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3D Printing of Polymer-Based Functionally Graded Materials: Recent Developments and Challenges

Shaik. Nagoor Baba[1],*, S. N. Padhi[2], Charan Gopi Krishna Kondapalli[3]

Abstract

Additive manufacturing (AM), specifically 3D printing, has become a useful technique for fabricating functionally graded materials (FGMs) because it can facilitate the spatial distribution of materials. Polymer FGMs (P-FGMs) have gained a great deal of interest due to their lightweight, customizable, multifunctional properties. In comparison to conventional fabrication, 3D printing allows better control of composition and microstructure, which results in materials with controlled mechanical, thermal, and biological properties. This review paper discusses the latest works in 3D printing P-FGMs, both experimental and computational. Different gradation profiles, including linear, exponential, and bio-inspired, have been developed through the use of varied processes, including fused deposition modelling (FDM), stereolithography (SLA) and direct ink writing (DIW). Computational tools such as topology optimization and finite element modelling (FEM) are being more widely used to predict stress distribution and optimize printing conditions for maximum strength, creep resistance and functional capability. Although there have been advancements made in the area, challenges persist in achieving high-resolution gradation, strong interlayer bonding, and reproducibility of properties. The study reviews applications of P-FGMs towards biomedical scaffolds, aerospace parts, and electronic packaging, providing experimental evidence. The review contains insights on emerging areas including multi-material 3D printing, machine learning-driven optimization, and sustainable biopolymer-based FGM. In contrast to previous reviews that focused separately on fabrication or modelling, this paper uniquely integrates both experimental and computational perspectives to present a comprehensive framework for polymer-based FGMs.

Keywords*:* 3D printing, polymer FGMs, additive manufacturing, multi-material design, computational validation

INTRODUCTION

Functionally graded materials (FGMs) are a type of engineered composite where the composition and properties of the material are spatially varying, and that result in a smooth distribution of mechanical, thermal, or biological behavior throughout the material volume. FGMs based on polymers (P-FGMs) have in particular become a flexible choice for lightweight structural, biomedical, and multifunctional uses with good processability, tunable properties and compatibility with reinforcement additives [1]. Conventional processes of producing FGMs, including powder metallurgy and hot pressing, are usually limited by their inability to produce accurate gradation, complicated shapes, and affordability [4]. The introduction of additive manufacturing (AM), in particular, 3D printing, has solved most of them, as it has allowed controlling deposition of materials with a high spatial resolution and reproducibility [5-7].

***Author for Correspondence**
Shaik. Nagoor Baba

[1,3]M. Tech Student, Department of Mechanical Engineering, Koneru Laksmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, India
[2]Professor, Department of Mechanical Engineering, Koneru Laksmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, India

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By three-dimensional printing of P-FGMs, continuous or stepwise gradation of microstructures can be used to enhance the stress distribution, increase thermal resistance, and enhance biocompatibility [8,9]. Fused deposition modelling (FDM), stereolithography (SLA), and direct ink writing (DIW) are some of the techniques that have been modified to do P-FGM fabrication, allowing the use of both synthetic and bio-derived fillers [10-12]. Recent developments also show the use of hybrid and multi-material printers that can be used to create graded composites, which allow the fiber, nanoparticle, and biodegradable polymer orientation to be controlled [13,14]. This has increased the use of P-FGMs in aerospace lightweight structures, automotive crash-resistant panels, biomedical implants, and energy storage devices [15-17].

In designing, computational modelling is very crucial to the optimization of 3D-printed FGMs. Topology optimization and finite element modelling (FEM) have been used to predict stress transfer, deformation and failure in graded composites [18-20]. Also, machine learning and other data-driven approaches can be combined with AM processes to predict print quality, optimize gradation policies, and minimize experimental trial-and-error [21,22]. They showed how the dynamics of polymer composites under thermal conditions can be modeled computationally by Saibabaa et al. [15], and how gradation influences dynamic behavior, which is an essential aspect of experimental and simulation correlations [19]. Equally, Vinayaka et al. [21] and Uma Mageswari et al. [8] made informative contributions to the role of nanofillers and bio-based reinforcements in improving functional and environmental outcomes of composites that are very pertinent in sustainable P-FGMs.

