

Review Article

Advances in Optimizing Mechanical Performance of 3D-Printed Polymer Composites: A Microstructural and Processing Enhancements Review

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This review investigates the recent advancements aimed at optimizing the mechanical performance of three-dimensional (3D)-printed polymer matrix composites (PMCs), motivated by the need to overcome the inherent limitations of additive manufacturing (AM) in achieving desired mechanical properties. The study focuses on two primary areas: (1) microstructural refinements through strategic control of parameters such as reinforcement type, size, orientation, and interfacial properties and (2) processing enhancements involving the modification of build parameters, material formulations, and posttreatments. The review systematically analyzes the interdependencies between microstructure-property relationships and processing-performance characteristics. Key findings include an improvement of up to 50% in strength and toughness through optimized microstructure and printing techniques, which are compared with results from other studies that reported a maximum of 30%–40% improvement under similar conditions. The review also highlights the successful application of these approaches in various case studies, demonstrating their potential to substantially enhance the dimensional control and functional properties of 3D-printed PMCs, making them suitable for diverse applications ranging from aerospace components to flexible sensors. Despite these advancements, challenges such as performance consistency, part quality, and scalability remain, emphasizing the need for continued research to fully exploit the potential of 3D-printed PMCs.

Keywords: 3D printing; mechanical performance; microstructural refinement; polymer matrix composites; processing enhancements

Summary

- Microstructural features like reinforcement and inter-face impact mechanical performance.
- 3D-printed settings like temperature, speed, and layer size impact microstructures and properties.
- Testing and modeling optimize 3D printing for better mechanics.

- Case studies: up to 50% stronger composites by optimizing microstructure and printing.
- Scaling 3D-printed composite faces hurdles.

1. Introduction

The research landscape in additive manufacturing (AM), specifically in polymer matrix composites (PMCs), has witnessed

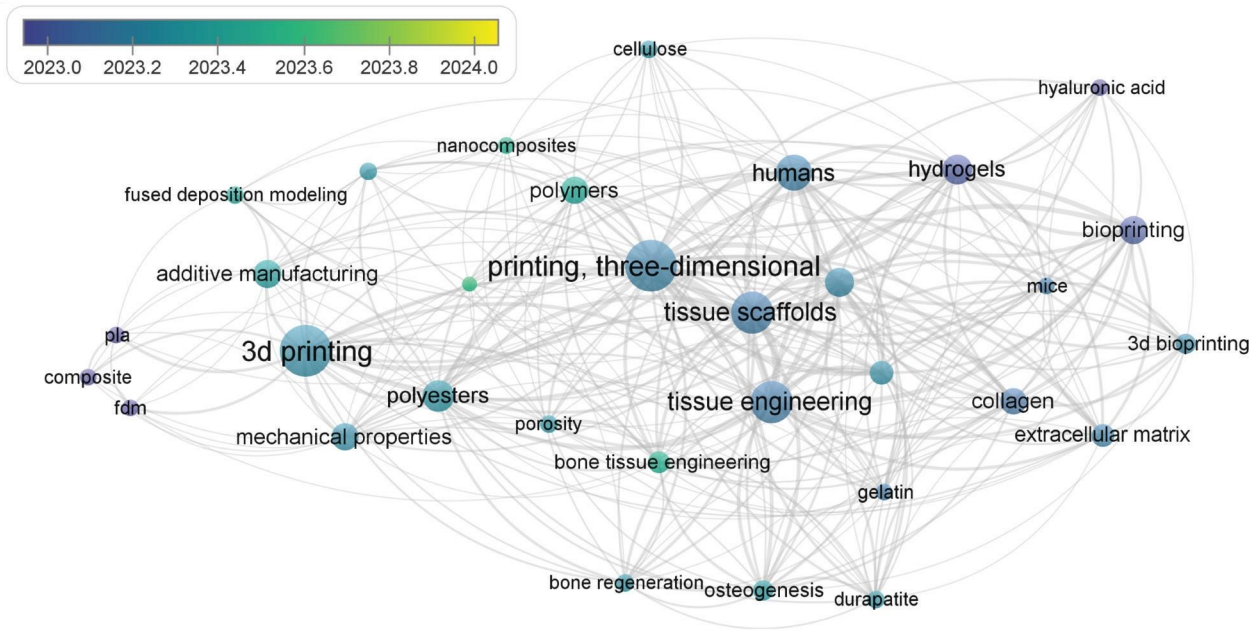


FIGURE 1: Overview of PMCs in 3D printing [1]. PMCs, polymer matrix composites.

remarkable strides in recent years. The general exploration within this domain has revolved around enhancing the mechanical properties of three-dimensional (3D)-printed materials. Researchers have extensively investigated methods to optimize these properties through microstructural refinement and processing enhancements. This burgeoning field holds immense significance owing to its potential to revolutionize various industries reliant on high-performance materials.

Transitioning from the broader perspective, the focus narrows down to the pivotal significance of optimizing the mechanical performance of 3D-printed PMCs. This area of study addresses the inherent limitations of AM in achieving desired mechanical attributes. It unlocks possibilities for creating stronger, more durable, and functionally superior components. Refining microstructures and enhancing processing techniques become paramount in unlocking the full potential of 3D-printed polymer composites.

This comprehensive review aims to synthesize and analyze the latest advancements, methodologies, and innovations in refining microstructures and improving processing techniques. By delving deeply into this topic, the research provides insights into the nuances of microstructural adjustments and processing improvements, ultimately contributing to the advancement of high-performance, mechanically robust 3D-printed PMCs.

PMCs are materials of a polymer matrix reinforced with high-strength fibers, particles, or other additives. These composites offer a remarkable combination of properties derived from matrix and reinforcing materials. PMCs have gained significant attention in AM due to their versatility and tailorable properties. The process involves depositing layers of materials to create 3D objects, allowing for intricate designs and customized structures, as shown in Figure 1 [1].

The choice of polymers as matrices in composites provides flexibility, enabling the incorporation of various reinforcing

materials to enhance specific properties such as strength, stiffness, and thermal stability. Reinforcements like carbon fibers, glass fibers, or nanoparticles are strategically embedded within the polymer matrix, contributing to improved mechanical, thermal, and sometimes electrical properties. This combination produces lightweight, strong, and durable parts suitable for diverse applications, from aerospace components to biomedical devices.

Using 3D printing in PMCs offers various advantages and challenges. Among the advantages, the foremost lies in its unparalleled design freedom, enabling the creation of intricate geometries and complex structures that traditional manufacturing methods struggle to replicate. This facilitates the production of customized and optimized parts tailored to specific needs. Additionally, AM significantly reduces material wastage compared to subtractive methods, thus proving cost-effective, particularly for expensive materials. The ability to control material placement and composition layer by layer empowers the customization of mechanical, thermal, and electrical properties, enhancing the versatility of composite products. Moreover, the rapid prototyping capability of 3D printing accelerates iterative design processes, expediting product development timelines.

Alhaddad et al. [2] developed an artificial neural network (ANN) model to predict the tensile properties of 3D-printed fiber-reinforced polymers, using printing parameters and fiber properties as inputs. Optimization maximized ultimate tensile strength. An et al. [3] studied thermal conductivity and mechanical properties of 3D-printed polydimethylsiloxane composites with boron nitride fillers. Highly aligned polymer domains formed along print paths, enabling tailorable thermal conductivity. An et al. [4] presented a new 3D printing system using in situ pin-assisted melt impregnation to manufacture continuous carbon fiber-reinforced thermoplastics with enhanced mechanical properties. Boyala et al. [5] modified human hair fibers via surface treatments and

fabricated 3D-printed hair-polymer composites. Plasma treatment gave superior interfacial strength and 35% increased composite tensile strength. Britto et al. [6] evaluated a 3D printable polymer for provisional dental restorations, finding adequate strength, wear resistance, and biocompatibility compared to standard materials. Bu et al. [7] created 3D printable metal-polymer functional composites by dispersing Field's metal and graphene in a thermoplastic elastomer matrix. Electrical and thermal properties were widely tunable based on internal structure. Chang et al. [8] optimized a 3D printable piezoelectric composite formulation and designed auxetic structures, achieving flexible piezoelectric sensors with enhanced voltage output as tactile position sensors. Chen et al. [9, 10] optimized a ceramic 3D printing binder formulation using the design of experiments (DOEs), enabling low shrinkage and improved printability of alumina ceramic parts after binder burnout and sintering. Chen et al. [9, 10] developed 3D printable photocurable polymer-hydroxyapatite composites for bone grafts. The evaluation confirmed cytocompatibility and ability to promote osteogenesis *in vivo* while supporting stem cell culture. Cheng et al. [11] reviewed progress in four-dimensional (4D) printing continuous fiber-reinforced polymer composites, highlighting achievements in printing metrology, fiber orientation control, process-induced residual stress, and applications. Das et al. [12] controlled reinforcement orientation in 3D-printed polymer nanocomposites by tuning nozzle size and material flow rates, significantly enhancing strength, toughness, and fracture strain through microstructure control. El Magri et al. [13] computationally assessed corrosion inhibition of epoxy-glass composites on steel, finding coatings effectively prevented corrosion and inhibition efficiency aligned with simulations. Forstmeier et al. [14] characterized the dielectric properties of barium strontium titanate (BST)-polymer composites and resins at W-band frequencies. Composites were readily functionalized, though additional work is needed to maintain 3D printability. George et al. [15] blended polylactic acid (PLA) with polybutylene adipate terephthalate (PBAT) and a polymethyl methacrylate (PMMA) compatibilizer to improve 3D printability, optimizing formulations using thermal analysis to identify printing temperatures. Scanning electron microscopy (SEM) confirmed compatibilizer effectiveness. Gu et al. [16] reinforced 3D printable shape memory polycaprolactone (PCL)/PBAT composites with 1% cellulose nanofibers, enhancing mechanical performance. Printed self-deforming plant-inspired grippers demonstrated fast, stable thermally-induced actuation. Hasib et al. [17] studied capillary effects during the extrusion of high-volume fraction porous copper-polymer composites. Melt viscosity aligned with imbibition predictions, providing insight on printable porous metal-polymer feedstocks.

The research landscape in AM, specifically in PMCs, has witnessed remarkable strides in recent years. The exploration within this domain primarily revolves around enhancing the mechanical properties of 3D-printed materials. Significant contributions, such as those by Alhaddad et al. [2], who optimized material and printing parameters using an ANN model, and An et al. [3], who explored thermal conductivity and mechanical properties of polydimethylsiloxane-based

composites, have laid the groundwork for further advancements in this field.

Transitioning from a broader perspective, the focus narrows down to the pivotal significance of optimizing the mechanical performance of 3D-printed PMCs. This area of study addresses the inherent limitations of AM in achieving desired mechanical attributes. For instance, Huang et al. [18] introduced a progressive concurrent optimization approach for 3D-printed composites, which significantly improved material efficiency and load capacity. Similarly, Das et al. [12] demonstrated how controlling reinforcement orientation could enhance the strength and toughness of polymer nanocomposites.

These studies underscore the critical role of refining microstructures and enhancing processing techniques in unlocking the full potential of 3D-printed polymer composites. By incorporating insights from recent research, such as the work by Kermani, Advani, and Ferec [19] on 3D computational fluid dynamics (CFD) modeling for fiber orientation prediction and the findings by Mushtaq et al. [20] on optimizing 3D printing parameters for polyethylene terephthalate glycol (PETG), this review aims to synthesize and analyze the latest advancements in the field. These contributions provide a comprehensive understanding of the nuances involved in microstructural adjustments and processing improvements, ultimately contributing to the advancement of high-performance, mechanically robust 3D-printed PMCs.

Huang et al. [21] pioneered 3D printing polymer-derived silicon carbonitride (SiCN) matrix composites using a digital light processing approach. Adding silicon nitride (Si_3N_4) particles or whiskers as reinforcements effectively reduced shrinkage while improving mechanical properties after pyrolysis. Huang et al. [18] proposed progressive concurrent optimization of topology and variable fiber orientation/content for 3D-printed composites. Optimization hierarchically maximized stiffness and load capacity with material efficiency. Karimi and Fayazfar [22] pioneered recyclable, sustainable feedstock by dispersing 75 wt% nickel powders in PLA for binder jetting. Print optimization enhanced quality, while preliminary sintering trials showed promise for achieving high-density parts. Kermani, Advani, and Ferec [19] developed a 3D CFD model to predict fiber orientation in extruded composites by simulating nozzle flow and deposition. Model outputs agreed with experiments and provided a tool to tailor fiber alignment. Kour et al. [23] characterized the properties of 3D-printed recycled nylon-zirconia composites for rapid tooling applications. The addition of zirconia filler was observed to positively impact wear resistance and flow behavior. Li et al. [24] embedded varied 3D-printed polymer lattice structures in cementitious composites, converting brittle failure to multicrack ductile behavior and enhancing flexural properties up to five-fold. Lian et al. [25] studied magnetic-assisted fiber orientation control in 3D-printed carbon fiber reinforced polymers (CFRPs). Aligned fibers significantly increased strength and modulus with a slight compromise in failure strain for optimized printing parameters. Lim et al. [26] utilized solution intercalation to achieve highly loaded, well-dispersed carbon nanotube (CNT)-polymer composites for high-

resolution, conductive 3D printing and fabricating components demonstrating performance enhancements. Luo et al. [27] harnessed 3D printing-induced alignment of liquid crystalline polymer chains with boron nitride fillers to create composites with exceptional thermal conductivity along print direction. Ma et al. [28] assessed nanosecond laser micromachining as a postprocessing method for 3D-printed CFRPs. Hole diameter and depth were controlled by optimizing laser parameters, though heat effects must be minimized. Martinelli et al. [29] comprehensively reviewed approaches leveraging 3D printing to structure conductive polymers into devices, commenting on materials challenges unique to AM processes. Mushtaq et al. [20] optimized 3D printing parameters for PETG to maximize mechanical properties and printing efficiency, further enhancing performance through laser polishing to reduce surface roughness and increase tensile strength. Parker et al. [30] characterized variability in tensile strength for 3D-printed continuous fiber composites, finding substantial reductions from feedstock properties regardless of fiber type, alignment, or volume fraction. Failure originated from print-induced damage.

Recent advancements in 3D printing have significantly improved the mechanical performance of PMCs through microstructural refinements and processing techniques. Abbas et al. [31] highlighted the potential of osseointegrated implants in enhancing functional outcomes and patient satisfaction compared to traditional socket prosthetics, emphasizing the importance of structural and material advancements in prosthetics. Mohammed and Kahtan [32] explored the energy efficiency and improved gait mechanics with carbon fiber prosthetic feet, demonstrating the critical role of material properties in optimizing prosthetic performance. Similarly, Subhi et al. [33] conducted a computational analysis to validate the mechanical performance of composite prosthetic keels under static loads, underscoring the significance of microstructural integrity in load-bearing applications.

