Research Progress in Material Systems, Forming Processes, and Structure–Function Integrated Technologies for Additively Manufactured Composites

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Abstract. Additive manufacturing of composites, with its high design freedom, near-net-shape capability, and rapid fabrication of complex structures, is driving the transition of composite manufacturing towards digitalised and structure–function integrated production. Through coordinated control of reinforcement distribution, fibre orientation, pore architecture, and structural configuration, it offers a promising route for high-performance lightweight and multifunctional components. This paper reviews recent advances in material systems, forming processes, structural optimisation, and functional integration, while summarising key challenges and future trends in high-performance, recyclable, intelligent, and digital-twin-driven manufacturing.

Keywords: Additive Manufacturing; Composite Materials; Material System

1 Introduction

Composite materials are a key platform for lightweight, multifunctional, and high-performance equipment due to their high specific strength and stiffness, corrosion resistance, and design flexibility. However, conventional mould-based fabrication methods remain limited by poor geometric adaptability, low material efficiency, long production cycles, and restricted customisation. Additive manufacturing provides a promising alternative through layer-by-layer deposition, enabling the fabrication of complex composite structures with programmable performance[1][2]. Recent advances in printing hardware, feedstock development, in situ monitoring, and computational optimisation have driven the field beyond short-fibre-filled thermoplastics towards continuous-fibre reinforcement, multi-material manufacturing, and integrated structural-functional design. In particular, additive manufacturing of continuous-fibre-reinforced polymer composites has attracted growing attention for its potential in efficient load transfer, lightweight design, and functional integration. Therefore, a systematic review of recent progress in this area is both timely and necessary to support broader engineering applications[3][4].

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2 Research Progress in Material Systems

2.1 Reinforcement Materials

The reinforcing phase governs the load-bearing capacity and functional performance of additive-manufactured composites, and is generally classified into fibres, particles, and nanofillers. Fibre reinforcements are further divided into chopped and continuous fibres. Chopped carbon, glass, and basalt fibres are readily incorporated into thermoplastic matrices for fused deposition modeling (FDM), although their reinforcing efficiency depends on fibre length, orientation, and fibre–matrix interfacial bonding. In contrast, continuous carbon, glass, and aramid fibres provide uninterrupted load transfer during deposition, markedly improving the mechanical performance of printed composites and making them attractive for high-performance structural applications[5][6]. Natural fibres, including flax, jute, sisal, and bamboo, have also gained increasing attention because of their low density, renewability, and sustainability. However, their hygroscopic nature and poor compatibility with non-polar polymer matrices often lead to weak interfacial bonding and unstable performance, requiring surface modification and process optimisation to improve printability[7][8]. Figure 1 illustrates representative bio-based elongated fibre systems, while Table 1 summarises the mechanical and thermal characteristics of representative continuous fibres.

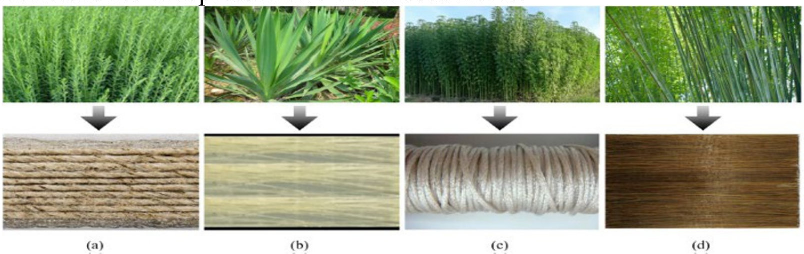

Fig. 1. Illustrative bio-based elongated fibers: (a) Flax-fiber-reinforced filaments for additive manufacturing [9], (b) Agave fiber-based 3D-printed composites[10], (c) Jute fiber-based 3D-printed composites[11], (d) Bamboo fiber-based 3D-printed composites [12]

