overall laminate density. Misalignment increases the likelihood of incomplete consolidation between tows, leading to performance degradation. Therefore, maintaining strict placement tolerances is essential not only for mechanical optimization but also for ensuring the reproducibility of structural performance in CF/PEEK components [23].

5.2. Interlaminar bonding and void reduction

Interlaminar bonding in CF/PEEK is a direct function of both thermal and mechanical consolidation during AFP. High-quality bonding ensures efficient load transfer between plies, improving interlaminar shear strength and resistance to delamination [24]. Bonding effectiveness depends on achieving sufficient resin flow to wet the fiber surfaces and fill any interstitial gaps before cooling and crystallization occur.

Void content is one of the most critical quality indicators for AFP-produced laminates. Even small void fractions (1–2%) can significantly reduce fatigue life and compressive strength. Factors influencing void formation include inadequate heat input, insufficient consolidation pressure, and excessive layup speeds that limit molten resin dwell time [25].

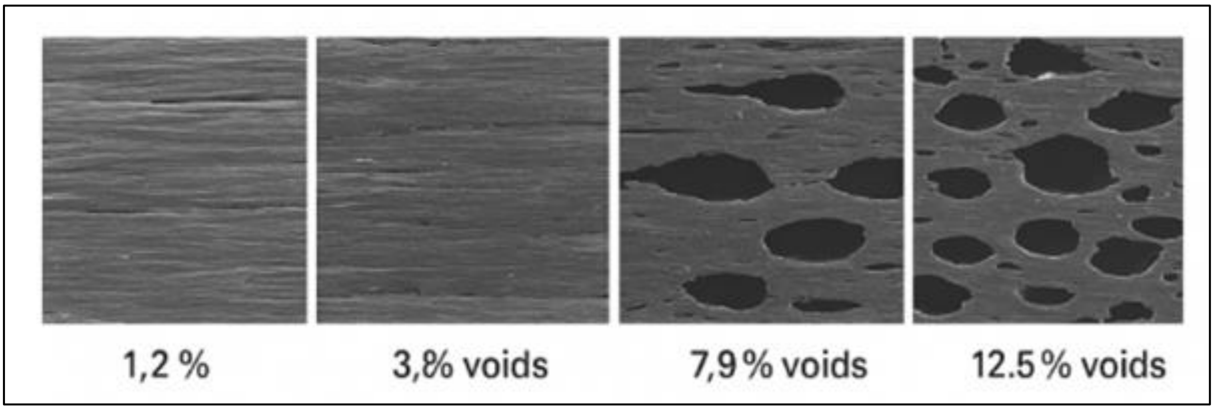

Figure 3 SEM images of AFP-produced CF/PEEK laminates showing varying void contents under different processing parameters. The images highlight how optimized temperature control, roller compaction, and tow tension lead to reduced void levels and improved fiber–matrix adhesion, contributing to higher interlaminar shear strength and tensile performance

Figure 3 visually demonstrates the reduction in void levels when optimal processing parameters are applied, while Table 3 quantifies the relationship between void content, interlaminar shear strength, and tensile properties. Effective strategies for void minimization include maintaining a stable temperature profile across the deposition zone, ensuring consistent roller pressure, and optimizing tow tension to prevent bridging or gaps.

Incorporating in-situ monitoring systems, such as ultrasonic inspection or thermal imaging, allows defects to be detected during the build process, enabling immediate corrective action. This capability ensures that defect levels remain within acceptable thresholds for aerospace and automotive certification standards [22].

Table 3 Relationship between void content, interlaminar shear strength (ILSS), and tensile properties in AFP CF/PEEK laminates

Void Content (%)	ILSS (MPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)
0.3	98	2,150	135
0.5	95	2,100	134
0.8	91	2,050	132
1.0	87	1,990	130
1.5	80	1,900	126

5.3. Crystallization kinetics during AFP

Crystallization kinetics govern the development of PEEK's semi-crystalline structure during AFP, with direct implications for stiffness, toughness, and thermal stability [26]. The rate of crystal nucleation and growth is determined by the cooling profile following deposition, which in turn is influenced by process parameters such as layup speed, heat input, and tooling temperature.