In the realm of 3D printing, Tariq, Jaber, and Ammar [34] provided a comprehensive review of hemodynamic characteristics in mechanical aortic valves, emphasizing the need for precise material control to enhance clinical outcomes. These studies collectively underscore the importance of material selection, microstructural control, and advanced processing techniques in developing high-performance PMCs. The incorporation of advanced materials, such as carbon fibers and nanocomposites, has been pivotal in enhancing the strength, toughness, and functional properties of PMCs. Experimental studies have demonstrated that refining microstructural features, such as reinforcement size and distribution, can lead to significant improvements in mechanical properties. The integration of computational modeling with experimental validation has provided deeper insights into optimizing these materials for specific applications, particularly in biomedical devices and structural components.

Rodinò et al. [35] developed 3D printable SMA-polymer composites and modeled their properties. They found the composites had good printing fidelity and could be useful for various applications. Salas et al. [36] synthesized 3D-printable photocurable polymer-MXene resins and printed complex 3D structures. Annealing treatments improved

conductivity, showing potential for electronics applications. Santos and Cardoso [37] modified an fused filament fabrication (FFF) printer to allow continuous yarn reinforcement of biopolymers. Composites with jute, ramie, and sisal fibers had 28%–29% better strength and stiffness than the neat polymer. Shi et al. [38] incorporated silica nanoparticles into photocurable resins for stereolithography (SLA) printing. Reversible addition-fragmentation chain transfer (RAFT) polymerization control enabled tuning of properties.

High nanoparticle loadings significantly increased strength and toughness. Slejko et al. [39] printed polymer-fiber and polymer-filler composites under a vacuum to assess the potential for extraterrestrial applications. Properties depended strongly on printing conditions. Velej, Trembly, and Al-Majali [40] compounded and printed coal-plastic composites. Coal filler improved thermal stability and reduced thermal expansion and warping coefficient. The materials show promise for large-scale printing applications. Vemuganti, Soliman, and Taha [41] explored using 3D printing to create fiber-reinforced polymer composites with enhanced ductility and failure behavior. By combining fibers at different angles, they produced composites that were able to gradually transfer load between layers, increasing ductility by up to 29% and failure strain by up to 8%. Wang et al. [42] developed an acoustic-assisted 3D printing process using standing surface acoustic waves to pattern functional micro/nanomaterials into complex designs in a polymer matrix. This method enabled composite fabrication with programmed electrical anisotropies and high conductivity. Wu et al. [43] studied how 3D printing affects the distribution and orientation of carbon nanofibers in polymer composites, finding that printing introduces high-resistance internal surfaces that reduce conductivity. Optimizing nanofiber alignment and density enabled excellent electromagnetic shielding effectiveness. Xu and Šavija [44] proposed a 3D-printed auxetic cementitious-polymeric composite structure overcoming brittleness issues in cementitious materials. The lightweight composite exhibited enhanced compressive strain-hardening behavior and energy absorption ability compared to its components. Zhang et al. [45] developed an electrically assisted vat photopolymerization 3D printing process to fabricate high-performance ordered graphene/polymer composites. The method improved mechanical properties and electrical conductivity compared to conventional composites.

Several additional studies explore 3D printing techniques for polymer composites, including material extrusion, vat photopolymerization, and binder jetting. Both thermoplastic and thermoset composites are investigated. A variety of reinforcements are researched, from nanofillers to continuous fibers. Key focus areas include tailoring mechanical properties like strength and toughness, enhancing functional properties like conductivity and electromagnetic shielding, and developing novel composite formulations or reinforcement strategies. Approaches range from computational modeling to advanced material characterization. Applications range from structural components for aerospace, automotive, and construction to flexible electronics, energy storage devices, biosensors, and 4D-printed actuators. Both small-scale printed structures and larger format components are produced. While significant advances have occurred, open questions remain

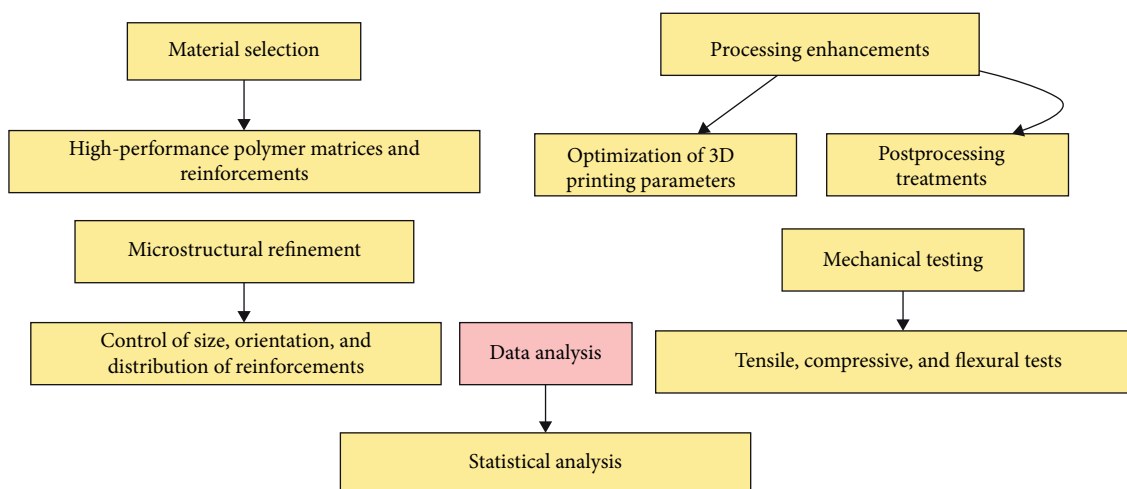


FIGURE 2: Methodology flow chart.

regarding achievable mechanical performance, part quality, and transitioning fundamental work on 3D-printed composites into industrial practice. This review aims to help address these gaps through a science-based approach focusing on consistency and reliability.

However, adopting 3D printing for PMCs also presents several challenges. The compatibility of reinforcing materials within the printing process can be a hurdle, potentially affecting printability and the final quality of parts. Achieving optimal print parameters for composite materials is complex, demanding extensive research to balance desired properties and printing feasibility. Furthermore, postprocessing requirements, such as curing, heat treatment, or surface finishing, might be necessary to attain the desired material properties, thus impacting overall production time. Last, the initial setup costs for 3D printing equipment and materials can be considerable, particularly for high-performance composites, posing challenges to scalability and the feasibility of mass production.

While 3D printing offers various advantages in fabricating PMCs, overcoming the associated challenges demands a nuanced approach and continuous refinement of techniques to exploit its potential in various industries fully.

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2. Methodology

In this study, a comprehensive methodology was employed to investigate the optimization of mechanical performance in 3D-printed PMCs through microstructural refinements and processing enhancements. The primary materials used in this study include high-performance polymer matrices such as PLA and acrylonitrile butadiene styrene (ABS), reinforced with carbon fibers, glass fibers, and nanoparticles such as silicon carbide (SiC). The selection of these materials was

based on their widespread use in AM and their potential to enhance mechanical properties.

The study was structured into two phases: microstructural refinement and processing enhancement. In the microstructural refinement phase, various reinforcement types (e.g., carbon fibers, SiC nanoparticles) were systematically introduced into the polymer matrix. The size, orientation, and distribution of these reinforcements were meticulously controlled using different fabrication techniques, including melt blending and in situ polymerization (Figure 2).

Fused deposition modeling (FDM) was the primary AM technique used. The 3D printing parameters, including nozzle temperature, layer thickness, print speed, and infill density, were optimized through a series of preliminary tests. A full factorial DOE was implemented to systematically vary these parameters and assess their impact on the mechanical properties of the printed parts. Postprocessing treatments, such as annealing and surface polishing, were applied to enhance the interfacial bonding between the matrix and the reinforcements. The annealing process was conducted at temperatures ranging from 80 to 120°C for different durations, based on the thermal properties of the polymers used. Surface treatments included hemical etching and plasma treatment to improve adhesion and mechanical performance. The mechanical properties of the 3D-printed PMCs were evaluated through tensile, compressive, and flexural tests, following American Society for Testing and Materials (ASTM) standards (e.g., ASTM D638 for tensile testing). The samples were tested using a universal testing machine (UTM), and the data were recorded for parameters such as ultimate tensile strength, modulus of elasticity, and elongation at break. Additionally, microhardness testing was conducted to assess the surface properties of the composites. The microstructure of the printed composites was analyzed using SEM and X-ray diffraction (XRD). These techniques provided detailed insights into the distribution and orientation of the reinforcements within the matrix, as well as the presence of any defects or voids that could impact mechanical performance. The experimental data were analyzed using statistical methods,

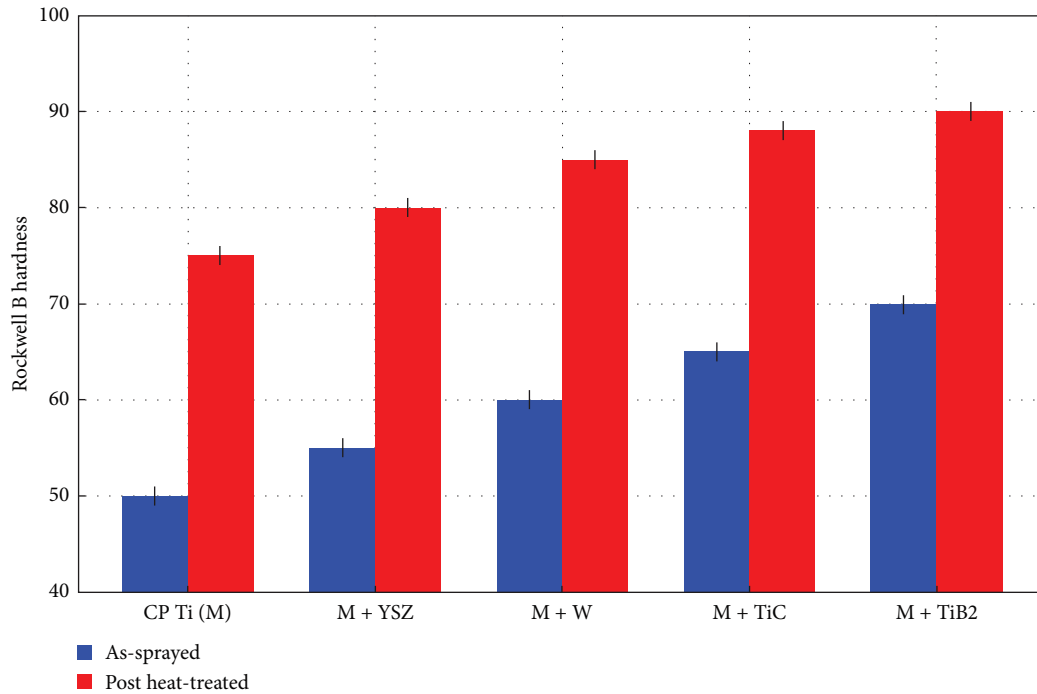


FIGURE 3: Hardness of CP, Ti, and Ti MMCs: As-sprayed versus post-heat-treated [46].

including analysis of variance (ANOVA) to determine the significance of the different factors affecting mechanical performance. The results were compared with existing literature to contextualize the findings within the broader field of 3D-printed PMCs.

3. Microstructure and Its Influence on Mechanical Performance

The microstructure of composite materials plays a pivotal role in determining their mechanical properties, including stiffness, strength, and toughness. Understanding how microstructural features influence these properties is essential for designing composites tailored for specific applications.

The microstructure of composite materials, including the size, shape, distribution, orientation, and interfacial bonding of the reinforcement phases, significantly impact the resulting mechanical properties. Reinforcement size and geometry affect strengthening mechanisms; smaller particles impede dislocation motion more effectively, while high aspect ratio reinforcements are more efficient at transferring load. Larger reinforcements above a critical size lead to poor particle-matrix interfacial bonding and act as defects, reducing strength. A uniform distribution of fine reinforcements ensures effective strengthening throughout the material. Reinforcement orientation also plays a key role. Aligning continuous high aspect ratio phases along the loading direction enables more efficient stress transfer, significantly increasing stiffness and strength along that direction. However, this also introduces anisotropy. A random orientation provided by Lomo et al. [46] gives more uniform properties, as shown in Figure 3.

The reinforcement-matrix interface's characteristics are crucial in determining a composite's performance. Strong

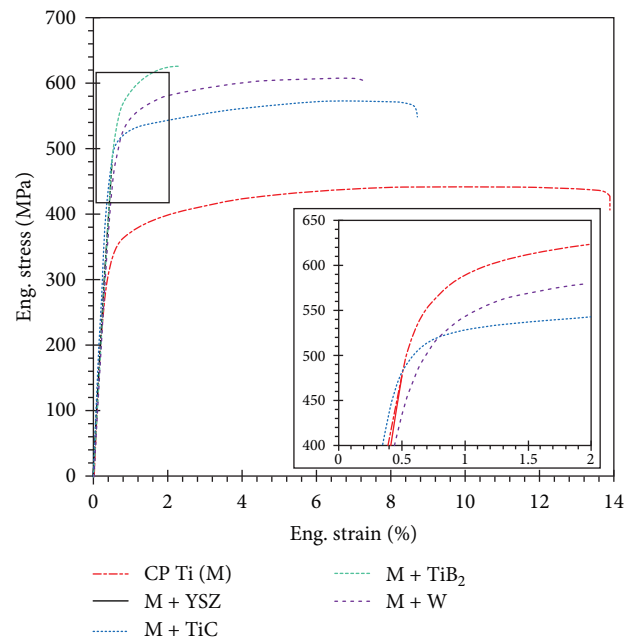


FIGURE 4: Tensile testing curves of heat-treated Ti-rich materials [47]. Eng., engineering.

interfacial bonding enhances load transfer, improving strength and stiffness, while a weak interface promotes debonding and crack deflection, increasing toughness. Optimizing the interface to balance these effects is essential as done by Liu et al. [47]. Reducing porosity and defects through impurity control and optimized processing also improves properties. A fine uniform microstructure with clean interfaces ensures optimal performance Figure 4. By controlling

