

A Review of Modeling and Preparation of Functionally Graded Materials for Bone Tissue Engineering

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Abstract. Functional gradient materials (FGMs) are contemporary materials that mimic the hierarchical and gradient structures of natural systems while performing various functions. Because biomedical implants frequently replace bone tissues, advanced materials are required to replicate the complex structure and mechanical behavior of natural bone. Given that bone is an organic, natural FGM material, it seems reasonable to apply the FGM concept in these applications. FGMs offer numerous benefits, including the ability to customize mechanical and biological responses through composition, porosity, and size. They also reduce stress-shielding effects, improve osseointegration, and enhance electrochemical behavior and wear resistance. Despite these benefits, there is still a need for more detailed norms and standards. This report aims to provide a detailed evaluation of the current state of FGM metallic materials in the biomedical field, specifically their dental and orthopedic applications. The article discusses the influence of various processing technologies, particularly additive manufacturing, on FGM production, including its prospects and potential applications. FGMs have the potential to change the trajectory of both industry and biomedicine. FGMs have the potential to change the trajectory of both industry and biomedicine. Advancements in FGM understanding and technology can lead to improved implant designs that are more biocompatible and comparable to natural tissues, thereby improving human quality of life.

Keywords: functionally graded material (FGM), manufacturing, applications, fabrication, Ti

Introduction

Niino and coworkers proposed the original idea of Functionally Graded Materials (FGMs) in 1987 while working on a space aircraft at Japan's National Aerospace Laboratory. Where a mixture of materials is utilized to create a thermal barrier that can tolerate a surface temperature of 2000 K and a temperature differential of 1000 K over a 10mm section. FGM, also known as "gradient material," is distinguished by a progressive change in material qualities with location. The material's property gradient is caused by its position-dependent chemical composition, microstructure, or atomic order. The geographical extent of the gradients may vary: in a mass FGM, the characteristic change spreads over a large part of the material, whereas in a grade coating or joint, it is restricted to the surface of the material or a small interfacial region. Although FGMs sparked scientific interest toward the close of the twentieth century, these materials are not novel. Living creatures have been exploiting shifts in the structure of materials for millions of years. In many plant structures, microstructural gradients are generated to provide optimal architectural and functional performance with minimal material use [1, 2].

The material's selection is critical since it must meet a variety of stringent specifications. It must, among other things, be corrosion-resistant, extremely durable, interact well with tissue cells, have no immunological or allergic reactions, and possess mechanical properties similar to those of human bone. According to these criteria, the most common materials used to make this device are polymers, ceramics, metals, and their alloys [3]. Functionally graded materials are a type of innovative technology that emerged in the twenty-first century. They are composed of a two-component composite whose characteristics are determined by the compositional gradient of one or both components.

In contrast, traditional composites have a homogeneous composition, which means that the composition possesses the ideal characteristics of its constituent components. The need to compromise on qualities is avoided, as the key properties of FGM include the pure structure of each component. Furthermore, the qualities of FGM components can be fully utilized; for example, the refractoriness of ceramic can be combined with the toughness of metal without needing to sacrifice either the toughness of the metal side or the refractoriness of the ceramic side [3].

Mechanical parameters, such as elastic modulus, Poisson's ratio, shear modulus, material density, and thermal expansion coefficient, vary smoothly and continuously in preferred FGM orientations. Due to their diverse qualities, functionally graded materials are utilized in biomedical applications, with several examples of natural functionally graded materials, including bones, teeth, skin, and bamboo trees.

Accidents happen, and important components of our bodies need to be replaced or repaired. At other times, as witnessed on a global scale, the same parts become worn out after a lifetime of service to their host. Thanks to the tireless efforts of several medical experts, scientists, and engineers. However, biocompatible materials, surgical methods, drugs, and antibiotics have been created to successfully treat this condition, dramatically enhancing the quality of life for millions of individuals. Nonetheless, the intricacy of our biological system, including its deep symbiotic interactions with microorganisms, can lead to materials, surgical operations, or therapies failing. These issues, along with longer life spans

and increased societal demands, have led to a compelling need for improvements and the creation of more enhanced products and technologies [5].