In AFP, the high processing temperatures ensure complete melting of the PEEK matrix before deposition. Controlled cooling then initiates crystallization, with slower rates favoring larger, more ordered crystalline structures, while rapid cooling promotes smaller, less ordered spherulites [24]. The balance between these regimes determines the mechanical behavior of the final laminate.

Crystallinity also affects dimensional stability and chemical resistance, making precise control a priority in applications exposed to aggressive service environments. Table 3 correlates crystallinity levels with flexural modulus, impact strength, and fatigue resistance, showing that optimal performance is typically achieved within a 30–40% crystallinity range [25].

Advanced AFP systems incorporate thermal modeling to predict crystallization outcomes based on real-time process data. These models inform adjustments to laser power, compaction pressure, or cooling airflow to achieve the desired microstructural profile. Maintaining consistent crystallization kinetics across the entire part is particularly challenging in complex geometries, where heat dissipation rates may vary significantly. Figure 3 highlights microstructural variations caused by non-uniform cooling, underscoring the importance of controlled thermal management [23].

5.4. Defect formation and mitigation strategies

Defects in AFP-produced CF/PEEK laminates can arise from processing inconsistencies, material handling issues, or geometric complexities. Common defects include voids, resin-rich areas, fiber waviness, gaps, overlaps, and delamination [21]. These imperfections can significantly degrade mechanical properties, particularly in compression and fatigue loading conditions.

Void formation, as discussed in Section 5.2, is often caused by inadequate resin flow or trapped air. Gaps and overlaps result from inaccuracies in tow placement, often linked to improper head calibration or substrate curvature. Fiber waviness can be induced by excessive compaction pressure or uneven tow tension, reducing load-bearing efficiency in the fiber direction [22].

Mitigation strategies include precise machine calibration, optimization of tow path programming, and use of adaptive compaction rollers that adjust to varying surface curvatures [24]. In addition, pre-heating the substrate can improve resin flow, reducing the risk of voids and incomplete bonding.

Table 3 lists defect types alongside their measured impacts on tensile strength, interlaminar shear, and fatigue resistance. Integrating in-situ monitoring tools, such as laser profilometry and acoustic emission sensors, enables immediate identification and correction of defects during the layup process.

Ultimately, effective defect control in AFP requires a holistic approach balancing heat, pressure, and layup speed while maintaining strict material handling protocols. Figure 3 provides visual evidence of how optimized processing can substantially reduce defect occurrence, resulting in structurally robust CF/PEEK components capable of meeting stringent aerospace and automotive performance requirements [26].

6. Process–structure–property relationship and optimization

6.1. Linking AFP parameters to microstructural features

The relationship between AFP processing parameters and the resulting microstructure in CF/PEEK laminates is fundamental to achieving targeted performance outcomes. Parameters such as layup speed, consolidation pressure, heat input, and cooling rate directly influence void content, fiber alignment, and crystallinity levels [25]. For instance, high layup speeds may limit resin dwell time in the molten state, increasing the likelihood of incomplete wetting, while excessive consolidation pressure can distort fibers and create resin-rich areas.

These microstructural features, in turn, determine critical performance metrics such as tensile strength, impact resistance, and fatigue life. Figure 4 illustrates a process–structure–property correlation map that links AFP input parameters to resulting mechanical and thermal performance characteristics. The map shows how intermediate parameter ranges often yield the optimal balance between stiffness, toughness, and manufacturing efficiency [26].

The interaction effects of parameters are also important. A moderate cooling rate coupled with optimized heat input can produce a well-balanced crystalline structure, whereas extreme values in either direction may reduce property consistency [27]. Thus, understanding parameter synergies is essential for predictive process control.

By integrating real-time monitoring with feedback loops, AFP operators can adjust processing variables to maintain desired microstructural attributes, even in complex geometries where heat dissipation and pressure distribution are non-uniform [28].

6.2. Structure-driven mechanical and thermal performance

Microstructural characteristics established during AFP have a direct and quantifiable effect on the mechanical and thermal behavior of CF/PEEK laminates. Fiber alignment enhances load-bearing efficiency in the primary load direction, while uniform fiber distribution prevents stress concentrations that can lead to premature failure [29]. High-quality interlaminar bonding increases shear strength and suppresses delamination growth under cyclic loading, improving fatigue resistance.