Table 1. Mechanical characteristics of representative continuous fibers

Fiber	Tensile modulus E (GPa)	Tensile Strength σ (GPa)	Elongation at break ε(%)	Pyrolysis temperature T_d(°C)
Linen fiber	50–80	0.5–0.9	1.2–3.0	200–400
Solanum nigrum fiber	15–25	0.4–0.7	2–3	220–380
jute fiber	20–55	0.3–0.8	1.5–1.8	250–400
Bamboo fiber	11–32	0.4–1.8	2.5–3.7	300–450
Polyamide fiber	2–5	0.8–1	15–30	300–450
Polyester fiber	10–15	0.5–1.2	10–15	250–400
Kevlar fiber	70–130	3–3.6	2.5–3.5	500–550
Carbon fiber	200–800	3–7	1.5–2.5	>2000
Fiberglass	72–85	2–3.5	3–5.5	>800
Basalt fiber	80–100	3–4.8	3–3.5	1255

Particle reinforcements, such as SiC, Al_2O_3, TiC, HA, and intermetallic compounds, are widely employed to improve hardness, wear resistance, thermal conductivity, high-temperature stability, and bioactivity. In additively manufactured metal- and ceramic-matrix composites, they enhance performance through grain refinement, crack suppression, and interfacial regulation, but may also introduce agglomeration, thermal cracking, and residual stress[13]. Nanofillers, including carbon nanotubes, graphene, MXenes, and nanoclay, are primarily used to endow composites with multifunctional properties such as electrical and thermal conductivity, electromagnetic shielding, self-sensing, and energy storage, thereby promoting structural-functional integration[14].

2.2 Matrix Materials

The matrix material governs the rheological behaviour, processing window, interfacial bonding, and environmental adaptability of composites, and is generally classified as thermosetting or thermoplastic according to its thermal response. Table 2 compares representative rheological characteristics, glass-transition temperatures, and curing or processing windows of selected thermosetting and thermoplastic polymers.

Thermosetting resins, such as epoxy, phenolic, and polyimide, form three-dimensional crosslinked networks during curing and typically exhibit high stiffness, thermal stability, and corrosion resistance, making them suitable for high-load and high-temperature applications[15][16]. However, their limited reprocessability, narrow curing window, and complex post-processing often lead to nozzle clogging, weak interlayer bonding, and poor recyclability in additive manufacturing[17].

Thermoplastic matrices, including PLA, PA, PETG, PEEK, and PEKK, provide remouldability, rapid forming, and recyclability. Among them, PLA and PETG are suitable for low-cost manufacturing, PA is widely used in continuous-fibre composite printing, and PEEK/PEKK are promising for high-performance applications because of their excellent thermal, chemical, and mechanical properties. However, their high melt viscosity, complex crystallisation behaviour, and elevated processing temperatures increase the demands on thermal management and interfacial wetting.

Table 2. Material property characteristics of representative thermosetting and thermoplastic polymers

Material Category	Base material	Rheological properties (viscosity)	Glass transition temperature Tg (°C)	Curing/Processing Temperature (°C)
Thermosetting polymer	epoxy-based polymer	700-2000 mPa s (at 28 ◦C)	60–90	60–120
	Phenolic resin	10^3 −10^4 mPa s (at 25 ◦C)	100–180	240–270
	Polyimide	> 10^5 mPa s (at 25 ◦C)	195–280	250–400
Thermoplastic polymer Thermoplastic polymer	PEEK	450 Pa s (at 400 ◦C)	150–160	350–450
	PA6	1000–3000 Pa s (at 265–285 ◦C)	50–60	260–280
	PLA	1200 Pa s (at 200 ◦C)	55–65	190–230

Beyond polymer-based systems, metal- and ceramic-matrix composites have also developed rapidly via selective laser melting, directed energy deposition, and slurry- or photopolymerization-based printing. Al-, Ti-, and Ni-based matrices are mainly applied in wear-resistant, heat-resistant, and lightweight structures, while ceramic matrices are favored for high-temperature, corrosion-resistant, and biocompatible applications. In all cases, matrix selection must comprehensively consider printability, reinforcement compatibility, interfacial stability, service requirements, and sustainability.

