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An Overview of Functional Gradient Biomaterials Manufacturing Process of Implants Types

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Abstract

Functionally graded material is one of the promising sectors of the material since because of the great ability to control with required product properties could be strongly used in biomedical applications exclusively in the implants sector, this review paper demonstrates briefly about the most prominent known manufacturing methods and focusing on the implants coated by FGM layer manufactured by using EPD method because the EPD has significant properties it could produce FGM layer in the Room temperature without depending on chemical reactions or heat adding, Biomedical application need highly accuracy when we deal with material that directly contact with human tissue because the heat effect could be change the biocompatibility properties and also the chemical reactions could make toxic effect on the produced implants, All these reasons make the EPD one of the favorable method for the FGM coated Implants. this paper will summarise and give the Gide line for the researcher about the most important substrate and suspension materials used in the EPD method and its application.

Keywords: Functionally Graded Material (FGM), Fabrications Biomedical Implants, Medical Applications, Orthopedic Implants, Orthodenticle Implants.

طرق تصنيع الغرسات الطبية باستخدام المواد ذات الخواص المتدرجة طبقياً – مراجعة عامة

نوزاد خليل كريم ، اياد مراد طخاخ ، عبد الله عبدالحي علي

الخلاصة:

تعد المواد ذات الخواص المتدرجة طبقيا أحد المجالات الواعدة في علم المواد نظرًا لقدرتها الكبيرة على التحكم في خصائص المنتج المطلوبة ويالتي يمكن استخدامها في مجالات عديدة لا سيا في التطبيقات الطبية الحيوية وبشكل خاص في صناعة الغرسات، يوضح هذا البحث نبذة عن أبرز طرق التصنيع المعتمدة في صناعة المواد ذات الخواص المتدرجة طبقيا وخصوصا الطرق التي يتم من خلالها تصنيع الغرسات المطلية باستخدام طريقة EPD كون ان طريقة EPD توفر امكانية مميزة من حيث ظروف العمل حيث يمكن انتاج غرسات ذات خصائص طبقية متدرجة بظروف قياسية (درجة حرارة الغرفة) دون الاعتماد على التفاعلات الكيميائية أو إضافة الحرارة ، تحتاج التطبيقات الطبية إلى الدقة العالية عند تصنيع المواد التي يتم استخدامها بشكل مباشر مع الأنسجة البشرية لأن عامل درجة الحرارة اثناء التصنيع يمكن ان يأثر على خصائص التوافق الحيوي بين المادة الطبية المصنعة و الانسجة الداخلية للجسم وأيضا الانتاج بواسطة التفاعلات الكيميائية يمكن أن يؤدي الى تأثير سام ، كل هذه الأسباب تجعل من EPD واحدة من الطرق المفضلة لانتاج الغرسات الطبية المغلفة. في هذا البحث سيتم عرض طرق تصنيع المواد ذات الخواص المتدرجة طبقيا ومن ثم استعارض المواد الأساسية المستخدمة في طريقة EPD وتطبيقاتها.

1. Introduction

Functionally graded materials (FGMs) are invented depending on a gradual change in, microstructure, composition, or density from one side to another. This amalgamation is correlated with a gradient of characteristics, either thermal, chemical, mechanical, electrical or magnetic. FGMs are advanced materials with excellent properties with a high controlling degree of direction and concentration of required properties, [1]. Due to the limitations of materials properties fabricated with conventional methods, such as metals in their purest form, ceramics, and conventional

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composites, as well as a new method of manufacturing need to be used to comply with the biomedical requirement and the FGM promising a good ability to mimic the natural human body components [2] the graded materials is unique because of their tribological, thermal, and mechanical properties, allowing the scientist to use that material in different biomedical applications [3]. FGMs could be categorized in different ways depending on the method that is generated under the actual industrial situations since they have a variety of structures and compositions Bassiouny Saleh and Lisha Wang [4]. because of the high potential need for new products with specific biomedical functions, there has been significant improvement in the use of FGMs in recent decades. Because there exist structures that mimic natural materials, the manufactured biomaterial rank depends on the degree to of it behaves like the replaced part of the human body [5]. Human body components including teeth, bones, and skin are the most notable examples of naturally functionally graded structures since they have a range of toughness and hardness qualities, Specific natural instances are shown in Fig.1, A tooth, and more specifically the crown of a tooth, is a key illustration of how FGM is employed. To reduce brittleness and fatigue in the natural human tooth, the inner surface needs to be very tough, and the outside surface needs to be highly hard to prevent wear [5]. As a result of the fine gradual gradient over the whole product, FGM has been utilized to retrain stress concentration via the fine transition of slight gradation throughout the entire product dimensions. The attraction of FGMs enabling research in a wide range of projects has been further enhanced by several biomedical applications [6]. Manufacturing methods for FGMs have evolved dramatically over the past 30 years, with a wide range of technologies currently in use, including centrifugal force methods, powder metallurgy techniques and vapour deposition techniques [7].