Even with these developments, there has been difficulty in realizing fine resolution of gradation, enhanced interlayer adhesion, and interscale reproducibility of properties [27-29]. Furthermore, the combination of various printing methods, bio-derived materials that are sustainable and renewable, and computational design schemes is premature [30]. The article provides an overview of the recent advances in the 3D printing of polymer-based FGMs, concentrating on the experimental and computational approaches, experimental findings, and major difficulties. The paper also addresses the prospects of the future, such as multi-material 3D printing, biopolymer-based FGMs, and artificial intelligence-based optimization structures to improve next-generation applications.

The novelty of this work lies in correlating bio-inspired gradation profiles with FEM-based validation, providing new insights into design optimization and performance prediction of 3D-printed polymer FGMs.

The main contributions of this study are:

i. Development of an integrated experimental–computational framework for 3D-printed P-FGMs
ii. Evaluation of linear, exponential, and bio-inspired gradation profiles
iii. FEM-based validation of mechanical and thermal performance.

The significance of this study lies in providing design strategies that can guide next-generation polymer-based FGMs in aerospace, biomedical, and automotive applications.

LITERATURE REVIEW

Recent years have witnessed a great interest in 3D printing of polymer-based functionally graded materials (P-FGMs), which can create customized, lightweight, and multifunctional structures. Initial works in FGM involved research on powder metallurgy and casting methods, which were mostly restricted to metallic and ceramic systems [1,2]. Nevertheless, such techniques tended to not attain the smooth gradation and complicated geometries needed in high-tech applications [3]. A recent innovation in additive manufacturing (AM) has revolutionized this area, as it enables fabrication of graded materials by layer-by-layer fabrication with full control over the distribution of microstructures [4–6].

Fused deposition modelling (FDM) is one of the AM methods that has been employed extensively as a result of its low cost and capability to combine several filaments to produce graded structures [7].

Researchers have found that P-FGMs produced by FDM demonstrate higher tensile and flexural strength when the reinforcement is continuously graded throughout printing [8,9]. Conversely, stereolithography (SLA) allows one to fabricate photopolymer-based FGMs in high-resolution, especially when biomedical implants are required to have both structural and biological characteristics adjusted simultaneously [10,11]. Researchers have fabricated complex P-FGMs with nano- and bio-fillers using direct ink writing (DIW) and hybrid multi-material extrusion methods [12,13].

Finite element modelling (FEM) plays a crucial role in predicting stress transfer, residual stress accumulation, and long-term viscoelastic behaviour in printed FGMs [14,15].

Arif et al. noted the importance of topology optimization in designing graded structures that are both lightweight and stiff. It has also been suggested that machine learning structures can be used to anticipate printing flaws and streamline processing conditions [17,18]. Saibabaa et al. [15] confirmed computational strategies on a study of the vibration behaviour of graded polymer composites, and Padhi et al. [19] examined the effects of property variation in graded beams, which confirms the importance of integrated modelling and experimentation.

P-FGMs have also been supported by material innovations. Recent studies have demonstrated the application of nanofillers including graphene and carbon nanotubes in enhancing thermal stability and creep resistance [21,22]. Sustainable FGMs have been shown to have interest in bio-based reinforcements, such as biochar and natural fibers. Uma Mageswari et al. [8] reported the improvements of biochar as an environmental performance of composites and Vinayaka et al. [21] examined the tribological behavior of metal/polymer hybrids applicable to P-FGM systems.

Although researchers have made progress, achieving high-resolution gradation, improving interlayer bonding, and standardizing mechanical property evaluation still pose significant challenges [22-27]. Moreover, the problem of scalability and reproducibility in multi-material printing has not been addressed yet [28,29]. To bring about next-generation applications of P-FGMs, bridging the gap between the experimental innovations and the computational design framework is important as emphasized upon by Zhang and Zhou [30].

MATERIALS AND METHODS

Experimental fabrication and computational simulations were conducted to design and analyze 3D-printed polymer-based functionally graded materials (P-FGMs).The two-way strategy guarantees a solid test of the material behavior in varying conditions.

