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Review

Advancements and Challenges in Additively Manufactured Functionally Graded Materials: A Comprehensive Review

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Abstract: This paper thoroughly examines the advancements and challenges in the field of additively manufactured Functionally Graded Materials (FGMs). It delves into conceptual approaches for FGM design, various manufacturing techniques, and the materials employed in their fabrication using additive manufacturing (AM) technologies. This paper explores the applications of FGMs in diverse fields, including structural engineering, automotive, biomedical engineering, soft robotics, electronics, 4D printing, and metamaterials. Critical issues and challenges associated with FGMs are meticulously analyzed, addressing concerns related to production and performance. Moreover, this paper forecasts future trends in FGM development, highlighting potential impacts on diverse industries. The concluding section summarizes key findings, emphasizing the significance of FGMs in the context of AM technologies. This review provides valuable insights to researchers, practitioners, and stakeholders, enhancing their understanding of FGMs and their role in the evolving landscape of AM.

Keywords: functionally graded materials; additive manufacturing; design concepts; manufacturing techniques; 4D printing; metamaterials

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1. Introduction

AM has emerged as a transformative force in modern manufacturing, enabling intricate designs and personalized structures through layer-by-layer deposition of materials. Within the diverse landscape of AM, the concept of functionally graded additive manufacturing (FGAM) has gained prominence. It represents a paradigm shift in material fabrication, involving the simultaneous deposition of different materials in predefined ratios. This process results in microstructural gradients within the manufactured component, endowing it with tailored material characteristics [1]. Figure 1 serves as a compelling visual representation of the evolutionary trajectory of FGM technology. The roots of FGMs can be traced back to the pioneering work of Japanese scientists in the 1980s. Initially proposed for high-temperature applications in space aircraft [2], the concept has evolved to encompass a broader spectrum of functionalities and applications. Since its inception, it has undergone a notable proliferation across a diverse spectrum in major engineering disciplines, marking a remarkable journey of adoption and advancement. This temporal visualization encapsulates the transformative nature of FGM, highlighting its substantial growth and integration within various fields of scholarly exploration. The apparent rise in its utilization attests to the escalating recognition of FGM's capacity to innovate and revolutionize conventional manufacturing paradigms, impacting industries and contributing to the expanded growth of the aerospace, biomedicine, materials science, and engineering sectors. Thus, Figure 1 stands as a testament to the transformative potential of FGM, charting its historical emergence and its dynamic role in shaping contemporary academic and industrial landscapes.

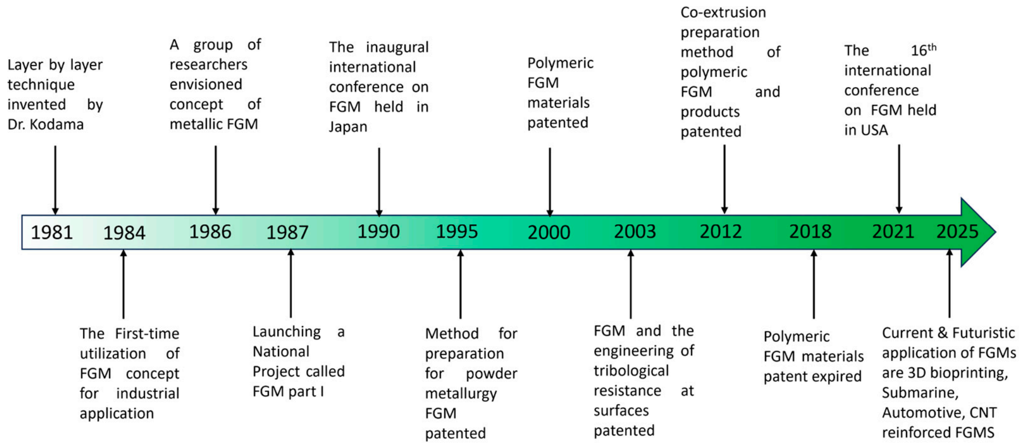

Figure 1. Timeline of FGAM technology.

Several patents and applications have been filed for different FGM techniques, In the beginning of 1990, the inaugural international conference on FGM was held in Japan. However, the first FGM polymeric material was patented in 2000. There are various applications for FGMs in the present and in the future, such as 3D bio-printing, sub-marine, and automotive applications, and the applications for Carbon Nano Tubes (CNT)-reinforced FGMs include soft robotics, electronics, 4D printing, and the development of metamaterials [3–14]. Their significance lies in their ability to address specific challenges posed by traditional materials. By tailoring material properties across a component, FGMs offer a more efficient distribution of mechanical, thermal, and chemical properties, contributing to improved overall performance [15]. This introduction sets the stage for a comprehensive exploration of FGAM, aiming to delve into the conceptual approaches guiding its design, the array of manufacturing techniques employed, the diverse materials integrated into FGMs through AM, and the broad spectrum of applications across industries. Additionally, this review will scrutinize critical issues and challenges associated with FGAM, explore emerging trends, and ultimately contribute to a deeper understanding of the evolving landscape of AM through the lens of FGMs. Conventional Material Extrusion (MEX) technology typically employs a distinct extrusion nozzle for each material, posing challenges for smooth material transitions [11]. A distinctive advantage of the FGAM method over traditional MEX lies in its capability to seamlessly swap materials without necessitating alterations to the extrusion head. However, the existing body of literature on FGAM is somewhat limited, predominantly focusing on experimental design, manufacturability, and behavior analysis of FGMs produced through the MEX process. Doubrovski et al. [16] introduced an innovative approach aimed at redefining FGMs by representing part geometry and material attributes. This novel methodology utilizes a bitmap approach to convert material attributes into a composite material composition. The workflow exhibited by Doubrovski et al. provides designers with a systematic framework to enhance the performance and utility of the produced products. In a parallel investigation, Ituarte et al. [17] concentrated on harnessing the multi-material Binder Jetting (BJ) technique for the design and production of functionally graded structures. Their findings underscored the significant potential of the multi-material BJ technique in the design and manufacturing of such structures. Subsequently, examples of FGM components produced through diverse manufacturing processes, including those naturally occurring, are showcased. In Figure 2, research efforts focusing on varied graded patterns [18] and bioinspired applications, such as dental implants, are depicted.

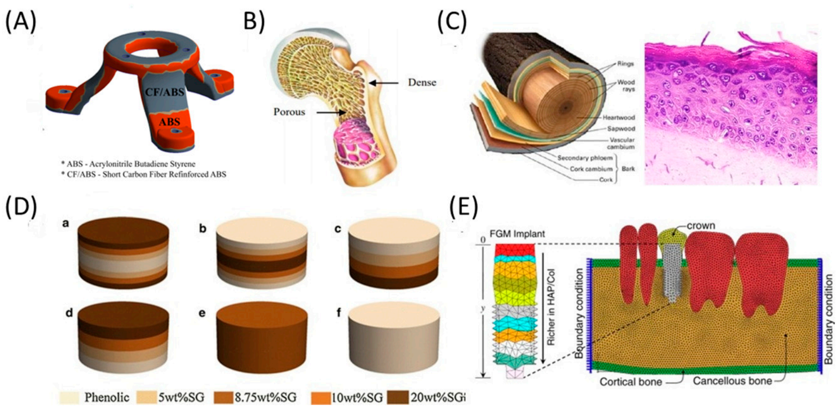

Figure 2. (**A**) Optimized multi material distribution in the fixture. Reprinted with permission from Ref. [2] (open access). (**B**) Natural example of FGM with human bone with graded structure. Reprinted with permission from Ref. [19] (License number 5695361450173). (**C**) FGM with FG sandwich structure pattern [20] (open access). (**D**) Different graded structures of FGM [21]. Reprinted with permission from Ref. (License number 5695371278953). (**E**) Optimal design of a functionally graded dental implant for bone remodeling. Reprinted with permission from Ref. [22] (License number 5695370435376).

FGM has experienced a notable surge in research and development, particularly in exploring innovative approaches. These approaches encompass the integration of multiple materials, including polymers, composites, ceramics, and metals, both individually and in combination. Density and gradient variations, the application of sandwich patterns, and the strategic alteration of material compositions at specific locations have been explored. Additionally, various AM techniques such as Material Jetting (MJ), Direct Energy Deposition (DED), Vat Polymerization (VAT), sheet lamination (SL), and Electron Beam Melting (EBM) are employed [23]. The primary objective is to enhance material properties in terms of functionality, hardness, wear resistance, and thermal performance. Figure 3 provides an overview of general material combinations, which are categorized based on the appropriate material types, serving as a fundamental guide.

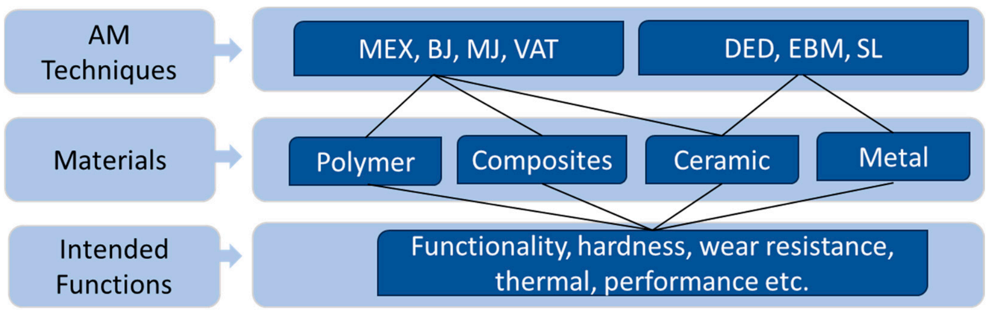

Figure 3. Overview of muti-material AM [2] (open access).

The objective of this review paper is to provide readers with a comprehensive understanding of the present state of FGMs and the immense potential that FGMs bring to the continually evolving landscape of AM. Dissecting the complexities of FGAM, not only to elucidate the current state of this technology but also to shed light on its future trajectory, contributes to a deeper comprehension of the pivotal role FGMs play in shaping the future of AM technologies.

2. Designing FGMs: Conceptual Approaches

Effective design for FGMs stands as a crucial foundational step towards achieving precise and high-quality components. Specialized design software for FGMs must possess the capability to model and simulate the intricate composition of multi-materials. While traditional AM workflows have demonstrated efficiency in creating complex geometries, adapting these workflows for FGMs presents scientific challenges in spatially tailoring material properties. Despite the maturity of AM workflows, FGAM encounters persistent challenges, ranging from inadequate data representation to limitations in software capabilities and material control. Overcoming these scientific hurdles is essential for achieving true customization and optimizing performance [24]. The transformational potential of FGAM will remain constrained until the scientific community addresses issues such as enhancing data representation, advancing software capabilities, and refining material control. To unlock the full capabilities of FGAM and usher in a new era of material-centric design and fabrication, collaboration among designers, engineers, and materials scientists is paramount. This collaboration should foster a deeper understanding of material science principles and the development of robust simulation tools. In this section, the initial focus lies on the importance of design in FGMs from a materials science perspective—a scientific endeavor demanding detailed control and deep understanding of material properties and behavior. Following this is precision in material distribution which is a design approach that delves into how material properties change with variations in microstructure, composition, and porosity. Subsequent attention is directed toward voxel modeling for deeper investigation of FGM design, facilitating a comprehensive exploration of the internal composition and property distribution. The section concludes by addressing specialized file formats for FGM design.

2.1. Importance of Design in FGMs: A Materials Science Perspective

FGMs represent a paradigm shift in materials science, surpassing the constraints of uniform materials by incorporating diverse functionalities within their spatial domain. To unlock their full potential, meticulous design and modeling are imperative [25]. This scientific endeavor necessitates precise control and a profound understanding of material properties and behavior. The design of FGMs is articulated in terms of material components, structure, compositional gradients, microstructural features, and their resulting properties. These specifications play a crucial role during processing to craft the desired FGM microstructure or predict the behavior of the larger system containing the FGM component. Effective communication between materials modelers and design engineers is pivotal in design studies, encompassing considerations such as geometry, loading conditions, performance requirements, and failure criteria for the FGM component. The designer must be well-informed about the specific properties, conditions, and accuracy required. This perspective underscores the nuanced control and comprehensive comprehension essential for orchestrating FGM design. The scientific pursuit is particularly evident in the precise manipulation of material properties and behavior. The synthesis of materials science principles forms the bedrock of a strategic design approach, facilitating the successful realization and optimization of FGM functionalities. This broader perspective sheds light on the intricate challenges and opportunities inherent in scientifically navigating the design landscape of FGMs.

2.2. Precision in Material Distribution: A Design Approach

The production of FGMs transcends mere material selection, evolving into a precisely calibrated process governed by the principles of compositional, microstructural, and porosity grading. These techniques afford the opportunity for seamless transitions throughout the material structure. In compositional grading [26], the alteration of metallic and ceramic ingredient ratios within an FGM leads to one end exhibiting robust mechanical strength akin to steel, while the other manifests lightweight resilience comparable to titanium. Microstructural grading involves the precise modification of grain size and orientation within the material microstructure. Thinner grains enhance mechanical strength, whereas thicker ones improve ductility. Through meticulous customization of the microstructure along a gradient, optimal combinations of these properties are achieved. Porosity grading, involving the strategic addition or reduction of pores, emerges as a potent tool for both reducing weight and improving thermal management. An FGM transitioning from a dense, robust core to a porous, insulating outer layer proves ideal for aerospace applications. This underscores the scientific importance of precision in material distribution within Functionally Graded Materials, where calibrated variations in composition, microstructure, and porosity pave the way for tailoring multifaceted material properties. Figure 4 illustrates the generation of one-dimensional, two-dimensional, and three-dimensional material distributions for the FGM using convolution surface-based material primitives.