2.3 Interface Control and Material Compatibility

The performance of a composite cannot be understood as a simple sum of the properties of the reinforcement and the matrix. The interface is a critical region for stress transfer, debonding suppression, and improved interlaminar bonding. During additive manufacturing, the reinforcement and matrix undergo rapid heating, melting, deposition, and cooling, which make interfacial formation more complex. Interfacial failure often manifests as fiber pull-out, interlaminar delamination, local pore accumulation, and insufficient wetting.

Interfacial control methods can generally be divided into two categories: physical modification and chemical modification. Physical modification mainly increases surface roughness and surface energy through methods such as surface roughening, plasma treatment, laser etching, and ultrasonic cleaning. These changes improve matrix wetting and mechanical interlocking. Chemical modification introduces reactive functional groups onto the reinforcement surface through coupling agents, oxidation treatments, polymer coatings, or nanocoatings. This approach enhances chemical bonding and interfacial stability with the matrix[18].

Interfacial issues in additive manufacturing depend not only on the material system itself but also on printing temperature, deposition rate, compaction load, and cooling history. Consequently, future research on interfaces will increasingly focus on the integrated optimization of the full process chain: material design, process control, and in-service evolution.

3 Forming Processes and Process Control

3.1 Typical Additive Manufacturing Processes

Composite additive manufacturing mainly includes fused deposition modeling (FDM/FFF), direct ink writing (DIW), stereolithography, selective laser sintering/melting (SLS/SLM), directed energy deposition (DED), automated filament or tape deposition, and laminated manufacturing. Among these, FDM is widely used for polymer-matrix composites because of its mature equipment, low cost, and high adaptability. Short-fiber- or particle-reinforced systems usually rely on pre-blended filaments, whereas continuous-fiber-reinforced systems employ approaches such as nozzle impregnation, in-line impregnation, prepreg filament extrusion, and co-extrusion. Continuous fibers can significantly improve the tensile and flexural properties of printed parts, although they also increase the difficulty of controlling wetting, compaction, and path continuity[19]. DIW is suitable for high-viscosity resin, ceramic, and multiphase functional inks, while photopolymerization is advantageous for high-precision and microstructured photosensitive composites. For metal- and ceramic-matrix composites, laser powder bed fusion and DED remain the main routes, though thermal stability, interfacial reactions, and thermal stress control are still critical challenges. At the industrial level, automated tape laying and laminated manufacturing remain important for high-performance continuous-fiber composites, and ongoing advances in robotic multi-axis printing, dual-nozzle coordinated deposition, and multi-material switching are extending composite additive manufacturing from planar layer-by-layer deposition to the fabrication of complex curved, shell, and three-dimensional structures.

3.2 Influence of Process Parameters on Performance

Process parameters critically govern melt flow, wetting, interlayer fusion, and defect evolution, and thus determine composite print quality. Key variables, including temperature, layer thickness, nozzle speed, infill spacing, compaction, fibre volume fraction, fibre tension, and impregnation rate, jointly affect mechanical performance [20]. Their optimisation constitutes a multivariable coupled problem involving rheology, heat transfer, wetting, compaction, and path continuity. Accordingly, response surface methods, multi-objective optimisation, machine learning, and physics-based modelling have been increasingly adopted to enhance optimisation efficiency and transferability. Table 3 provides a concise comparison of representative composite additive and automated manufacturing routes, including reinforcement continuity, matrix type, resolution, common defects, and typical performance features.