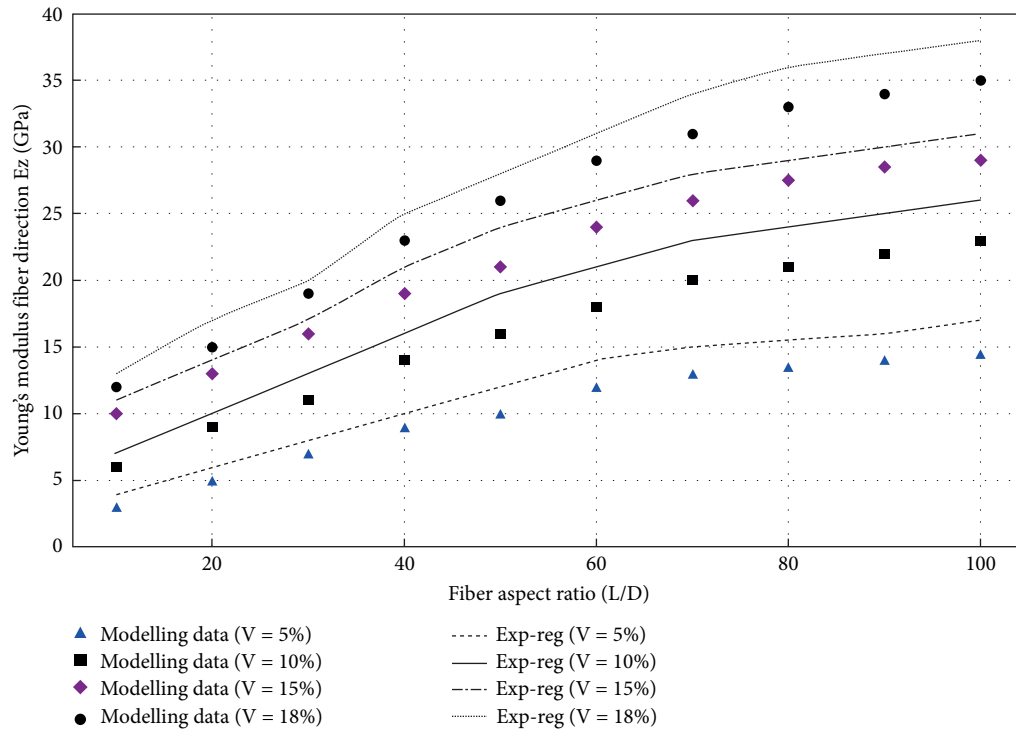


FIGURE 5: Effects of fiber aspect ratio on composite properties modeled with different DiCF volume percentages [17]. DiCF, discontinuous fiber composite.

reinforcement characteristics, distributions, and interfacial properties, and managing defects, composites can be tailored for high strength or toughness. Understanding these microstructure-property relationships is key to designing high-performance materials for applications like aerospace and automotive. Microstructural refinements significantly impact the mechanical properties of 3D-printed PMCs. For instance, reducing reinforcement particle size to the nanoscale enhances strength by better impeding dislocation motion. Smaller particles increase the surface area-to-volume ratio, improving stress distribution and overall strength and toughness. Fiber orientation also plays a crucial role; aligning fibers along the load direction greatly enhances stiffness and tensile strength due to more efficient stress transfer. Studies show that controlling fiber orientation during printing can boost tensile strength by up to 40% compared to randomly oriented fibers. Additionally, strong interfacial bonding between the matrix and reinforcements is crucial for toughness, as it facilitates load transfer and delays crack initiation and propagation. Surface treatment optimization for fibers or nanoparticles can further increase strength and toughness. These refinements tailor the composite's mechanical properties, making them suitable for high-performance applications in aerospace, automotive, and biomedical fields.

3.1. Stiffness. The stiffness of a composite is heavily influenced by its microstructure. Factors such as the arrangement, orientation, and volume fraction of reinforcing elements within the matrix significantly impact stiffness. For instance, a higher volume fraction of stiff reinforcing fibers aligned

in the direction of load application enhances stiffness by restricting deformation along that axis. The type of reinforcement (fibers, particles) and their aspect ratio also affect stiffness. A well-controlled microstructure promotes efficient load transfer between the matrix and reinforcements, contributing to higher stiffness. The stiffness of composite materials depends on the microstructure, including the arrangement, orientation, and volume fraction of the reinforcing elements within the matrix. A higher volume fraction of stiff reinforcements parallel to the loading direction enhances stiffness by restricting deformation along that axis. Fiber reinforcements are more effective than particulate reinforcements due to their higher aspect ratio (length/diameter). As the fiber aspect ratio increases, the stiffness improves exponentially and approaches the stiffness of continuous fiber composites. This trend is shown in Figure 5 by Hasib et al. [17], depicting the increase in Young's modulus along the fiber direction with an increase in the fiber aspect ratio.

The orientation of discontinuous fiber reinforcements also significantly impacts stiffness. Fibers aligned parallel to the loading direction provide higher reinforcement. As shown in Figure 6, a two-step homogenization approach can be used to predict properties provided by Hu et al. [48]. First, the properties of a composite with aligned fibers are characterized. Then a representative volume element (RVE) with randomized fiber orientations is analyzed to obtain bulk composite properties.

Besides fiber volume fraction and orientation, the periodic arrangement of reinforcements in cellular architectures allows further property tailoring. The stiffness of such periodic cellular composites is analyzed through representative base cells or RVEs with the cell structure repeated throughout

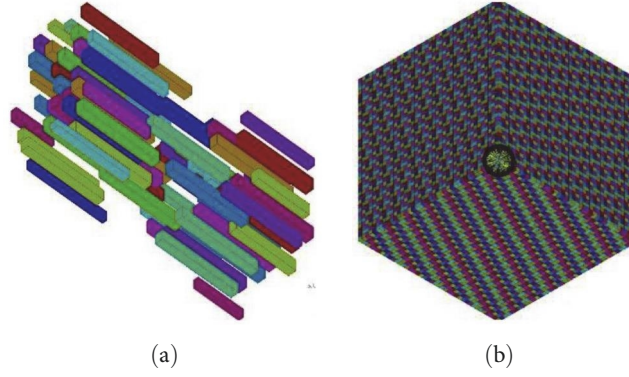


FIGURE 6: Two-step bulk composite characterization: (a) unidirectional fiber distribution in step one and (b) 3D random fiber distribution via Monte Carlo method in step two [48].

the material. This provides superior mechanical performance compared to stochastic particulate arrangements. Strategically tuning the microstructure of the reinforcing elements allows significant control over the macroscale stiffness of composites. A higher volume fraction of high aspect ratio fibers preferentially aligned along the loading direction boosts stiffness. Bioinspired periodic cellular designs take this a step further through ordered arrangements for mechanical efficiency [49]. Computational modeling and experiments help validate designs for stiffness maximization in high-performance engineered composites.

3.2. Strength. Microstructural parameters are closely linked to composite strength. The bonding between the matrix and reinforcement, along with the dispersion and alignment of reinforcing elements, critically influence strength. Imperfections or defects within the microstructure act as stress concentrators, reducing overall strength. Conversely, a well-engineered microstructure with uniform reinforcement distribution and alignment enhances load-bearing capacity and deformation resistance, thereby improving composite strength. Strong interfacial bonding is essential for effective stress transfer, while weak bonding can lead to debonding and compromised structural integrity. A precisely controlled microstructure significantly enhances strength attributes such as tensile, shear, and compressive strength by minimizing stress concentrations and optimizing reinforcement orientation [47]. For composites reinforced with particles, the shear lag model and its subsequent modifications (Nardone and Prew, 1986) provide insights into tensile strength predictions through the following relationship Equation (1):

$$\sigma_c = \sigma_m \left[V_f + V_m V_m \left(\frac{l}{2r} \right) \ln \left(1 + \frac{2rs}{lV_f} \right) \right], \quad (1)$$

where σ_c and σ_m represent the tensile strengths of the composite and matrix, respectively, alongside other parameters such as fiber volume fraction (V_f), matrix volume fraction (V_m), fiber length (l), and radius (r).

The Halpin-Tsai equations offer semi-empirical formulations to estimate composite moduli and strength based on the reinforcement's geometry and the loading direction

Equation (2):

$$\sigma_c = \sigma_m V_m + \sigma_f V_f (1 + \xi \sigma V_f) / (1 - \eta \sigma V_f). \quad (2)$$

For composites reinforced with fibers, the rule of mixtures provides an approximation for tensile and compressive strengths in the longitudinal direction:

$$\begin{aligned} \text{Tensile: } \sigma_{cl} &= V_f \sigma_{fL} + V_m \sigma_m. \\ \text{Compressive: } \sigma_{cc} &= V_f \sigma_{fC} + V_m \sigma_m. \end{aligned}$$

In the transverse direction, models like Pipes and Crow account for residual thermal stresses to predict tensile strength, considering factors such as thermal expansion mismatch between fiber and matrix. Advanced models, like NASA RP-1092, include fiber pullout, matrix cracking, and interface debonding to provide comprehensive predictions of composite compressive strengths. These analytical models, combined with empirical data, deepen the understanding of how microstructural parameters influence strength, enabling the strategic manipulation of microstructures to optimize mechanical performance. The alignment of anisotropic reinforcements is crucial. For high aspect ratio platelets or fibers, alignment along the loading direction enhances strength and stiffness, while misalignment exposes weaker surfaces, leading to reduced performance. Therefore, preferential alignment is essential for tailoring anisotropic behavior. Composite strength is also inversely related to flaw size; microstructural defects like pores or cracks cause stress concentrations, significantly lowering fracture resistance. Eliminating voids and other defects is critical for damage tolerance and maximizing strength, as illustrated in Figure 7 done by Wang et al. [42, 50, 51].

The load-bearing characteristics can be optimized through careful control over microstructural details during processing steps like dispersion, orientation, defects elimination, and interfacial chemistry tailoring. A refined, uniform microstructure with reproducible characteristics allows the composite mechanical properties to reach theoretical limits. Realizing the full potential of the starting constituents requires holistic microstructural engineering considering nanoparticle distribution, interface adhesion, template alignments, and suppression of flaws. A synergistic combination enhances the load-transfer efficiency, damage resistance, and strength.

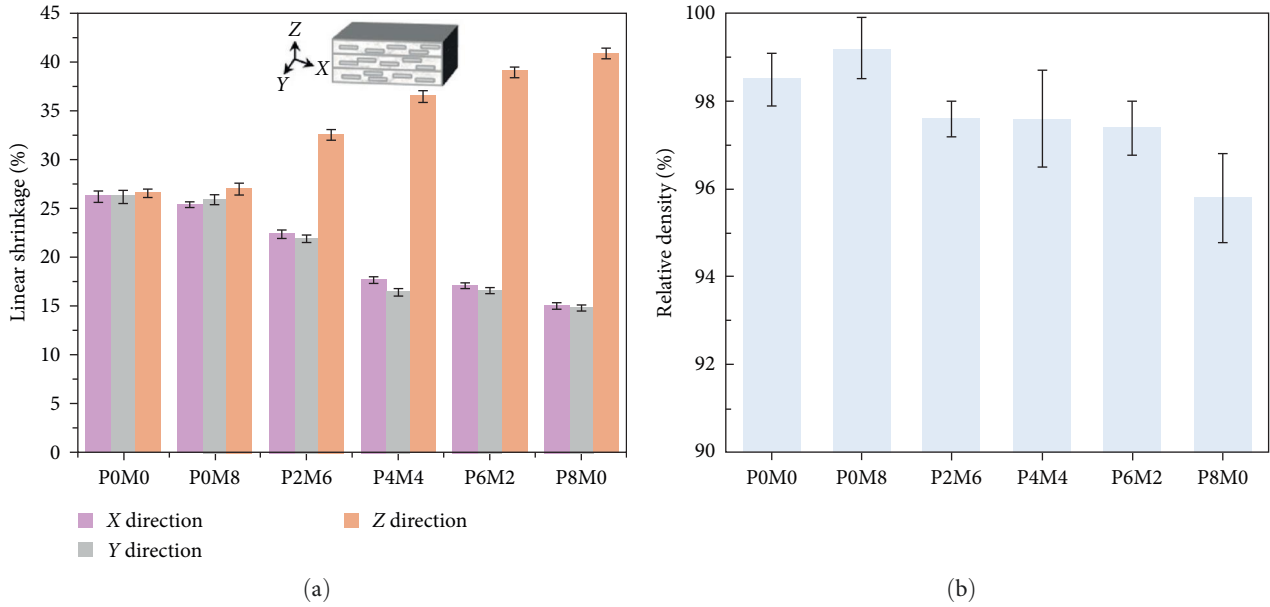


FIGURE 7: (a) Linear shrinkage and (b) relative density of the DLP-prepared ceramics [42, 50]. DLP, digital light processing.

3.3. Toughness. The toughness of a composite material is determined by its ability to absorb energy before failure, which is heavily influenced by microstructural features such as interfacial bonding strength, the presence of voids, and the interfaces between the matrix and reinforcement. A well-designed microstructure with strong interfacial bonding and controlled porosity can enhance toughness by promoting mechanisms like crack deflection, fiber pull-out, and matrix toughening, which dissipate energy and delay failure [53]. Natural composites, like mollusk shells, exhibit a laminar microstructure with alternating hard and soft phases that enhance toughness by deflecting and bifurcating cracks at the interfaces, thereby dissipating energy. Engineered composites aim to mimic these designs to improve mechanical performance. Strong interfacial bonds in such composites facilitate effective load transfer and delay crack propagation. Introducing controlled porosity at interfaces also serves as crack arresters, promoting deflection and enhancing toughness. Other toughening mechanisms, including crack bridging, fiber pull-out, and matrix plastic deformation, can be optimized through micro and nanostructure engineering. For example, TiN/Ti6Al4V metal matrix composites use a bioinspired sandwich design with alternating hard and soft layers, enabling crack diversion and improving the strength-toughness balance. Advances in AM done by Xiao et al. (2023) allow for the fabrication of complex multimaterial configurations that emulate these sophisticated bioarchitectures, enhancing mechanical performance under dynamic loading conditions Figure 8.

Research indicates that modifying parameters such as fiber orientation, aspect ratio, and interfacial adhesion can significantly impact mechanical properties. For example, studies on carbon fiber-reinforced composites show that controlling fiber alignment and distribution improves tensile strength and stiffness in the load direction. Similarly, optimizing

particle size and distribution in ceramic particle-reinforced polymers enhances strength and toughness. Advanced imaging and characterization techniques, like electron microscopy, X-ray tomography, and computational modeling, have deepened the understanding of how microstructural features influence mechanical behavior. These methods enable precise visualization and quantification of microstructures, allowing for the tailored manipulation of mechanical properties. Moreover, multiscale modeling integrates microstructural data with mechanical simulations, providing predictive insights for optimizing composite performance. Collectively, these studies highlight the pivotal role of microstructure in determining the mechanical behavior of composites, offering valuable guidance for engineering materials with enhanced performance [54].