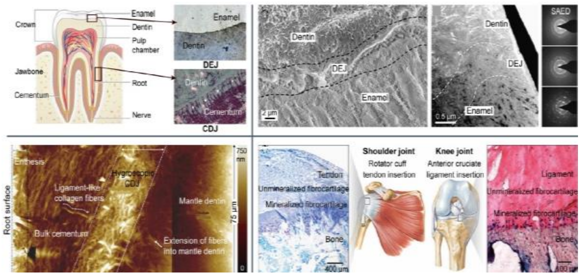

Figure (1): Few natural FGMs that had structures with the graded features are shown in the following examples [5].

The main purpose of the emanation of many fabrication approaches of FGMs is that these compounds have a wide range of uses in several medical applications [7]. The production methods of FGM in the beginning depend on the component's mixture, such as ceramic/ceramic, ceramic/polymer, metal/metal, and ceramic/metal. Many classifications exist now to illustrate the FGM methods of production by state (liquid, solid and deposition), graded type (microstructure, porosity and composition) and structure (continuous and discrete) [7]. This introduction focuses on the FGM improvement in manufacturing technology during the last three decades and the recent FGM processed methods depend on the state in the process to introduce the placement of manufacturing methods and the role of properties controlling the graded structure and how FGM important in enhancement of biomedical application.

2. FGM manufacturing Methods

Today, a variety of ways are well-known and were frequently utilized for the routes of fabrication for the methods of producing FGMs, as shown in Fig. 02. These advancements included a variety of chemical and physical principles as they went from simple, outdated approaches to complex, modern ones. Lamination and infiltration processes, centrifugal casting, plasma spraying, chemical and physical vapour deposition (CVD/PVD), powder metallurgy, and additive manufacturing (AM) or solid freeform fabrication (SFF) with its subcategories are all examples of FGM production techniques. Different types of materials, including metallic materials in DMD and LENS, polymer materials in SLA and FDM, and biological materials in micro extrusion and inkjet printing, could currently be employed in AM procedures [8]. Numerous books have examined the specifics of various production techniques, identifying their technicalities, drawbacks, benefits, and industry uses [9]. The examination of experimental mechanical qualities (hardness, fatigue, and tensile) or thermal properties [10]. which is the wide-regular foundation for research, The high level of complexity for the modelling of the interfaces and the gradual structural change, many constituents and their graded properties, may be the reason why few research groups considered the FGMs numerical simulation. The primary characteristics, constraints, and benefits of the many manufacturing processes and families that are currently available are of great relevance to the various process categories [11]. The optimization of production FGM aimed at or parameters at the achievement of the specification qualities was the subject of several recent published studies that were summarized in this assay. These deal with a wide range of product sizes, productivity, complexity, price, and durability. Centrifugal casting, which is best suited for basic and bulky goods, is still in competition with advanced additive manufacturing technologies and high-quality powder metallurgy processes for the production of parts with intermediate levels of complexity (AM). The reader was given an overview of the key technical aspects of each manufacturing process using the information from the accessible resources. This exercise was very helpful for taking a broad view and comprehending the causes of the necessity for the various types of classifications [8], as illustrated in Fig 2.

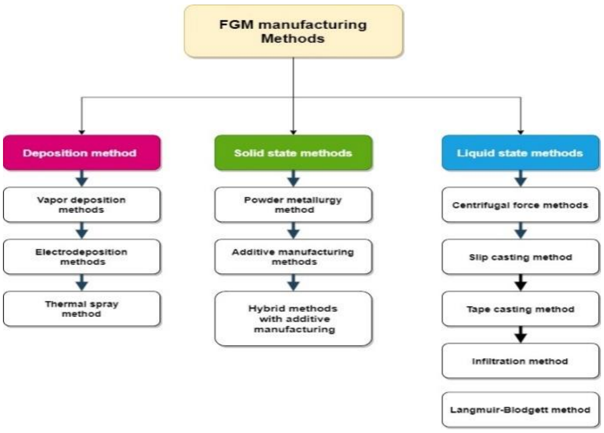

Figure (2): FGM Manufacturing Methods [15]

2.1. Methods of deposition

The depositions methods of thin FGM on a micro-scale, such as electrophoretic deposition, thermal spraying, and vapour deposition, are considered highly relevant [12]. These approaches allow us to create a discontinuous or continuous graded layer, as well as FGMs with graded properties in 1, 2, or 3 dimensions [12].