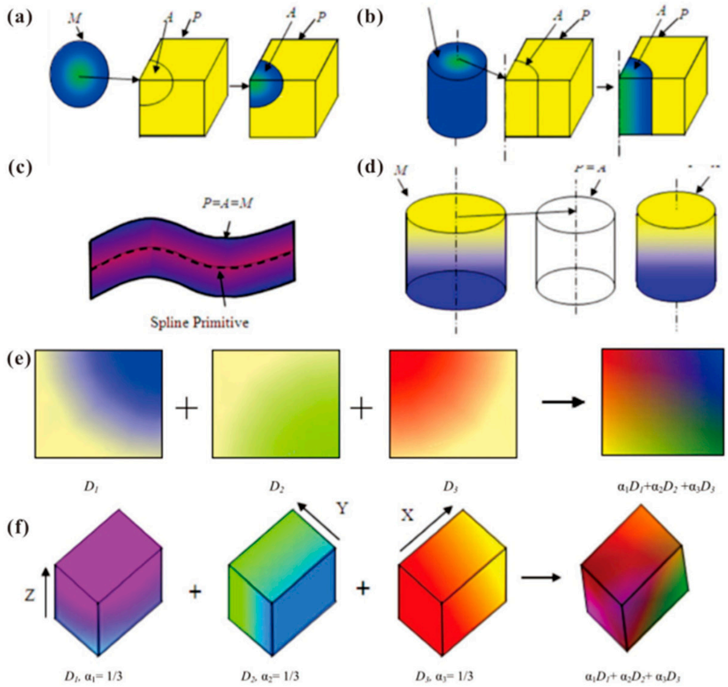

Figure 4. Material modeling with convolution surface-based material primitives: (**a**) Point; (**b**) Straight line; (**c**) Spline; and (**d**) Plane. (**e**) A 2D material distribution in an object obtained by merging three 1D material distributions. (**f**) A 3D material distribution in an object [24] (open access).

2.3. Voxel Modeling for Deeper Investigation in FGM Design

The pursuit of a comprehensive understanding of internal composition and property distribution in Functionally Graded Materials (FGMs) necessitates a profound exploration, and herein lies the pivotal role of voxel modeling [25]. This technique involves segmenting the material into infinitesimal 3D cubes, each encapsulating vital information about its material composition. Specialized software such as VoxCAD assumes the role of a digital architect in this intricate process, providing engineers with the capability to design diverse FGM models utilizing voxels [27,28]. Significantly, VoxCAD integrates Finite Element Analysis (FEA) properties, facilitating virtual testing and optimization. This convergence of voxel modeling and FEA empowers engineers to predict the FGM's behavior under varying loading and environmental conditions, offering valuable insights before transitioning to physical fabrication. This not only enhances the efficiency of the design process but also conserves time and resources [28]. The scientific application of voxel modeling emerges as a cornerstone in advancing the precision and predictive capabilities essential for the intricate design and optimization of FGMs. Luo conducted [29] an in-depth exploration of voxel-based structures for FGMs with a focus on design and characterization. Two distinct approaches to voxel modeling were employed: micromechanics-based and statistics-based.

Notably, four representative FGMs were meticulously designed and characterized using these proposed approaches. The outcomes revealed that the statistics-based approach exhibited greater reliability and accuracy, positioning it as a more viable option for industrial applications. Figure 5 visually depicts an FGM image created through the statistics-based method, employing varying resolutions. Additionally, the author employed two gradation functions: Equation (1) for 1D sandwich FGM and Equation (2) for 2D sandwich FGM, where "n" and "m" denote the gradation indices. These functions, as expressed in Equations (1) and (2), play a crucial role in defining the gradation patterns, showcasing the author's systematic and comprehensive approach to FGM design. Here, $V1$, $V2$, and $V3$ represent volume fractions, while "x" and "z" denote the directions.

$$V1 = 1 - \left|\frac{2Z-L}{L}\right|^n, V2 = 1 - \left|\frac{2Z-L}{L}\right|^n \tag{1}$$

$$V1 = \left(1 - \left|\frac{2Z-L}{L}\right|^n\right)\left(1 - \left|\frac{x}{L}\right|^m\right),\ V2 = \left(1 - \left|\frac{2Z-L}{L}\right|^n\right)\left(\left|\frac{x}{L}\right|\right)^m \\ V3 = \left|\frac{2Z-L}{L}\right|^n \tag{2}$$

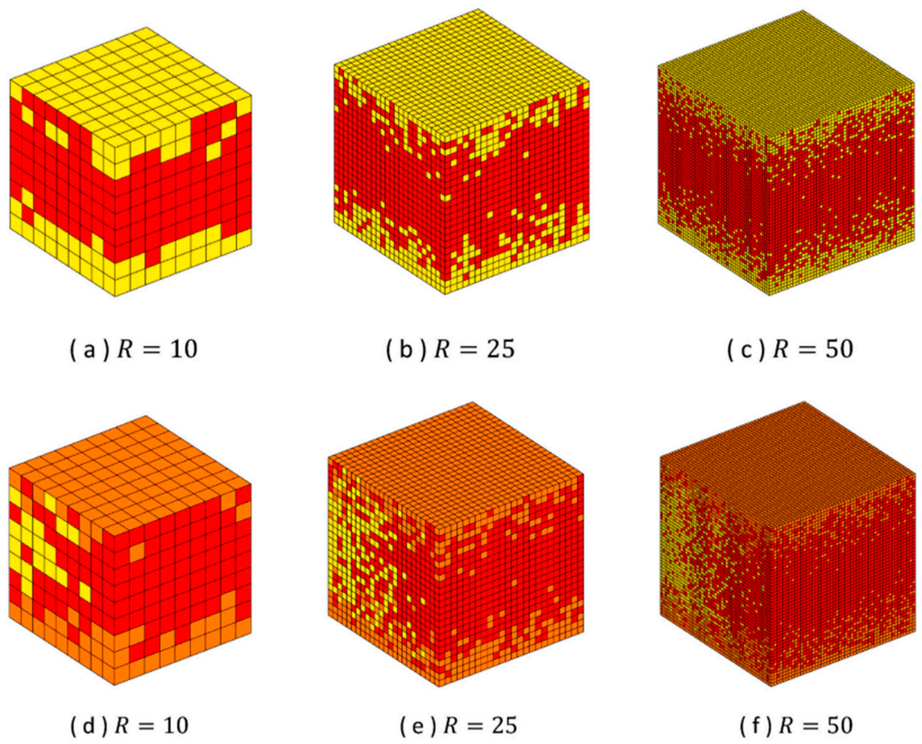

Figure 5. FGM images created with a micromechanics-based (Voigt formula) method using different resolutions (R). (**a**–**c**)—One-dimensional FGMs with gradation index n = 2.5 in Equation (1); (**d**–**f**)—Two-dimensional FGMs with gradation indices n = 2.5, m = 1.5 in Equation (2). The variation of color represents the change in the Young's modulus of the FGM [29] (open access).

2.4. Specialized File Formats for FGM Design

Traditional mesh based STL files find relevance in uniform materials but fall short for FGMs due to the absence of information regarding internal structure and graded characterization. Moreover, FGMs often exhibit complex and continuously varying material compositions and properties, making it challenging for standard meshing techniques to capture such intricate details. The inherent discretization in mesh structures may lead to inaccuracies in representing the gradual transitions within FGMs, compromising the fidelity of the model [30]. Additionally, the mesh-based approach might struggle with the seamless integration of different materials within FGMs, as the traditional mesh elements are not inherently designed to handle the nuanced variations in composition. This limitation can impact the precision of simulations and analyses conducted on FGMs, hindering the accurate prediction of their mechanical, thermal, or electromagnetic behavior. As FGMs become more prevalent in advanced engineering applications, addressing these limitations in traditional mesh-based representations becomes imperative for ensuring accurate and reliable computational analyses. This deficiency underscores the importance of specialized file formats such as Additive Manufacturing Format (AMF) and Fabricable Voxel (FAV). AMF, an XML-based format, intricately stores details encompassing material constituents, lattice structures, and substructures within volumes. This provides a robust language for articulating the complexities of FGMs [14]. On the other hand, FAV, pioneered by Fuji Xerox and Keio University, elevates voxel modeling by enabling each voxel to maintain diverse attributes, including material composition, porosity, and color. AMF and FAV enable the representation of volumetric data at a finer level, using voxels to describe the material composition and properties within the FGM [31]. This voxel-based approach allows for a more precise representation of the gradual transitions and variations in material characteristics within the FGM structure. The ability to encode detailed voxel information contributes to enhanced accuracy in simulations, analyses, and, ultimately, the fabrication process. This advancement facilitates seamless design, analysis, and inspection within a unified workflow. The choice of the appropriate file format ensures accurate communication of every voxel's story, ultimately contributing to the precision and high-quality fabrication of FGMs. This scholarly perspective emphasizes the significance of tailored file formats in addressing the unique challenges posed by FGMs in the realm of AM.

3. Manufacturing Techniques of FGMs

Materials which exhibit sustainable variations in their final qualities and properties with dimensions are called functionally gradient materials, or FGMs. Recent advancements allow businesses to produce functionally gradient materials at affordable prices; as a result, these materials have become available in numerous research facilities, educational institutions, and even homes [32]. The convenience of access to AM technology allows researchers and engineers to create products by combining different FGMs. Their objective is to incorporate mechanical, physical, electrical, and other engineering characteristics into their products. However, evaluation in conventional manufacturing methods is prohibitively expensive due to the number of post-processing steps required [33,34]. Earlier material description composite materials have undergone recent advancements that have eliminated their functional drawbacks while preserving their advantages, which include the capacity to produce different gradations [32] such as composition, porosity, and size; mitigate some constraints, such as stress-shielding effects; improve osseointegration; and raise the resistance to wear and electrolytic conductivity in order to modify the desired mechanical and biological response [35]. FGMs can be created, depending on their purpose and unique application as per demand, by changing the chemical composition behavior, microstructure properties (to remove extra voids that can create structural deficient), or design features from one end to the other. FGM can have the highest material qualities in the necessary amounts only where they are needed. There are several ways to produce FGMs, and recent advancements in additive-based metal-deposition technologies—such as those using lasers, electron beams, plasma, etc.—are captivating significant attention [36]. This section aims to cover the fundamental manufacturing techniques of FGM and how they have evolved in response to 21st-century demand and supply [37].

3.1. Methods of Manufacturing of FGMs

There are various methods that are used to manufacture FGMs, including both traditional and current AM methods. The following sections provide an in-depth look at several key manufacturing techniques used in the production of FGMs, highlighting their respective processes, advantages, and potential applications.

3.1.1. Vapor Deposition Methods

Vapor deposition methods represent a sophisticated approach to the fabrication of FGMs, offering precise control over material composition and properties. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) techniques are prominently employed. In CVD, precursor gases undergo chemical reactions on a substrate surface, resulting in the deposition of thin films with tailored compositions. PVD involves the physical transfer of material from a source to a substrate through methods like sputtering or evaporation [38]. These methods enable the creation of FGMs with gradual transitions in composition and structure, ensuring a seamless integration of different materials. Vapor deposition techniques provide a versatile platform for designing FGMs with enhanced mechanical, thermal, and electrical properties, making them pivotal in advanced materials engineering for various applications.

3.1.2. Physical Vapor Deposition

A collection of surface coating techniques known as PVD are employed in tool coating, equipment coating, and ornamental coating applications. The method is essentially using vaporization coating, with the atom-by-atom transfer of material from the solid as the main mechanism phase to the vapor phase and then back to the solid phase, progressively forming layers as shown in Figure 6 [39]. Reactive deposition occurs when a gaseous environment and the depositing material interact with material that is co-deposited to create a complex material film, like an oxide, carbide, nitride, or carbonitride. Metal film deposition using physical evaporation is among the most traditional techniques. The substrate's surface is covered in a thin layer of aluminum, gold, and other metals that have been heated to the point of vaporization. Every film deposition process happens in a vacuum or in an extremely precisely regulated environment [40]. Physical vapor deposition plays an important role in the advancement of technologies for applications in the optics, automotive, and aerospace industries. Metallic or ceramic coatings are applied to a high percentage (75%) of aircraft engine components to improve performance and reliability [39]. As a result, there is a continuous effort to engineer surface properties to extend the life of components under harsh environmental conditions such as corrosion, high-temperature oxidation, and wear. Multilayered ceramic and metallic films are also used in the manufacture of microelectronic components. Processes for controlling thin film properties are also critical in the microelectronic industry [40].