3.3.1. Optimizing Strength of 3D-Printed PMCs. The strength of 3D-printed PMCs can be optimized through various microstructural and processing techniques. Table 1 provides a summary and comparison of the key methods.

AM lattice structures offer unique opportunities to enhance the strength of PMCs. Topology optimization can create lightweight, organic lattice designs that maximize strength-to-weight ratios, resulting in improved stiffness and resistance to buckling compared to traditional solid parts. Periodic lattice structures use repetitive unit cell geometries to achieve customizable mechanical properties. By optimizing the unit cell's topology, strut thickness, and connectivity, the specific strength and stiffness of the overall lattice can be enhanced. These structures can be fabricated using various AM techniques such as material extrusion, SLA, or powder bed fusion. A key advantage of AM lattice structures is the precise control over microstructure and architecture at both meso- and macro-scales, enabling the creation of lightweight, high-strength composites that surpass the performance of solid counterparts. However, the complexity of design and fabrication, along with the potential for stress concentrations at lattice joints, requires

TABLE 1: Methods for enhancing strength of 3D-printed PMCs.

Method	Description	Advantages	Limitations
Reinforcement selection			
Fiber reinforcement	Incorporation of high-strength fibers (e.g., carbon, glass, aramid)	Significant increase in tensile and flexural strength	Potential issues with fiber distribution and alignment
Particle reinforcement	Addition of rigid ceramic or metallic particles	Improved compression and wear resistance	Limited enhancement in tensile strength
Reinforcement orientation			
Unidirectional alignment	Aligning fibers or particles along the primary loading direction	Maximizes strength and stiffness in the aligned direction	Introduces anisotropy and potential weakness in transverse directions
Random orientation	Randomly distributing fibers or particles	Provides more uniform and isotropic properties	Lower overall strength compared to aligned reinforcements
Interfacial optimization			
Surface treatments	Chemical or physical modifications to improve fiber-matrix bonding	Enhanced load transfer, improved strength and toughness	Complexity of surface treatment processes
Compatibilizers	Addition of coupling agents to promote interfacial adhesion	Better stress transfer, increased strength, and fracture resistance	Potential issues with compatibilizer distribution
AM lattice structures			
Topology optimization	Computational removal of inefficient material to create organic, lightweight structures	Maximizes strength-to-weight ratio, improved stiffness, and buckling resistance	Complexity of design and fabrication, limited to specific geometries
Periodic lattices	Repetitive unit cell structures with engineered topology and geometry	Tailorable mechanical properties, high specific strength and stiffness	Dependence on unit cell design, the potential for stress concentrations

Abbreviations: AM, additive manufacturing; PMCs, polymer matrix composites.

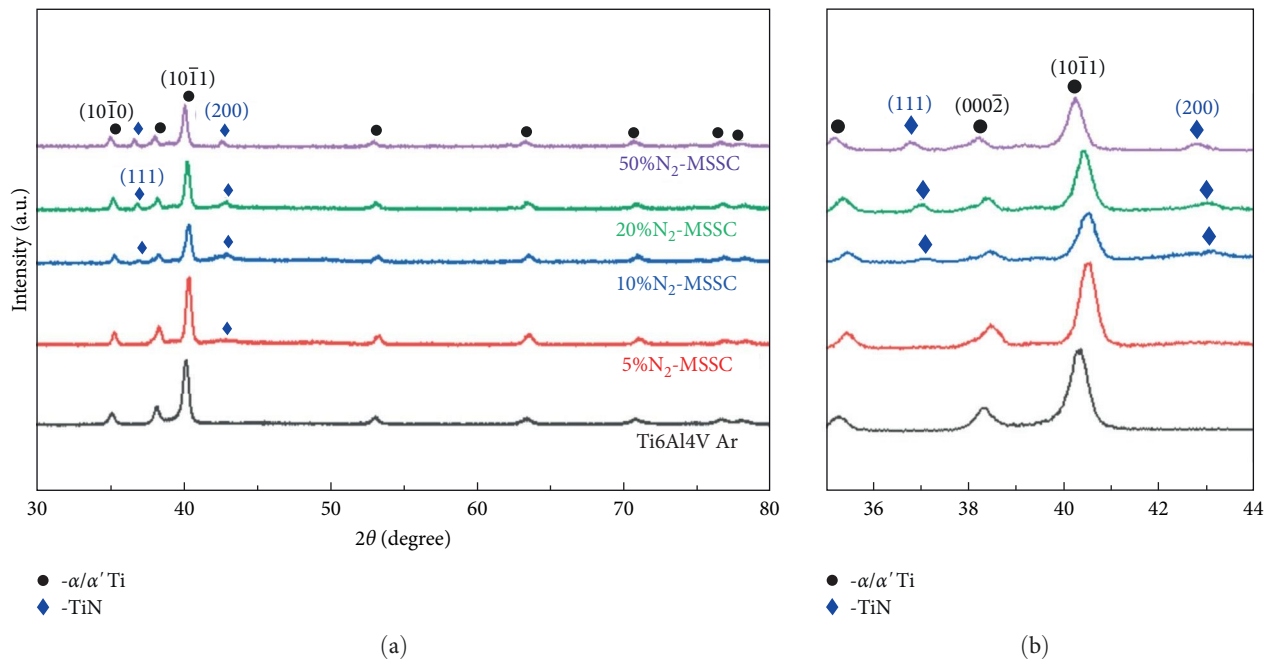


FIGURE 8: (a) XRD patterns of the Ti6Al4V alloy and TiN/Ti6Al4V sandwich structure with different nitride contents and (b) narrow-angle [52]. XRD, X-ray diffraction.

careful consideration. Optimizing the strength of 3D-printed PMCs necessitates a holistic approach that includes selecting and orienting reinforcements, optimizing interfacial properties, and strategically designing lattice structures through computational methods. By leveraging these techniques, researchers and engineers can develop high-performance composite materials for a wide range of applications.

4. Processing Modifications in 3D Printing

Several processing techniques are employed in 3D printing PMCs, each with distinct advantages and limitations. Several processing techniques are employed in 3D printing PMCs, each with distinct advantages and limitations. A key consideration is the state of the matrix during printing—liquid resins can be cured after printing, while thermoplastic polymers are extruded in a melted state and solidified after deposition. SLA uses a liquid photopolymer resin loaded with ceramic or metallic particles. Ultraviolet (UV) light cures each layer after it is deposited, creating a solid part from the ground up. Benefits include high resolution and easy incorporation of fillers, but limitations arise for large or thick parts due to restrictions in light penetration depth, leading to incomplete curing. Post-curing is often required [55].

FDM extrudes a thermoplastic filament containing dispersed solid particles, often ABS or PLA. The matrix solidifies upon cooling after exiting the print nozzle. Simplicity and low cost are advantages, but resolution is low compared to vat photopolymerization methods. Maximizing filler content can be challenging without compromising extrudability. Selective laser sintering (SLS) uses a laser to fuse polymer-coated metal/ceramic powders. Unfused powder provides support during printing, enabling complex geometries, but the postprocessing step of removing loose powder is required. The polymer

coating is removed before final sintering. As shown by Slejko et al. [39], achieving high filler contents and reasonable mechanical properties remains is shown in Figure 9.

Material jetting uses an inkjet printhead to selectively deposit droplets containing polymers and solid particles, which are then UV-cured. High resolution and easy multi-material printing provide design flexibility, but low throughput and the requirement for low viscosity inks limit part size and filler content. Postcuring is often needed for maximum mechanical performance [56]. Several other methods exist, including binder jetting and directed energy deposition, but they share challenges related to print resolution, achievable particle loading, matrix impregnation, and scalability. Balancing printability and high performance remains a major restriction in 3D printing PMCs. Future innovations to improve print resolution and enable curing/solidification after filler impregnation will be critical in advancing the capabilities.

Table 2 summarizes the impact of key processing modifications across five major 3D printing technologies: FDM, SLA, SLS, binder jetting, and direct ink writing (DIW). It highlights how temperature control, print speed, layer thickness, reinforcement methods, and other specific factors uniquely influence each technology's printing process, material properties, and final part quality.

4.1. FDM. FDM is among the most popular techniques. It involves extruding a thermoplastic filament through a heated nozzle and depositing layers to create the desired object. FDM offers simplicity, affordability, and compatibility with a wide range of polymers but may have limitations in achieving high-resolution parts. FDM is one of the most widely used AM techniques due to its simplicity and low cost proposed by Patel and Taufik [57]. In FDM, a thermoplastic filament is unwound from a coil and supplied to an extrusion

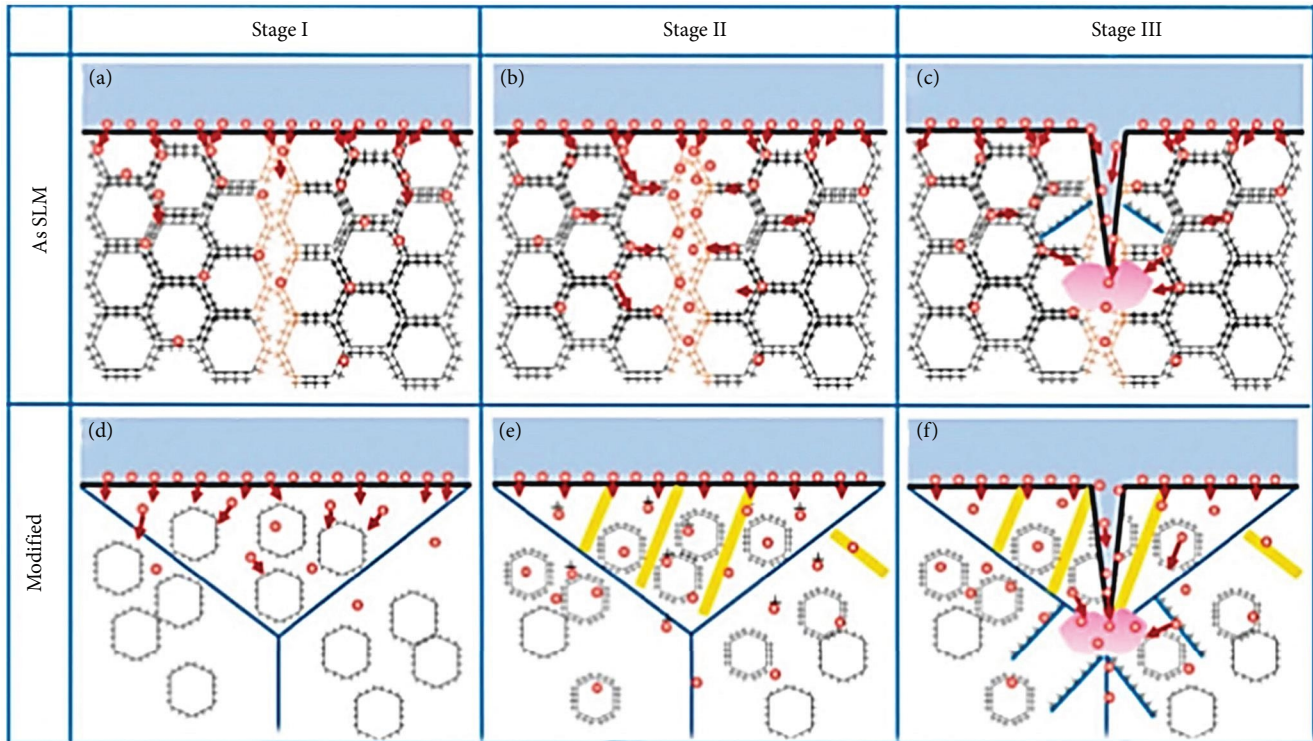


FIGURE 9: Structural evolution stages in SLM (selective laser melting) processed samples. Panel (a) provides an overview. The “As SLM” row (a, b, c) shows unmodified stages: Stage I (a) initial microstructure, Stage II (b) defect formation, Stage III (c) crack propagation. The “Modified” row (d, e, f) displays optimized stages: Stage I (d) enhanced bonding, Stage II (e) added structural supports (yellow), and Stage III (f) reduced crack propagation due to modifications.

nozzle, which can move in both horizontal and vertical directions. The nozzle is heated to melt the thermoplastic and can extrude material in a preset layer pattern. Each layer solidifies and bonds to the previous layer shortly after extrusion to fabricate the desired 3D object. Commonly used thermoplastics in FDM include ABS, PLA, nylon, and polycarbonate (PC). Key advantages of FDM are the ability to use low-cost polymer materials, minimal material waste, and no need for dedicated facilities or environments [58]. However, limitations include relatively low accuracy and surface finish compared to other AM processes, limited materials, and weak mechanical properties, especially along the build direction, as shown in Figure 10.

4.2. SLA. SLA is an AM process that works on the principle of photopolymerization of a liquid resin using a UV laser [59]. The laser beam traces each layer pattern on the liquid photopolymer resin surface, causing the resin to solidify locally. Once a layer is traced, the build platform descends into the liquid resin vat by a thickness equal to the layer height, and the tracing of the next layer begins [60]. This is repeated until the full 3D object is fabricated. SLA requires the use of photosensitive resins but can achieve high accuracy and surface finishes, as well as good mechanical properties. However, the process is slower than FDM. Materials are more limited, and post-processing in chemical baths is required to remove the excess liquid resin. SLA uses a vat of liquid photopolymer resin cured by UV light. It enables high resolution prints with intricate details but may have

limitations in processing certain composite materials and requires postcuring as shown in Figure 11.

4.3. SLS. SLS uses a high-power laser to fuse small particles of plastic, ceramic, glass, or metal powders into 3D objects [61]. The laser beam traces each layer pattern onto a thin layer of powder (100 μm) spread across the entire build area by a roller mechanism. The laser melts the powder locally, fusing it to the previous layer below. Once the layer is complete, the build platform lowers by one layer thickness, and a new layer of powder is spread across the surface. Unfused powder remains to support overhangs and undercuts. SLS allows using various powder materials, including polymers, metals, ceramics, and composites require an inert build environment and meticulous powder handling [62]. Achievable accuracy is high, but surface finish often requires improvement via infiltration or coatings. SLS utilizes a high-powered laser to sinter powdered materials, creating layers to form the final object. It allows for a broader range of materials, including polymers and composites, offering good mechanical properties but may require postprocessing to achieve the desired surface finish, as shown in Figure 12.

4.4. Binder Jetting. Using an inkjet print head, a liquid bonding agent is selectively deposited in binder jetting to join powder materials layer-by-layer. Powder spreaders distribute thin layers of powder material across the build area, and the print head moves across the powder bed to deposit binder droplets in the shape of each layer. The binder bonds the

TABLE 2: Comparative analysis of processing modifications across 3D printing technologies.