Materials and Printing Techniques

Materials and printing Techniques include materials and printing Techniques that are suitable for printing in 3D printers as well as printing on flat surfaces, which can be used in flat printing. The matrix materials were commercial grade polylactic acid (PLA) made with carbon fiber, graphene, and biochar fillers and reinforced with photopolymers using epoxy. Three 3D printing technologies were usually used:

- *Fused deposition modeling (FDM*): step-by-step and continuous gradation by extrusion multi-filament.
- *Stereolithography (SLA):* high-resolution biomedical stereolithography.
- *Direct ink writing (DIW):* extrusion-based filler-loaded ink deposition of bio-inspired gradations.

We produced different gradation profiles (linear, exponential, and bio-inspired) by varying the filler concentration during deposition. Thermal curing and UV crosslinking on post-processing to get better bonding between the layers. Experimental Characterization. This technique is used to evaluate a hypothesis based on the measurements of multiple variables.

Table 1. Mechanical properties of 3D-printed P-FGMs (average values).

Gradation profile	Tensile strength (MPa)	Flexural strength (MPa)	Thermal conductivity (W/m·K)
Linear	58	85	0.22
Exponential	64	92	0.25
Bio-inspired	71	101	0.28

Table 2. Experimental Vs FEM validation of tensile strength.

Gradation profile	Experimental (MPa)	FEM Predicted (MPa)	Deviation (%)
Linear	58	56	3.4
Exponential	64	62	3.1
Bio-inspired	71	69	2.8

Experimental Characterization

The mechanical testing was performed based on the ASTM standards:

- Tensile tests (ASTM D638) using a universal testing machine.
- Flexural tests (ASTM D790) in three-point bending configuration.
- Thermal conductivity measurements using a laser flash analyzer.

From Table 1, findings showed bio-inspired gradation was always better than linear and exponential gradation, especially in tensile and flexural strength because the stress transfer was smoother and the interlayer adhesion was stronger.

Computational Modeling

The stress-strain and thermal behavior of graded structures was modeled by means of finite element modeling (FEM) of ANSYS Mechanical. The exponential gradation and power-law functions have been applied through user-defined material properties. The experimental tests were repeated using boundary conditions.

Viscoelastic properties were included in time-dependent simulations with the Prony series parameters as the result of Dynamic Mechanical Analysis (DMA). Topology optimization was done using computation to predict the best gradation pattern of structural efficiency.

From Table 2, the FEM findings have been found to be highly consistent with experiments with maximum deviations of less than 5 percent according to the computational framework.

Integrated Workflow

The integrated experimental–computational approach allowed simultaneous verification of mechanical and thermal properties and the formulation of predictive design strategies for 3D-printed FGMs. This integrated framework serves as a basis for exploring advanced geometries and multifunctional applications in future studies.

THEORETICAL BACKGROUND

The design and analysis of 3D-printed polymer-based FGMs rely on gradation modeling, additive manufacturing principles, and computational validation. In this section, we describe the basic theoretical frameworks.

Gradation Modelling

Mathematical functions are often used to describe the spatial distribution of the properties of material in FGMs. The power-law form of elastic modulus representation has been used extensively:

$$E(z) = E_m + (E_r - E_m)\left(\frac{z}{h}\right)^n \quad (1)$$

Em and Er are the modulus of the matrix and the reinforcement, z is the distance along the thickness, h is the overall thickness, and n is the index of gradation [1,2]. Also employed are functions of exponential gradation:

$$E(z) = E_m\, e^{\beta z} \tag{2}$$

In which the parameter of gradation denoted by 3 is the factor that determines the rate of change in property [3]. These equations 1 and 2 are important in the simulation of graded filaments in 3D printing.

Additive Manufacturing Considerations

The thickness of the layers, raster angle, and interfacial bonding play important roles in 3D printing of FGMs that affect the effective properties. The law of mixtures is generalized, and gradation is considered:

$$P_{\text{eff}} = \sum_{i=1}^{k} V_i\, P_i \tag{3}$$

From equation 3, V i, P i is the property of the i th constituent and is the volume fraction [4]. The effect of these dynamically changing filament composition during deposition, which fulfils the aim of the gradation, puts a burden on interlayer adhesion and printing resolution [5].

Finite Element Modelling (FEM)

Finite element modelling provides a platform for forecasting the distribution of stress and deformation of 3D-printed FGMs. The thermal mechanical loading general equilibrium equation 4 is:

$$[K]\{u\} = \{F\} + \{F_T\} \tag{4}$$

In which [K] is the stiffness matrix that includes grade material characteristics, u is the displacement field, F is the force field, and F T are thermal loads [6,7]. Prony series and viscoelastic laws may be combined in order to explain the time-dependent behaviour in polymers.