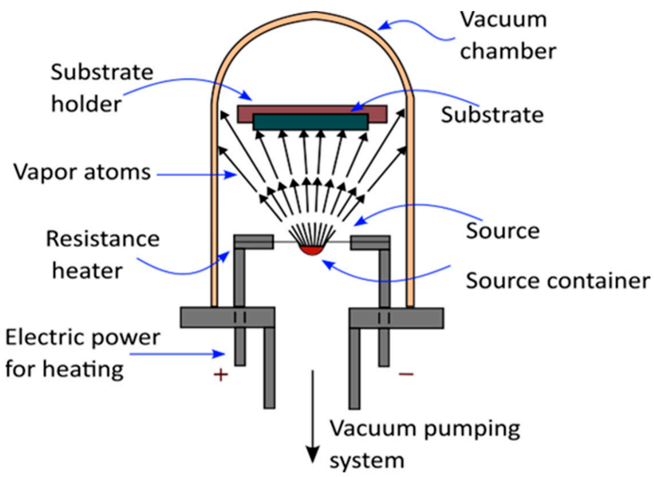

Figure 6. Schematic representation of PVD process.

3.1.3. Chemical Vapor Deposition Methods

Chemical vapor deposition, or CVD, is a process that can be used to make fibers, coatings, powders, and monolithic components. Using CVD, a wide range of compounds, including carbides, nitrides, oxides, inter metallics, and many more, can be produced, along with many metals and nonmetallic elements like silicon and carbon. The production of semiconductors and other electronic components, the coating of tools, bearings, and other wear-resistant parts, as well as other optical, optoelectronic, and corrosion applications, all depend heavily on this technique today [39]. Pursuing scalable material production methodologies and moving them from the laboratory to industry is beneficial to novel everyday applications. In this regard, CVD provides a good compromise between efficiency, controllability, tunability, and excellent run-to-run repeatability in monolayer coverage on substrates, as shown in Figure 7. As a result, CVD meets virtually every requirement for industrialization, including for use in polymer coatings, metals, water-filtration systems, and solar cells [41].

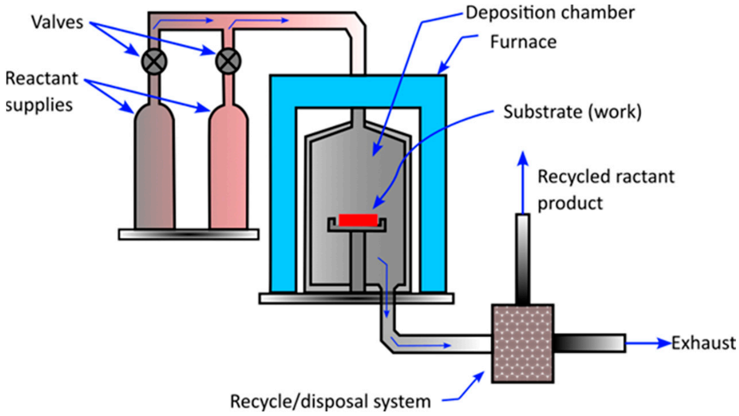

Figure 7. Schematic representation of CVD process.

3.2. Powder Metallurgy in Additive Manufacturing

Powder-bed foundational AM is an additive manufacturing technique that employs the basic four steps for producing FGMS, as illustrated in Figure 8, making it easier to create things with intricate shapes. Understanding the powder characteristics required to consistently manufacture components of acceptable quality becomes crucial as AM technology moves from prototyping to manufacturing finished parts [42]. Consequently, in order to both qualitatively and quantitatively study the effect of powder characteristics on part properties, powder characterization techniques like scanning electron microscopy (SEM), laser light diffraction, X-ray photoelectron spectroscopy (XPS), and differential thermal analysis (DTA) have been used. Significant progress has been made in the study of powder microstructure, chemical content, and particle size and morphology using various powder characterization methods [41].

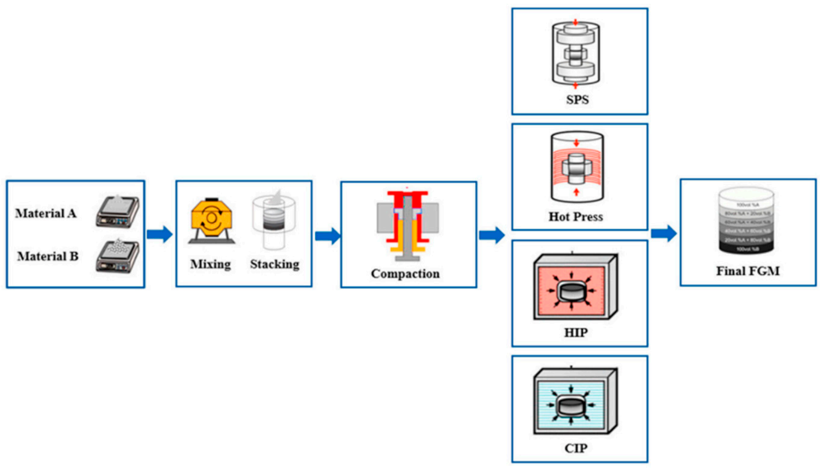

Figure 8. Schematic representation of powder metallurgy AM process. Reprinted with permission from Ref. [19]. License number (5715460837720).

3.3. Solid Free Form

Solid Freeform Fabrication (SFF) is a pioneering technique within the realm of AM, enabling the creation of 3D objects layer-by-layer from digital designs without the constraints of traditional subtractive manufacturing methods, as shown in Figure 7. However, this approach allows for the precise and intricate construction of complex geometries, facilitating the production of prototypes, customized components, and functional end-use parts [43]. By depositing material layer upon layer, it empowers designers and engineers to realize intricate structures with unprecedented freedom, ultimately revolutionizing the manufacturing landscape by offering increased flexibility, efficiency, and customization in the production process. The method finds applications across various industries, ranging from aerospace and automotive to healthcare and consumer goods [44]. One of the key advantages of SFF in AM lies in its versatility across a diverse range of materials, including polymers, metals, ceramics, and composites. This adaptability allows manufacturers to choose materials that best suit the specific requirements of the intended application, whether it be for lightweight aerospace components, durable automotive parts, or biocompatible medical implants [45]. Moreover, SFF promotes sustainability by minimizing material waste compared to traditional manufacturing processes, as it selectively deposits material only where needed. Additionally, it contributes to cost-efficiency and sustainability by utilizing materials more judiciously. It provides design freedom for creating intricate geometries and complex internal structures. Versatility in material compatibility and design capabilities makes SFF suitable for a broad spectrum of industries.

It is adaptable to the fabrication of customized and complex structures according to specific requirements. As technology continues to advance, the solid freeform technique is poised to play a pivotal role in the ongoing evolution of AM, offering innovative solutions to intricate design challenges and pushing the boundaries of what is achievable in the realm of product development and manufacturing [46].

In these methods, a powerful laser beam is used to create a molten pool on the base material, and a powdery substance is injected into the molten pool through nozzles. The fine powder delivered at the laser beam point gets absorbed into the melt pool and creates a deposit. As shown in Figure 9, the working table can be adjusted in the x–y axis to obtain the desired sectional area of the sliced model, and the following layers can be deposited by increasing the deposition head in the direction of z to complete the object [47]. Layer deposition continues until the desired three-dimensional component is additively formed. Metal powder is injected through nozzles and spread around the entire perimeter of the deposition head via gravity or inert carrier gas [48]. AM-FGM is a novel technique for continuously mixing metallic materials or altering the composition/microstructure within a 3D space. It aims to use AM technology to produce a metallic FGM with a wide range of characteristics. In other words, AM-FGM relates to the progressive mixing of materials utilized to generate a near-net-shaped element with variable properties. AM-FGM may gain the benefits of both AM and FGM at the same time. Powder-fed LDED is the primary technology for AM-FGM [41].

Electron Beam Direct Manufacturing

Electrons emitted by a heated tungsten filament in the upper column are collimated and accelerate to a kinetic energy of roughly 60 keV. Two magnetic coils situated within the lower column regulate the electron beam. The radiation is first focused to the essential diameter using an electromagnetic lens, and then it is deflected to the desired location on the building surface using a second lens, as shown in Figure 10. There are no moving mechanical elements in the electron beam gun itself, so it does not cause beam deflections [42]. Moreover, various types of FGMs can be manufactured with EBAM technology by connecting a single EB gun to multiple wire feed nozzles, as illustrated in Figure 5. This can be used to independently regulate, and feed multiple wires made from different metal alloys simultaneously into a single molten pool to form recommended sources [49]. It is feasible for coatings, and bulk FGMs can be formed in a continuous or discontinuous manner.

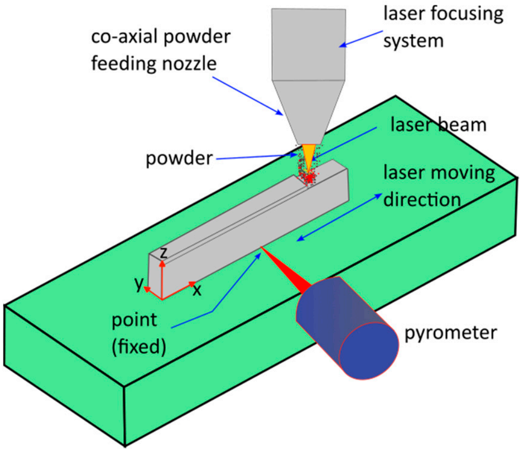

Figure 9. Schematic representation of LASER metal deposition process.

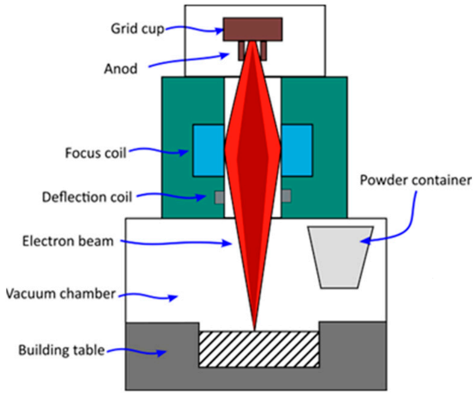

Figure 10. Schematic representation of Electron beam direct deposition process.

3.4. Use of Artificial Intelligence in Manufacturing of FGMs

The utilization of artificial intelligence (AI) in the manufacturing of FGMs represents a groundbreaking approach that enhances the precision and efficiency of the production process. AI technologies, such as machine learning algorithms, are employed to optimize the design and composition of FGMs, as shown in Figure 11, ensuring the seamless integration of different materials with varying properties. By harnessing AI-driven tools, manufacturers can analyze vast datasets related to material characteristics, performance requirements, and production parameters [50]. This enables the identification of optimal material combinations, deposition strategies, and process parameters for FGMs, ultimately leading to enhanced product quality and functionality. Additionally, AI is instrumental in real-time monitoring and control during manufacturing, utilizing techniques like predictive maintenance, process optimization, and quality assurance to ensure the consistent and high-quality production of FGM [51]. AI tools are incorporated in various stages of FGM manufacturing; some are used for testing or in quality control tools, as discussed in the following articles.

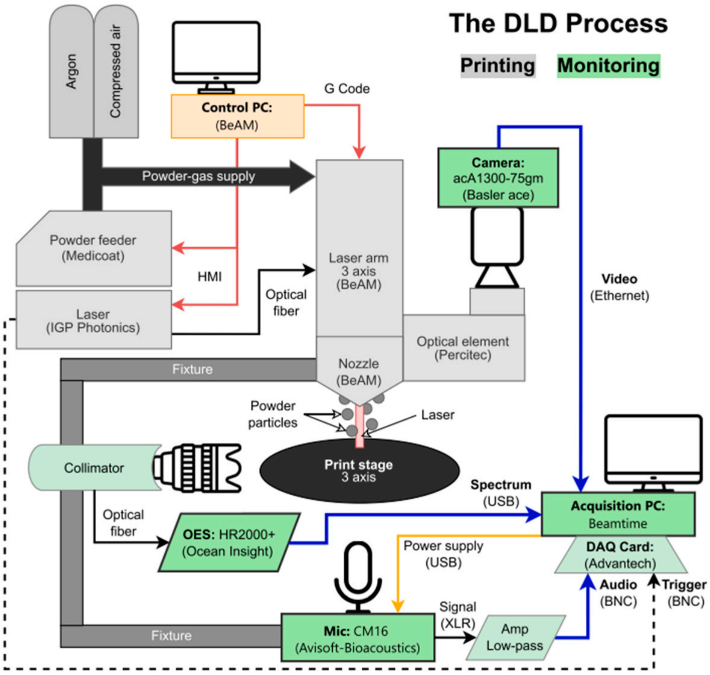

Figure 11. Application of artificial intelligence in monitoring FGM during DLD process [52] (open access).