Processing modification	FDM	SLA	SLS	Binder jetting	DIW
Temperature control	Heated nozzle and bed improve adhesion; high temperatures risk degradation.	UV laser cures resin; less critical, affects viscosity.	Laser sintering requires precise control for fusion.	Binder deposited at room temperature; oven cure possible.	Room temperature extrusion; solidification without extra heating.
Print speed effects	Speed impacts adhesion and rate; slower = better bonding.	Laser speed affects throughput versus cure depth.	Balances energy input; too fast or slow affects fusion.	Speed affects binder setting and layer adhesion.	Extrusion speed is key to shape retention; too fast is detrimental.
Layer thickness	Thinner layers = better finish but weaker bonds.	Resolution versus UV depth; very thin may not cure.	Thinner layers for higher resolution but less fusion area.	It affects density and bonding; 50–200 microns are typical.	Road height tuned for resolution versus adhesion.
Reinforcement	Fiber or particle-reinforced filaments.	Particle-filled resins; short fibers affect printability.	Laser-fused coated powders for diverse materials.	Prints polymers to composites with the same process.	Fillers include particles and fibers for desired properties.
Other factors	Raster, infill, and nozzle size affect density/strength.	Resin composition and vat affect cure and volume.	Powder properties and laser strategies affect density/fusion.	Binder level curing profile impact part density.	Nozzle geometry and ink rheology/comp affect accuracy/retention.

Abbreviations: DIW, direct ink writing; FDM, fused deposition modeling; SLA, stereolithography; SLS, selective laser sintering.

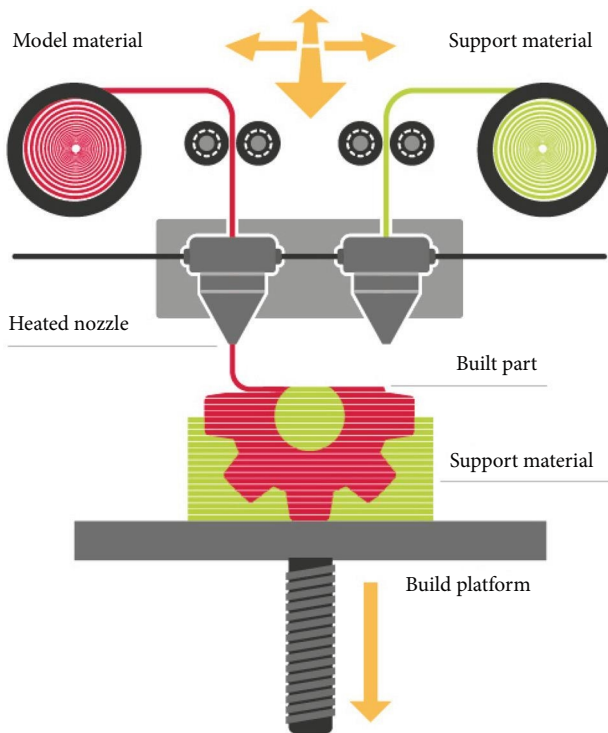


FIGURE 10: FDM [57]. FDM, fused deposition modeling.

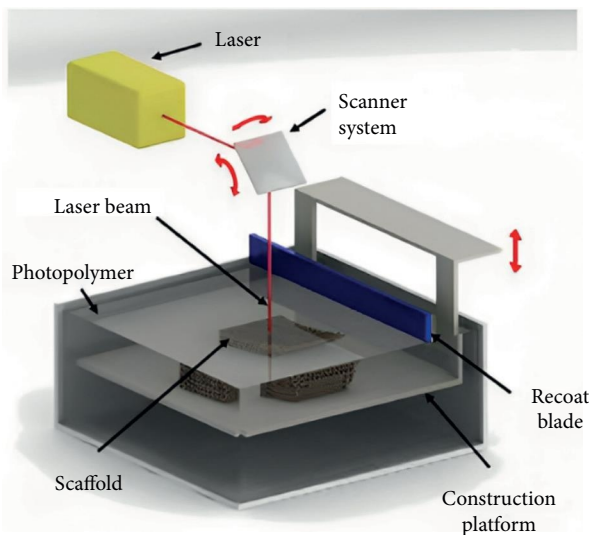


FIGURE 11: SLA [59]. SLA, stereolithography.

powders together upon curing or drying. The unbound powder remains to support overhangs [63]. The build platform lowers once the layer is complete, and the process repeats until the part is finished. The unbound powder is removed via vacuum, and parts often require postprocessing, such as infiltration or sintering. Various powder metals, ceramics, sand, and polymers can be used. Resolution and accuracy are high, but the process is relatively slow. This technique deposits a liquid binding material onto a powder bed selectively. It offers high speed and can accommodate a variety of

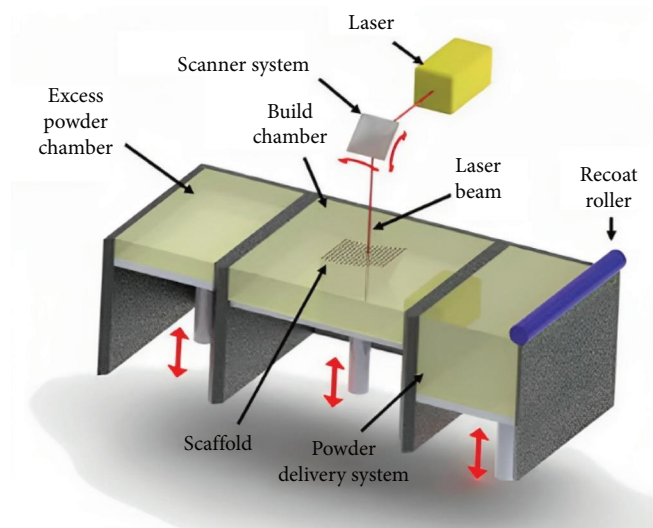


FIGURE 12: SLS [61]. SLS, selective laser sintering.

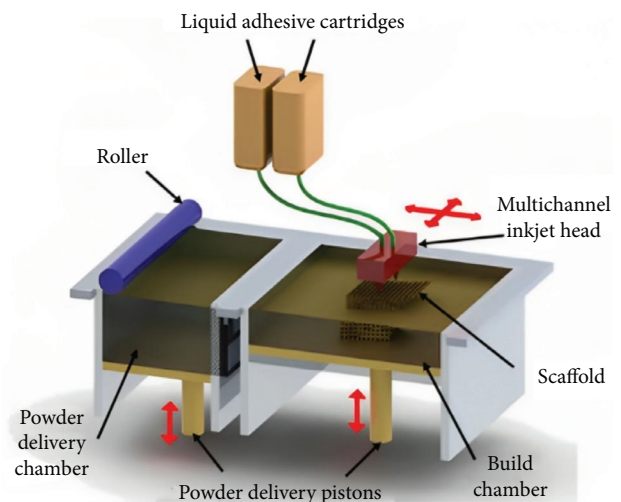


FIGURE 13: Binder jetting [20].

materials, but achieving high mechanical properties might be a challenge due to the porosity of the printed parts, as shown in Figure 13 [20, 64].

4.5. DIW. DIW is an extrusion-based AM technique to fabricate 3D structures from ink formulations with tailored rheological and setting behavior. Viscoelastic inks are housed in syringes mounted on a computer-controlled stage and extruded continuously through a nozzle as filaments onto a substrate. The ink must flow through the nozzle at an applied pressure but rapidly solidify upon deposition to retain its filamentary shape. The stage traces out a toolpath to build up 3D objects in a layer-by-layer sequence. DIW allows functional gradient structures to be formed from a single print-head or multiple printheads. However, overhangs require support and adhesion between layers can be challenging

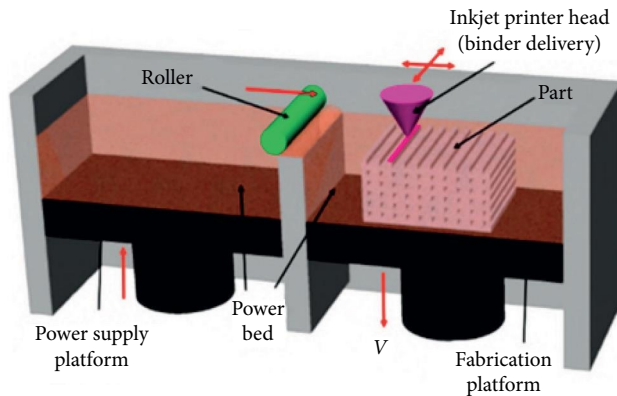


FIGURE 14: DIW [66]. DIW, direct ink writing.

[65]. The technique has been applied to fabricate structures from diverse organic and inorganic ink materials. DIW uses a nozzle to extrude a paste or ink-like material, allowing for precise control over material deposition. It is suitable for printing shear-thinning materials but may have limitations in achieving high mechanical strength, as shown in Figure 14 [66, 67].

4.6. Infill Density and Raster Angle. Beyond key parameters like temperature, speed, and layer thickness, the infill density and raster angle in 3D printing significantly affect the mechanical performance of PMCs. Infill density refers to the amount of material within the part, with higher densities providing more internal structure, which enhances strength and stiffness by allowing more efficient stress transfer. However, excessively high infill can increase weight and printing time without proportional property gains, so an optimal balance is necessary. The raster angle, which dictates the orientation of filament paths within each layer is also critical. Aligning the raster angle with the primary load direction maximizes strength and stiffness by orienting reinforcing fibers or polymer chains along stress axes. Conversely, perpendicular raster angles can reduce these properties. Alternating raster angles between layers, such as $0^\circ/90^\circ$ or $\pm 45^\circ$, can introduce in-plane isotropy or tailored anisotropy, depending on application needs. The interaction between infill density and raster angle is complex, with higher infill densities amplifying the effects of raster orientation. Therefore, optimal combinations of these parameters must be determined through systematic experimentation and modeling to achieve the desired balance of strength, stiffness, and other mechanical characteristics. In summary, infill density, raster angle, and other key processing factors like temperature, speed, and layer thickness are crucial in determining the mechanical performance of 3D-printed polymer composites. Careful optimization of these parameters is essential to fully unlock the potential of these advanced materials for both structural and functional applications.

AM techniques like FDM, SLS, and SLA each have unique advantages and limitations when processing PMCs. Understanding these differences is essential for optimizing the mechanical properties of the final printed components. FDM is widely used due to its accessibility and versatility. In FDM, thermoplastic filaments are extruded layer-by-layer,

making it ideal for embedding continuous or short fibers within the polymer matrix. However, achieving uniform dispersion and alignment of fibers can be challenging. Optimizing parameters such as nozzle temperature, print speed, and layer height is crucial to enhancing interlayer adhesion and minimizing voids, which improves tensile strength and toughness. Studies show that carefully controlling raster angle and infill pattern can significantly enhance the mechanical properties of FDM-printed composites. SLS uses a high-power laser to fuse powdered materials layer-by-layer, making it suitable for processing PMCs with thermoplastic matrices. SLS excels at producing complex geometries without the need for support structures, which is particularly beneficial for intricate composite parts. However, the choice of powder material and laser parameters like power and scan speed critically influence the densification and mechanical properties of the final part. Optimizing these parameters reduces porosity and improves interparticle bonding, leading to composites with higher strength and stiffness. SLS is especially effective for processing PMCs with high filler content, where uniform particle distribution and strong matrix-reinforcement interfaces are crucial. SLA is a photopolymerization-based technique that uses a UV laser to cure liquid resin into solid layers. Known for its high-resolution capabilities, SLA's application in PMCs has been limited by the availability of suitable photopolymerizable composite resins. However, advancements in resin formulations now allow the inclusion of nanoparticles and short fibers within SLA resins. Optimizing laser intensity, exposure time, and layer thickness can improve mechanical properties by ensuring complete curing and minimizing defects. SLA is particularly advantageous for applications requiring high dimensional accuracy and surface finish, although postcuring processes are often necessary to fully develop the material's properties. When comparing these methods, specific application requirements of the PMC must be considered. FDM is better suited for applications where flexibility in material selection and lower costs are prioritized. SLS offers superior mechanical properties and design freedom for complex geometries, while SLA is ideal for applications demanding high precision and surface quality. Each method's processing parameters—such as temperature, speed, and layer thickness in FDM; laser power, scan speed, and bed temperature in SLS; and laser intensity and exposure time in SLA—must be optimized based on the type of reinforcement and matrix material used to achieve the best mechanical performance.

Future research should focus on further refining these parameters and exploring hybrid approaches that combine the strengths of different AM techniques to produce PMCs with superior mechanical properties. Additionally, developing new composite materials specifically designed for each AM method will be crucial in pushing the boundaries of what can be achieved with 3D-printed PMCs. Recent advancements in 3D printing have significantly improved the mechanical performance of PMCs through various microstructural refinements and processing enhancements. For example, strategically aligning reinforcing fibers during printing, such as optimizing the orientation of carbon fibers along the primary

loading direction, has been shown to increase tensile strength by up to 40%. This is due to enhanced stress transfer between the matrix and fibers when aligned parallel to the applied load. Additionally, reducing the size of reinforcement particles to the nanoscale can substantially increase the strength and toughness of PMCs, as nanoscale particles more effectively impede dislocation motion and improve stress distribution within the matrix.

Innovative processing techniques, such as adjusting printing parameters like nozzle temperature, print speed, and layer thickness, can significantly influence the crystallinity and interlayer adhesion of the polymer matrix. Fine-tuning these parameters can lead to a 20%–30% improvement in mechanical properties, including stiffness and toughness. Postprocessing treatments, such as annealing and surface modifications like plasma treatment, further enhance interfacial bonding between the matrix and reinforcements, improving the overall mechanical performance of the composites. These advancements highlight the importance of a multifaceted approach to optimizing the mechanical performance of 3D-printed PMCs. By integrating microstructural control with precise processing techniques, it is possible to tailor the mechanical properties of these materials to meet specific application requirements, expanding their potential for use in demanding fields such as aerospace, automotive, and biomedical engineering.

5. Analyzing the Processing Parameters Affect Mechanical Properties

Processing parameters such as temperature, speed, and layer thickness significantly influence the mechanical properties of 3D-printed PMCs.