The first and most important prerequisite for selecting a biomaterial is its suitability to the live organism. The implanted material should not induce any undesirable consequences, such as allergy, inflammation, or toxicity, either immediately following surgery or throughout the postoperative period. Second, biomaterials must have sufficient mechanical strength to withstand the forces to which they are subjected, preventing them from fracturing. More importantly, a bioimplant should exhibit very high corrosion and wear resistance in a highly acidic body environment and under varying loading conditions, in addition to fatigue strength and fracture toughness [6,7].

The success of a biomaterial or implantation is highly dependent on three major factors: (i) the properties (mechanical, chemical, and tribological) of the biomaterial in question, (ii) the implant's biocompatibility, and (iii) the recipient's health and the surgeon's competency [6,7]. Biomedical material is defined as any substance that has been created to interact with biological structures for medical use, which might be therapeutic (i.e., to treat, enhance, repair, or replace defective tissue in the body) or diagnostic. Metallic materials are commonly employed in biomedical applications due to their strong load-bearing capacity, favorable wear and friction properties, and acceptable biocompatibility [8].

1. Types of Biomaterials

A biomaterial is any natural or artificial material that constitutes all or part of a living building or biomedical device that performs, augments, or substitutes the function of nature [9]. These biomaterials are particularly constructed using the following material classes: polymers, ceramics, metals, and composite materials. Most biomaterials accessible today are produced either alone or in combination with materials from these classes. These types of materials exhibit varied atomic arrangements, resulting in diverse structural, physical, chemical, and mechanical properties, and thus offer a range of potential applications in the body. The sorts of materials are shown in the following parts [10].

Biomaterial is defined as "a nondrug substance suitable for use in systems that enhance or restore the function of body tissues or organs" [11]. Biomaterials are divided into three primary groups based on biocompatibility: bioinert, active, and bioresorbable.

i. Bioinert: These are materials that have limited contact with the surrounding tissue, resulting in osteogenesis. A few examples are steel made from stainless steel, titanium, zirconium, alumina, and ultra-high molecular weight polyethylene.[11]

ii. Bioactive: These are compounds that, once deposited in the mouth cavity, react with both hard and soft tissues. Examples include synthetic hydroxyapatite, glass ceramics, and bioglass.[11]

iii. Bioresorbable: Upon installation, these materials begin to resorb and are gradually replaced with bone. Examples include tricalcium phosphate, polylactic-polyglycolic acid copolymers, calcium oxide, calcium carbonate, and gypsum [12].

Bioinert and bioactive materials are dubbed "osteoconductive" materials because they can function as "scaffolds" for bone formation on their surfaces. [12]. Biomaterials can also be classed chemically into metals, ceramics, and polymers, as follows:

- i. Metals: titanium, which is titanium alloys, stainless steel, cobalt chrome alloys, gold alloys, and tantalum.
- ii. Ceramics include alumina, hydroxyapatite, beta-tricalcium phosphate, carbon, carbon/silicon, bioglass, zirconium, and zirconia-toughened alumina [13].
- iii. Polymers include polymethyl methacrylate, polytetrafluoroethylene, polyethylene, polysulfone, polyurethane, and polyether ketone ether [13].

2. Titanium and titanium alloys

Titanium and titanium alloys. Titanium and titanium alloys are among the most commonly used implant materials in biomedical applications due to their exceptional properties, which include excellent biocompatibility, resistance to bodily fluid effects, high tensile strength, flexibility, and corrosion resistance [14]. Titanium and its alloys possess a unique combination of strength and biocompatibility, rendering them suitable for various medical applications. For example, a key problem in orthopedic biomaterials is designing material surfaces that offer excellent osseointegration while also promoting implant longevity. After more than 50 years of employing biomaterials as implant materials [15] (metals: stainless steel, cobalt alloys, titanium alloys; ceramics: aluminum and zirconium oxides, calcium phosphates, synthetic and natural polymers), titanium and titanium alloys continue to be regarded as one of the most appealing and significant materials due to exceptional features like as resistance to bodily fluid effects, high tensile strength, flexibility, and corrosion resistance. This unique combination of strength and biocompatibility makes them ideal for medical applications [16,17]. In dental implants, commercially pure titanium (c.p. Ti) is prevalent, whereas Ti-6Al-4V is more commonly used in orthopedics. When assessing the desired biomedical use, the alloy composition must be examined to provide both biocompatibility and mechanical strength. Dental titanium alloys include Ti-6Al-7Nb, Ti-6Al-4V, Ti-13Cu-4.5Ni, Ti-25Pd-5Cr, and Ti-20Cr-0.2Si [18].