1. AI in prefabrication of design: AI has contributed a lot of assistance to AM design. AI can be used at an early stage in the process to determine whether AM is the most cost-effective option for generating specific types of designs. Beyond this point, artificial intelligence can also be used in generative design, which encourages creativity and speeds up the design process by generating a design according to a set of requirements [53]. Employing machine learning for rendering designs for maximum effective manufacturing is possible, and AI in 3D printing design is also helpful for topology optimization [32].
2. Quality check and defect prediction tool: AI can be used to enhance the fatigue performance of layered deposited specimens subjected to different cyclic loadings; an internal predictive code is developed for each technique. An analysis of all is presented, based on values obtained from an empirical determination of fatigue life, to confirm the efficacy of the ML technique [33]. It has been demonstrated that RF is the best method, yielding maximally synchronized data sets in the shortest amount of time with the lowest possible error percentage. Ref. [37] reports on how machine learning was used to make those predictions in order to improve the operational effectiveness of fatigue life prediction in the future.
3. Controlled material selection according to design: AI may encourage a more proactive strategy besides the mentioned application if potential weaknesses in the AM process are discovered. This can help regulate the use of materials in real time and substantially decrease rejected material [54]. By recognizing potential weaknesses before assisting operators or technicians in correcting the problem, or by enabling the process of manufacturing make those decisions on its own thanks to machine learning, 3D printing AI can achieve this. AI systems can cut down on the number of faulty parts that would otherwise be thrown away by using this kind of real-time control [33,37].

4. Materials Used to Fabricate FGMs Parts with AM Technologies

FGMs are a class of materials that exhibit a gradual change in composition, structure, and properties over their volume. AM technologies, commonly known as 3D printing, provide a unique capability to fabricate complex structures with varying material compositions, making them suitable for creating FGM parts. The choice of materials for FGMs in AM depends on the specific application requirements and desired property gradients. Here are some materials commonly used in AM technologies for fabricating FGM parts:

4.1. Metal Alloys

- Titanium Alloys: Titanium and its alloys are commonly used for their high strength-to-weight ratio and excellent corrosion resistance.
- Aluminum Alloys: Aluminum-based FGMs can be tailored for specific applications, providing a combination of light weight and good mechanical properties.
- Stainless Steel Alloys: Various grades of stainless steel can be used with FGMs to achieve different levels of corrosion resistance and strength [55].

Metals that are frequently employed in biomedical applications exhibit distinct attributes. These metals must contain qualities such as nontoxicity, nonimmunogenicity, nonthrombogenicity, noncarcinogenicity, and a high level of resistance to corrosion [56,57]. Corrosion phenomena are observed in body fluids due to the presence of large concentrations of chloride ions, as well as diverse amino acids and proteins. Various oxide-reduction reactions occur when biological fluid comes into contact with metallic surfaces, leading to their alteration and the potential release of ions within the body. This phenomenon can lead to several adverse consequences, including allergic reactions or the development of cancer [58]. Until now, the majority of metallic implants have been fabricated using traditional processes including forging, investment casting, hot rolling, and machining [59]. AM technologies employ a concentrated heat source to selectively liquefy the raw material and subsequently solidify it in order to construct a component. The various techniques can be categorized according to the type of raw material utilized (plastics, metals, or ceramics), the initial state of the material (powder or wire), the heat source employed (electric resistance, laser, or electron beam), and the manner of deposition (spreading or depositing). The most often used AM methods for metals include powder bed fusion (PBF) processes, such as selective laser melting (SLM) and EBM, as well as direct deposition processes like LMD.

Previous studies have provided evidence indicating that the adhesion, development, and differentiation of osteoblastic cells play a crucial role in facilitating the integration of implants with bone tissue. These cellular processes have been found to be influenced by the surface energy and roughness of the implant [60,61]. The specimens of SLM and EBM exhibited distinct morphologies and surface textures. The EBM specimens had distinct granules, while the SLM specimens had smoother surfaces in comparison to the EBM surfaces. The disparity in precision between the two technologies likely accounts for the variations in porosity and surface treatments. LMD, in contrast to SLM and EBM, enables the fabrication of structures consisting of various biomaterials. This is achieved by altering the chemical composition of materials from one layer to another, resulting in a component with a graded composition [62]. LMD has also been used to coat titanium with tricalcium phosphate ceramics to improve bone–cell–materials interactions [63]. Considering the LMD process, by contrast, Sterling et al. [64] produced samples with 908 and 1038 MPa of yield and UTS, respectively, and an elongation at break of 3.8%. Hence, compared with EBM and SLM results, LMD parts possess lower ductility and intermediate tensile strength values, probably due to the cooling rates involved [65]. Furthermore, wire arc additive manufacturing (WAAM) also has been applied for the AM products produced by FGMs. A functional gradient made of Ti, Nb, and Mo with a gradient in niobium composition is created utilizing a WAAM method. The Nb and Mo composition ranges from 0 atomic percent to over 100 atomic percent. The cross-sectional microstructures changed in grain morphologies as anticipated, and this is in line with the intended composition gradient. At the bottom of the deposition parts, there are large columnar grains, while in the higher half, there are equiaxed grains. Both types of grains are rich in iron. At the very top, there are lump-shaped grains that are rich in Nb and Mo. The grains in the sample exhibit epitaxial growth as a result of the layer-by-layer deposition process [66]. The experimental findings indicated that the desired chemical composition in the construction wall can be precisely attained by modifying the proportion of iron and aluminum wire feed. The constructed vertical wall has a consistent change in composition from 100% steel at the base to more than 50 atomic percent aluminum content. The chemical composition is predominantly uniform in the transverse direction, but it is less consistent in both the diluted region at the bottom of the wall and the outermost layers on the upper surface. The mechanical properties of the deposited wall have been measured, and the specimens have exhibited room temperature strength and ductility values that are comparable to those observed in prior studies. Given the importance of corrosion resistance in the application of this material, future research will concentrate on understanding the corrosion mechanism of the Fe–FeAl FGM [66]. Most recently, the deposition methods were advanced to enhance the properties of the FGM parts by hybrid additive manufacturing (HAM). Yin et al. [67] studied the HAM of Al-Ti6Al4V FGM with SLM and cold spraying. The majority of the FGMs exhibited a compact structure with significant pores present in both the CS part and the SLM component that were formed during the manufacturing process.

The HAM approach successfully prevented the creation of a brittle intermetallic phase at the connecting interface. This resulted in the production of thick, dense, and machinable FGMs composed of non-weldable metals. The created FGMs, despite their increased density, nevertheless exhibited certain flaws. The SLM Ti6Al4V component had a defect characterized by the presence of large pores due to the build-up of unmelted particles and surface roughness. On the other hand, the defects in the CS part primarily consisted of small pores caused by inadequate particle plastic deformation. Furthermore, the analysis of the grain structure indicates that the SLM Ti6Al4V component had a completely acicular martensitic microstructure, which is different from the $\alpha + \beta$ microstructure found in the original material. Hence, the SLM Ti6Al4V component exhibited a marginal increase in hardness compared to the Ti6Al4V raw material. The grain structure of the CS Al part remained unchanged compared to the Al feedstock; however, the hardness of the CS Al part was significantly greater than that of the Al feedstock due to work hardening. Moreover, the examination of the fracture surfaces reveals the superior adhesive and cohesive bonding of the FGM [67]. In addition, in order to improve the fabrication of FGM and the deposition rate using AM methods, steel and copper FGM was produced by Twin-WAAM [68].

A Cu–Al alloy/HSLA steel FGM part was successfully produced by the AM process, as shown in Figure 12. The part exhibited a defect-free structure, with no presence of cracks or pores. A blend of a prevailing Cu (FCC) phase (white areas) with β phase in the intercellular regions (black areas) is observable. The mixture is formed due to vigorous convection in the molten pool caused by the Lorentz force, buoyancy force, surface tension gradient, and arc shear stress. It is important to note that the wires were not deposited simultaneously [69]. Table 1 summarizes the thermal and mechanical properties of the metal alloys of FGM.

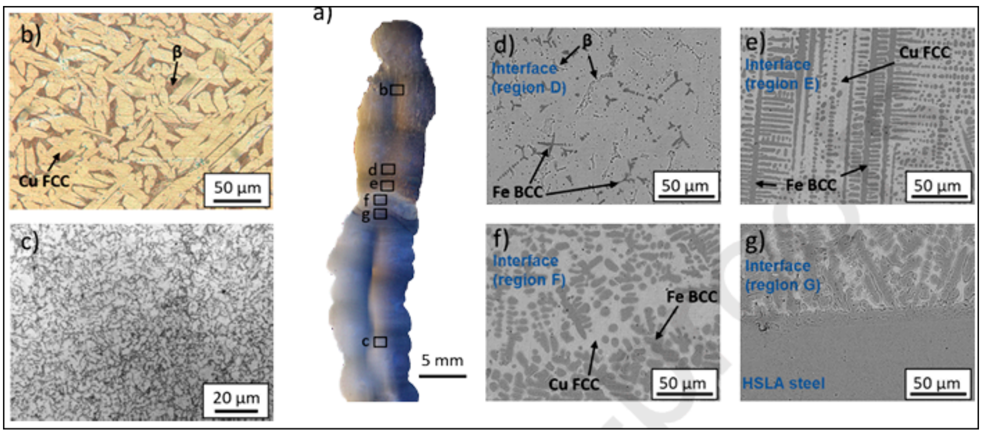

Figure 12. Cross-section overview of as-built FGM part; Detail of the region with (**b**) 100% HSLA steel, (**c**) 100% Cu–Al alloy, and (**d**–**g**) the interfacial regions. Reprinted with permission from Ref. [68] (License Number 5678750726423).

Table 1. Thermal and mechanical characteristics of metal-alloy-based FGM.

Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Melting Temperature (°C)	Printing Temperature Range
Titanium	4.5	120	210–1380	1668	700–1600 [70,71]
Aluminum	2.7	70	100–400	660	570 [72,73]
Copper	8.96	130	210–220	1085	225 [74]
Stainless Steel	7.5	190	515–625	1375–1450	831 [75–77]
Niobium	8.57	105	275–585	2477	250–600 [78]

4.2. Ceramic Materials

Alumina (Al_2O_3): Ceramic materials like alumina are known for their high hardness, wear resistance, and electrical insulating properties. Zirconia (ZrO_2): Zirconia-based FGMs can offer improved toughness and fracture resistance compared to traditional ceramics [79]. Al_2O_3/ZrO_2 functionally graded components are highly favored ceramic FGMs due to the enhanced fracture toughness provided by zirconia (ZrO_2) and the increased hardness achieved by alumina (Al_2O_3). An example of potential uses for this FGM is in the production of orthopedic implants, such as the femoral head of a prosthetic hip joint. Zirconia might be employed as the core material in this application because of its superior fracture toughness. At the same time, a gradual transition to alumina at the surface would be beneficial, as alumina possesses higher hardness, resulting in enhanced resistance to wear [80,81]. A sinuous pathway was created by applying zirconia and alumina pastes as a layer one upon another. The mixing blade was rotating at a speed of 900 revolutions per minute (rpm). The series of commands begins with the extrusion of zirconia paste. At point 1, a directive is issued to transition to alumina paste by deactivating one extruder and activating the other extruder. The switch commands are iterated during the printing process from points 1 to 5. Li et al. [82] concluded that the implementation of a novel extrusion-based AM method, known as Ceramic On-Demand Extrusion (CODE), involved the incorporation of a dynamic mixer to facilitate the production of functionally graded ceramics. The effectiveness of the suggested methodology was assessed through the production of several samples that exhibited varying compositions, ranging from pure alumina to a 50% mixture of alumina and zirconia, featuring preset material gradients.

The sintering process was conducted at a temperature of 1500 °C, and the composition of each layer was verified by employing Energy Dispersive Spectroscopy (EDS) to measure the atomic percentage of aluminum and zirconium. The mean discrepancy between the observed and intended compositions was approximately 1%. Deformations were quantified on the sintered specimens. The presence of bigger material composition gradients led to more significant deformations of the samples. The Vickers hardness exhibited a decline from an initial value of 18.4 GPa to a final value of 15.0 GPa, corresponding to an increase in the volume percentage of zirconia from 0 to 50 vol%. In conclusion, the present study successfully produced demo pieces exhibiting a mild and continuous composition gradient. This achievement serves as a demonstration of the technique's capabilities to manufacture functionally graded ceramics with intricate geometries and material grading within the layers. The mechanical strength of functionally graded ceramics is a significant characteristic. The impact of residual strains on the pieces throughout the cooling process from sintering temperature to room temperature is significant. In forthcoming investigations, an extensive array of experiments will be undertaken to explore these subjects. This will involve the creation of a wider range of sample types, including various designs for material composition distributions. Additionally, the experimental procedures will entail the utilization of Raman spectroscopy to estimate residual stress levels, as well as the implementation of bending tests and fracture toughness testing.

The most recent studies conducted by Wu et al. [83] have been on depositing the FGM materials using Al_2O_3 and ZrO_2 with four different gradient transitions through the LDED process. Figure 10 illustrates the schematic representation of the four different

FGM materials with different composition gradients. This study involved the development of four different types of gradient transition FGCs. As illustrated in Figure 10, there are four distinct transitions between Al_2O_3 and ZrO_2. The first transition, referred to as AZ100, involves a direct transformation. The remaining three transitions, namely AZ50, AZ25, and AZ20, correspond to an increase in ZrO_2 content by 50 wt%, 25 wt%, and 20 wt%, respectively. Cylindrical specimens with dimensions of Φ4 × 38 mm were created and utilized for the purpose of analyzing the microstructure and conducting mechanical properties testing. Every layer utilizes arc interpolation. The arc is characterized as having a radius of 2 mm. Once the deposition of a single layer has been concluded, the deposition head is elevated by a distance of 0.4 mm at the initial location. The trajectory for the deposition of the subsequent layer is determined in order to finalize the preparation of the desired structure. It is important to acknowledge that every sample is deposited. The entire preparation process is characterized by a constant and uninterrupted progression.