2.1.1. Vapor methods of deposition

An extremely significant producing way of a thin, graduated layer (nm to sub-mm) in construction procedure is the vapor method of deposition. Materials were condensed into solids by using this approach, described as a vapour deposition [12]. The layer gradation method was primarily utilized to manage the mechanical, corrosion, wear, and thermal properties of the substrates [13]. As depicted in Fig. 03, the vapour deposition was divided into two broad categories: chemical (CVD) and physical (PVD) [13].

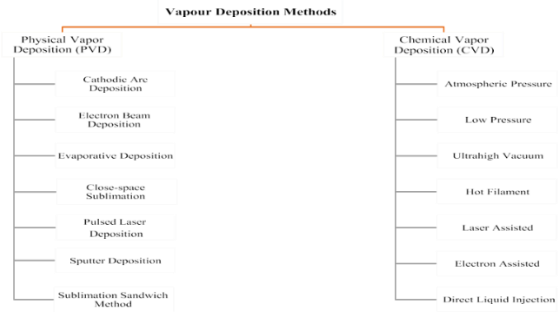

Figure (3): Classifications of FGMs production by Vapour Deposition processing Methods.

2.1.1.1 Method of Physical Vapour Deposition

The physical vapour deposition (PVD) method depends on the physical change of the material by changing tin from the sold state to the vapor state after that condensing it as thin-film layers according to Fig.4. The PVD is producing thin FGMs is one of the millstone ways of huge advantages such as the ability to produce high pure thin films with structural gradation, ability to create a wide range of compounds, from simple metal deposition to the formation of alloys. The environmental friendship of this method is also considered as one of its advantages when we are competing with other techniques [14]. Vacuum deposition methods for thin-film coatings could be used to represent PVD as well. PVD processes like a method of electron beam deposition, cathodic arc deposition, method of close-space sublimation, evaporative deposition, method of pulsed electron deposition, pulsed laser deposition, sublimation sandwich, and the sputter deposition method can all be utilized to create a proper smooth thin film with properties gradient [14]. Because of its increased mechanical characteristics and wear resistance, (PVD) is employed in a wide range of industries, including automotive and aerospace, as a thin layer coating with attributes gradation [15]

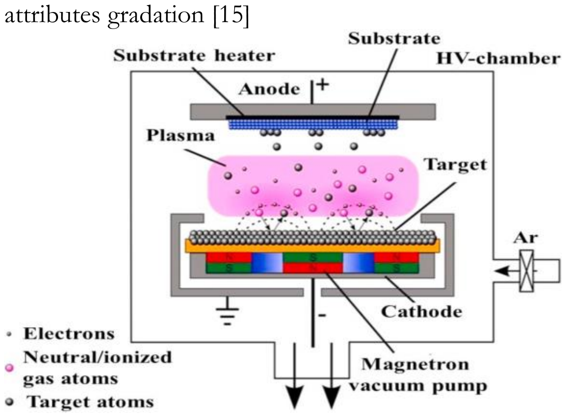

Figure (4): Simple Schematic diagram for PVD manufacturing process [4].

2.1.1.2 Method of Chemical Vapour Deposition

Solid materials with high quality can be produced by utilizing the method of vacuum deposition equipment and chemical vapour deposition (CVD). CVD methods such as ultrahigh vacuum, low pressure, atmospheric pressure, electron-assisted, laser-assisted direct liquid injection, and hot filament are all used to create a smooth thin coating with variable characteristics [16]. Thin films for semiconductor applications are commonly made using the CVD process, which has been around for a long time. Volatilized precursors were often exposed to the reacted substrate in a regular CVD process, where desired decompositions and precursors were present [17]. It is possible to use this procedure by first heating the substance to be coated, followed by the coating material, and finally by cooling the coating material until it condenses on the substance's surface [18]. Heat or lower surface pressure can be used to evaporate coating materials, as depicted in Fig. 05 (see below). Coatings having varying mechanical characteristics, such as wear and corrosion resistance, can be enhanced and improved by using CVD to generate thin FGM films with properties gradation [19]. In addition to the behavior of the microstructure, the prior study emphasized the thermal graded properties of the coating layers. FG WC/Co/diamond nanocomposites can also be produced and studied via the CV infiltration method to improve the properties of the produced graded layers [20].