Ti-6Al-4V alloy was replaced in permanent implants with Ti-6Al-7Nb, Ti-13Nb-13Zr, and Ti-12Mo-6Zr [17] due to the potentially harmful consequences of vanadium or aluminum leaching. Extensive research has been conducted to determine the optimal surface topography for use in biotechnological applications [19]. In recent years, research on

materials for biomedical applications has shifted from microtopography to nano topography [20-22]. As a result, the current focus is on the application or testing of nanotechnology for biomedical purposes. A recent study found that titanium implants with rough surface topography and free energy promote osteoblast adhesion, maturation, and eventual bone formation [18].

Furthermore, the surface properties of titanium implants impact the adherence of various cell types. Titanium, namely topography, charge distribution, and chemistry [23, 24]. As the focus of biomaterials shifted to tissue engineering, complex medical applications, and biotechnology, it became necessary to identify and analyze the unique interactions between biomaterials and tissue components. Following a thorough examination of the biomaterials sector at the time, Williams [16] presented a unified notion of biocompatibility. This unified concept is as follows: "Biocompatibility refers to the ability of a biomaterial to perform its desired function about medical treatment, without producing any not desirable systemic or local effects in the recipient or beneficiary of that therapy, but generating the most appropriate beneficial cellular or tissue response in that particular scenario, and optimizing the clinically relevant performance of that therapy [16]. Titanium and its alloys are physiologically stable or inert [25], meaning they remain virtually unchanged when implanted in human bodies. However, titanium has limited wear and abrasion resistance because of its low hardness, which may result in a shorter service life for the implants. This difficulty can be significantly alleviated by using an appropriate surface modification approach [18].

One important factor to consider is that the fate of the implant material is determined by both the bulk of the material (which is critical in determining biological performance) and its surface properties (including surface chemistry and structure), with the latter being a crucial factor in the material's interactions with the surrounding tissue. The bulk material should be able to sustain high stress (too high for ceramic and polymeric materials, but possible for metallic materials). Nonetheless, the biomaterial's surface qualities do not allow for a permanent attachment between the implant surface and surrounding tissue. In that case, a fibrous layer may form, undermining load transfer at the bone-implant interface. In that case, micro-movements will be preferred, which can lead to implant failure [26].

The reaction of the titanium biomaterial is entirely dependent on its biocompatibility and surface characteristics. As a result, to enhance the performance of these biomaterials in biological systems, their surfaces need to be modified [27]. Improvements can be represented by: i) morphological modifications (increasing roughness, shifting topography from micro- to nanoscale, and tailoring the nanoscale morphology) caused by mechanical [28], chemical, and physical methods [27-30]; ii) modification with coatings based on hydroxyapatite, biomimetic calcium phosphate coatings, or hybrid coatings. Organic components and calcium phosphate minerals), or biomolecule functionalized coatings; or iii) a mixture between morphological changes and coatings for a combined synergistic effect.

The overall objective is to enhance the bioactivity, biocompatibility, blood compatibility, wear resistance, and corrosion resistance of titanium and titanium alloys for their intended applications. Of the aforementioned strategies, nanoscale surface tailoring produced breakthrough results, namely that roughness alone affects osteoblast cell adherence, spreading, and proliferation on titanium nanostructures [22,31]. The high surface energy of nanoscale surfaces enables an elevated initial amount of protein adsorption, which is critical for controlling cellular interaction at the implant surface. Surface characteristics influence cell adhesion, and charge distribution and material chemistry [32,33] may have an additional impact. With the rise of the tissue engineering and nanotechnology sectors, surface modification of implants has become necessary to promote tissue adhesion and implant integration while minimizing bacterial adhesion and inflammation. Response, or avoid the foreign body response. Summary and remarks concluding.