Figure 13 illustrates the AZ100 sample morphology, where the sample can be categorized into three sections based on distinct macro morphological characteristics: an Al_2O_3 section, a transition section, and a ZrO_2 section. Under identical process circumstances, the diameter of the Al_2O_3 section measures approximately 6 mm and exhibits a light grey hue. In contrast, the ZrO_2 section has a slightly wider diameter of approximately 6.5 mm and displays a yellowish-white tint. The transition between these two parts is characterized by a conical shape, as depicted in Figure 13b, with a vertical extent of approximately 2.5 mm. Longitudinal cracks are observed in the transition section through penetrant imaging, as depicted in Figure 10. These cracks originate at the interface between the Al_2O_3 portion and the transition section, extend towards the interface between the transition section and the ZrO_2 section, and eventually come to a stop. Furthermore, there exist transverse cracks at the contact between the Al_2O_3 portion and the transition region. During the process of laser directed energy deposition (LDED), the presence of a temperature disparity across the interface and variations in the thermophysical properties of the materials involved might result in the development of stress.

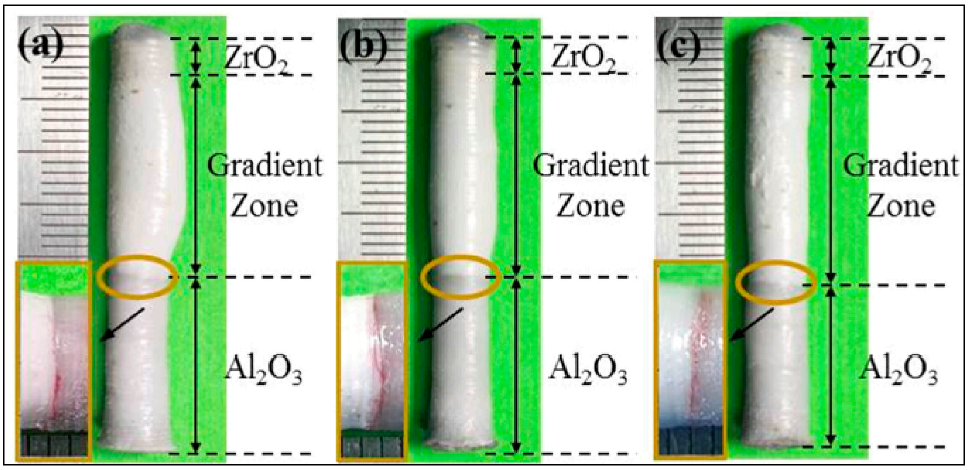

Figure 13. Macroscopic morphology of gradient transition samples: (**a**) AZ50; (**b**) AZ25; (**c**) AZ20. Reprinted with permission from Ref. [83]. (License Number 5678741291333).

Figure 10 depicts the morphology of the gradient transition samples. The distinction in color between the Al_2O_3 region and the gradient transition section remains evident, with a clearly defined boundary. However, in the part of gradient transition, there is a lack of a distinct visual interface between the gradients of different components. Instead, there is a rather consistent white look. The ZrO_2 region exhibits a somewhat gray hue, although the demarcation with the gradient transition part is not readily discernible. In relation to the precision of shape, it is evident that the cylindricity of the Al_2O_3 section and ZrO_2 section surpasses that of the gradient transition section. This phenomenon can be attributed to the presence of a specific fraction of eutectic composition within the gradient transition section under identical heat input conditions. The resulting melt viscosity is comparatively low, rendering it susceptible to instability. Consequently, the cylindricity of this section is relatively subpar. Table 2 summarizes the thermal and mechanical properties of the ceramic metal alloys of FGM.

Table 2. Thermal and mechanical characteristics of ceramic-material-based FGM.

Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Melting Temperature (°C)	Printing Temperature Range
Al_2O_3	3.99	215–413	260	2072	175–365 [84]
ZrO_2	5.68	21	115	2715	1500 [85]
AZ100	1.00	42	315–430	265	230 [86]
Ceramic powders	2–6	-	260–300	1900	1200 [79]

4.3. Composite Materials

Metal Matrix Composites (MMCs): Combining metals with ceramic reinforcements, such as carbides or borides, can enhance strength and wear resistance. Scholarly investigation conducted in this particular domain has primarily concentrated on the examination of various material systems and their corresponding efficacy [87]. As an example, Nurminen et al. conducted a comparative analysis of different material systems comprising a metal binder and dispersed carbides [88]. The researchers directed their attention towards the resolution of material compatibility concerns and their subsequent impact on performance, with a specific focus on the tribological aspect. The researchers reached the determination that the characteristics of MMCs were significantly influenced by the choice of materials and the chemical affinity between the constituents. Undoubtedly, material systems exhibiting a strong affinity have been observed to facilitate the dissolution of the ceramic phase, resulting in adverse effects on the coating's overall performance. Jiang and Kovacevic conducted a study in which they produced MMC coatings, including TiC and AISI H13 tool steel. They then proceeded to analyze and compare the tribological characteristics of this specific material system with other material systems that have been previously documented in the relevant literature [89]. The study conducted by Adam et al. examined the efficacy of several material systems in the context of ballistic applications. Additionally, the researchers assessed the viability of LDED (laser directed energy deposition) as a means of producing MMC coatings [90]. Zhang and Kovacevic conducted a study to examine the tribological characteristics of MMC coatings. These coatings were composed of an AISI 420 steel matrix and various carbides. The objective of their investigation was to gain a better understanding of material selection in this context [91]. The aforementioned investigations have provided evidence to support the effectiveness of MMC coatings produced using LDED for enhancing the surface properties of components that are subjected to harsh operating conditions. Additionally, these studies have also established a set of recommendations to assist in the process of selecting suitable materials for this purpose. However, there was a lack of emphasis on comprehending the influence of processing variables on the efficacy of MMC coatings in a single material system [87].

Polymer Matrix Composites (PMCs): Using a combination of polymers and reinforcing fibers or particles allows for tailoring mechanical and thermal properties. The accelerated advancements in AM techniques used to produce polymeric composites have facilitated the emergence of a contemporary circular economy model that emphasizes large-scale production and decentralized recycling [89]. The concept of a circular economy, referred to as "circularity", pertains to an economic framework and system that seeks to eradicate waste and promote the sustainable utilization of resources [92,93]. The notion of distributed recycling for additive manufacturing (DRAM) pertains to the utilization of recycled materials inside the process chain of 3D printing via a mechanical recycling procedure. According to research, the implementation of a circular economy has promise in terms of substantial reductions in material, waste, and production expenses [92].

The Fused Deposition Modeling (FDM) method is a versatile AM methodology commonly employed for the three-dimensional (3D) printing of polymers and PMCs. The process of constructing a 3D item involves the controlled deposition of material through the utilization of a computer-controlled 3D printer, which operates by adding consecutive layers. The research on FDM-based polymers has seen a notable surge in recent years due to its remarkable adaptability in the development of polymers and PMCs [94]. FDM-based polymers exhibit significant promise for utilization across a wide variety of applications. The FDM process is capable of manufacturing components at a relatively low cost, while still achieving an acceptable level of surface polish and demonstrating good endurance. Table 3 summarizes the thermal and mechanical properties of the metal alloys of FGM.

Table 3. Thermal and mechanical characteristics of composite-material-based FGM.

Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Melting Temperature (°C)	Printing Temperature Range
MMC	1.3	250	380	380–430	220–235 [95]
PMC	-	-	40	-	230–250 [96]

4.4. Polymer Composites

Researchers and manufacturers have shown interest in polymeric composites that utilize fibers for reinforcement. These composite materials provide a high strength-to-weight ratio, making them suitable for a wide range of applications [97]. The following are the major reinforced polymers.

Carbon Fiber Reinforced Polymers (CFRPs): CFRPs combine the lightweight properties of polymers with the high strength and stiffness of carbon fibers.

Glass Fiber Reinforced Polymers (GFRPs): GFRPs provide a good balance between strength and cost-effectiveness.

The emergence of AM has provided a solution to the difficulties, enabling cost-effective production of polymeric composite materials with enhanced flexibility [98]. According to the ASTM International Technical Committee F42 on AM technologies, the various methods of creating fiber-reinforced polymeric composite materials through AM can be categorized as follows: powder bed fusion, sheet lamination, photo polymerization, and material extrusion. The components fabricated by the selective laser sintering technique exhibit superior strength compared to those manufactured through injection or extrusion molding. The pieces produced by standard manufacturing procedures exhibit lower elastic modulus and strength [99]. The primary cause is the elevated internal porosity and inadequate dispersion of fibers inside the powder feedstock. A study conducted by Arai et al. [100] examined the impact of laser intensity on mechanical characteristics. Augmenting the laser intensity can lead to a reduction in viscosity, hence improving the adhesion between the glass fibers. Exceeding a specific threshold of laser intensity led to a decrease in mechanical characteristics. This fact was ascribed to the reduced molecular weight of the composite–copolymer poly powder. A significant limitation of using selective laser sintering for composite manufacture is its ability to only process discontinuous composites [101]. Laser cutting is employed to cut fiber sheets, which are subsequently stacked and joined through the application of pressure, heat, and adhesive. The sheet material might consist of any type of fiber preform. The utilization of prepreg sheets composed of e-glass fibers and an epoxy matrix demonstrated excellent fiber and interlayer adhesion. The published values for tensile and flexural strength were 716 MPa and 1.19 GPa, respectively [102]. The integration of curved layer building into the process of laminated object manufacturing can further boost its effectiveness. The mechanism facilitates the elimination of the staircase effect, reduces material waste, and has the capacity to consistently align fibers along a specified curvature [103]. Table 4 illustrates the utilization of materials, accompanied by their mechanical characteristics, highlighting the materials' capabilities.

Table 4. Thermal and mechanical characteristics of various materials employed in FGM.

Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Glass Transition Temperature (°C)	Melting Temperature (°C)	Printing Temperature Range
ABS		2.28	43		200–250	210–250 [104]
PLA	1.21–1.25 [105]		21–60 [106]	45–60 [105]	150–162 [105]	190–230 [104]
PC	1.21 [106]	2.57 [105]		140 [106]	270 [106]	260–310 [104]
PEEK	1.32 [107,108]		90–100 [107]	143 [109]	343 [107]	360–420 [104]
PEI	1.27 [110]			217 [110]		340–380 [104]
Nylon	1.15 [109]				190–350 [109]	240–270 [104]
HIPS						220–250 [104]
Polyester	1.2–1.5 [111]		40–90 [111]			
Vinyl ester	1.12–1.32 [111]		73–81 [111]			

4.5. Biocompatible Materials

Biocompatible Polymers: FGMs with varying degrees of biocompatibility are used in medical applications, such as implants and prosthetics.

Hydroxyapatite (HA): A bioactive ceramic that can be incorporated into FGMs for bone tissue engineering. The growing utilization of 3D printing in the medical field to directly administer treatment to patients has created a need for novel materials that offer diverse biocompatible properties to cater to many prospective applications. Biocompatible refers to materials that are intentionally designed to interact with live tissues without eliciting an immune response [112]. In terms of their intended applications, the materials can generally be classified into three categories: dental, medical, and general medical use. In order for a material to be categorized as suitable for dental or medical purposes, it must be specified for the creation of a particular device, such as a temporary dental crown or a hearing aid shell. Dental resins accounted for the largest proportion of the stiff materials, with 61 instances, followed by general medical use with 26 instances and medical usage with 12 instances. The bulk of flexible resins were used for general medical purposes, followed by dental applications and, finally, medical use. The materials suitable for general medical applications were characterized based on their chemical, mechanical, or biocompatible qualities, without any device being specified [112].

Hydroxyapatite (HA) is a ceramic substance that has a hexagonal crystallographic structure. It is chemically represented by the formula $Ca_{10}(PO_4)_6(OH)_2$. Composites utilized for AM purposes, such as biomaterial inks or bioinks, can be categorized into two groups, hard and soft materials, based on the specific matrix employed for each application [113]. Hydrogel-based materials are the primary components of soft matrix composites, which are commonly manufactured using extrusion-based AM techniques. These soft-based composites are typically printed at a phase where they exhibit a predominant liquid-like activity. Afterwards, the printed matrices that are reinforced with HA often undergo a post-processing phase to enhance the long-term durability of the printed structures under physiological settings. The effectiveness of these techniques relies primarily on the printed material, and numerous writers have undergone significant endeavors to determine the most suitable crosslinking approach for each material candidate.