Table 3. Concise comparison of key additive and automated composite manufacturing routes

Method	Continuity	vol.%	Matrix	Resolution	Defects	Representative performance
FFF/FDM	Short or path-continuous	5-25 (short); 20-45 (cont.)	PLA, PA, PETG, PEEK/PEKK	0.2-0.8 mm bead; low-medium output	Inter-bead voids, dry spots, waviness	Continuous-fiber systems often show ~2-6x strength and ~3-10x stiffness vs. neat prints
DIW	Continuous tow or aligned short fiber possible	10-55	Thermosets, filled thermoplastics, ceramic/resin slurries	0.1-1.0 mm filament; low-medium output	Ink collapse, drying cracks, resin-rich zones	Well-aligned systems can deliver large stiffness gains, but strength remains void-sensitive
SLA/DLP	Usually discontinuous	0.5-20	Photocurable acrylate/epoxy	25-100 um feature scale; medium for small parts	Sedimentation, trapped bubbles, cure gradients	Typically ~1.1-2.5x vs. neat resin unless high filler alignment is achieved

4 Structural Design Methods

4.1 Style and Spacing

Unlike isotropic materials, composites are strongly affected by the spatial distribution and orientation of the reinforcement. Consequently, path planning is a central challenge in the structural design of additively manufactured composites. In continuous-fiber-reinforced systems, the deposition path determines not only the alignment between the fibers and the principal stress directions, but also the formation of corner defects, fiber continuity, and the quality of interlaminar bonding.

Current methods mainly include isoparametric planning, stress-field-guided planning, curved-fibre placement, and spatial continuous path generation. Aligning fibres with principal stress directions has been shown to significantly enhance the stiffness, strength, and load-bearing capacity of typical structures[21].To further improve manufacturability, continuous path generation, B-spline fitting, and surface-based spatial planning have been developed to reduce path discontinuities and fibre breakage. Overall, existing strategies can be grouped into stress-field guidance, manufacturing-constraint coupling, and continuous path generation.

4.2 Lattice and Lightweight Structural Design

Lattice structures are a key lightweight design strategy for additively manufactured composites owing to their low mass, high specific performance, and superior energy absorption. Compared with conventional methods, additive manufacturing is better suited to fabricating complex lattice unit cells, graded porous structures, and multiscale lightweight architectures. Overall, research is shifting from printability demonstration and mechanical enhancement towards application-oriented manufacturing and evaluation. For aerospace and automotive applications, the main challenges increasingly concern the coordinated control of process stability, defect evolution, and service reliability, rather than reinforcement selection or structural design alone. Because impregnation, interfacial bonding, path continuity, thermal history, and defect formation are strongly coupled, performance is highly governed by integrated process–structure–property relationships. Meanwhile, limitations in continuous reinforcement processing, standardised evaluation, multi-material compatibility, and the processing window of high-performance thermoplastics continue to impede large-scale implementation. Future work should therefore prioritise digitalised and standardisable strategies integrating material design, process optimisation, defect control, structural manufacturability, and multifunctional integration to promote reliable and scalable engineering application. Representative lattice and lightweight configurations for CFRPCs are summarised in Figure 2.