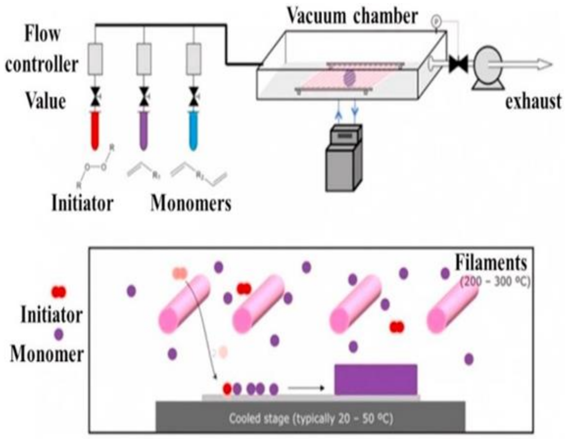

Figure (5): Simple Schematic diagram for PVD manufacturing process [4].

2.1.2 Electrodeposition methods

The electrophoretic deposition (EPD) method is used nowadays in the manufacturing of FGM applications because of its reliability, and elegancy and is considered a simple trusted straightforward method for graded properties production based on the electrophoresis principles [21]. The substrate coating formation is done by the action of chemical reaction or electrolysis, when the particles with different activities are subjected to the chemical reactions instantaneously the deposit activity will be done on the surface [21]. In the beginning, interaction with the additives and solvent was used to give charge to the process particles. Then charging particles passed under the control of the field of electrical applications. Finally, the particles produce a developed accumulated electrode deposition, as shown in Fig. 06. The equipment of the Process is very easy to operate, easy to control the accuracy, simple, with low cost, with important limitation which was only used for the production of FGM body's thin foil. The method of EPD was widely utilized in different sectors of applications, like coatings (nm-mm), textured materials and lamination of Infiltration [22]. Material influence kinds on hardness values and microstructure behaviour in FG composites were studied by the studs in the past. The EPD approach was used to create four FG composites (Al2O3/Ni YSZ/Ni Al2O3/MoSi2, and Al2O3/YSZ). Particle dispersion was discovered to be an important component in FG composite product mechanical characteristics. A gradient stepwise for the FG C–C/SiC composite materials using the method of EPD is studded to enhance the oxidation resistance and mechanical properties of FG C–C/SiC composite materials was produced using the identical conditions of production as the FG Ni/Al2O3 composites. When compared to a different composite, the FG layer improves oxidation resistance and mechanical qualities [23]. Graded continuous characteristics can be generated using this approach, which builds on the property's gradient of many materials, like, ZrO2–Al2O3. For example, WC-Co. discovered an intriguing result when it adjusted and monitored the sintering temperature [24].

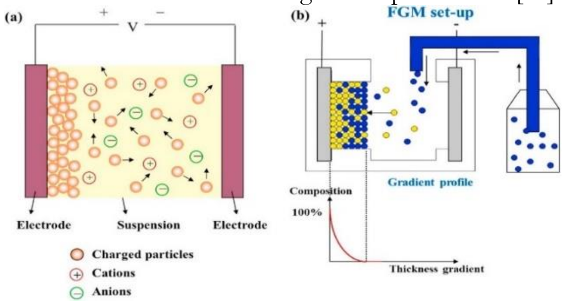

Figure (6): (a) Simple Schematic diagram of EPD manufacturing process, (b) Concept of EPD manufacturing process for FGM production [4].

2.1.3 Method of thermal spray

Transformation The thermal spray method is one of the important methods that utilized in the production of FGMs for produce creating a thin dimensions surface coating by using spraying process [4]. The graded layers of surface give the protection for components because of their surface treatment against wear, corrosion, electrical, and thermal isolation as a result of difficulty of these components to be served with single case of service [25]. There are many processes that could be utilized for the FGMs manufacturing with gradient properties by using the thermal spray coating as shown in Fig .07 [26]. In the beginning of this process, the source of heat was utilized for melting the coating raw materials, then gases used to make treating before spraying the melted coating on a base material, these melted coating materials are pushed to be they solidify and forming a regular layer as shown in Fig .08 [65].