4.6. Functionally Graded Polymers

Polymer Blends: Different polymer blends or copolymers can be used to create FGMs with tailored mechanical, thermal, or electrical properties. A polymer blend refers to the combination of two or more polymers that have been mixed in order to produce a novel material exhibiting distinct physical characteristics. Usually, the polymer powders used in the SLS process are semi-crystalline thermoplastics, although it is also possible to find amorphous polymeric powders and elastomers. Laser sintering is particularly suitable for thermoplastic polymer materials because of their comparatively low melting temperatures. Ultimately, polymer blends were created and examined to produce components with enhanced characteristics. This type of material provides an alternate method for acquiring components with distinct attributes, hence enabling the creation of novel applications. However, polymer blends have been far less studied in research as compared to pure polymers. This difference arises due to the need for chemical compatibility among the materials in the blend and the heat limits that make the sintering of such blends more difficult. Moreover, the temperature ranges required for the sintering process are typically more limited for polymer blends compared to their individual polymer components. This indicates that polymer blends are highly sensitive to fluctuations in the bed temperature of the component, highlighting the crucial significance of accurate temperature regulation. The use of SLS in polymer blends depends on the availability of a wide range of appropriate blend components. However, significant advancements have occurred in the utilization of SLS in different polymer mixes [114].

4.7. Advanced Materials

Shape Memory Alloys (SMAs) can be incorporated into FGMs for applications requiring shape memory and super elasticity. They are a distinct category of materials that possess the capacity to regain their original shape even after experiencing significant distortion, surpassing the typical elastic strain limit of metals. This behavior is linked to a thermoelastic martensitic phase transition from a parent phase austenite (A) to a product phase martensite [115]. Out of all the many SMAs, NiTi is the most commonly utilized due to its exceptional mechanical qualities, strong resistance to corrosion, and favorable compatibility with biological systems. NiTi has seen significant growth in its applications within the medical field. These include its use in orthodontic wires [116], endodontic files [117], cardiovascular devices such as stents and filters [118], orthopedic devices like spinal vertebrae spacers and artificial bone implants [119], and surgical tools including guide wires and grippers [120]. Figure 14 illustrates the AM techniques applied to different SMA systems. The primary emphasis is placed on investigating the impact of process parameters and heat treatment on the microstructure, printability, and the structural and functional properties of additively manufactured samples [121].

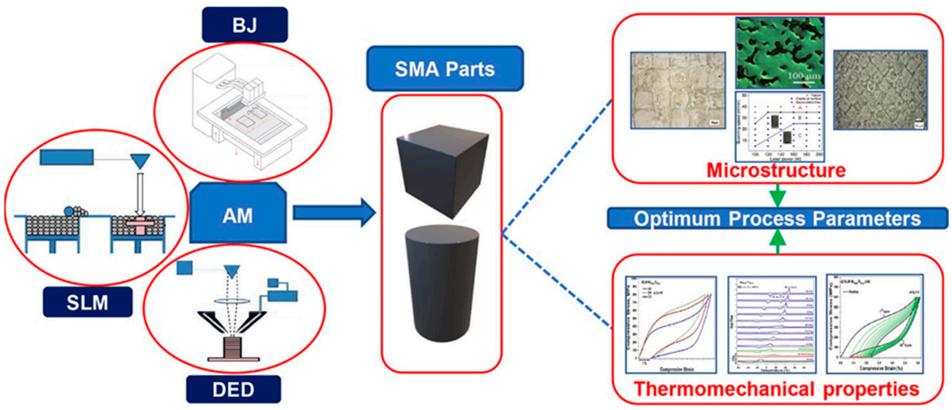

Figure 14. AM of shape memory alloys of FGMs and their mechanical and microstructural properties. Reprinted with permission from Ref. [121] (License Number 5678750396509).

The temperature gradient generated in the vicinity of the laser point is crucial in influencing the resulting microstructure for laser-based AM. Furthermore, the uneven solidification caused by varying cooling rates at different positions inside the printed samples results in the formation of epitaxial grains. When fabricating FGM parts using AM technologies, it is essential to consider the compatibility of the selected materials with the specific AM process (e.g., PBF, DED, or VAT) and the intended application requirements.

Additionally, understanding the thermal and mechanical compatibility between adjacent materials is crucial for achieving successful FGM fabrication. Table 5 summarizes some of the major FGM materials and their applications, as well as the possible AM techniques and their categories.

Table 5. Summary of FGM materials and their applications developed by different AM techniques.

FGM Materials	Applications	AM Techniques	Category	References
ZrB_2–SiC/ZrO_2, ZrO_2 and B4C	Wear resistance materials and molds (Gas lens)	SPS, Thermoplastic 3D printing (T3DP)	Solid phase process	[79,122,123]
PEEK polymer	Orthopedic applications	The modified and developed 3D printer	Extrusion-based process	[96]
SiC/C, ZnO TiO_2/Ti–O–Si	Optoelectronics	CVD, CVI (vapor deposition methods)	Gas phase processes	[96,124]
Ceramic powder	Ceramic components	Tape casting	Liquid phase processes	[96,125]

4.8. Nanomaterials

Materials that show a gradual variation in composition, microstructure, and characteristics over their volume are referred to as Functionally Graded Materials, or FGMs. These materials are made to maximize particular qualities for various uses. The term "Nano Functionally Graded Materials" (Nano-FGMs) refers specifically to graded material that has nanoscale structures and characteristics incorporated into it. Some essential features and possible uses of Nano Functionally Graded Materials are discussed briefly. Based on the composition gradient, Nano-FGMs often involve a gradual change in composition, where different nanomaterials or nanoparticles are strategically placed to achieve desired properties. For example, a ceramic–metal Nano-FGM might transition from a ceramic-rich composition at one end to a metal-rich composition at the other, providing a combination of high-temperature resistance and toughness. In addition, they also vary with their microstructure. Mechanical, thermal, and electrical properties of Nano-FGMs can be influenced by nanoscale variations in their microstructure. Engineers can modify a material's behavior to suit a given purpose by adjusting the nanoparticles' orientations and distribution. It is possible to optimize a single material's strength, conductivity, heat resistance, or biocompatibility by using Nano-FGMs.

This adaptability is especially useful in situations where it is necessary to compromise between opposing material properties. Nano-FGMs can be produced using a variety of manufacturing processes, such as chemical vapor deposition, powder metallurgy, and other nanofabrication techniques. To obtain the correct gradient and qualities, control over the manufacturing process is essential. It is difficult to develop trustworthy methods for creating precise control over the nanoscale features of Nano-FGMs. Predicting and optimizing the material's behavior requires an understanding of how the nanoparticles interact with the bulk matrix. Structural Components: A progressive change in material properties makes Nano-FGMs useful in structural components that must resist variations in loads and temperatures, like turbine blades. Biomedical Implants: Nano-FGMs can be used in the biomedical field to build implants that have mechanical characteristics similar to those of bone and to lessen stress shielding. Thermal Management: In applications like heat exchangers, where thermal conductivity needs to be adjusted, Nano-FGMs are helpful. Two types of materials that are useful in small-scale structures include porous materials and FGMs, which were developed in response to the growing need for new materials in micro- and nanotechnology. Therefore, it is necessary to understand how these materials behave in micro- and nano-scale systems. The size-dependent nonlinear vibration behavior of defective FG microbeams has been studied [126]. The free vibration of an FG porous cylindrical microshell under heat influences was examined by Ghadiri and Safarpour [127]. Zhang [128] investigated the nonlinear vibration behaviors and thermal post-buckling of FGM beams, as well as the FGM rectangular plates [129].

4.9. Metamaterials

Metamaterials play a pivotal role in enhancing the capabilities of FGMs by introducing tailored properties beyond those found in conventional materials. By incorporating metamaterial elements into FGM structures, it becomes possible to engineer materials with unprecedented functionalities, such as negative refractive indices, acoustic cloaking, and tunable electromagnetic properties [130]. This strategic integration enables FGMs to exhibit superior mechanical, thermal, and electromagnetic responses, expanding their application potential in areas like aerospace, telecommunications, and medical devices. Metamaterial-infused FGMs offer a unique avenue for overcoming traditional material limitations and unlocking innovative solutions across diverse engineering domains, marking a significant advancement in the realm of advanced materials science. Additionally, Li et al. invented [131] a novel design approach for super materials by combining three cutting-edge concepts: topology optimization, functionally graded cellular composites, and metamaterials. It uses a level set technique to optimize the internal structure of these composites, creating intricate lattices with varying material properties across different layers. This allows the material to achieve tailored functionalities, like stiffness variation or negative refraction, not seen in natural materials. By embedding tiny, engineered structures—metamaterials—into the cellular lattice, the researchers gain precise control over these properties, opening doors for the design of materials with unprecedented performance for applications like lightweight aircraft components, energy-efficient thermal devices, or even cloaking technology. Moreover, Kim et al. [132] presented a groundbreaking method for creating functionally graded metamaterials, a class of materials with precisely controlled property variations, using digital light processing (DLP) AM. Two key strategies are employed; by manipulating the brightness of projected light patterns, the degree of polymerization across the printed structure is varied, resulting in gradients in material properties like hardness. Different sections of the printed part are then selectively exposed to additional curing, further refining the property distribution. Combining these techniques, the researchers successfully fabricated hard yet flexible metamaterials, a seemingly contradictory property set which is valuable for applications like novel structural components with both robustness and maneuverability. This innovation showcases the potential of DLP AM for creating complex metamaterials with tailored functionalities, paving the way for advanced engineering solutions. Figure 15A demonstrates the investigation of energy absorption properties in various functionally graded lattice metamaterial beams (FGLB). Four FGLB types were de-signed and analyzed: ascending graded radial lattice (ARL), descending graded radial lattice (DRL), descending graded axial lattice-filled tube (DAL), and ascending graded axial lattice (AAL). Figure 15B illustrates the FGLB components, including aluminum face-sheets, carbon fiber reinforced plastic (CFRP) sheets, and two core options: uniform metamaterial and functionally graded metamaterial.

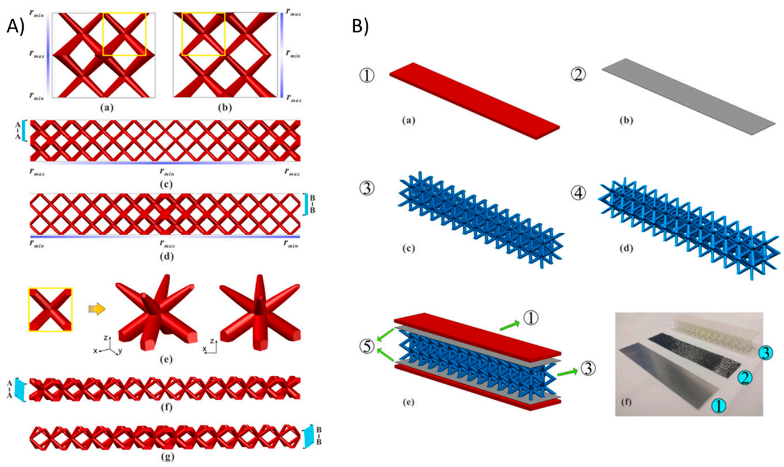

Figure 15. (**A**) Typical cross-section schematic diagram of functionally graded metamaterial beam. (**a**) ARL; (**b**) DRL; (**c**) DAL; (**d**) AAL; (**e**) the cell unit illustration of radial (**f**,**g**) the cell unit illustration

of axial graded metamaterial core. (**B**) The components of FGLB structures. (**a**–**d**): aluminum face-sheet, carbon fiber reinforced plastics sheets, uniform metamaterial core and functionally graded metamaterial core; (**e**,**f**) components and their layout in individual layers. Graded metamaterial core [1] License number (5712021049142). Reprinted with permission from Ref. [130] License number (5710411082294).

5. Applications Using FGMs

The utilization possibilities of FGMs can be in various industries, including automotive, aerospace, soft robotics, and many others. As mentioned previously, FGMs allow the production of multi-material parts without an external bonding mechanism, like using fasteners or adhesives for assembly. This concept alleviates the need for some manufacturing steps, which directly increases the efficiency of manufacturing in some instances and allows the design to not adhere to typical manufacturing limitations such as fastening tool clearances. Figure 16 shows that parts display distinctive and lifelike aesthetics concerning color and material shifts when constructed using FGMs.

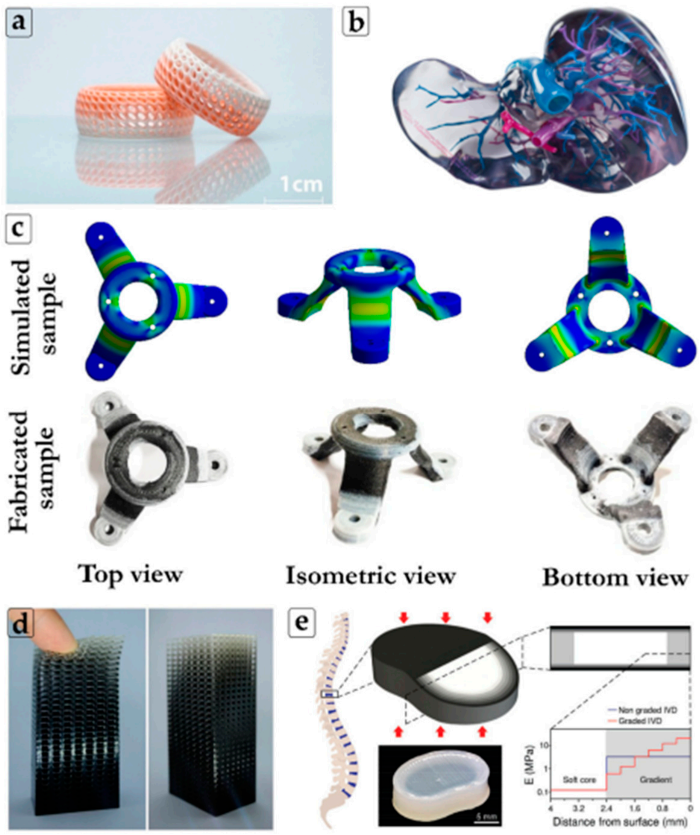

Figure 16. (**a**) Three-dimensional printing of FGM ceramics using the CeraFab Multi 2M30 printer. (**b**) Creation of a 3D-printed educational model representing the medical field. (**c**) Production of an FGM bracket using ABS with carbon fiber. (**d**) Generation of a functionally graded lattice structure on the Stratasys J750 with GradCAD Voxel Print. (**e**) Illustration of gradient design of a 3D-printed human intervertebral disk. Reprinted with permission from Ref. [2] (open access).