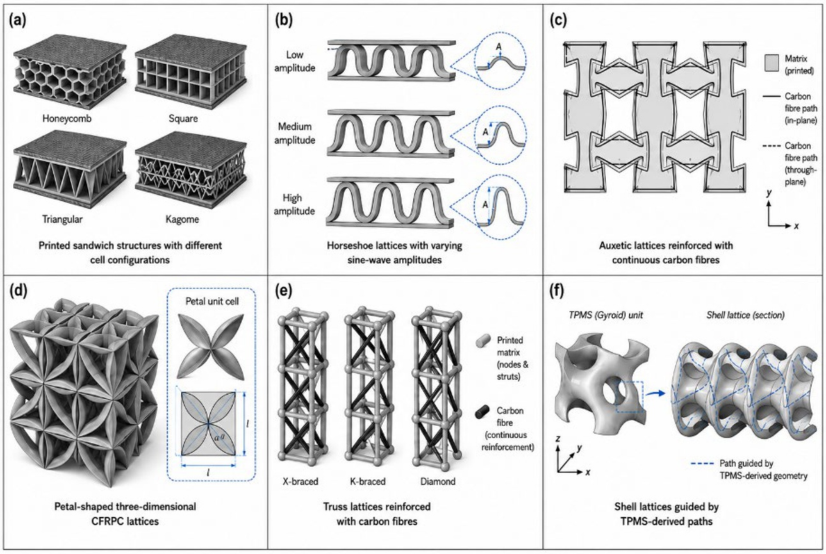

Fig. 2. High-resolution schematic redrawing of lattice and lightweight structural design strategies in CFRPCs**:**(a) continuous-fibre-reinforced sandwich lattice structures with representative core configurations [22];(b) sine-wave-amplitude-regulated horseshoe lattice structures for deformation control [23];(c) continuous-carbon-fibre-reinforced auxetic lattice structures with programmed fibre paths [24];(d) petal-shaped three-dimensional CFRPC lattice architectures for lightweight energy absorption [25];(e) carbon-fibre-reinforced truss lattice structures with different load-bearing configurations [26];and (f) TPMS-derived shell lattice structures enabled by continuous path-guided reinforcement [27].

In continuous-fibre-reinforced lattice structures, fibre continuity mitigates the brittleness and low load-bearing capacity of conventional polymer lattices, thereby enhancing bending, compression, impact resistance, and energy absorption. Accordingly, diverse architectures, including sandwich honeycomb, auxetic, corrugated, truss, and TPMS-based shell lattices, have been developed. Structural design is also evolving from geometric lightweighting to mechanically and functionally integrated lightweighting, achieving both mass reduction and added functionalities such as electrical conductivity, electromagnetic shielding, thermal management, and deployability.

4.3 Topology Optimisation

Topology optimisation offers an integrated design framework for additively manufactured composites by coordinating material distribution and fibre orientation. Unlike conventional topology optimisation, it must simultaneously consider macroscopic configuration, microscale reinforcement orientation, and process manufacturability, resulting in coupled multiscale, multiphysics, and multiconstraint problems. Current approaches are broadly divided into discrete and continuous orientation optimisation: the former is easier to implement but may produce suboptimal and discontinuous paths, whereas the latter is more suitable for smooth fibre trajectories and direct printing guidance[28][29].Recent progress in density-based, level-set, and moving morphable component methods has enabled the integrated optimisation of material layout, fibre orientation, and deposition paths. Future developments will likely emphasise multiscale parallel design, real-time optimisation, and intelligent design, with path continuity and process feasibility remaining key constraints.

5 Multifunctionalisation Trends

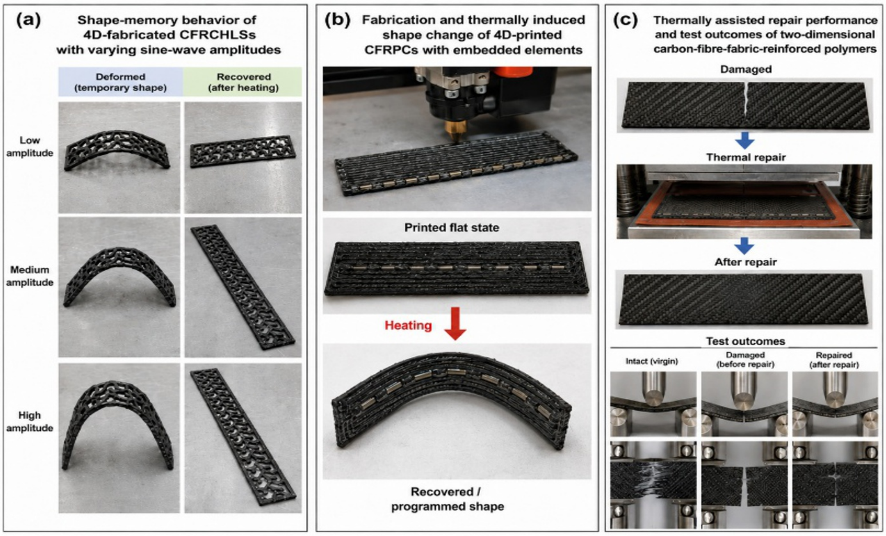

Fig. 3. High-resolution schematic redrawing of smart-response characteristics of CFRPCs: (a) shape-memory behaviour of 4D-fabricated CFRCHLSs with varying sine-wave amplitudes [23], (b) fabrication and thermally induced shape change of 4D-printed CFRPCs with embedded elements [24], and (c) thermally assisted repair performance and test outcomes of two-dimensional carbon-fibre-fabric-reinforced polymers [25].