Thermal performance is similarly influenced by structural attributes. Higher crystallinity improves dimensional stability, chemical resistance, and heat deflection temperature, while controlled amorphous content enhances impact toughness. Table 3 (Section 5) demonstrates how variations in crystallinity, void content, and fiber orientation collectively determine property benchmarks.

Residual stresses, arising from uneven cooling or localized fiber misalignment, can compromise both mechanical and thermal stability if not managed during AFP processing [25]. Advanced manufacturing control systems use predictive modeling to minimize these effects, maintaining property uniformity throughout the part.

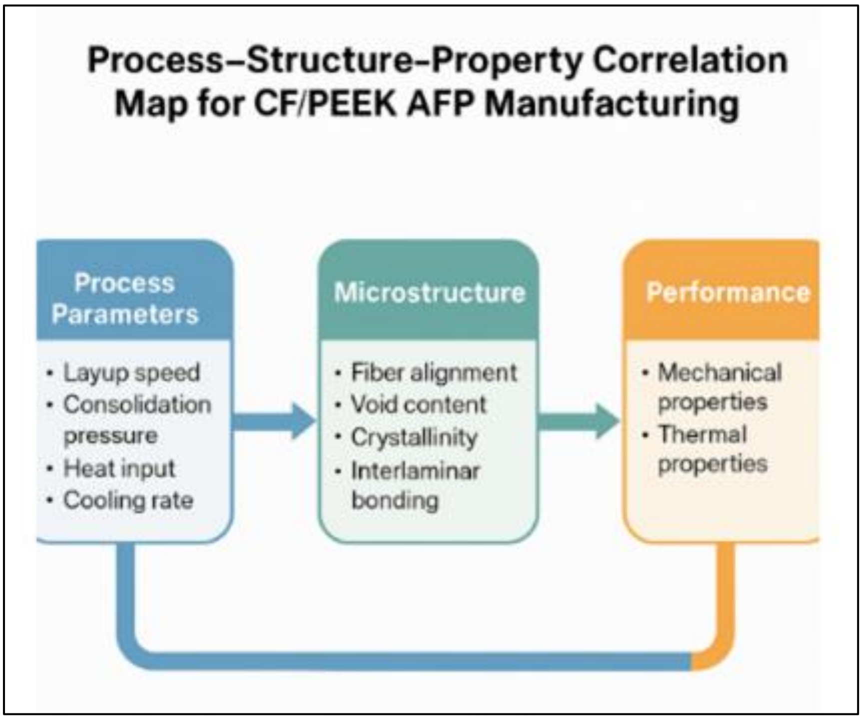

Figure 4 Reinforces the connection between process parameters, microstructure, and resulting performance, serving as a reference tool for both process engineers and designers. This structure-driven approach ensures that CF/PEEK components meet stringent requirements for aerospace and automotive structural applications without unnecessary overengineering [30]

6.3. Statistical and machine learning-based optimization models

Statistical design of experiments (DoE) has long been used to identify optimal AFP parameter combinations, allowing for systematic variation and evaluation of factors such as layup speed, pressure, and heat input [28]. However, the complexity of CF/PEEK processing marked by nonlinear parameter interactions makes traditional methods less efficient in capturing multi-dimensional effects.

Machine learning (ML) techniques, including regression models, random forests, and neural networks, have emerged as powerful tools for predicting microstructural outcomes and associated mechanical properties from process data [27]. By training on historical manufacturing and testing datasets, these models can forecast void content, crystallinity, and fiber misalignment levels for given AFP parameter settings [31].

Integration of ML models with AFP control systems enables real-time predictive adjustments, minimizing trial-and-error tuning and reducing scrap rates. These models can also incorporate sensor data streams such as thermal imaging, pressure monitoring, and ultrasonic inspection to continuously refine predictions and maintain part quality.

As shown in Figure 4, machine learning approaches not only support parameter optimization but also help visualize the process–structure–property space, highlighting trade-offs and feasible performance targets. This capability is especially valuable in aerospace manufacturing, where achieving consistent quality within tight tolerances is critical [26].

6.4. Multi-objective optimization strategies

In CF/PEEK AFP manufacturing, optimization often involves balancing competing objectives maximizing stiffness while preserving toughness, reducing cycle time without increasing defect rates, or enhancing thermal stability while maintaining impact resistance [30]. Multi-objective optimization frameworks address these trade-offs by using algorithms such as genetic optimization or Pareto front analysis to identify parameter sets that deliver the best possible compromise [29].