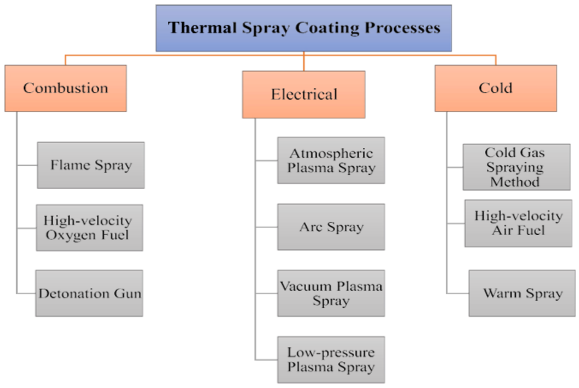

Figure (7): Simple Schematic diagram of thermal spray manufacturing process.

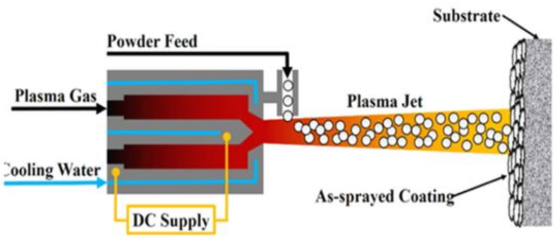

Figure (8): Schematic of thermal spray coating processes [65].

For FG ZrO_2/NiCoCrAlY coatings, many investigations have looked into the effect of thermal characteristics on the graded layers applied through the thermal spray method. The FGM coatings will be made with five different ZrO2 fractions of weight (0, 25, 50, 75, and 100 wt per cent). Increased ZrO_2 weight fraction in the FG coatings improves thermal properties [27]. The FGM coating's residual stress has been examined in a separate study. ZrO_2 has been shown to reduce residual stress in FG-coated products by increasing the ZrO_2 weight fraction. Thus, the residual stress may be adjusted by the gradation of FG coatings' characteristics [27]. The detonation gun spray approach might be used to build an FG thermal barrier, which would increase its thermal and mechanical qualities. NiCrAlY was used as a substrate for the FG thermal barrier coatings, and a topcoat of yttria-stabilized zirconia (YSZ) was applied. In their research, they discovered that the amount of YSZ present in the FG-coated goods had a significant impact on their mechanical, microstructural, and thermal properties [28]. The powders of the FGM TiO_2-HA coatings are produced by using the method of atmospheric plasma spraying to improve the mechanical qualities [29]. To produce FG Ni/YSZ composites with enhanced microstructure and thermo-mechanical properties, researchers used a plasma high-temperature torch to create the composite material. The FG layers were constructed using five YSZ powder different weight fractions of (20, 40, 50, 60, and 80 wt per cent). The white phase was used to represent the Ni, while the black parts were used to depict the YSZ particles. With careful consideration of spraying characteristics such as particle size and density of metal and ceramic particles, a homogeneous coating has been obtained [30]

2.2 Solid State Methods

The methods of solid-state FGMs of production, classified as, additive manufacturing, powder metallurgy and friction stir collective manufacturing process, this method considered as most promising methods for production FGM. On the other hand, these techniques could be created a discontinuous gradient FGM and this gradation could be controlled high degree of accuracy to be available to many industrial applications [31].

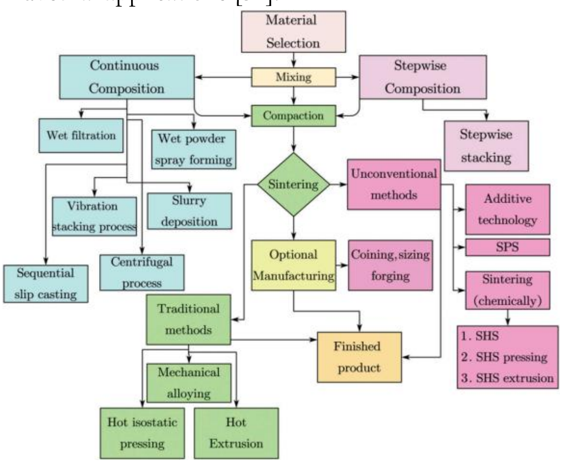

Figure (9): Main steps of production of discrete FGM powder metallurgy [35].