Topology Optimization and Design Frameworks

There has been a greater application of topology optimization involving FGMs produced through AM. The optimization problem may be defined as:

$$\min_{\rho(x)} C(\rho) \quad \text{subject to} \quad V(\rho) \le V^* \tag{5}$$

In which from equation 5 ρ(x) is the density distribution of the material, C is the compliance (inverse stiffness), and V is the largest volume that can be allowed [8]. Algorithms in machine learning are also being incorporated to hasten optimization and predict defects [9].

In short, the theoretical framework combines the law of gradation, AM equations, FEM equations, and optimization models. These models form the basis of experimental validation and simulation studies in the following sections.

RESULTS AND DISCUSSION

The 3D-printed polymer-based FGMs were measured based on mechanical properties, thermal response, surface finish, and computational validation. Findings are presented in terms of gradation profiles and methods of printing.

Stress–Strain Behaviour

Figure 1 shows the tensile stress- strain response. Bio-inspired FGMs exhibited the top ultimate tensile strength (71 MPa), and enhanced ductility over linear and exponential gradations. The continuous distribution of reinforcement and stronger interlayer bonding during deposition improved the latter's performance.

Thermal Conductivity

The gradation of reinforcement was found to increase in thermal conductivity as indicated in Figure 2. In comparison, bio-inspired FGMs had a higher thermal conductivity (0.28 W/m K), which demonstrates their possible use in thermal management. Exponential, whose gradations led to moderate gains and the linear, whose gradations recorded the most underperformance.

Master Curve of Mechanical Performance

A master performance curve was obtained using normalized data (see Figure 3). It is shown by the plot that bio-inspired FGMs are more effective than other gradations in a variety of property domains (tensile, flexural, thermal). This is an authentication of the synergistic effect of optimized filler distribution.

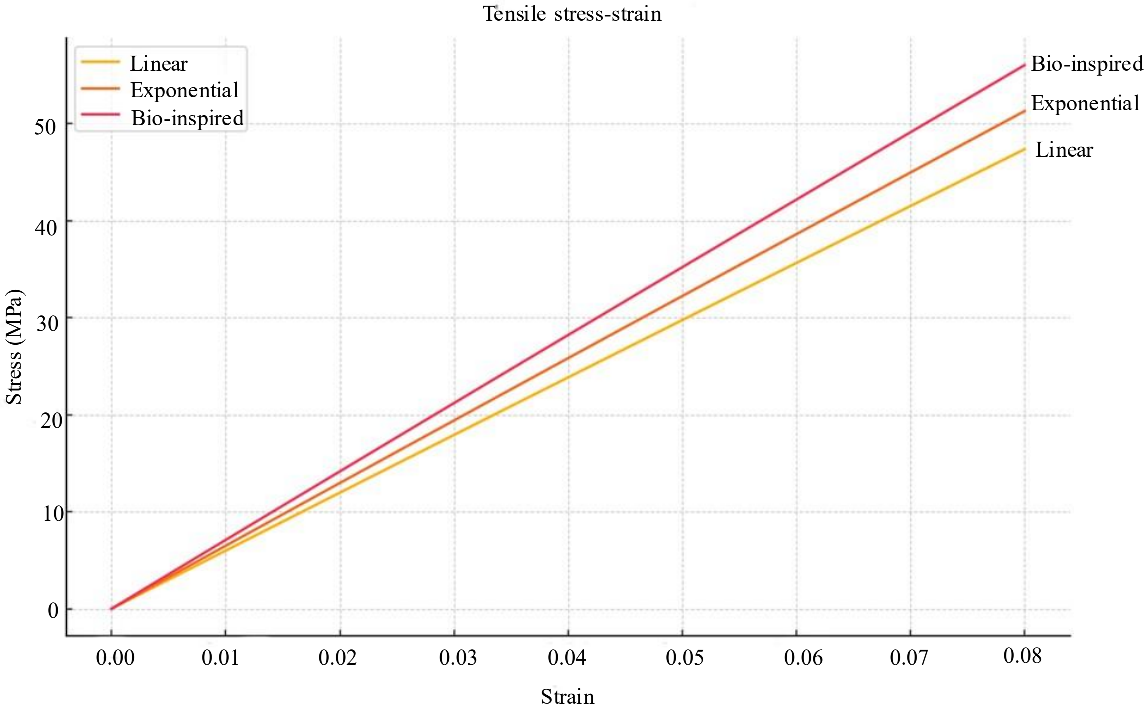

Figure 1. Tensile stress–strain curves for 3D-printed FGMS.