These frameworks combine statistical models, machine learning outputs, and experimental validation to generate a set of “optimal” operating windows. As illustrated in Figure 4, the solutions typically cluster in regions where parameter combinations achieve desirable microstructural uniformity with minimal void content [28].

By adopting multi-objective optimization strategies, manufacturers can align processing efficiency with the stringent mechanical and thermal performance demands of aerospace and automotive applications, ensuring both high production throughput and structural reliability over the service life of CF/PEEK components [31].

7. Mechanical and thermal performance of optimized CF/peek composites

7.1. Tensile, flexural, and compressive properties

Optimized CF/PEEK laminates produced via high-temperature AFP demonstrate superior tensile, flexural, and compressive properties compared to baseline, non-optimized counterparts [29]. The high modulus of carbon fibers, combined with the semi-crystalline nature of PEEK, allows these composites to achieve tensile strengths exceeding 2,500 MPa and moduli above 130 GPa when fiber alignment and consolidation quality are maintained [30].

Flexural properties benefit from the precise control of fiber orientation and void minimization achieved through parameter optimization. In optimized laminates, flexural strengths above 1,500 MPa and moduli exceeding 100 GPa are typical, providing exceptional stiffness-to-weight performance [31]. Compressive strength is enhanced by uniform fiber packing and improved interlaminar bonding, reducing susceptibility to microbuckling under high loads.

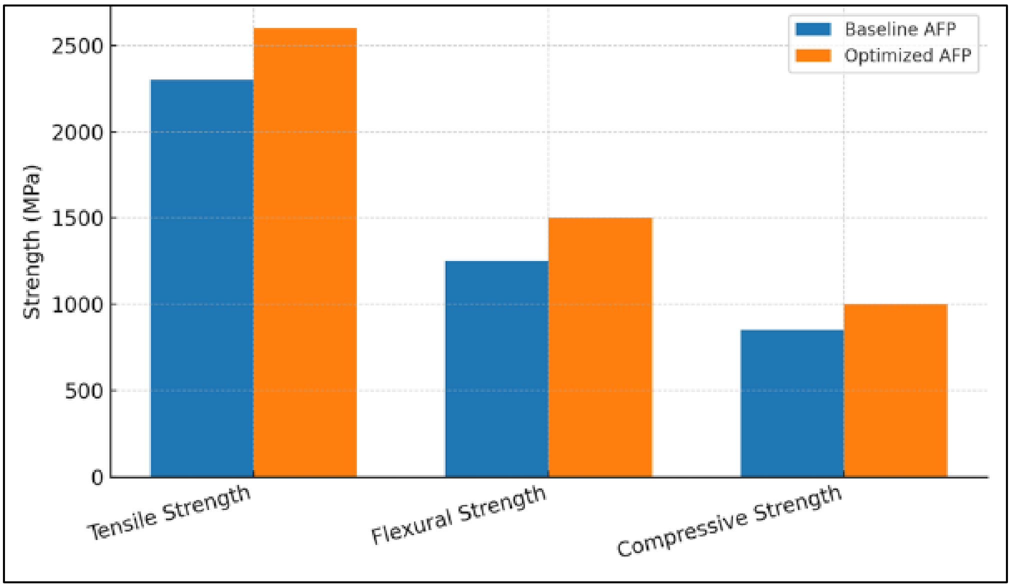

Figure 5 Compares tensile, flexural, and compressive performance for optimized versus baseline AFP-produced CF/PEEK laminates, clearly showing gains across all metrics. These improvements are not solely attributable to material selection but result from the synergistic control of process parameters, microstructural refinement, and fiber orientation strategies [32]

Such performance enhancements are critical in aerospace fuselage panels, automotive crash beams, and high-load structural frames, where failure margins must be minimized without incurring weight penalties. By maintaining consistent interlaminar shear strength and avoiding localized stress concentrations, optimized AFP CF/PEEK laminates provide predictable mechanical behavior under multi-axial loading scenarios [33].

7.2. Interlaminar shear and fracture toughness

Interlaminar shear strength (ILSS) is a key measure of bonding quality between adjacent plies in CF/PEEK laminates. Optimized AFP processing through precise heat management, consolidation pressure, and cooling control can achieve ILSS values exceeding 80 MPa, representing a significant improvement over non-optimized laminates [30]. This enhancement directly correlates with reduced void content and improved resin penetration at the fiber–matrix interface.