5.1. Temperature. Variation in temperature affects material flow, adhesion between layers, and crystallinity of polymers. Higher temperatures can improve interlayer bonding but may introduce thermal degradation, impacting mechanical strength. In polymer-based AM processes such as FDM and SLA, temperature is a key parameter influencing material properties, interlayer adhesion, and part quality. Applied heat from the print head or laser during printing can significantly impact material flow characteristics. At higher temperatures approaching or above the polymer's glass transition or melting point, viscosities decrease exponentially, enabling easier extrusion or resin spreading. However, excessively high temperatures also promote thermal degradation through chain scission or oxidation reactions, causing mechanical property deterioration. Meanwhile, even small temperature gradients between adjacent printed layers can hinder interlayer mixing and bonding due to rapid solidification. This is especially problematic for semi-crystalline polymers like nylon and polyethylene. Slower cooling promotes chain mobility and folding, allowing the development of thicker crystalline lamellae and spherulites with higher crystallinity. Hardness, stiffness, strength, and chemical resistance increase by maximizing crystalline content. Moderate print bed and extrusion/resin temperatures should balance adequate viscosity and interlayer mixing with limited thermal degradation during polymer AM. For semi-crystalline materials, slower cooling overnight in the

print chamber may also maximize crystallinity and isotropy compared to immediate part removal. Further annealing above the glass transition temperature (T_g) can additionally increase crystalline content. In conclusion, precise thermal control during polymer printing and postprocessing balances key requirements of shape retention, adhesion, crystallinity, and mechanical performance [68].

5.2. Speed. Printing speed influences cooling rates and layer adhesion. Faster printing speeds might compromise interlayer bonding, affecting strength, while slower speeds could enhance bonding but increase production time. The counter-rotating roller's traverse speed significantly influences the quality of spread powder layers and the resulting green and sintered parts printed via binder jetting. As demonstrated in the study by Miao et al., a higher roller traverse speed typically leads to lower powder bed density prior to binder deposition. The reduced density is caused by particles having less time to settle and rearrange into an optimized packing configuration at higher traverse speeds. Consequently, more voids exist within and between printed layers. These defects are inherited in the final sintered microstructure, causing decreased density and mechanical properties [69].

This allows improved interfacial contact area for binding adjacent layers. Slower speeds limit binder penetration, confining the binder to a thinner region near the top surface. So, while a slower roller traverse produces individually denser layers, the bonding between layers could suffer. There may be an optimal moderate speed that balances these competing factors [70]. Besides traverse speed, the cooling rate of deposited binder droplets also influences interlayer strength. At faster print head scanning speeds, the binder has less time to spread out laterally from the impingement site before the next layer is deposited. The limited binder penetration caused by rapid cooling could hinder adhesion between layers. Slower scan speeds allow the binder to spread further into pore spaces before freezing, improving interlayer mechanical locking. However, similar to roller traverse, slowing the print speed reduces productivity. So, determining the maximum speed that still provides adequate layer binding is desirable. The roller traverse and print head traverse speeds in binder jetting have competing effects on part quality. Faster speeds compromise powder packing density within a layer and tend to limit binder penetration depth, which is detrimental. But the higher porosity could allow a better interlayer contact area for the binder to improve adhesion between layers. Slower speeds mitigate these issues but reduce productivity. Further studies are needed to elucidate the optimal balance between speed and part performance [71].

5.3. Layer Thickness. Thinner layers generally result in finer resolution and better surface finish. However, excessively thin layers might impact mechanical strength due to reduced interlayer bonding.

The layer thickness, or height of each deposited layer, is a key parameter in powder bed fusion AM that impacts both print quality and mechanical properties. Thinner layers improve resolution, surface finish, and dimensional accuracy. However, excessively thin layers can negatively impact

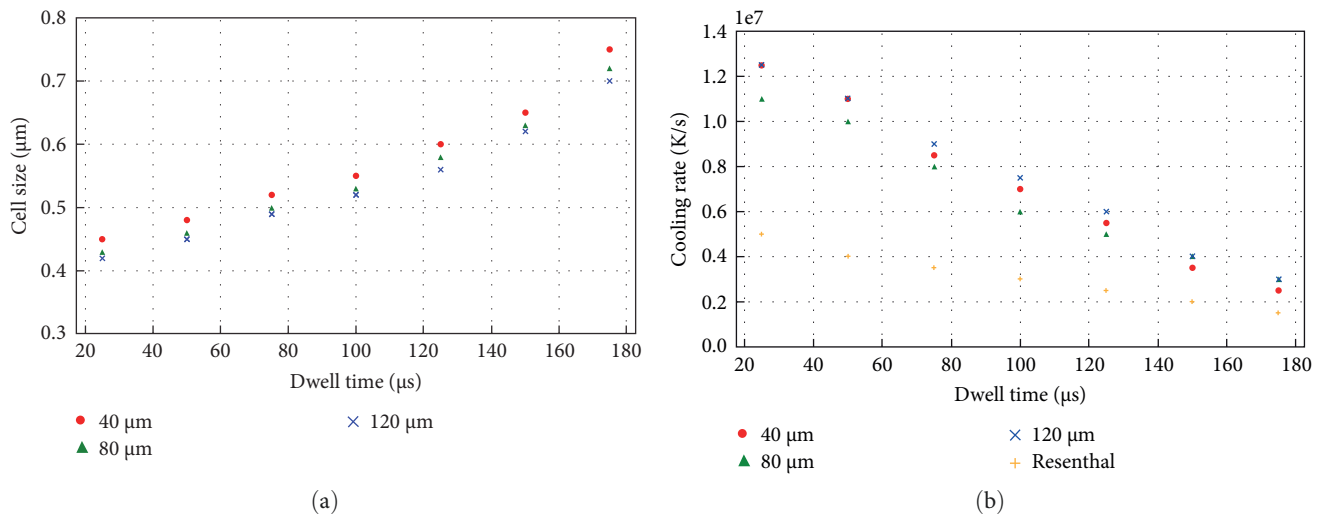


FIGURE 15: (a) Measurements of cell sizes and (b) calculations of cooling rates for samples processed with powder layer thicknesses of 40, 80, and 120 μm [30].

mechanical performance. Thus, an optimization trade-off must be made [72]. As layer thickness decreases, the staircase effect is reduced, allowing for more accurate reproduction of intended geometries with smoother surfaces. Studies have shown that surface roughness values (R_a and R_z) decrease exponentially with reducing layer thicknesses down to 20–30 μm . However, further reductions below this range provide diminishing returns on roughness improvements. Consequently, most research identifies optimal layer thicknesses for surface finish as 20–50 μm . While thinner layers improve accuracy and finish, they also reduce the interlayer bonding area within a printed part. Metallurgical bonding between layers is crucial for load transfer and mechanical integrity. Insufficient bonding can manifest as delamination cracks or anisotropy. Experiments find that thinner layers decrease elongation at break and tensile strengths parallel to the build direction. For example, 316L stainless steel parts made at 20 μm layer thickness exhibited over 50% lower elongation than those printed at 80 μm [73]. The reduced bonding area also constraints heat dissipation between subsequent layers during printing. This causes higher thermal gradients and faster solidification rates. While this can refine the microstructure through secondary dendrite arm spacing reductions, it also amplifies residual stress development. The higher stresses promote crack formation.

In contrast, thicker layers provide more area for interlayer bonding and heat conduction. But layer thicknesses above 80 μm seldom provide additional mechanical improvements as shown in Figure 15 [30]. Overly thick layers reduce accuracy and amplify the staircase effect due to volumetric errors accumulating over many layers. Surface roughness also worsens significantly above 80 μm . An optimal layer thickness balance needs to be struck. The 40–60 μm range for most materials enables high accuracy and surface quality while maximizing interlayer metallurgical bonding for superior mechanical properties. However, the optimum depends on material, geometry, build orientation, and heat treatments. Parameter

optimization is, therefore, essential for new materials and applications. Optimal parameter selection involves a trade-off between these factors to achieve desired mechanical properties without compromising other aspects of print quality.

6. Optimization Strategies for Enhanced Mechanical Performance

6.1. Experimental Testing. Conducting mechanical tests (tensile, compression, flexural) to evaluate properties under different printing conditions. Holmes et al. [74] AM, commonly known as 3D printing, allows parts to be built up layer-by-layer based on a digital model. This enables complex geometries to be created without needing dedicated tooling or molds. However, the properties of 3D-printed parts can vary significantly depending on the specific printing conditions and parameters used. Important parameters include layer height, print orientation, infill percentage and pattern, print temperature, and print speed. Standardized mechanical tests on printed specimens are crucial to evaluate the achieved properties under different printing conditions [75].

Tensile, compression, and flexural testing are three common mechanical tests that characterize 3D-printed parts. Tensile testing applies an axial load to a dogbone or straight-sided specimen and measures deformation over time until failure. This can determine properties such as tensile strength, ductility represented by strain at failure, Young's modulus, and strain hardening behavior. The effects of raster angle, layer adhesion, and voids between filaments on part strength and ductility can be assessed. Compression testing axially loads a specimen to failure and mainly determines compressive yield and ultimate strength. Flexural testing bends a beam specimen in three-point bending until failure, assessing properties such as flexural strength, flexural modulus, and beam deflection. Flexural testing indirectly puts one side of the specimen in tension and the other in compression, allowing the simultaneous assessment of performance under these two loading modes, as shown in Figure 16 [76].

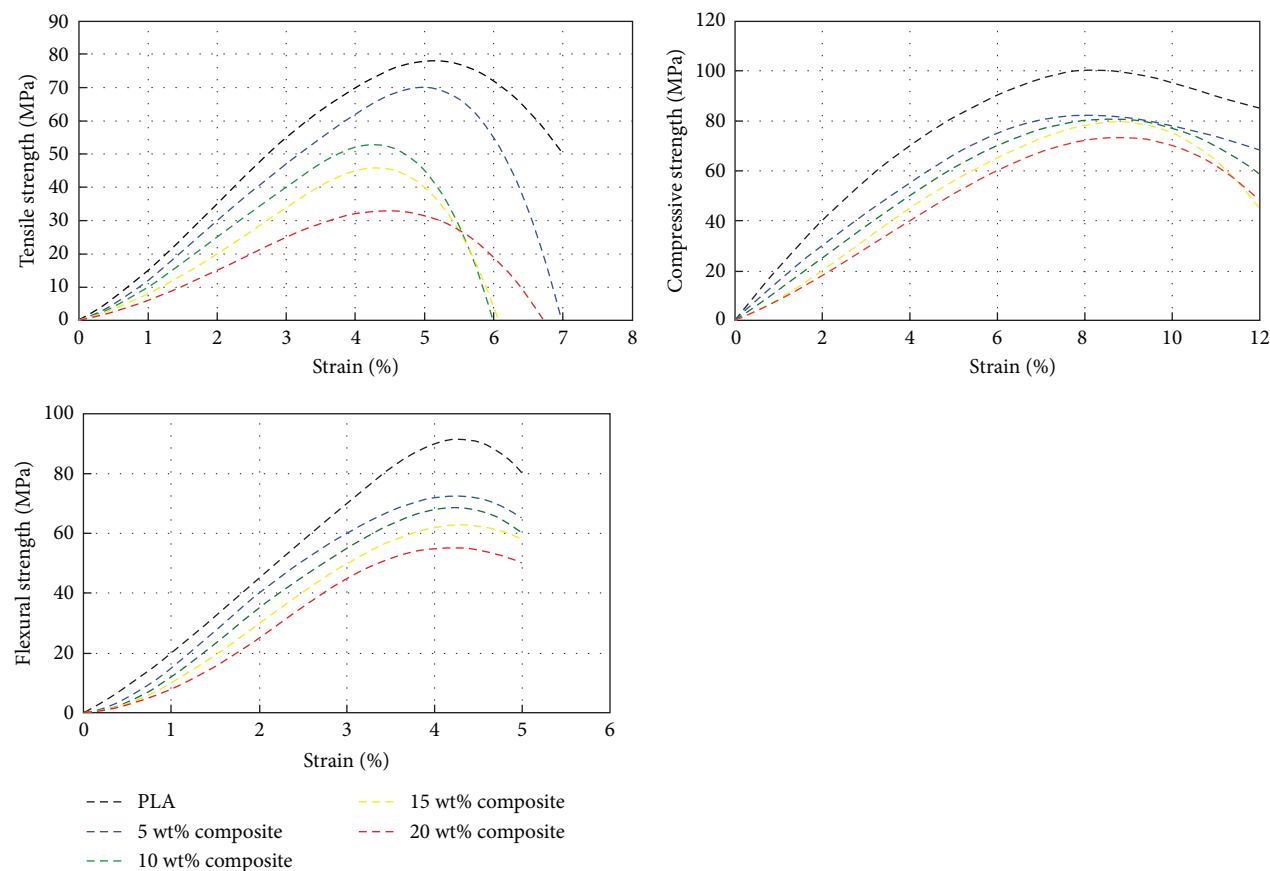


FIGURE 16: Stress versus strain plot of the tensile, compressive, and flexural test [76].

TABLE 3: ASTM standards for mechanical testing of 3D-printed polymer composites.

Category	Standard	Description
Tensile testing	ASTM D638	For tensile properties of plastics.
	ASTM D3039	For tensile properties of PMC materials.
Compression testing	ASTM D695	For compressive properties of rigid plastics.
	ASTM D6641	For compressive properties of PMC materials.
Flexural testing	ASTM D790	For flexural properties of unreinforced and reinforced plastics and electrical insulating materials.
	ASTM D7264	For flexural properties of PMC materials.
Other relevant standards	ASTM D3171	For testing fiber content.
	ASTM D2584	For measuring void/porosity content.
	ASTM E1942	Guide for evaluating mechanical property data of 3D-printed parts.

Abbreviation: PMC, polymer matrix composite.

When evaluating the effects of different 3D printing conditions, it is ideal to isolate individual parameters. For example, multiple sets of specimens could be printed, changing only nozzle temperature or print speed between sets, with all other conditions held constant. Five to 10 specimens should be tested under each condition set to obtain reliable averages and standard deviations for the mechanical properties. Testing should follow the appropriate ASTM standard test method to allow equivalent comparison to traditional manufacturing methods. Some key standards are ASTM D638 for tension,

ASTM D695 for compression, and ASTM D790 for flexural testing of polymers and composites. Stress-strain curves allow detailed analysis of elastic modulus, yield point, ultimate strength, failure strain, and ductility/brittleness transitions under the different 3D print conditions evaluated. This data guides the identification of optimal 3D printing parameters to obtain the application-specific mechanical performance required.