3. Functionally Graded Materials (FGMs)

Two distinct criteria are utilized to classify functionally graded materials. The first is based on material structure, while the second is based on the size of functionally graded materials. Figure 2 illustrates that functionally graded materials can be categorized into two broad classes based on their material structure: FGMs exhibit both continuous and discontinuous structures. Continuous FGM has a continuous gradient from one material to another. However, in the case of discontinuous FGM, the material gradient is stacked. FGMs are divided into two categories based on their material size: thin FGM and bulk FGM. Thin FGMs have relatively thin parts, such as surface coatings, whereas bulk FGMs are complete. Volume of materials. Thin FGM is manufactured using technologies like physical vapor deposition (PVD), chemical vapor deposition (CVD), and self-propagating high-temperature synthesis (SHS). Bulk FGMs are produced utilizing processes such as powder metallurgy, centrifugal casting, and solid freeform/additive manufacturing procedures.

Functionally graded materials have established themselves as a prominent category among contemporary, sophisticated materials. They were fierce competitors in a wide range of applications, particularly in the energy, military, aviation, and medical sectors. The growing interest in FGMs in the scholarly and industrial areas necessitates the establishment of many classifications from various perspectives. These provide more insight into the link between FGM qualities, processing approaches, level of control, and cost. This publication provided a critical assessment of several classification methods. Used in the field of FGM. These examined the merits and limits of the classified groupings from several engineering perspectives. Designers and manufacturers proposed new classifications for FGM production methods based on product form and wall thickness, control over gradient properties, residual stresses, equipment and manufacturing costs, energy consumption, and environmental impact over the entire life cycle. Some areas were identified as obstacles for FGMs on an industrial scale, including material modeling, numerical simulation, systematic selection and

design procedures, and an FGM data bank. The adaptability to mass manufacturing, process repeatability, dependability, and cost-effectiveness are among the future frontier for FGMs. Types of Functionally Gradient Materials (FGMs)

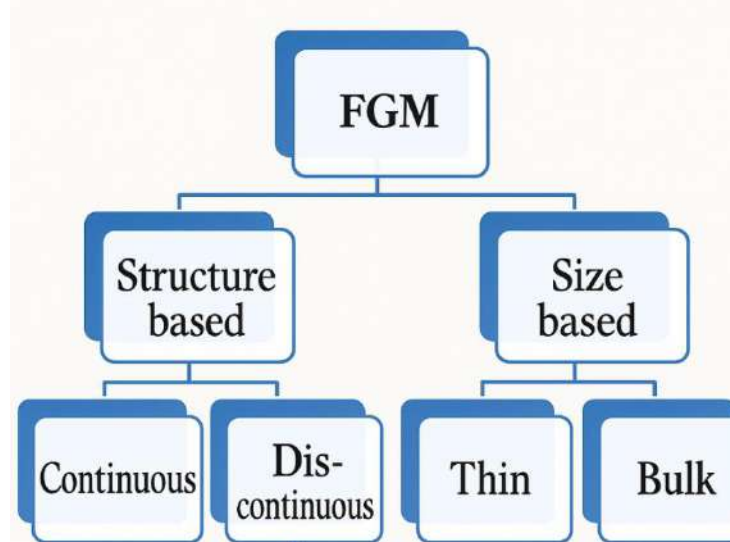


Fig. 1. - Classification of Functionally Gradient Materials [34].

4. Methods of producing FGM

There are several approaches for producing functionally graded materials (FGMs). A few of these are discussed in further depth below.

1. Vapour deposition technique

Vapor deposition techniques refer to a range of vacuum deposition procedures used to form thin films on base materials. All of these procedures may be utilized to create thin FGMs exclusively. There are two types of vapor deposition techniques: physical vapor deposit (PVD) and chemical vapor deposition (CVD). These are energy-intensive and create hazardous byproducts [35]. Other deposition-based processes capable of depositing thin, functionally gradient coatings include electrostatic deposition (ED), ion beam deposition (IBD), and self-propagating high-temperature synthesis (SHS) [36]. All of the aforementioned methods are uneconomical to produce bulk-type FGMs.

2. Powder metallurgy

Powder metallurgy-based techniques can be utilized to create bulk-type FGMs with a discontinuous (stepwise) structure. The process is carried out in several steps, including weighing and mixing powder according to a pre-designed spatial distribution based on functional requirements, stacking and ramming premixed powders, and, finally, sintering [37].

