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Mechanical properties and their enhancement of 3d printed polymethyl methacrylate (PMMA) resin: A review of the literature

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Abstract
Poly-methyl methacrylate (PMMA) is a thermoplastic that has gained increasing popularity in additive manufacturing for its transparency, biocompatibility and dimensional stability. The mechanical properties of 3D-printed PMMA components, however, are frequently not as good as those of components made by conventional methods, which restricts their use in load-bearing situations. The present review summarizes literature pertaining to recent research on mechanical properties of 3D-printed PMMA and discusses how to enhance the material properties. The use of nanofillers like carbon nanotubes (CNTs), zirconia, titanium carbide, and antibacterial agents; optimization of printing parameters such as the raster angle, layer thickness, and print speed; and design innovations such as lattice hybridization. The literature shows that the tensile strength can be improved by up to 58% with the reinforcement of nanoparticles[1] and strength and stiffness can be optimized simultaneously through the optimized printing parameters[4]. There are however compromises between strength and ductility and environmental aging will severely affect mechanical properties[2]. This review highlights various challenges that are currently standing in the way of the potential of 3D-printed PMMA in biomedical and engineering applications and suggests future research avenues to overcome such challenges.

Keywords: 3D-printed PMMA, mechanical properties, nanofillers reinforcement

Introduction

The advent of additive manufacturing (AM) or 3D printing has revolutionized the manufacturing of complex parts in various applications such as biomedicine, automotive, and aerospace [1]. Polymethyl methacrylate (PMMA) is a thermoplastic that stands out among the different materials used in AM. PMMA is commonly called organic glass due to its remarkable characteristics: it is highly transparent, light, it is highly hard, it is weather resistant, has a very high elastic modulus, and has very little shrinkage [1]. In addition to all this, PMMA is biocompatible, which make it essential for bone cement, denture bases, optical components and barriers [1, 7].

The addition of PMMA to 3D printing platforms, especially material extrusion (MEX) and vat photopolymerization (VAP) processes, has broadened its applications. The challenges that come with an AM method, however, are not seen in conventional manufacturing, as it is a method that is fabricated layer-by-layer. Several factors including material formulation, printing parameters and post-processing conditions are involved in the mechanical properties of 3D printed PMMA, which is complicated. Furthermore, printed parts are usually anisotropic, with inferior bonding between layers, causing inferior mechanical performance compared to injection-molded or milled parts [9].

This review summarizes the state-of-the-art in the mechanical properties of 3D-printed PMMA and discusses the possible ways to improve these properties. The literature is categorized according to three main approaches: nanocomposite reinforcement, optimization of the process parameters and innovation of the structural design. The benefits, the mechanisms and the limitations of each approach are discussed. The review ends with a discussion of the research gaps and recommendations for future research directions.

Mechanical Properties of Neat 3D-Printed PMMA

1. Baseline Performance and Limitations

The mechanical properties of unmodified 3D printed PMMA are used as the standard by which the process improvement methods are judged. Pure PMMA filaments have a tensile strength of 60 MPa and an elastic modulus of ~ 2.4 GPa. These values are actual optimum conditions, however, the performance of printed parts depends greatly on processing parameters and print orientation.

The flexural properties are strongly affected by print orientation, but some studies indicate that this effect might not be as strong as originally thought. In a recent study, the zirconia-reinforced PMMA resins did not show a significant difference in “flexural strength or flexural modulus ($p > 0.05$) between print orientation (0° versus 90°) [7]. But the same study showed that artificial aging, which is simulating service for one to three years in the oral cavity, significantly reduced flexural strength and modulus after 10,000 thermal cycles with more signs of ageing after 30,000 thermal cycles [2]. The finding highlights the importance of environmental stability for biomedical applications.

2. Influence of Process Parameters

Optimization of printing parameters is the easiest path towards mechanical improvement. The impact of six generic control factors (infill density, raster deposition angle, nozzle temperature, print speed, layer thickness, and bed temperature) has been studied systematically [3]. Of these, the first two factors, namely the deposition angle of the raster and the printing speed, have the largest impact on tensile strength, and the second two, namely the layer thickness and the printing speed, have the largest impact on considerations of energy consumption.

Multiple responses optimization has been done by using advanced modeling techniques. The second-order regression models of tensile strength and elastic modulus of PMMA filaments were developed using a Box-Behnken design of experiments (BBD), with R [2] values of 97.81% and 97.26%, respectively4. These results were also confirmed using the neural network models, where the correlation between the inputs and outputs is 97.62%, 99.74%, and 98.08% during training, validation and testing, respectively. These models are descriptive models that can be used to predict the process parameters required to produce desired mechanical properties.