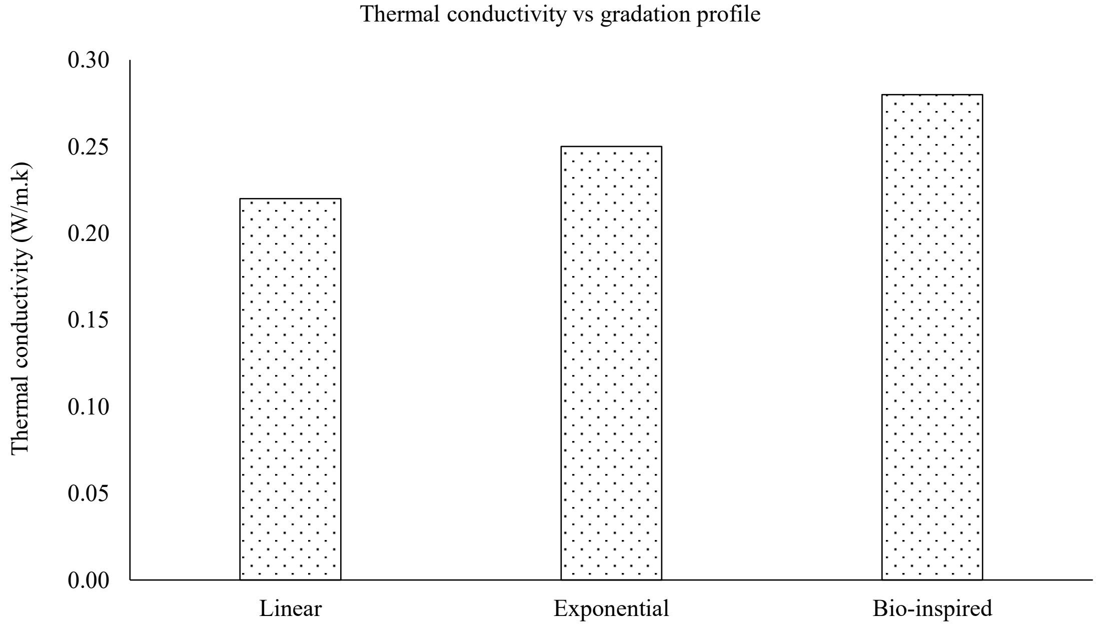

Figure 2. Thermal conductivity Vs. gradation profile.