3. Centrifugal technique.

The centrifugal process is capable of producing continuously structured bulk-type FGMs. It produces functionally graded materials by spinning a mold using gravity [38]. FGMs are formed when material densities differ and a mold is spun. There are two drawbacks to this method: it can only manufacture cylindrical-shaped FGMs and has a restriction on the sort of gradient that can be formed.[38].

4. Techniques for additive manufacturing (AM) and solid free-form fabrication

Solid freeform fabrication (SFF)/Additive manufacturing (AM), often referred to as 3D printing, is a technique that involves connecting materials to create items from 3D model data, typically layer by layer, as opposed to subtractive manufacturing technology [39]. This toolless manufacturing process can make completely dense metallic pieces quickly and precisely. Metal AM methods are widely categorized into two types: Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) technologies. Both of these technologies can be further divided according to the energy source employed. Thermal energy is utilized in PBF-based technologies to fuse portions of the powder bed selectively. The two primary typical methods are select laser sintering/melting (SLS/SLM) and electron beam melting (EBM). PBF-based technology. DED-based technologies utilize concentrated heat energy to melt and fuse materials (in powder or wire form) as they are deposited. Some of the most prominent DED-based technologies include Laser Engineered Net Shaping (LENS)/Direct Metal Deposition (DMD), Electron Beam Free Form Fabrication (EBFFF), and arc-based Additive Manufacturing (AM). Most of the SFF/AM processes discussed above may generate functionally gradient materials (FGMs), ranging from thick coatings to complex FGM bulk pieces.[39] The advantages of AM methods, including improved material utilization, faster production, design flexibility, the ability to produce complex components, and lower energy intensity, are generating significant interest in producing FGMs for various purposes. Powder bed fusion (PBF)--based AM methods such as selective laser melting (SLM) and electron beam melting (EBM) are extremely popular. Methods for producing complicated parts owing to their high accuracy and surface finish as compared to directed energy

deposition (DED) based technologies. However, PBF-based technologies are less flexible than DED-based technologies in terms of functionally gradient material manufacturing because it is not possible to vary the material gradient by changing the chemical composition of the powder. However, these technologies may enable bulk FGMs by regulating porosity or incorporating various forms of lattice structures into the components to be manufactured. Directed energy deposition (DED) based additive manufacturing (AM) techniques are the most convenient for producing functionally graded materials (FGMs) because they can manufacture FGMs from thick coatings to bulk sections with continuous or discontinuous gradients. These techniques can create FGMs with superior adhesion and mechanical properties compared to powder bed technologies. Laser metal deposition (LMD) and electron beam free form deposition (EBFFF)/electron beam additive manufacturing (EBAM) are prominent technologies based on DED-based additive manufacturing (AM) equipment that can be utilized to produce various functionally graded materials (FGMs) [39].

5. Laser Metal Deposition (LMD)

The primary techniques based on DED technology are laser-engineered net shaping (LENS) and direct metal deposition (DMD), which employ a laser beam as a power source and powder as the raw material. The LENS method was developed by Sandia National Laboratories in 1997 and later licensed to Optomec (USA), whereas the DMD technique was jointly developed by the POM group and the University of Michigan [40, 41]. In this method, a high-power laser beam is used to form a molten pool on the base material and powder material is fed into the molten pool through nozzles. Powder delivered to the laser beam point is absorbed into the melt pool, resulting in a deposit on the surface. Figure 3 illustrates that the worktable can be moved in the x-y direction to obtain a desired cross-section of the sliced model, and subsequent layers can be deposited by incrementing the deposition head in the z-direction to complete the object. Deposition of layers is repeated until the desired three-dimensional component has been additively formed. Metal powder is delivered through nozzles and distributed around the circumference of the deposition head either by gravity or by using an inert carrier gas. The entire process is conducted under a controlled argon atmosphere where oxygen levels are maintained below 10 ppm [40, 41].