Recent advances in shape-memory polymers, thermoresponsive resins, and reversible crosslinking have transformed additively manufactured composites from passive load-bearing materials into intelligent multifunctional systems. Coupling continuous-fibre thermal conductivity, path design, and shape-memory matrices enables thermally actuated deformation, self-deployment, self-healing, and adaptive shape morphing. Meanwhile, carbon fibres, conductive fillers, embedded optical fibres, conductive networks, FBG sensors, piezoresistive pathways, and magnetoresponsive fillers provide integrated electrical and optical functionalities for in situ monitoring of strain, temperature, impact, and damage. Compared with surface-mounted sensors, embedded sensing offers superior structural integration, lower weight penalty, and higher spatial localisation. These features make such composites highly promising for aerospace deployable structures, flexible electronics, soft robotics, and adaptive grippers. However, their performance remains strongly governed by fibre architecture, matrix transition temperature, and multiphysics coupling, necessitating further advances in design optimisation and predictive modelling. Representative smart-response behaviours of CFRPCs, including shape-memory recovery, thermally induced shape change, and repair, are summarised in Figure 3.

6 Existing Challenges and Development Trends

Despite rapid advances in additively manufactured continuous-fibre-reinforced polymer composites (CFRPCs), their large-scale engineering application remains constrained by coupled challenges in manufacturing quality, qualification, sustainability, and design integration. Key limitations include inadequate control of fibre alignment, difficulty in maintaining fibre continuity in complex geometries, and persistent process-induced defects such as interlayer voids and fibre waviness, which lead to discrepancies between designed and realised performance. The absence of standardised protocols for AM-specific defect characterisation and reliable predictive models for defect evolution and structural effects further hinders certification in safety-critical applications. Meanwhile, thermoset systems remain difficult to recycle, and multifunctional CFRPCs are still largely limited to laboratory-scale studies, with the coupling between structural and functional performance insufficiently understood. Future research should therefore proceed along a phased roadmap: in the short term, emphasis should be placed on standardised defect characterisation, qualification-oriented testing, and multiphysics process modelling of thermal history, impregnation, interfacial bonding, and defect formation; in the medium term, priorities should include stable continuous-fibre and prepreg feedstocks, multi-material and multi-axis manufacturing platforms, and multimodal in situ sensing with closed-loop control to enhance robustness and reproducibility; in the long term, development should focus on digital-twin-enabled qualification frameworks integrating simulation, real-time sensing, and AI-assisted non-destructive evaluation, together with recyclable high-performance thermoplastics and bio-based matrix systems for sustainable deployment. Across all stages, priority should be given to recyclable high-performance materials, robust process control, manufacturability-oriented design optimisation, and integrated life-cycle assessment.

7 Conclusions

Additively manufactured composites are moving beyond printability towards a new stage characterised by high performance, design flexibility, and multifunctionality. Continuous fibres, high-performance thermoplastic matrices, and interfacial control technologies provide the material foundation for performance enhancement, while FFF, DIW, and automated tape laying continue to improve forming precision and enlarge component scale. At the structural level, path planning, lattice design, and topology optimisation enhance material-use efficiency, whereas functional advances such as 4D responsiveness, self-sensing, and energy storage broaden application scope. As a result, additively manufactured composites have become a rapidly growing field at the intersection of advanced manufacturing and high-performance materials, with strong prospects in aerospace, transportation, energy equipment, and smart devices.

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