5.1. Automotive Applications

The automotive industry is constantly performing research and development to create a more efficient transportation system. The automotive industry on its own includes components that overlap with various other industries like micro-electronics and power generation. In addition, the safety and structural stability of automobiles are critical aspects of the automotive industry. Currently, some automotive companies use aluminum foam structures installed within the car frame for their lightweight attribute as well as their impact absorption ability. Fernandez-Morales et al. [133] designed and manufactured custom density metallic foams that were manufactured through AM-assisted investment casting. Their designed foams exhibited higher impact absorption than commercially available metallic foams. Their experiment can further be enhanced by FGM design to optimize weight and impact absorption characteristics. Automotive components are considered demanding when it comes to heat and wear resistance, as well as longevity. Thus, many components like the engine, suspension, and chassis can benefit from the use of FGMs [134]. Asiri [135] investigated three types of material structures in simulating and analyzing bending and torsional stresses, as well as vibration analysis in an engine crankshaft. The types of material structures investigated were homogenous, composite, and FGM. His study concluded that FGM is ideal for durability of the crankshaft. Another example is that Greer et al. [136] employed Wire-Arc AM, or WAAM, to fabricate an excavator arm that was functionally graded using topology optimization. In Figure 17, an FGM is showcased in the construction of the Super Car Light (SLC) body, utilizing a blend of aluminum, steel, plastic, and magnesium. The overarching scientific aim of this approach is to systematically decrease mass while simultaneously enhancing resistance against crash forces [137].

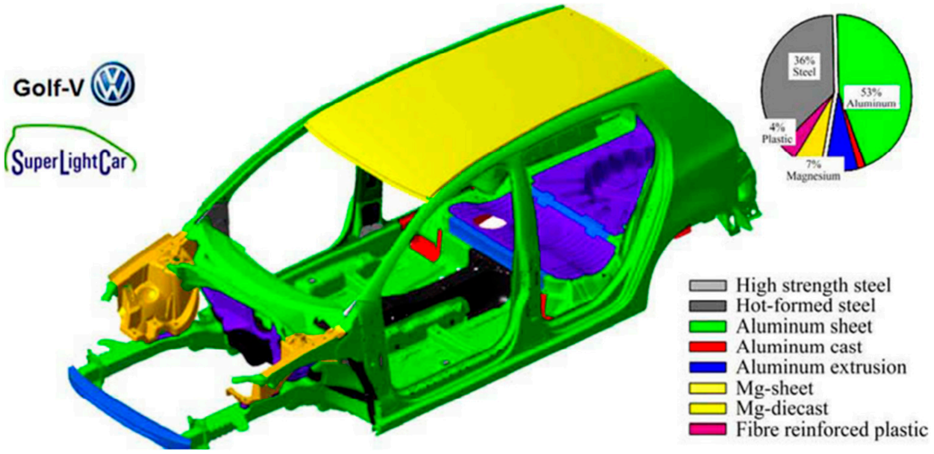

Figure 17. Final SLC body "multi-material" concept (SLC project). Reprinted with permission from Ref. [137] License number (5710290749618).

5.2. Aerospace Applications

The aerospace industry is constantly growing and continuously enlarging the area of research. One of these areas revolves around structural components in a flying vehicle. FGMs can be used similarly in the automotive industry for lightweighting applications. For example, Lie et al. [138] designed, and fabricated through AM, a gyroid-based functionally-graded quadcopter arm with an enhanced strength-to-weight ratio compared to a traditionally designed arm. Further components in an airplane can utilize FGMs, such as an airplane wing, which has multiple components rather than a single component due to the multi-degree of freedom requirements during operation. FGMs can be used in this case to eliminate the multi-component assembly system. FGMs are also popular for use in high-temperature and low-weight [139] applications. For this reason, there are numerous opportunities for improvement in the aerospace industry considering how vital reliable heat-resistance and weight efficiency are. In fact, the initial development of FGMs for use in aerospace industry aimed to employ FGMs' thermal properties. Currently, FGMs are being used in general structural components as well. In addition, FGMs are critical components in optoelectronic sensors, which are an essential part of the aerospace industry and other industries [140,141]. Figure 18 illustrates the utilization of FGMs in the aerospace industry. This choice is rooted in the pursuit of lightweight structures, achieved through the strategic incorporation of optimal materials. The objective is to enhance efficiency in aerospace applications by leveraging scientifically informed material selection.

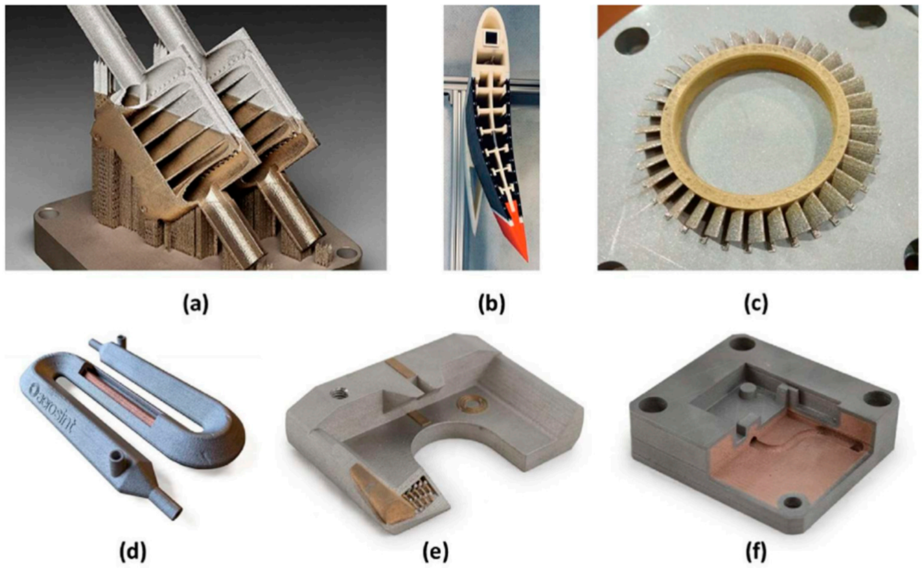

Figure 18. (**a**) Aerospace heat exchanger AM using stainless steel SS 316 and Inconel 718. (**b**) FGM wing section inspired by fishbone to adjust wing curvature. (**c**) FGM aircraft engine disk fabricated using 316L stainless steel and Cu10Sn materials. (**d**–**f**) Dual-metal components fabricated using copper on Aerosint recoater metal 3D printer. Reprinted with permission from Ref. [142] (open access).

5.3. Biomedical Applications

The use of engineered materials is not innovative, as they have been used for decades in applications like dental implants or stents in the blood system [143]. However, researchers recently investigated the use of FGMs in the biomedical field. One of the most prominent fields that utilizes FGMs and FGM research is the dental industry. Researchers tend to use bioinspired systems to create stronger and better alternatives than existing solutions. For example, Kumar et al. [144] employed an MEX multi-material system to create a lattice structure that exhibits hard shell and soft internals. This is achieved by extruding polyurethane into the printed hard shell. The inspiration came from understanding the anatomy of a human tooth. The human tooth has hard shell and soft internals, thus allowing the tooth to endure multidirectional loading, which is a weakness for typical MEX parts. In their findings, they were able to enhance the impact absorption of the lattice structure by using the concept of FGMs.

Medical implants are another field that could prominently benefit from the employment of FGMs. Fuji et al. [145] employed a plasma-based powder sintering method to fabricate metallic components. Their aim was to fabricate porous titanium components that are fit for medical implants. Their findings prove that their method is successful in producing uniformly porous titanium (UP-Ti) components as well as functionally graded porosity titanium (FGP-Ti) components. They discovered that UP-Ti exhibited less strength than bones and similar stiffness. The FGP-Ti, however, exhibited superior properties to bones in terms of both strength and stiffness. Furthermore, ceramic-based implants are known for their excellent performance. For this reason, Schwarzer et al. [146] aimed to achieve high-strength components made of alumina-toughened zirconium using lithography-based ceramic manufacturing technology. Their aim was to achieve components with 500 MPa on average of biaxial strength, but they was only able to achieve an average of 430 MPa with some components reaching the 500 MPa mark. Their low strength is believed to be due to non-optimized manufacturing parameters as well as observed porosity within the manufactured components. Nevertheless, their research contributed highly to the advancement of FGM research and their corresponding applications. Figure 19a depicts the schematic representation of the 3D organ or bioprinting process, a technique dedicated to crafting three-dimensional structures, specifically organs or tissues. Furthermore, in Figure 19b, the schematic illustrates the creation of vascularized tissues through the application of bioink—a composite of living cells and a supportive biomaterial. Lastly, Figure 19c portrays the implementation of the organ-on-a-chip methodology, an alternative technique for engineering biological tissues [142].

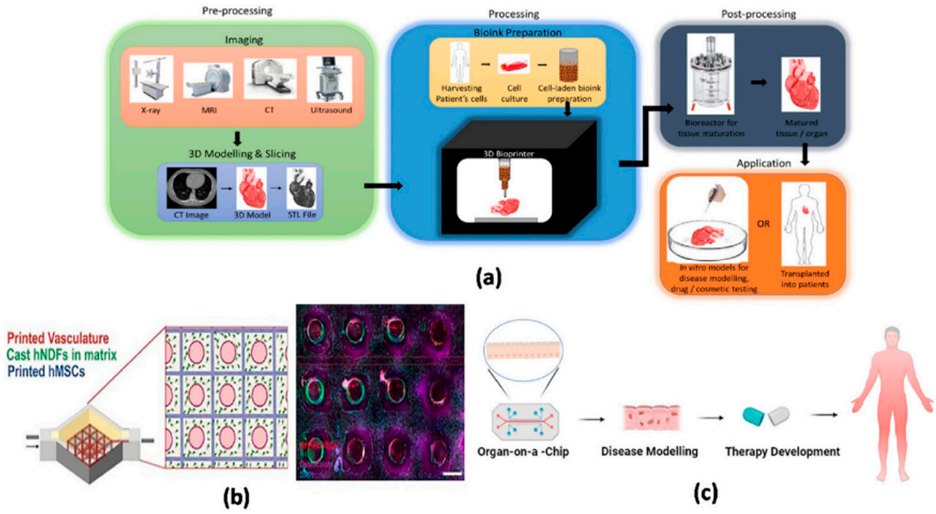

Figure 19. (**a**) Diagrammatic representation of the 3D bioprinting process. (**b**) Vascularized tissues fabricated by simultaneously printing cell-laden bio-ink and sacrificial bioink. (**c**) Organ-on-a-chip development for disease modeling and therapy development for precision modeling [142] (open access).

6. Critical Issues and Challenges Associated with FGMs

FGMs exhibit considerable promise for diverse applications. Nevertheless, several pivotal challenges associated with FGMs, such as manufacturing, design, testing, and cost-related hurdles, must be addressed. Ongoing research endeavors aim to tackle these challenges in various engineering and technology fields. Overall, FGMs possess the potential to revolutionize numerous industries. Scientists are actively addressing the crucial challenges linked to FGMs, and there is an anticipation that these materials will see broader utilization in the future.

6.1. Manufacturing Challenges

Manufacturing FGMs presents a significant hurdle, primarily due to the imperative to meticulously regulate the composition and properties of the material across its entire volume. Achieving this precision is often challenging and can result in material defects. Moreover, numerous manufacturing processes employed for FGM production are not only costly but also time intensive. Overcoming these challenges is pivotal for advancing the development and accessibility of FGMs in various applications [147]. Various commonly used alloys and ceramics in FGM manufacturing are beta-tested or directly used across different engineering fields. The development of fabrication techniques is linked to industrial needs, highlighting their advantages and drawbacks. Research findings on FGM control, coating precision, stress distribution, energy consumption, commercialization, and environmental impact are compared for producing high-quality and sustainable outcomes. The correlation of product requirements guides FGM designs to achieve desired gradations and geometries for specific applications. Additionally, the current studies explore the impact of integrating advanced FGM development with emerging trends such as smart manufacturing, nanotechnology, biotechnology, AM, and AI, offering insights for both industry professionals and academic researchers into current FGM trends and potential future research areas [148,149].