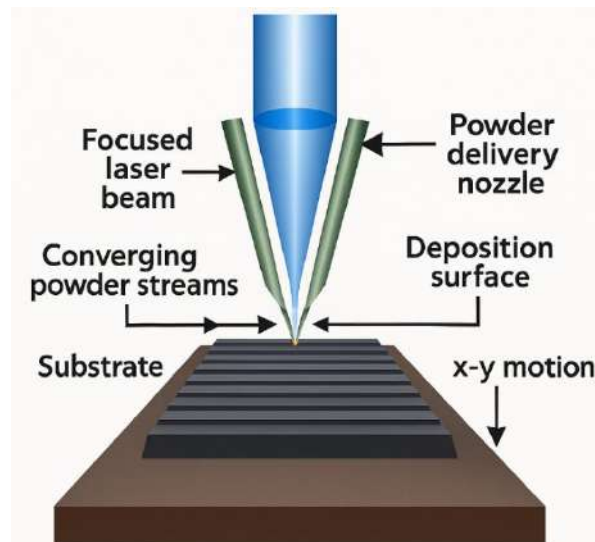


Fig. 2. - Basic laser-engineered net shaping procedure [42].

The laser-based Directed Energy Deposition (DED) approach in metal additive manufacturing (AM) is the most suitable technology for producing Functionally Graded Materials (FGMs). All varieties of FGMs, including continuous/discontinuous structured and thin/bulk types, may be readily fabricated using laser metal deposition (LMD). Pre-alloyed powders can be used to create discontinuous FGM. At the same time, elemental powders may be fed in exact proportions to the melt zone via different feeders to produce various alloys and composite materials in a continually graded method. With the use of this approach, the number of FGMs can be manufactured into complicated forms, as the rate of elemental powder deposition can be regulated for each feeder during fabrication for each layer. The final product can be obtained within hours [43].

6. Direct production using electron beams

Electron Beam Direct Deposition (EBDD) is another directed energy deposition (DED) process that employs an electron beam as a power source and wire as the raw material. Sciaky (Chicago, USA) developed this method, also known as electron beam additive manufacturing (EBAM). This technology can manufacture medium to large-sized near-net-shaped components within a vacuum chamber that are directly used as deposition material. The basic electron beam

system includes a Sciaky 60 kW/60 kV welder. The electron beam is electrically focusable, and the output power is scalable across a wide range, which allows for a wide range of deposition rates to be obtained with the same apparatus. The typical deposition rates of EBAM systems range from 3 to 9 Kgs/hrs, depending on the material used and part complexity. Additionally, the EBAM system features a closed-loop control system in which the melt pool size is continuously monitored, and parameters are adjusted to maintain a constant size, ensuring consistent part geometry, uniform microstructure, and mechanical properties.



Fig. 3. - Electron beam additive manufacturing using twin wire deposition [44].

EBAM technology may also manufacture a variety of functionally graded materials (FGMs) by connecting numerous wire feed nozzles to a single EB gun. Two or more wires of various metal alloys can be controlled individually and fed into a single molten pool to generate graded materials. Both coating and bulk FGMs can be generated in a continuous or discontinuous way.

FGMs are created using arc deposition technology. A wide range of arc-based additive manufacturing technologies are available, using arc (plasma, TIG, MIG) as the power source and material in the form of powder or wire. Plasma transferred arc (PTA) and plasma arc welding (PAW) are free from additive manufacturing (AM). Methods that employ plasma arc as a power source and raw material in the form of powder and wire, respectively. Shaped metal deposition (SMD) is another additive manufacturing (AM) technology that employs tungsten inert gas (TIG) or metal inert gas (MIG) welding with wires to create free-form fabrications. Because most of these systems involve wire-fed, they are also known as wire-assisted additive manufacturing (WAAM) systems. A wide range of system configurations can be created by combining traditional welding methods with robots, manipulators, or gantries for automation. All of these techniques, with suitable inert gas shielding, offer a high potential for producing near-net-shaped medium to large-sized components at a far cheaper cost than laser and electron beam-based procedures.

Several welding-based additive manufacturing (AM) techniques have been developed to deposit functionally graded materials. In this example, two filler wires are controlled independently and fed into the arc (TIG or MIG) for deposition. Several experiments have been conducted to establish the efficacy of arc-based additive manufacturing (AM) setups for producing functionally graded materials (FGMs). Sajan Kapil et al. [45] effectively synthesized an Al-Si alloy with varying thermal conductivity. It was built utilizing a hybrid layered manufacturing machine (HLM), which combines a three-axis CNC with a gas metal arc welding (GMAW) deposition technology. S. Suryakumar et al. [46] proposed two methods for fabricating functionally graded materials using weld deposition. FGMs can be created by altering process parameters or by employing a twin-wire feeder that can be guided and controlled independently.