Nanocomposite Reinforcement Strategies

1. Carbon Nanotube (CNT) Reinforcement

Considering the exceptional mechanical properties and high aspect ratio of carbon nanotubes, considerable attention has been paid to strengthening PMMA using CNTs. A pioneering study on PMMA/CNT nanocomposite filaments for 3D printing work combined experimental analysis and multi-scale finite element modelling [1]. The research used a new representation of the CNTs as three-dimensional, randomly oriented, curved cylinders, which are more accurately able to describe the complex mechanical interactions that occur than previous models [1].

The experimental results showed that the CNTs significantly enhanced the tensile strength of the PMMA matrix by around 58% when 0.5 wt% of CNTs was used in the matrix of PMMA1 alone. This improvement was, however, accompanied by an 8.4% decrease in elongation at break which appears to be a compromise between strength and ductility1. The study also investigated the effect of CNT slenderness factor on the tensile strength, which showed that it could be further optimized by adjusting the slenderness factor of CNTs [1].

The mechanism underlying CNT reinforcement involves improved load transfer from the polymer matrix to the nanotubes, enhanced by the high surface area and stiffness of the nanofillers. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) analyses confirmed the importance of CNT dispersion quality and interfacial bonding for achieving optimal mechanical performance [1]. However, the challenge of uniform dispersion within the polymer matrix persists, with agglomeration reducing reinforcement effectiveness [1].

2. Ceramic and Metallic Nanoparticle Reinforcement

Beyond carbon-based nanomaterials, ceramic and metallic nanoparticles have demonstrated significant potential for PMMA reinforcement. Zirconia-reinforced PMMA resins, investigated for dental applications, showed that print orientation effects were minimal but aging significantly degraded flexural properties [2]. The microhybrid resin composite exhibited higher flexural strength than 3D-printed materials throughout aging protocols, highlighting the gap between current 3D-printed materials and conventional composites [2].

Titanium carbide (TiC) reinforcement of recycled PMMA presents a dual advantage: sustainability combined with mechanical enhancement. Research on MEX additive manufacturing of PMMA/TiC nanocomposites revealed that the 2.0 wt% composite demonstrated the most favorable impact on strength, with 28.5% and 27.3% increases in tensile and flexural loadings, respectively [6]. The 8.0 wt% composite exhibited the greatest enhancement in stiffness, with a 47.2% increase in Young's modulus [6]. These findings demonstrate that TiC concentration can be tuned to prioritize either strength or stiffness depending on application requirements.

3. Functional Nanocomposites

Recent innovations have expanded the scope of PMMA nanocomposites beyond purely mechanical enhancement to include multifunctional capabilities. The incorporation of antibacterial blend nanopowder into PMMA represents a novel approach addressing infection control—a critical consideration for biomedical applications [5]. PMMA/antibacterial blend nanocomposites exhibited improved tensile strength (~20% increase at 2 wt%) and flexural strength (~10.8% increase at 4 wt%) while simultaneously demonstrating strong antibacterial properties against *Staphylococcus aureus* and mild antibacterial activity against *E. coli* [5].

This dual functionality broadens the application spectrum of 3D-printed PMMA in the defense and medical sectors, where both mechanical integrity and infection prevention are paramount [5]. Micro-computed tomography analysis confirmed that the addition of antibacterial agents did not compromise the geometrical accuracy of printed structures, while rheological and thermal characterization validated the processability of the nanocomposites [5].

Structural Design for Mechanical Enhancement

1. Lattice Structures

Structural design optimization offers an alternative to material modification for enhancing mechanical performance. Lattice structures—characterized by repeating interconnected elements—provide high strength-to-weight ratios that are particularly valuable for lightweight applications [7]. Advancements in additive manufacturing have facilitated the fabrication of such complex geometries, which are difficult to produce using conventional methods [7].

A study investigating the effect of 3D hybridization of PMMA lattice structures revealed significant improvements in compressive strength [7]. Hybridization of Schwarz primitive (SP) and Gyroid structures along three mutually perpendicular directions (X, Y, and Z) demonstrated that the GSP(Z) hybrid exhibited the highest compressive strength at 6.53 MPa, representing a 26.06% increase compared to the GSP(X) lattice [7]. The SP lattice showed the lowest ultimate compressive strength at 1.29 MPa, confirming that hybridization substantially enhances mechanical performance [7]. The strength per unit material consumption (S/UMC) was highest for GSP(Z) at 0.826, compared to 0.198 for the SP lattice, indicating superior material efficiency [7].

2. Comparison with Conventional Manufacturing

The mechanical performance of 3D-printed PMMA relative to conventionally manufactured counterparts remains a subject of active investigation. A systematic review and meta-analysis comparing bonding strength of reline materials and denture teeth between 3D-printed and milled complete denture bases identified significant variability in outcomes [9]. The review included 20 studies published between 2020 and 2024, encompassing various printing technologies including DLP, SLA, DLS, LCD, and FDM [9]. Flexural strength comparisons reveal substantial variation depending on material formulation and printing technique.