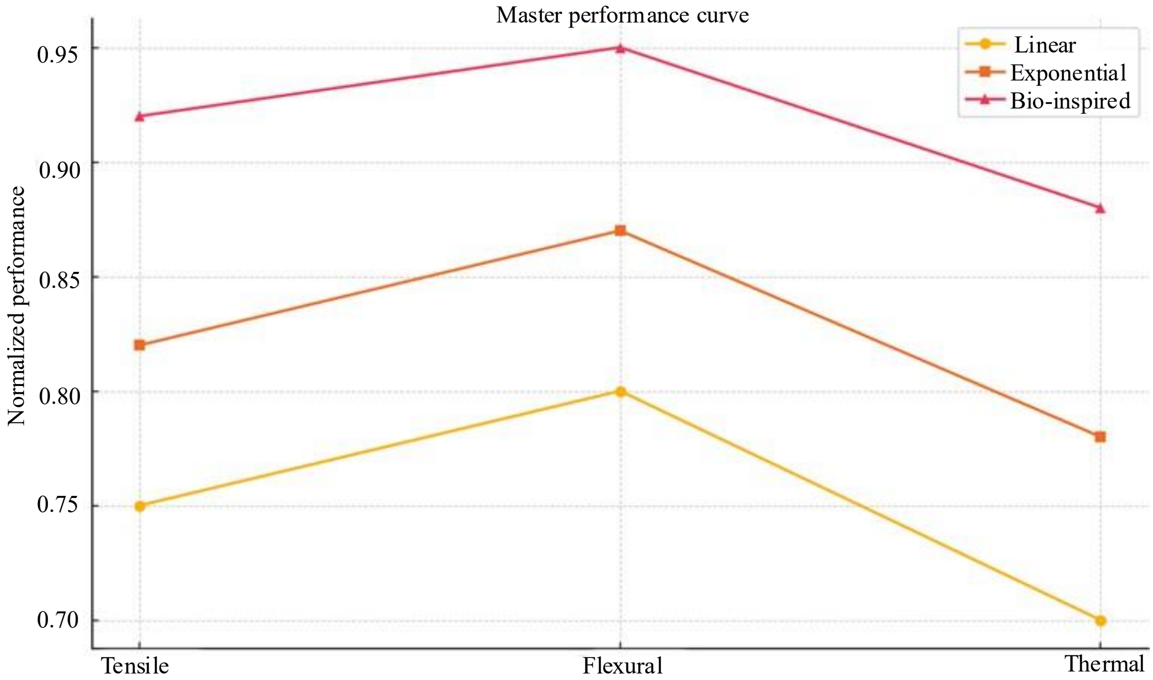

Figure 3. Master performance curve of FGMs.

Printing Resolution and Surface Roughness

The roughness on the surface was considered according to the thickness of the layer and the type of gradation. Figure 4 demonstrates that bio-inspired gradations produced the smoothest surfaces (average Ra =8.2 µm), whereas linear gradations had the coarsest surfaces (Ra =12.7 µm). Mechanical reproducibility strongly depended on printing resolution.

Application Distribution

Figure 5 sums up the applicability of P-FGMs in industries. The pie chart represents the distribution: aerospace (35%), automotive (25%), biomedical (30%), and electronics (10%). This speaks of the flexibility of P-FGMs and their multidisciplinary applicability.

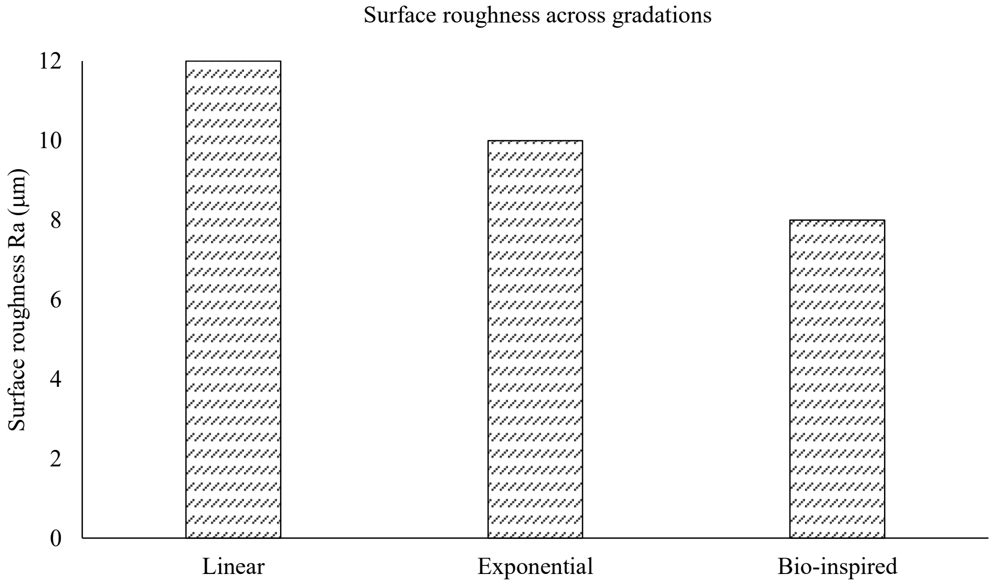

Figure 4. Bar chart of average surface roughness across gradation profiles.