Processing Techniques for FGMs

The manufacturing process of an FGM is typically separated into two stages: constructing the Gradation, which involves transforming an inhomogeneous structure into a bulk substance, also known as consolidation, and then forming the Gradation. Gradation processes are categorized into three types: constitutive, homogenizing, and segregating. Constitutive processes begin with precursor materials or powders and gradually develop into a graded structure. [47]

Automation advancements in recent decades have made constituent grading methods more highly advanced. Economically feasible. Homogenizing processes transform a sharp contact between two materials into a gradient by material transfer. Segregating processes begin with a homogenous substance that is transported to a graded state by an external source, such as gravity or electricity. Homogenizing and segregating processes result in continuous gradients, but they have their limits. Different gradients can be made. After grading, the material is often dried, sintered, or solidified. Consolidation techniques for FGMs require careful consideration of processing conditions to prevent uncontrolled destruction or alteration of the gradient.[47]

FGMs may shrink unevenly during free sintering. To optimize sintering behavior, it is important to consider factors such as porosity, particle size, shape, and content of the powder mixture. Each material combination and gradient type should be addressed separately, taking into account the current understanding of sintering mechanisms [47].

Surface coatings are often used for thin, functionally graded materials, with many deposition techniques available. Service requirements vary based on the procedure.[47] There are many applications for functionally graded materials (FGMs), and below are some of them:

1. Aerospace

(FGMs) are used in aerospace industries due to their ability to withstand high thermal gradients, making them suitable for structures such as airplane bodies, rocket motor components, and other space applications [48].

2. Medical

The human body contains many tissues that are classified as natural functionally graded materials, such as teeth and bones. During accidents, human tissues suffer damage, and in most cases, these damages are irreversible, necessitating the use of alternative parts to replace them. According to [49], functionally graded materials may be used in the medical field to replace damaged tissues, such as teeth and bones, with biomedical materials [50-52].

3. Defense

The qualities of functionally graded materials are widely recognized, and they have an exceptional capacity to prevent fractures from propagating. These properties enable the use of these materials in defense, particularly to shield soldiers from firearms through the production of armor plates and bullet-proof vests [53].

4. Energy

According to [(Müller et al., 2003) and (Niino et al., 2005)], functionally graded materials (FGMs) are used to generate energy because they are used to produce solar power, devices for energy conversion, and as thermal protection to protect the coating of the turbine blades in gas turbine motors [54-55].

5. Optoelectronic

Due to their graded refractive index, functionally graded materials can be utilized in the field of optoelectronics, such as low-threshold current edge lasers (GRIN SCH), storage media, notably magnetic discs (audio-video), and tunable photodetectors [56].

6. Construction

The construction sector faces several issues related to material performance, material costs, and environmental impacts. Additionally, the variation in building structure functionality with location opens the door to the use of functionally graded materials (FGMs) in the construction sector [57]. When employing (FGMs), the structure and content of materials will progressively vary across the volume, resulting in diverse material characteristics [58].

7. Other applications

Furthermore, (FGMs) might be used as foundation materials in a variety of industries, including cutting tool coating [59]. Components of vehicle engines, components of nuclear reactors, turbine blades, heat exchangers, fire sensors, tribology (advanced materials), fire retardant doors, and many more applications. All of these applications are emerging as a result of lower manufacturing costs and the ability to regulate and improve the characteristics of FMGs [60].

IN (2016) A. Kumar et al. [61] This article explores the link between method, structure, and property in implantable biomaterials utilizing additive manufacturing-based rapid prototyping techniques. Traditional procedures, such as freeze casting and sintering, are limited due to adaption difficulties and incompatibilities with host tissues. Additive manufacturing provides the benefit of Creating patient-specific designs. The article examines 3D printing scaffolds for tissue regeneration, focusing on their biocompatibility and mechanical properties. It also covers functionally graded scaffolds and the vascularization of 3D porous scaffolds to fulfill biomedical industry standards. Functionally graded 3D structures with excellent strength and energy absorption are appealing.