Heat-polymerized PMMA generally exhibits higher flexural strength than 3D-printed alternatives, with reported values ranging from 89.54 MPa for conventional PMMA to 168.57 MPa for milled PMMA [9]. However, DLP bisacrylic photopolymers have demonstrated flexural strengths up to 146.37 MPa, approaching the performance of milled materials [9]. This suggests that careful material selection and process optimization can narrow the performance gap between 3D-printed and conventionally manufactured PMMA components.

Challenges and Future Directions

1. Dispersion and Interfacial Bonding

The most significant challenge in nanocomposite reinforcement remains achieving uniform nanofiller dispersion within the polymer matrix. Poor dispersion leads to agglomeration, reducing the effectiveness of nanofillers in enhancing mechanical properties [1]. Weak interfacial bonding between nanofillers and the polymer matrix further limits load transfer, particularly in brittle polymers like PMMA where premature failure can occur under tensile loading [1].

Surface functionalization of nanofillers—including the addition of chemical groups to improve compatibility with the polymer matrix—has shown promise in enhancing dispersion and interfacial bonding [1]. Multi-scale finite element models incorporating different adhesion models (e.g., bilinear and exponential traction-separation curves) have been employed to optimize the simulation of interfacial behavior [1]. Continued development" of such modeling approaches, combined with advanced characterization techniques, will be essential for understanding and controlling reinforcement mechanisms.

2. Trade-offs in Mechanical Properties

A recurring theme in the literature is the trade-off between strength and ductility. CNT reinforcement significantly increases tensile strength but reduces elongation at break [1]. Similarly, while nanoparticle reinforcement enhances stiffness, it may compromise toughness. Strategies to mitigate this trade-off include optimizing nanofiller concentration and geometry, as well as exploring hybrid reinforcement approaches that combine multiple filler types [10].

The addition of cellulose nanocrystals (CNCs) and silver nanoparticles (AgNPs) to PMMA resin demonstrates the potential of hybrid reinforcement. Flexural strength increased by up to 31.6% with the addition of 0.1 wt% AgNPs and 1 wt% CNCs, while impact strength increased by up to 24.2% [10]. The synergistic effect of CNCs and AgNPs enhanced interfacial adhesion between the polymer matrix and reinforcement particles, suggesting that hybrid approaches may overcome limitations of single-filler systems [10].

3. Long-Term Durability and Aging

Environmental aging represents a critical concern for PMMA components in service. Artificial aging studies simulating intraoral conditions reveal significant degradation of flexural strength and modulus after thermal cycling [2]. The mechanisms underlying this degradation include moisture absorption, thermal stress, and incomplete cross-linking in printed parts [9]. Post-processing treatments, such as extended polymerization and thermal annealing, have been investigated to improve cross-linking density and enhance long-term stability [9].

4. Standardization and Clinical Translation

The substantial heterogeneity observed in flexural strength studies—evidenced by I [2] values of 99% in meta-analyses—highlights the need for standardized testing protocols and reporting. Variability in printing technologies, resin formulations, post-processing protocols, and testing conditions complicates direct comparison of results across studies [9]. Development of consensus standards for 3D-printed PMMA characterization will accelerate clinical translation and enable more robust engineering applications.

Conclusion

The literature on mechanical properties of 3D-printed PMMA reveals a rapidly evolving field characterized by diverse enhancement strategies and expanding application potential. Nanocomposite reinforcement—particularly with CNTs, TiC, and zirconia—has demonstrated significant improvements in tensile and flexural strength, with reported increases of up to 58% [1]. Process parameter optimization provides a complementary approach, with modeling techniques enabling predictive control of mechanical outcomes [4]. Structural design innovations, including lattice hybridization, offer additional routes to performance enhancement through geometry optimization [7].

However, several challenges must be addressed to realize the full potential of 3D-printed PMMA. The trade-off between strength and ductility persists, environmental aging degrades long-term performance, and substantial variability in reported properties highlights the need for standardization [1, 2, 9]. Future research should focus on hybrid reinforcement strategies that synergistically enhance multiple mechanical properties, advanced interfacial engineering to improve load transfer, and development of predictive models that integrate material formulation, processing parameters, and service conditions.

The integration of multifunctional capabilities—such as antibacterial properties combined with mechanical reinforcement—represents a particularly promising direction for biomedical applications [5]. As additive manufacturing technologies continue to advance, 3D-printed PMMA is positioned to expand its role from prototyping to production of functional components in engineering and medicine, provided that ongoing research addresses the challenges identified in this review.

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