6.2. Design Challenges

Designing components of FGMs poses some additional challenges. The intricate nature of these materials makes it challenging to predict how they will respond to stress. This complexity can hinder the creation of components that are both safe and efficient. Also, it is pretty much known that the design stage is more intricate compared to conventional materials. This complexity arises from the varying properties of FGMs across their volume, making it challenging to anticipate how these components will behave under loads. Today, traditional geometric design concepts have restricted applicability for FGMs. To create components with tailored properties at distinct locations, there is a requirement for multi-scale design concepts spanning from geometric patterning to microstructural design. FGMs are increasingly captivating for a wide array of industrial sectors and applications, including aerospace, automotive, biomedical implants, optoelectronic devices, energy-absorbing structures, geological models, and heat exchangers [150]. Currently, FGM design primarily centers around two-phase materials, with material composition typically being altered based on a predetermined direction and mode [151]. However, this approach often falls short of fully unlocking the potential of FGMs. For a comprehensive overview of FGM's design methodology applied to fundamental engineering structures like beams, plates, and shells, refer to the literature [152].

Today, multi-material AM stands out as the optimal manufacturing method for FGMs [153]. Nevertheless, numerous challenges warrant further investigation, encompassing the fusion mechanisms of multiple materials, material properties, and limitations within the manufacturing process. The thermal history of mixed metal powders in this process involves intricate stages, including melting, molten pool flow, and crystallization under laser influence. Structural imperfections such as pores, unmelted regions, and cracks are highly sensitive to AM process parameters, significantly influencing the performance of FGMs. The diverse thermodynamic properties of multi-materials pose a challenge, as a constant laser power may inadequately melt materials with high melting points or low laser absorption rates [154]. Consequently, dynamic adjustments of laser parameters are essential in order to accommodate the changing gradients in material distribution.

6.3. Testing Challenges

Evaluating FGMs presents its own set of challenges. Conventional testing methods may not consistently pinpoint defects in these materials, and devising tests relevant to the specific application for which the FGM is intended can be a formidable task. Overall, FGMs pose several challenges due to their unique composition and properties. Testing and characterizing FGMs pose several challenges due to their unique composition and properties. Some of the key challenges include [24,155]:

- Defect Identification: Detecting defects in FGMs using traditional testing methods is often challenging due to the heterogeneous nature of these materials. Conventional techniques may not effectively reveal flaws in their structure.
- Relevance of Tests: Designing tests that accurately reflect the specific application for which the FGM is intended proves to be a difficult task. Standard testing procedures may not fully capture the material's performance under real-world conditions.
- Multi-material Fusion Mechanisms: In the realm of AM for FGMs, comprehending and managing the fusion mechanisms of multiple materials can be intricate. Ensuring a seamless integration of different materials without compromising structural integrity poses a significant challenge.
- Material Properties: The properties of FGMs exhibit significant variations across the material gradient. Specialized techniques are required for testing and characterizing these diverse properties, including mechanical, thermal, and electrical behaviors, to capture the full spectrum.
- Structural Defects: FGMs are prone to structural defects such as pores, unmelted regions, and cracks. These defects are responsive to the parameters of the manufacturing

process, emphasizing the need to understand how they form and impact the material's overall performance.

- Thermal History: Throughout AM processes, especially those involving mixed metal powders, FGMs undergo a complex thermal history, encompassing stages like melting, molten pool flow, and crystallization under the influence of lasers. Gaining insight into and controlling this thermal history is crucial for achieving the desired material properties.
- Adaptation to Changing Material Distribution: The diverse thermodynamic properties of multi-material FGMs present challenges during testing. For example, a constant laser power may prove inadequate to melt materials with high melting points or low laser absorption rates. Consequently, dynamically adjusting testing parameters to accommodate fluctuations in material distribution becomes imperative.

Addressing these challenges requires a multidisciplinary approach, involving materials science, manufacturing processes, and high-tech testing methodologies tailored to the specific characteristics of FGMs. Researchers are continually exploring innovative techniques to overcome these issues and unlock the full potential of FGMs in various applications.

6.4. Cost Factor

The production costs of FGMs are generally higher than those of conventional materials, primarily attributable to the difficulties encountered in both manufacturing and testing these advanced materials [156]. Here are some of the primary cost challenges associated with FGMs [155,157,158]:

- Raw material costs: FGMs often necessitate high-performance materials like ceramics and metals, which can be relatively expensive.
- Manufacturing costs: The manufacturing processes for FGMs are typically intricate, requiring specialized equipment that can elevate production costs.
- Testing and quality control costs: Due to their unique composition and properties, FGMs present challenges in testing and characterization, resulting in higher quality control costs.

In addition to these direct cost barriers, there are indirect costs linked to FGMs, including the limited supply chain. The supply chain for FGM materials and components is currently restricted, contributing to increased costs. Despite these challenges, there is a growing interest in FGMs for applications like aerospace, automotive, and healthcare. As technology advances and the supply chain expands, the costs associated with FGMs are anticipated to decrease. Here are some strategies to mitigate the cost of FGMs:

- Develop new manufacturing processes: Researchers are exploring more efficient and cost-effective manufacturing processes for FGMs. For instance, AM holds promise in significantly reducing the production cost of complex FGM components.
- Standardize FGM processes and testing methods: Standardizing manufacturing processes and testing methods for FGMs will streamline procedures, lower costs, and facilitate broader adoption.
- Expand the supply chain: Enlarging the supply chain for FGM materials and components will introduce more competition, fostering cost reduction.

As these challenges are addressed, FGMs are expected to become more affordable and accessible across a broader spectrum of industries.

6.5. Lack of Standardization

Currently, there are no established standards for FGMs detailing the comparison and selection of FGMs from various manufacturers. Moreover, the absence of standards can pose difficulties in designing, manufacturing, and testing components constructed from FGMs. The increasing utilization of FGMs in various industries has spurred a growing demand for standardized FGM materials, processes, and testing methods. Several initiatives are underway to address standardization challenges in FGMs [157,159]. STM International: ASTM International has formed a committee on FGMs dedicated to establishing standards for FGM materials, processes, and testing methods.

- ISO: The International Organization for Standardization (ISO) has instituted a technical committee on FGMs, actively developing standards for FGM terminology, classification, and characterization.
- European Committee for Standardization: The European Committee for Standardization (CEN) has created a technical committee on FGMs, focused on developing standards for FGM design, manufacturing, and testing.

While these initiatives are in their early stages, they indicate a significant stride toward the standardization of FGMs. As the standardization process matures, it is poised to streamline and make the development and utilization of FGMs in diverse applications more cost-effective. Overall, despite these obstacles, FGMs hold the potential to revolutionize diverse industries. Ongoing research efforts aim to tackle the challenges associated with FGMs, and there is an anticipation that these materials will gain more widespread use in the future.

7. Future Trends

FGAM is evolving towards performance-driven design, integrating material properties directly into the fabrication process. Future trends indicate a shift from traditional conventional geometrical representation to advanced design methods that prioritize material information, fostering a new era of computational modeling in FGAM. This trend is reinforced by the exploration of voxel-based methods and topology optimization, enabling more precise control over material distribution and internal structures.

7.1. Broadening Biomedical Applications

FGMs have shown promising results in biomedical applications, particularly in dental and orthopedic implants. In this area, will focus on tailoring mechanical and biological responses to mimic natural tissues, thereby improving osseointegration and wear resistance, as well as mitigating stress-shielding effects. Advanced manufacturing techniques, such as SLM and EBM, are crucial in producing complex structures for patient-specific implants, demonstrating FGAM's capability to meet diverse medical needs. Expanding the horizons of biomedical applications necessitates a nuanced exploration of cutting-edge technologies and materials. The integration of advanced biomaterials, such as biocompatible polymers, hydrogels, and bioactive ceramics, holds immense promise in revolutionizing medical interventions. In the realm of tissue engineering, these materials play a pivotal role in scaffolding structures, facilitating cell adhesion, and fostering tissue regeneration. Moreover, advancements in nanomedicine enable precise drug delivery systems, leveraging nanoparticles for targeted therapies with minimized side effects. The interdisciplinary synergy between materials science, nanotechnology, and biomedicine is catalyzing breakthroughs, ranging from the development of bioresorbable implants to the creation of smart diagnostic tools. As the frontiers of biomedical research continue to expand, the intricate interplay between innovative materials and biomedical applications opens avenues for transformative medical solutions and enhanced patient outcomes.

7.2. Overcoming Manufacturing and Design Challenges

Challenges in FGAM persist, particularly in material compatibility and design intricacies. Addressing these challenges involves developing new computational tools for material information management and enhancing current AM technologies for better material utilization. The future will likely see more sophisticated approaches to material selection and a deeper understanding of multi-material fusion in AM processes. The recent advancements in AM techniques offer promising avenues for researchers to explore and create FGMs. Looking ahead, the evolution of technology in FGAM systems holds the potential to enable the realization of spatial gradients in material compositions and architectures. An ideal future direction involves the development of sophisticated software capable of designing highly intricate FGM patterns, allowing for precise control and customization of material gradients. Presently, commercially available slicers can only slice and export FGMs for fabrication using MEX technology. Embracing and enhancing FGAM systems through innovative software solutions will significantly expand the design possibilities and practical applications of FGMs, advancing the field of materials engineering and AM.

7.3. Integrating of AI in FGAM

The use of AI in FGAM is emerging as a key trend. AI can aid in optimizing designs for manufacturing efficiency, enhancing quality control, and predicting defects in FGAM. This integration promises to streamline FGAM processes, reduce waste, and improve the overall quality of FGM parts. AI also has promise to revolutionize computational modeling in FGAM, offering advanced solutions beyond the capabilities of conventional CAD methods. Machine learning algorithms could predict optimal material distributions, adaptively adjusting the constraints and requirements of specific applications. This includes AI-driven topology optimization, where AI algorithms will be crucial in determining the material distribution in the design domains to maximize the performance of 3D parts fabricated by via AM methods like DED. The implementation of standardized models is imperative to ensure the precise and consistent fabrication of parts. By utilizing these standardized models, any potential manufacturing flaws or errors that may arise during the build process are promptly recorded and monitored as the part is being printed. This real-time feedback and knowledge enable users to proactively identify and address any defects or mistakes, leading to a reduction in the utilization of flawed components. As the field of FGAM advances, integrating AI into the manufacturing process holds significant promise. By leveraging AI-based systems, the manufacturing process of FGAM can be further enhanced, optimizing design, improving quality control, and streamlining the production of complex, high-performance parts. Additionally, embracing standardized models and AI-based approaches in FGAM paves the way for greater efficiency, accuracy, and reliability in AM practices.

7.4. Standardization and Cost Management

The standardization of FGAM processes and materials is important for broader adoption. Efforts are underway to establish consistent testing methods and manufacturing processes. Managing the higher production costs of FGMs will also be a focus, with strategies including the development of more efficient manufacturing techniques and expanding the supply chain to foster competition and cost reduction. The integration of FGMs in various industries necessitates a strategic focus on standardization and cost management. Standardization efforts aim to establish consistent protocols in the design, manufacturing, and evaluation of FGMs, ensuring reliability and interoperability across applications. This standardization is crucial for fostering widespread acceptance and integration of FGMs into diverse sectors. Simultaneously, effective cost management strategies are imperative to address the challenges associated with manufacturing complexity and material intricacies in FGMs. Balancing the need for precision and innovation with cost-efficient production processes is vital for realizing the full potential of FGMs in modern manufacturing, enabling their seamless adoption across industries while maintaining economic feasibility.

7.5. Challenges and Future Research Directions

Addressing current challenges such as material compatibility, structural integrity, and process control will remain vital. Future research should focus on interdisciplinary approaches that encompass advanced design, simulation, and material science to mitigate these issues. The exploration of novel materials, fabrication techniques, and the development of comprehensive guidelines and standards will be key areas for future research and development. Overall, FGMs, with their potential for innovation in various fields and industries, face a dynamic future shaped by technological advancements and research efforts. The future is marked by significant advancements in design integration, material distribution methods, simulation techniques, and applications in the biomedical field. Addressing current challenges and harnessing the capabilities of emerging trends, including AI and advanced design methodologies, will be pivotal for the widespread application and evolution of FGAM in numerous sectors.

8. Conclusions

This review delves into how FGMs play a transformative role in modern manufacturing, particularly emphasizing their applications in AM. The key points are summarized as follows:

- We explored the significant impact of FGMs in modern manufacturing, focusing particularly on their application in AM.
- We traced the evolution of FGMs from high-temperature applications in space aircraft to their diverse applications in aerospace, biomedicine, materials science, and engineering.
- We examined FGMs comprehensively, covering design approaches, manufacturing techniques, and materials utilized in AM technologies.
- We emphasized the crucial role of precision in material distribution and highlighted the integration of advanced technologies, such as Artificial Intelligence, in FGM manufacturing.
- We outlined the broad range of materials, including metal alloys, ceramics, and polymers, employed in the fabrication of FGM parts.
- We explored practical applications of FGMs in aerospace, emphasizing their suitability for meeting high-temperature and low-weight requirements. We highlighted their potential in biomedical applications as well.
- We identified critical challenges in FGM adoption, including manufacturing complexity, design intricacies, testing difficulties, and the absence of standardization.
- We recognized the promising future of FGMs, anticipating their pivotal role in shaping the future of AM across various industries as the technology advances and as awareness grows.

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