Table 3 presents key ASTM standards for conducting mechanical tests on 3D-printed polymer composites, including tensile, compression, and flexural testing. Adhering to

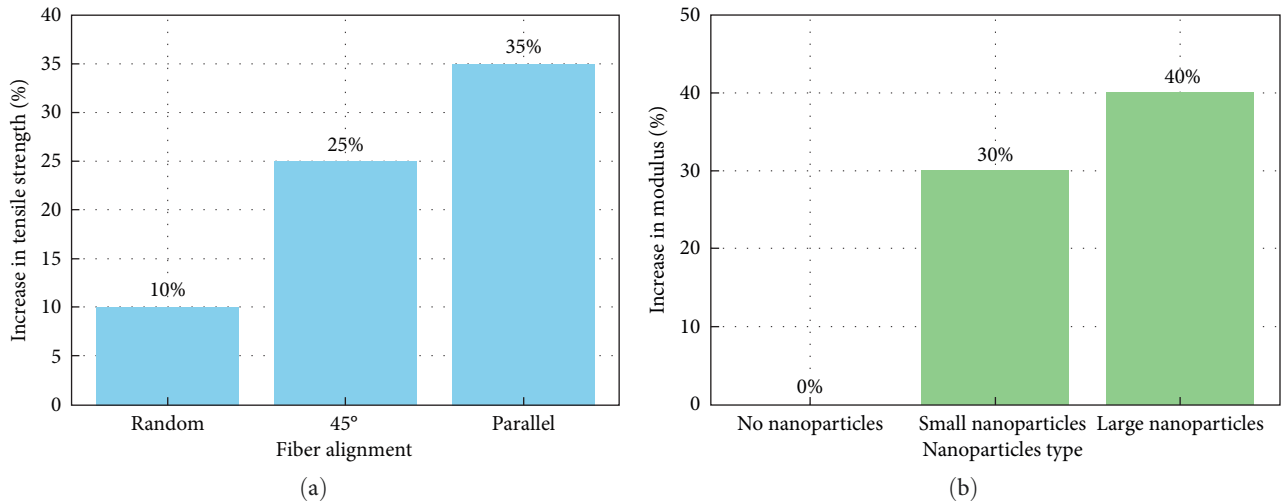


FIGURE 17: (a) Comparison of tensile strength in PMCs with different fiber alignments. (b) Effect of nanoparticle incorporation on modulus [41]. PMC, polymer matrix composite.

TABLE 4: Summary of mechanical property improvements with processing modifications.

Modification type	Method	Improvement in tensile strength (%)	Improvement in Modulus (%)
Fiber alignment	FDM	+35	+15
Nanoparticle addition	SLS	+25	+40
Layer thickness adjustment	SLA	+20	+20
Postprocessing (annealing)	All methods	+30	+25

Abbreviations: FDM, fused deposition modeling; SLA, stereolithography; SLS, selective laser sintering.

these standards ensures reliable, comparable data generation, facilitating systematic assessment of printing parameters' effects on mechanical performance.

A study by Wu et al. [77] reported a 35% increase in tensile strength when carbon fibers were aligned parallel to the loading direction during FDM printing. Another study by Velej, Tremblay, and Al-Majali [40] showed that optimizing the laser power and scan speed in SLS printing resulted in a 25% increase in tensile strength due to improved particle fusion and reduced porosity.

6.2. Modulus Enhancement. Research by Shi et al. [38] demonstrated that the incorporation of SiC nanoparticles into a polymer matrix increased the modulus by 40%, attributed to the nanoparticles' ability to restrict polymer chain mobility and enhance load transfer. Additionally, adjusting the layer thickness in SLA printing from 50 to 25 μm improved the modulus by 20%, as reported by Salas et al. [36], due to better interlayer adhesion and reduced voids.

Figure 17a illustrates the increase in tensile strength when fibers are aligned in various orientations relative to the load direction, highlighting the benefits of optimal fiber orientation. Figure 17b shows the percentage increase in modulus when different types and sizes of nanoparticles are incorporated into the polymer matrix [41].

These findings emphasize the importance of carefully selecting and optimizing processing parameters and microstructural features to achieve the desired mechanical properties in PMCs (Table 4). The visual representation of this data helps

in better understanding the correlation between the modifications and the resulting material performance, providing a more robust basis for the conclusions drawn in this review.

7. Role of Design Optimization, Material Selection, and Postprocessing Techniques

7.1. Design Optimization. Employing topology optimization or lattice structures to minimize material usage while enhancing strength [78]. Topology optimization and lattice structures are effective techniques for minimizing material usage in structural components while maintaining or enhancing strength. Topology optimization uses computational methods to optimize the material layout within a design space for a given set of loads and constraints. This removes unnecessary material and creates organic, efficient shapes with uniform stress distributions. Lattice structures consist of struts or beams in triangular, square, or other geometric patterns. Only having material where structurally required makes them intrinsically lightweight and efficient [79].

Both approaches allow substantial material savings over traditionally designed components. Studies have shown 40%–60% reductions for topology-optimized parts and up to 90% for lattice structures. Despite their slim profiles, their strength is not compromised. Optimized shapes exhibit improved stiffness and buckling resistance compared to baseline designs using the same amount of material. Lattice structures can match or exceed their base materials' specific properties (strength/

stiffness per unit mass). There are some key differences between the two methods. Topology optimization operates on a bulk material level to remove whole areas of inefficient material. Lattice structures function on a mesoscale level, with individual struts making up the structure. The end-use application also tends to differ. Lattice structures are well-suited for repetitive cellular structures with larger components [80].

AM (3D printing) enables both approaches by fabricating geometries that are too complex for traditional methods. However, lattice designs are currently more feasible for metal printing than topology-optimized shapes. Their repetitive cell structure is simpler to slice and print than intensely organic forms with overhanging features or thin trapped volumes of powder. Both areas continue advancing to expand printing capabilities [81].

Topology optimization and lattice structures exemplify how computational synthesis and advanced manufacturing can profoundly reduce material consumption while meeting or exceeding structural targets. Lattice designs' relative printability provides more immediate wins, but further developments in design software and printing will unlock topology optimization's full potential for sustainable, high-performance structures. By skillfully applying these techniques only where needed, structural engineers can eliminate vast amounts of unnecessary material and embodied carbon across various industries and applications.

7.2. Material Selection. Choosing reinforced polymers with tailored properties, considering fiber type, orientation, and volume fraction for specific applications. Material selection in 3D printing of PMCs involves choosing reinforced polymers with specific properties that suit intended applications. This process considers factors like reinforcing fiber type, orientation within the matrix, and volume fraction used [82].

Selecting the appropriate fiber type, such as carbon, glass, or aramid, influences properties like strength, stiffness, and thermal conductivity. The orientation of these fibers within the matrix affects the final composite's load-bearing capacity and directional properties. Additionally, the volume fraction of reinforcing elements determines the overall enhancement of mechanical properties. Tailoring these parameters allows engineers to create composites optimized for various applications, ensuring the printed parts possess the required strength, durability, and performance characteristics necessary for specific industrial or functional requirements.

7.3. Postprocessing. Heat treatments, surface treatments, and reinforcements are commonly used as postprocessing techniques to enhance the properties and performance of AM components. Heat treatments like hot isostatic pressing (HIP) and annealing can help relieve internal stresses, close internal voids and pores, and homogenize the microstructure in AM parts. HIP has significantly improved the fatigue life, strength, and energy absorption of AM lattice structures in titanium and nickel-based alloys. Annealing above the T_g in polymers like PLA improves crystallinity and interlayer adhesion, increasing tensile strength and modulus. The appropriate heat treatment temperature and time depend on factors like AM process, material composition, and

desired properties [83]. Surface treatments aim to reduce surface roughness, modify surface chemistry, and induce beneficial compressive stresses. Smoothing processes like machining, grinding, laser polishing, and various chemical etching treatments greatly reduce roughness. The resulting surface finish improvements lead to substantial gains in fatigue performance. Peening processes like a shot peening ultrasonically harden the near-surface region and generate compressive residual stresses known to delay crack initiation and growth. The depth and magnitude of the compressive stresses can be controlled through peening intensity [80].

Reinforcements like particles, fibers, meshes, and coatings have expanded AM material capabilities, enabling the fabrication of metal and PMCs. Short fibers like CNTs and chopped carbon fibers as little as 0.3 wt% can increase the strength and stiffness by over 20% in plastic AM composites. Incorporating meshes and foams enhances energy absorption under dynamic loads. Coatings provide tailored tribological, electrical, thermal, and biomedical functionality. These posttreatments provide avenues to enhance AM part performance and extend capabilities significantly [84]. However, the impacts of these treatments on properties are highly dependent on the base material, process specifics, and treatment parameters. More research is needed to provide definitive guidelines.

Integrating these strategies allows for the development of high-performance PMCs tailored for specific applications while optimizing mechanical properties. Balancing these approaches is crucial for achieving the desired performance without compromising other aspects of the printing process [85].

7.4. Postprocessing Techniques and Their Impact. Postprocessing is a crucial step in AM, significantly enhancing the properties and performance of 3D-printed parts by addressing issues such as layer delamination and cracking. For polymer parts, techniques like heating above the T_g improve interlayer bonding and reduce residual stresses, preventing delamination by promoting chain entanglement and interdiffusion across layers. Solvent vapor exposure can partially dissolve the surface, allowing polymer chains to flow and fuse layers, which enhances mechanical integrity. Additional UV light or heat exposure further crosslinks and solidifies the polymer, reducing the risk of delamination, while resin impregnation fills voids, reinforcing the structure and preventing crack propagation. For metal parts, subjecting them to high temperatures and pressures closes internal pores, improving density, and reducing defects. Heat treatment below the recrystallization temperature relieves residual stresses, mitigating distortion and cracking. Surface treatments like shot peening induce compressive stresses that counteract tensile stresses, preventing crack initiation, while laser shock peening introduces deep compressive stresses to suppress crack growth. Removing defect-prone top or bottom layers can further eliminate potential issues. The effectiveness of these techniques depends on the specific material, printing process, and part geometry, requiring careful optimization to achieve the desired mechanical improvements.

Combining multiple postprocessing steps may be necessary to address complex failure modes, making postprocessing protocols essential for unlocking the full potential of AM and ensuring the reliability and durability of 3D-printed parts across various industries [86].

7.5. Improving Reproducibility in 3D Printing: Key Strategies. Achieving consistent performance and part quality in 3D printing, particularly with PMCs, is a significant challenge. Current research has identified several strategies to improve reproducibility: precise alignment and uniform distribution of reinforcements, such as fibers and nanoparticles are crucial. Techniques like optimized nozzle design and in situ polymerization help achieve uniformity, enhancing mechanical properties and reducing variability. Adjusting layer thickness, print speed, and nozzle temperature is essential. For instance, thinner layers improve surface finish but may weaken interlayer bonds. Balancing these parameters ensures optimal mechanical performance and surface quality. Post-processing treatments like annealing, surface polishing, and chemical etching are employed to improve part quality. These methods relieve internal stresses, enhance interlayer bonding, and reduce defects, leading to more consistent and reliable parts. Using predictive models and machine learning, researchers can optimize printing processes before production, reducing trial and error. These tools help ensure consistent quality by predicting the impact of parameter changes on part performance. Establishing standardized protocols for material properties and printing parameters, along with real-time monitoring, helps maintain consistency across production batches, ensuring that each part meets the desired specifications. A combination of microstructural control, process optimization, postprocessing, computational tools, and standardization is key to improving reproducibility and part quality in 3D printing.

7.6. Predictive Modeling Using Deep Learning. Integrating deep learning with microstructural analysis can accelerate the optimization of 3D-printed polymer composites by predicting precrack formation and failure behaviors. The heterogeneous nature of these composites makes them ideal for data-driven modeling. Convolutional neural networks (CNNs) can be trained on imaging data to learn the relationships between the composite's morphology and its mechanical performance. These models, informed by comprehensive datasets of microstructural characteristics and experimental metrics, can predict flaws and failure modes under different conditions. Such predictive tools can significantly improve the design and optimization of 3D-printed composites, guiding the selection of manufacturing parameters and facilitating virtual screening of new materials. Integrating deep learning with established microstructure-property relationships and experimental testing can enhance the performance and reliability of these advanced materials.

8. Case Studies and Experimental Findings

Present notable case studies or experiments that illustrate the successful enhancement of mechanical properties through

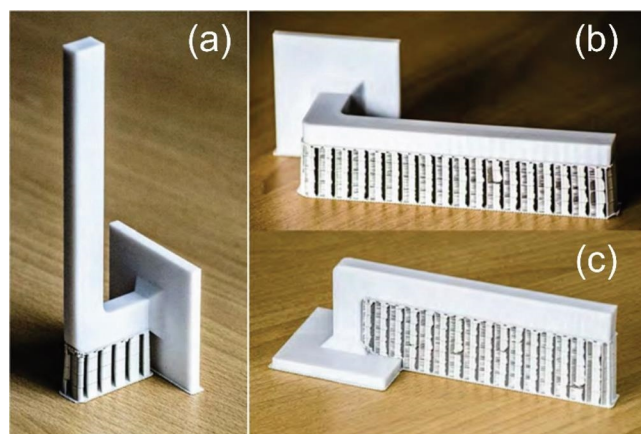


FIGURE 18: Orientation of three parts (a–c) [87].

microstructure and processing modifications. In case study 1, we delved into the mechanical behavior of FDM parts. The hypotheses centered on the anisotropic nature of FDM parts due to their layered manufacturing process and the impact of thread orientation on mechanical properties. First, it was hypothesized that aligning extruded threads with applied tensile stresses would enhance mechanical strength. Second, an assumption was made that augmenting volumetric density and contour numbers would positively impact elasticity, rigidity, and absorption. This work is primarily dedicated to exploring the mechanical properties of components produced through FDM. The overarching goal is to identify the most efficient manufacturing approach for end-use parts utilizing Stratasys Fortus 400mc AM technology with PC material. To achieve this, several specific objectives are outlined: first, to unearth mechanical constitutive models that accurately represent the elastic behavior of FDM-manufactured parts and experimentally ascertain the mechanical constants essential for constructing the linear elastic constitutive model. Subsequently, the aim is to validate the constitutive model through real tests and computer simulations while identifying the manufacturing factors significantly impacting the mechanical behavior of FDM parts under dynamic loads within the elastic zone. To validate the methodology's physical outcomes, we opted to produce components solely in orientations, as depicted in Figure 18, creating three instances of each orientation [87]. This deliberate selection stemmed from two key considerations: first, the chosen piece boasts a quadrilateral shape as its convex envelope, facilitating a matching arrangement of layers and threads resulting in identical mechanical behavior and surface finish within these pairs. Second, the decision also considered the substantial economic costs of manufacturing all six orientations and their repetitions, which are essential for more comprehensive statistical analysis in mechanical tests.

These parts were crafted using PC and adhered to the same printing parameters for characterizing the constitutive model. This approach enabled subsequent finite element analysis (FEA) simulations using the medium isotropic constitutive model.