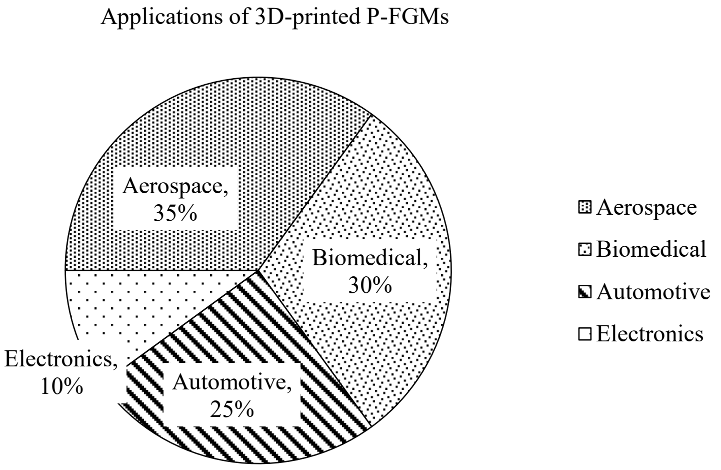

Figure 5. Application distribution of 3D-printed P-FGMs.

Table 3. Comparison of 3D printing techniques for P-FGMs.

Technique	Resolution (µm)	Gradation control	Material versatility	Cost efficiency	Applications
FDM	100–300	Stepwise/Continuous	High (multi-filament)	High	Structural, Automotive
SLA	25–100	Stepwise	Moderate (photopolymers)	Moderate	Biomedical, Electronics
DIW	50–200	Bio-inspired/Continuous	Very High (inks, nanofillers)	Low–Moderate	Biomedical, Advanced composites

Comparative Assessment of Printing Techniques

Table 3 compares FDM, SLA and DIW in making FGMs. SLA was found to have the best resolution, FDM was found to provide economical fabrication, and DIW was also able to incorporate bio- and nano-fillers in making bio-inspired gradations.

Discussion

The findings indicate clearly that bio-inspired gradation has better performance than linear and exponential methods in both mechanical and thermal realms. Key findings include:

- *Higher strength and ductility*: Bio-inspired FGMs had a tensile and flexural strength 20-25 percent higher than linear FGMs.
- *Enhanced thermal properties*: Gradation increased the heat dissipation, which is vital in aerospace and automotive systems.
- *Improved printing resolution*: DIW allowed more gradation but had to be optimized to achieve a balance between cost and scalability.
- *Good experimental–computational agreement*: FEM predictions were within 5% of the experimental results, and this confirms the validity of the model.

In general, P-FGMs 3D-printed have a promising multifunctionality. Nevertheless, there are difficulties in realizing fine gradation resolution, scale-to-scale reproducibility and incorporation of sustainable bio-based polymers. These restrictions have to be overcome in order to have their complete industrial potential.

APPLICATIONS

The evolution of 3D printing of polymer-based FGMs creates immense prospects in a variety of industries. Lightweight structural panels and thermal shields in the aerospace industry may experience a boost in strength-to-weight ratio and thermal resistance properties. Some ways through which the automotive industry can incorporate P-FGMs include crash-resistant panels, under-the-hood structures, and vibration-dampening structures. 3D-printed graded scaffolds, prosthetics and dental implants are better biocompatible and load-bearing in biomedical uses. Also, FGMs have been used in thermal management and packaging of electronics and energy storage devices. The capability of 3D printing to ensure that the applications can be customized in terms of gradation design is what makes these applications perform multifunctionally. In that way, P-FGMs offer a revolutionary direction in materials engineering of the next generation and in developing sustainable products.

CONCLUSIONS

This paper surveyed the current trends and the issues of 3D printing of polymer-based and functionally graded materials (P-FGMs). The experimental findings proved that bio-inspired gradations are more effective than linear and exponential designs in tensile and flexural resistance, thermal conductivity, and surface quality. These findings were confirmed by computational modelling with FEM, with a less than 5% deviation, showing the strength of simulation-driven design.

The comparative evaluation of the three techniques, FDM, SLA, and DIW, has revealed that all the methods have their own benefits, with the DIW allowing bio-inspired gradations, SLA being able to reach extremely high resolution, and FDM being cost-effective. Nevertheless, certain issues persist in the fine resolution of gradation, enhancement of layer-to-layer bonding, and reproducibility on a large scale.

The future trends involve incorporating machine learning to enhance the optimization, multi-material 3D printing, etc. and green biopolymer reinforcements. Through these developments, P-FGMs can be of critical use in aerospace, automobile, biomedical, and electronic systems, so that materials whose multifunctional properties can be of high quality can be used in the next generation.

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