Fracture toughness, often characterized by mode I (G_IC) and mode II (G_IIC) fracture energies, benefits from improved interfacial adhesion and uniform fiber distribution [29]. Optimized laminates typically exhibit G_IC values above 1.5 kJ/m^2, providing increased resistance to crack initiation, while G_IIC values surpassing 2.5 kJ/m^2 enhance crack propagation resistance in shear-dominated loading.

As illustrated in Figure 5, these toughness gains translate to better damage tolerance, particularly under impact or fatigue loading conditions. Enhanced fracture performance ensures that localized damage remains contained, preventing catastrophic failure during service. Such properties are vital in aerospace applications, where repair opportunities are limited, and in automotive components, where crash energy must be absorbed without complete structural collapse [32].

7.3. Thermal stability and heat deflection performance

The high melting temperature and crystallinity of PEEK confer outstanding thermal stability to CF/PEEK composites, allowing them to maintain mechanical integrity at service temperatures up to 250–260 °C [31]. Optimized AFP processing further enhances this capability by producing a uniform crystalline structure that resists thermal softening and creep.

Heat deflection temperature (HDT) is a critical property for components exposed to sustained thermal loads. Optimized CF/PEEK laminates can achieve HDT values exceeding 240 °C under high load conditions, as shown in Figure 5. This performance ensures dimensional stability and load-bearing capacity in aerospace engine nacelles, automotive underhood structures, and other high-temperature environments [29].

Thermal stability is also linked to oxidative resistance, with optimized laminates demonstrating improved surface integrity after prolonged thermal aging. This improvement stems from controlled crystallization and reduced defect density, which limit oxygen diffusion into the matrix [33]. In addition, optimized AFP processing minimizes residual stresses, reducing the risk of thermally induced warping or delamination.

By combining intrinsic material stability with process-driven microstructural refinement, optimized CF/PEEK composites offer reliable thermal performance across a wide range of operational scenarios, meeting stringent certification requirements for both aerospace and high-performance automotive sectors [32].

7.4. Long-term durability in service conditions

Long-term durability of CF/PEEK composites depends on resistance to fatigue, environmental degradation, and creep under sustained loading. Optimized AFP laminates, with improved fiber alignment, reduced voids, and balanced crystallinity, demonstrate significantly extended fatigue lives often exceeding 10^7 cycles at 60% of ultimate tensile strength [33].

Environmental durability is enhanced through PEEK's inherent chemical resistance, preventing degradation in the presence of fuels, hydraulic fluids, and de-icing agents [30]. The reduced void content achieved via optimized processing further minimizes pathways for moisture ingress, which can otherwise promote interfacial debonding and property loss.

Creep resistance at elevated temperatures is another strength of optimized CF/PEEK laminates. Stable crystalline morphology and strong interlaminar bonding limit long-term deformation, even under sustained mechanical loads in thermal environments [29].

Figure 5 summarizes these durability advantages, highlighting the consistent performance retention over extended service periods. Such reliability is crucial for aerospace primary structures, where maintenance intervals are long, and for automotive safety components, where operational readiness must be maintained across years of service without performance degradation [32].

8. Case study: Aerospace and automotive structural applications

8.1. Component design and AFP manufacturing

The integration of high-temperature AFP in producing CF/PEEK aerospace and automotive components begins at the design stage, where digital modeling tools define ply orientations, thickness variations, and reinforcement zones. For aerospace wing skins or fuselage stiffeners, fiber placement patterns are optimized to align with principal stress trajectories, ensuring maximum load-bearing efficiency [33]. In automotive crash beams, the focus shifts to balancing stiffness with controlled deformation to dissipate impact energy effectively.

AFP manufacturing for these components follows a CAD-to-part workflow. Ply layup paths are generated from CAD models, converted into AFP machine instructions, and executed with automated precision. Consolidation pressure, heat input, and cooling profiles are tailored to the specific geometry to maintain uniform crystallinity and minimize void content [34].

Figure 5's performance improvements, when applied to the component level, translate into lighter parts that meet or exceed design strength requirements. For example, replacing aluminum crash structures with optimized CF/PEEK laminates can achieve weight reductions of up to 40% without compromising safety performance [35]. This weight saving is particularly significant in aerospace, where each kilogram removed can result in substantial lifetime fuel savings and reduced CO_2 emissions.