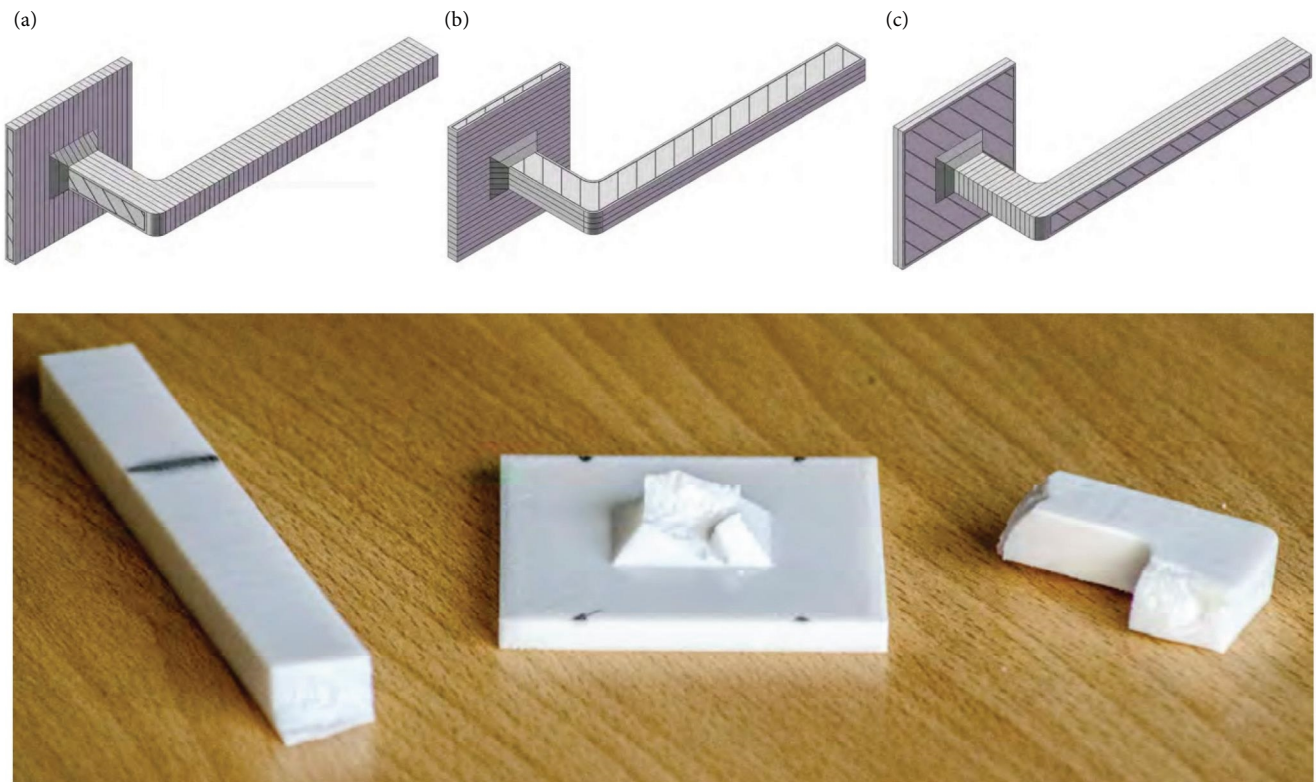


FIGURE 19: Different arrangement of layers and contours in orientation (a–c), specimen broken after testing [87].

Beyond this, a secondary objective emerges: developing a methodology enabling the determination of optimal orientations for FDM part production, considering mechanical behavior, surface finish, and cost. This secondary objective encompasses specific goals such as studying the impact of various part geometries and orientations on surface finish, analyzing factors influencing part cost, devising numerical indexes for prioritizing orientations based on their effects on different properties, and ultimately, validating the methodology's effectiveness.

A multifaceted methodology was employed to test these hypotheses. Tensile and elongation tests were conducted on PC specimens to develop an orthotropic constitutive model. Physical testing involving cantilever beam FDM parts subjected to bending and torsion loads was performed. Furthermore, dynamic mechanical properties were evaluated using a Taguchi experimental design [88].

This function was assessed using a setup and methodology similar to that employed for correlating simulation outcomes via FEA and mechanics. The setup underwent a specific alteration: the elevation of the support structure. This modification aimed to induce higher displacement, surpassing the material's elastic limit, and potentially causing specimen fracture. The Figure 19 illustrates the consistent fracture pattern observed across all specimens, occurring at two distinct locations: the base of the overhang (where stress accumulates significantly) and the elbow (another highly stressed area) [87]. A notable trend emerges when examining Figure 20, which depicts test results for each orientation and their

repetitions (X.a, X.b, X.c) [89]. Across orientations, a linear relationship between force and displacement holds until reaching approximately 20 mm of deformation. Beyond this threshold, linearity diminishes, attributed to two primary factors [90].

Deformation weakens the bonds between threads within or between layers, leading to a loss of linearity in the force–displacement relationship. As deformation progresses, the material surpasses its elastic limit, transitioning into the plastic zone where deformation becomes irreversible. This shift from elastic to plastic behavior is critical for understanding the material's structural integrity under stress. The mechanical behavior of FDM-manufactured parts was studied experimentally, with tensile tests on PC specimens to develop an orthotropic constitutive model. A cantilever beam was also tested under bending and torsion loads, and the results were validated using FEA simulations. A Taguchi experimental design evaluated the dynamic mechanical properties while varying manufacturing parameters such as raster width, air gaps, and nozzle diameter [91–94].

3D-printed PMCs have advanced significantly in industries like aerospace and automotive, where lightweight, high-strength materials are essential. For instance, Airbus and Boeing use 3D-printed PMCs for components that require a high strength-to-weight ratio, resulting in weight reductions and fuel savings. Similarly, Bayerische Motoren Werke (BMW) GmbH and Ford have implemented these materials in prototypes and functional parts, benefiting from rapid prototyping and reduced costs.

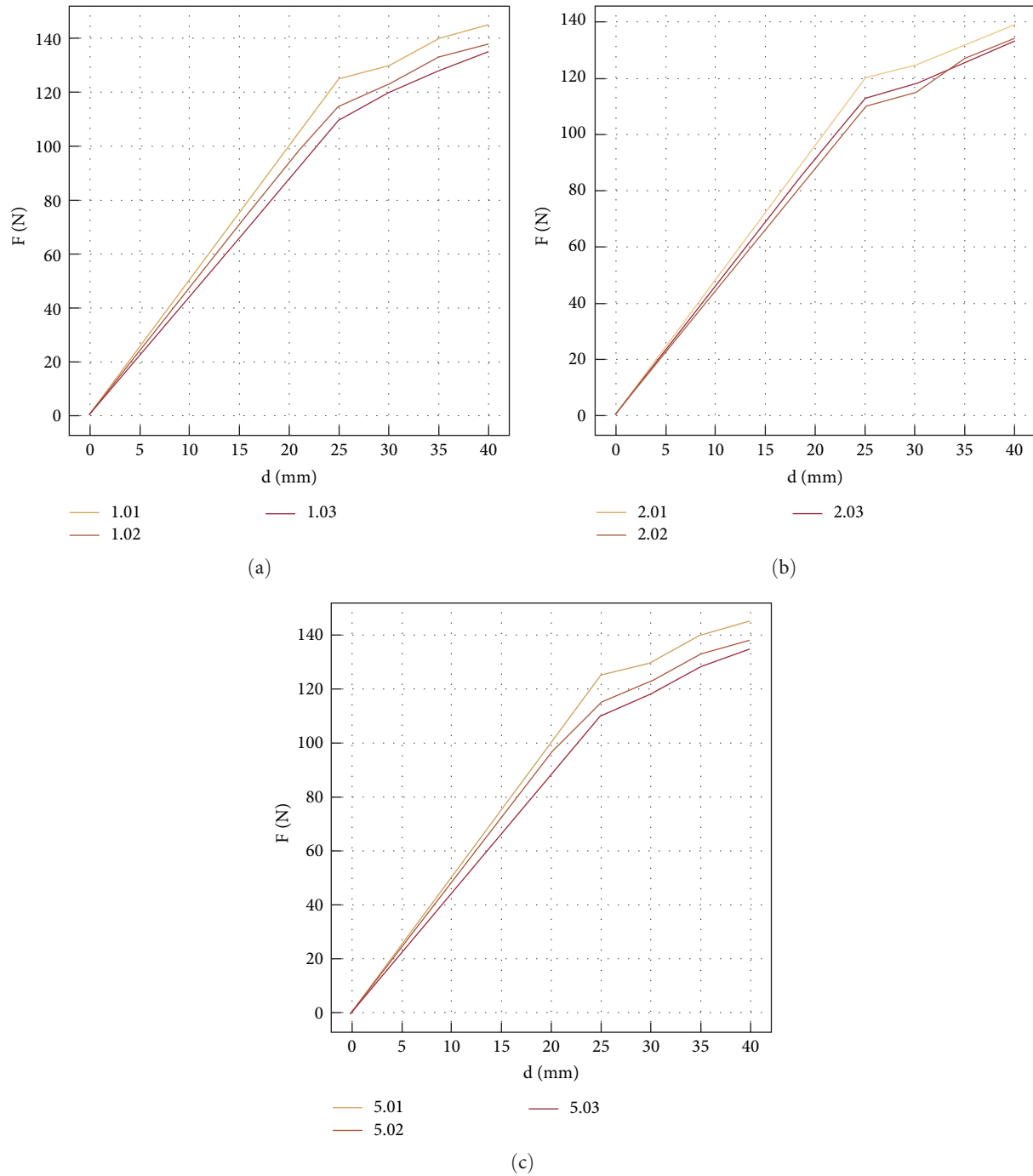


FIGURE 20: (a–c) Effect of orientation [89].

A methodology was developed to determine the optimal orientation for FDM parts, considering surface finish, cost, and mechanical behavior. The methodology used quantitative objective functions for surface finish (considering the staircase effect and layer height), cost (calculated from material volume and build time), and mechanical behavior (using FEA simulation results). The rankings were verified through tensile, bending, and torsion tests, highlighting the anisotropic nature of FDM parts, where strength depends on contour orientations.

The experimental results showed that FDM-manufactured PC parts exhibit anisotropic mechanical behavior, with strength and modulus varying significantly between directions due to thread and layer arrangements. An orthotropic constitutive model was developed and validated using FEA, which accurately predicted displacements in physical bending and torsion experiments. The study also found that increasing contours and reducing raster air gaps improved storage modulus and rigidity [95].

This work demonstrates that FDM parts exhibit anisotropic mechanical performance, which must be considered in loading applications. While the orthotropic model accurately predicted elastic behavior, a simpler isotropic model was often preferred for practical applications. The study provides insights into how to tailor dynamic mechanical properties by adjusting FDM processes and offers a quantitative methodology for optimizing part orientation based on surface finish, cost, and mechanical behavior.

9. Environmental and Economic Aspects

The integration of 3D-printed PMCs into industrial applications necessitates an examination of both environmental and economic impacts, particularly in the context of scalability. The environmental benefits are significant, as 3D printing inherently minimizes material waste compared to traditional subtractive manufacturing techniques. By precisely depositing material layer by layer, the process ensures that only the necessary amount of material is used, which is crucial when dealing with high-cost or rare materials. Additionally, the potential to recycle or reuse materials within the 3D printing process can further enhance sustainability, reducing the environmental footprint [96–98].

On the economic front, while the initial setup costs for industrial-scale 3D printing can be substantial, the technology offers long-term cost-effectiveness. The ability to produce complex geometries without the need for molds or tooling reduces production costs, especially for small to medium-sized batches or customized products. Moreover, advancements in material formulations and processing techniques have the potential to lower energy consumption during production, contributing to both economic savings and reduced environmental impact. However, challenges remain in achieving consistent part quality and performance at scale, which are crucial for fully realizing these economic and environmental benefits. Therefore, ongoing research and development are essential to optimize these processes, ensuring that 3D-printed PMCs can be produced sustainably and economically on an industrial scale [99, 100].

Future research in the field of 3D-printed PMCs should explore several promising avenues. Emerging technologies such as machine learning and artificial intelligence could be leveraged to optimize printing parameters and predict material behavior, thereby accelerating the development cycle. Additionally, interdisciplinary collaborations that integrate materials science, mechanical engineering, and computational modeling could lead to innovative solutions for overcoming current limitations in performance consistency and scalability. Exploring novel material systems, including hybrid composites and smart materials with embedded sensing capabilities, could push the boundaries of what is achievable with 3D-printed PMCs. Furthermore, advancements in postprocessing techniques, such as tailored thermal treatments and surface modifications, hold potential for significantly enhancing the mechanical properties and functional performance of these composites. By addressing these challenges, future research can unlock new applications and

elevate the role of 3D-printed PMCs in industries ranging from aerospace to biomedical engineering.

10. Conclusion

This review offered crucial insights into optimizing the mechanical performance of 3D-printed PMCs. It was evident that microstructural engineering is pivotal, with features like reinforcement type, size, distribution, orientation, and interfacial adhesion enabling tailorable property enhancements. However, processing techniques strongly impact achievable microstructures and resultant performance. Enhancements to build parameters, material formulations, and posttreatments are thus imperative alongside microstructural control. The interplay between structure and processing necessitates a holistic approach to uniting these domains.

The case studies and experimental findings demonstrated successful composites strengthening, toughening, and multifunctionalization by strategically controlling micro and nanoscale features while modifying 3D printing processes. This facilitated performance improvements ranging from 20% to 50% increases in strength, stiffness, and toughness to precise tailoring of functional properties. However, substantial gaps remain in transitioning this fundamental research into largescale manufacturing practices. Ensuring consistency and reliability of high mechanical performance continues to hinder widespread adoption. Part quality issues like porosity and anisotropy also require mitigation. Furthermore, demonstrations beyond the lab scale must validate these approaches' scalability and economic viability.

Tackling these barriers demands persistent microstructural and processing refinements underpinned by the latest material characterization techniques. Sustained developments expanding 3D printing capabilities can unlock the tremendous potential of these engineered composites across diverse industries. A nuanced, scientifically grounded approach optimizing the symbiosis between composition, and processing is key to realizing next-generation lightweight, high-performance structures for largescale applications.

Data Availability Statement

The data supporting this study's findings are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Sivakumar Jaganathan contributed to the conceptualization and design of the study and played a major role in the interpretation of data. Raju Kandasamy was involved in the experimental work, data collection, and initial data analysis. Ravikumar Venkatachalam assisted in refining the experimental methodology and was a key contributor in data analysis. Muthu Gunalan provided critical feedback and helped shape the research, analysis, and manuscript. Ratchagaraja Dhairiyasamy took the lead in writing the manuscript and

was responsible for the overall project administration. All authors discussed the results and implications and commented on the manuscript at all stages.

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