In 2017, Dalia Mahmoud et al. [62] This research examined the use of additive manufacturing (AM) technology to create orthopedic implants from lattice structures and functionally graded materials. It investigates the benefits of these technologies, their design flexibility, and the obstacles associated with their implementation. It also examines current case studies and proposes future research areas to improve their usage in orthopedic implants.

In (2018) Ezgi Onal 1, et al. [63]. Functionally graded lattice structures from additive manufacturing show promise for bone tissue engineering. However, the relationship between mechanical qualities and biological reactions remains unclear. Creating continuous gradient structures and examining their mechanical and biological properties may help enhance orthopedic implant design and establish standards for these materials. The best gradient structures must have small pores in the core for increased strength and large pores for enhanced cell penetration and proliferation.

In 2019, Qifeng Jiang et al. [64] This article assessed the biomechanical response and stress distribution of a new disc prosthesis made from functionally graded polymers (FGP). The kinetics of FGP parameters are based on experimental data from linear ethylene copolymers. The findings suggest that FGP parameters can be customized to manage stiffening, non-linear behavior, inelastic effects, and stress distribution, thereby paving the way for patient-specific FGP prostheses utilizing 3D printing technology.

(2020), Syed Saad Bin Qasim et al. [65]. Researchers are working on innovative treatment ways to restore damaged tissue structure and function. Current synthetic biomaterials are basic when compared to natural ones; however, the capacity to include biologically inspired features has improved. Functionally graded materials mimic natural tissue shapes, resulting in a more pronounced reaction.

On targeted tissue. This review provides an overview of spatiotemporal arrangement in clinical dentistry, ranging from additive manufacturing to conventional techniques.

In 2021, Douglas Fabris et al. [66] employed the finite element technique (FEM) to compare the biomechanical behavior of one-piece zirconia implants with a functionally graded bioglass (BG) layer to that of monolithic zirconia and BG-coated implants. Zirconia disks were infiltrated with bioglass S53P4 and examined morphologically using a scanning electron microscope (SEM). The study found that BG coating resulted in a 30% reduction in stress in the implant body compared to monolithic zirconia implants. The BG-graded system demonstrated improved overall biomechanical behavior, indicating that these enhancements should be paired with the osseointegration benefits of bioactive glasses.

In (2022) Ganesh Kumar Sharma et al. [67]. Biomechanics employs mechanical principles to simulate biological tissues, and recent advances in additive manufacturing (AM) have enabled the production of functionally graded biomaterials for orthopedic bone replacements and implants. However, no functionally graded buildings have been 3D printed using biodegradable materials. This work utilizes computational and analytical tools to calculate the mechanical behavior of biomaterials composed of repeating unit cells, with a focus on the bi-pyramid hexagonal lattice structure. The Timoshenko beam theory was discovered to be closer to numerical values.

In (2023), Amir Najibi et al. [68]. This study investigates the application of Functionally Graded Materials (FGMs) and coatings in orthopedic implants to mitigate stress shielding and prevent loosening. It proposes two areas of research: 1) FGM manufacturing technologies and 2) design and optimization of knee and hip arthroplasty components. The study emphasizes the importance of optimal design for long-span goods and recommends incorporating 2D and 3D FGMs into the design of TKA and THA.

In 2024, Mohaddeseh Fatemi et al. [69] investigated the use of functionally graded materials (FGM) in dental implants to increase biocompatibility, fracture toughness, and wear resistance. Porous FGM implants are proposed to minimize stress shielding while improving bone ingrowth properties. To investigate material characteristics and stress transmission, the researchers employ ABAQUS software's UMAT subroutines and parametric analysis. The study discovered that porous FGM implants can achieve early stability when compared to pure titanium implants. This study fills a gap in FGM implant research and may be beneficial in dental implant design.

Conclusion

In conclusion, Functionally Graded Materials (FGMs) represent a promising class of advanced materials with significant potential in biomedical and engineering applications. Their ability to tailor mechanical and biological properties makes them particularly suitable for bone tissue engineering. Although production costs remain a limitation, advances in additive manufacturing - especially Directed Energy Deposition (DED) technologies - offer practical pathways toward cost reduction and large-scale implementation. Future research should focus on material modeling, optimization, and clinical translation to fully exploit the capabilities of FGMs.

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