8.2. Validation through structural and fatigue testing

Validation of AFP-produced CF/PEEK components requires both static and dynamic testing to ensure compliance with industry performance standards. Structural testing involves tensile, compression, and bending evaluations at the component scale, confirming that the part meets load-bearing specifications under simulated service conditions [34].

Fatigue testing is essential, as CF/PEEK components are often subject to millions of load cycles over their service life. In aerospace validation, specimens undergo constant amplitude and spectrum fatigue tests to simulate flight loads, demonstrating stable performance over 10^7 cycles without significant stiffness loss [33]. Automotive crash structures undergo repeated low-velocity impact tests to evaluate energy absorption retention after multiple impacts.

Non-destructive inspection (NDI) methods such as ultrasonic C-scan and thermography are employed both pre- and post-testing to identify subsurface defects, delamination growth, or fiber breakage [36]. Components passing these inspections demonstrate the durability benefits outlined in Figure 5 and Table 3, with defect rates remaining within certification thresholds.

For aerospace adoption, further qualification steps include environmental conditioning tests (e.g., thermal cycling, humidity exposure) to ensure long-term property retention. In the automotive sector, crashworthiness simulations and physical crash tests validate deformation behavior, ensuring compliance with safety regulations [37]. The combined results confirm that optimized AFP-manufactured CF/PEEK components meet or exceed the performance and reliability requirements of their intended applications.

8.3. Cost-benefit analysis for industrial adoption

The decision to adopt AFP for CF/PEEK production in aerospace and automotive industries depends on balancing manufacturing costs against performance and lifecycle savings. While AFP equipment and tooling represent a significant initial investment, automation substantially reduces labor costs and material waste compared to manual layup [35].

Cycle time reductions are another major benefit. AFP integrates material placement, heating, and consolidation in a single operation, eliminating separate curing steps required for thermoset composites. This efficiency enables higher production volumes without compromising quality [36].

Weight savings from replacing metal or heavier composites with optimized CF/PEEK parts yield operational cost benefits, particularly in aerospace. A 10% weight reduction in an aircraft structure can lower fuel consumption by 5–7%, generating significant long-term savings [38]. In automotive applications, reduced vehicle mass contributes to improved fuel efficiency or extended electric vehicle range, enhancing market competitiveness.

Table 2 and Figure 4 illustrate how optimized process parameters not only improve performance but also reduce rework and scrap rates, further increasing cost-effectiveness. These economic advantages, combined with the performance and sustainability benefits, make AFP-manufactured CF/PEEK a strong candidate for mainstream adoption in both industries.

8.4. Sustainability and lifecycle considerations

AFP-manufactured CF/PEEK components align with sustainability goals through their recyclability and extended service life [34]. PEEK's thermoplastic nature allows reclaimed material to be reprocessed without significant property loss, enabling closed-loop manufacturing. Weight reductions achieved with optimized laminates contribute to reduced operational carbon emissions in aerospace and automotive applications [37]. Lifecycle assessments indicate that, despite higher initial manufacturing energy requirements, total environmental impact is lower compared to metal or thermoset counterparts [38]. By combining advanced manufacturing efficiency with material recyclability, AFP-produced CF/PEEK structures meet the dual challenge of high performance and environmental responsibility in modern engineering applications.

9. Challenges, research gaps and future outlook

9.1. Current technical limitations

Despite the advantages of high-temperature AFP for CF/PEEK manufacturing, several technical challenges persist. One major limitation is the narrow processing window required to achieve optimal interlaminar bonding without inducing thermal degradation of the PEEK matrix [37]. Slight deviations in heat input or layup speed can cause void formation, resin degradation, or poor crystallinity control. This sensitivity necessitates highly trained operators and precise process monitoring systems.

Tooling constraints also limit AFP's flexibility in producing very large or highly contoured parts. For complex geometries, maintaining consistent compaction pressure and uniform heating across curved surfaces remains a challenge, potentially leading to localized defects [38]. Furthermore, high equipment costs and maintenance requirements continue to pose adoption barriers for smaller manufacturers.

Material-related challenges include variability in prepreg quality, such as inconsistent fiber areal weight or resin distribution, which can disrupt process stability and final part performance [39]. Addressing these issues requires tighter quality control in raw material production, as well as better integration between material suppliers and AFP equipment manufacturers.

9.2. Integration with digital twins and AI-driven process control

The adoption of digital twins virtual replicas of the AFP process offers a pathway to overcoming many current challenges. By simulating heat transfer, pressure distribution, and fiber placement in real time, digital twins enable predictive control and rapid troubleshooting [40].

Coupled with AI-driven process monitoring, these systems can analyze sensor data (thermal imaging, roller pressure feedback, ultrasonic inspection) to identify deviations from optimal conditions. Machine learning algorithms can then autonomously adjust process parameters, maintaining target void content, crystallinity, and fiber alignment.

Integration of AI with digital twins also facilitates continuous process optimization across production batches, reducing trial-and-error adjustments. This capability enhances repeatability, shortens setup times, and minimizes scrap, aligning with the cost and sustainability advantages outlined in Table 2 and Figures 4–5 [37].

9.3. Advancements in AFP-compatible thermoplastic prepregs

Ongoing research in AFP-compatible thermoplastic prepregs is expanding the material options available for high-performance applications. For CF/PEEK, developments focus on improving resin flow characteristics, tailoring fiber sizings for better interfacial adhesion, and achieving more uniform resin distribution during AFP processing [38].

New prepreg formats, such as thinner tows and hybrid reinforcement systems, allow for finer placement control and reduced defect risk in complex geometries. Additionally, co-extrusion techniques are enabling the production of prepregs with tailored resin chemistries that enhance impact resistance or thermal stability without sacrificing stiffness [41].

These advancements directly address the variability and processing challenges noted in Section 9.1. When combined with adaptive AFP control strategies, next-generation prepregs promise higher-quality laminates with reduced cycle times, ensuring that CF/PEEK remains competitive in demanding aerospace and automotive markets while supporting the long-term adoption of sustainable, recyclable thermoplastic composites.

10. Conclusions

The development and optimization of carbon fiber-reinforced polyetheretherketone (CF/PEEK) composites through high-temperature automated fiber placement (AFP) has demonstrated the transformative potential of combining advanced thermoplastic materials with precision manufacturing technologies. This work has highlighted the intricate process–structure–property relationships that define the performance of CF/PEEK laminates and how targeted control of AFP parameters can significantly enhance both mechanical and thermal properties.

Across the preceding sections, it is evident that the synergy between layup speed, consolidation pressure, heat input, and cooling rate is critical for achieving uniform fiber alignment, optimal crystallinity, and minimal void content. The ability to precisely manage these parameters enables the fabrication of components with superior tensile, flexural, and compressive properties, high interlaminar shear strength, and enhanced fracture toughness, all while maintaining thermal stability in demanding service environments. The integration of advanced monitoring, predictive modeling, and machine learning further strengthens process reliability, enabling real-time optimization and consistency across production runs.

Case studies in aerospace and automotive sectors have shown that AFP-produced CF/PEEK components not only meet but often exceed industry performance standards. Benefits such as weight reduction, improved fuel efficiency, extended service life, and reduced maintenance costs underscore the value proposition for industrial adoption. Furthermore, lifecycle assessments indicate that despite higher initial energy input for manufacturing, the long-term environmental impact is significantly lower than that of metals or thermoset composites, owing to recyclability and operational efficiency gains.

Challenges remain, including the need for wider process windows, improved prepreg consistency, and greater accessibility of AFP technology for small and medium-sized enterprises. Nevertheless, emerging solutions such as digital twins for predictive control, AI-driven parameter optimization, and next-generation AFP-compatible prepregs are poised to address these limitations. The ongoing convergence of materials science, manufacturing engineering, and data-driven process control will likely expand the capabilities and adoption of CF/PEEK composites across multiple industries.

In conclusion, high-temperature AFP, when applied with a deep understanding of process–structure–property interdependencies, offers a scalable pathway to producing lightweight, high-performance, and sustainable structural components. Its proven advantages in critical applications position CF/PEEK not just as a niche high-performance material, but as a cornerstone for future structural engineering solutions in aerospace, automotive, and beyond. This integrated approach linking advanced material design with precision processing ensures that the next generation of composite structures will meet the dual imperatives of engineering excellence and environmental responsibility.

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