2.2.1 Powder Metallurgy Method

The reactance vast range of beneficial properties possessed by the powder metallurgy (PM) method of component manufacture, which is used for the fabrication of FGMs and is regarded as the oldest approach utilized in this industry [31]. In addition to this, it is considered to be one of the most essential ways of solid-state manufacturing of FGMs in bulk situations with discontinuous feature gradation [31]. Mixing, stacking, pressing, and sintering are the four primary phases that comprise this method's application in the manufacturing of FGMs, as depicted in Fig. 13 [32]. The first thing that needs to be done is to mix the powder, and the selection of the material group that you use will depend on the desired conditions of graded features. Then, the powder's weight and how it was mixed are skittered for evaluation, as this plays a key role in determining the properties of the final product [32]. The second stage is to place the mixture in the mould in the appropriate order, taking into account the supplies that are available in each location. In this essential stage, the step-by-step qualities have been specified in each layer, and this precision was achieved by controlling the composition. After this, the loaded powder was crushed to give the structure its integrity and strength. Last but not least, the sintering stage is often carried out at a temperature that is lower than the melting point of the primary component. This step can be carried out using a variety of procedures of sintering including hot isostatic pressing (HIP) [33].

2.2.2 Methods of Additive Manufacturing

Additive manufacturing (AM) methods used in actual manufacturing field because of its significant impact on the FGMs development in additional it contributed to change the conventional metallic model of production by using developed layer-by-size machinery instead of the easy mold [34]. Now days, several AM methods turn out to be popular in different products such as energy, medical, construction, automotive, sports, robots and space functions, which required properties gradation as they could process a different materials range [34]. Methods of AM are used to gain better quality and higher productivity. The selection of one of these procedures depends not only on the shape and design of the component, but also on the needed gradation of qualities. These processes can vary, even when working with the same grade of material [35]. materials jetting process, stereo-lithography method Laser-based methods, and simulation of fusion deposition could be classified significantly as AM approaches for the fabrication of FGMs with distinct gradation [35].

2.2.3 Method of Friction Stir Additive Manufacturing

The invented FGM manufacturing procedure using the friction stir Additive manufacturing (FSAM) method. When the FGMs are manufactured by using FSAM compared with the traditional techniques it shows more controllable and provides the greatest advantages. Friction stir welding (FSW) is considered one of the solid-state welding techniques [36]. The FSW and FSAM have the same fundamental principle. In FSW, the principle of rotating places a pin tool on the surface, which will generate tension while the material is moving. This is done to achieve the desired result. Welding the metal together is accomplished by applying downward force, and rotating the tool head, which results in pressure, and friction heat [37]. This caused the pin that will be used to mix the mixture to move the material at the same time. Layer-thin structures are created in FSAM by welding packets of weld plates together, and after that, the friction stir is fused, which is illustrated in Fig.10. FSAM can be utilized in a variety of fields, including aerospace and defence [38]. The FSAM production process FGMs with characteristics gradation has numerous variables that can be controlled and impacted, including tool parameters and machine parameters When compared to powder bed fusion, the FSAM methods produce larger pieces, making them better suited to the production. of entire satellite structures or spacecraft [39].

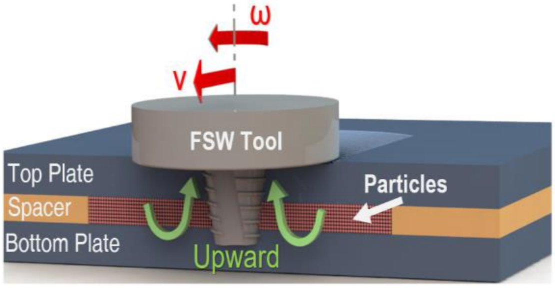

Figure (10): Concept of FSAM of FGM manufacturing process [40].

2.3 Liquid State Methods

FGMs can be made in a variety of ways, including centrifugal slip casting, infiltration, and tape casting [41]. When compared to other approaches, these techniques are more cost-effective and can create continuous-graded material qualities. It's also difficult to control wettability across materials and characteristics gradation, as well as the molten metal issues that come with techniques [41].

2.3.1 Methods of Centrifugal Force

Centrifugal force is the primary driving force behind the manufacturing process of bulk FGMs. This force is the cause of the continuous particular feature gradation, which is very suitable for a variety of industrial applications [42]. It is possible for an uneven distribution to take place between two or more phases of the material if it is viewed from the radial perspective. As a consequence of the centrifugal force that was produced as a result of the rotation of the mould as shown in Fig. 11 [42]. These days, many methods are used for the production of FGMs, all of which are directly dependent on the characteristics of centrifugal force. Some examples of these methods include the centrifugal slurry method, the centrifugal pressurization method, and the centrifugal casting method, which are all illustrated in Figure 16. In the course of the production of FGMs during the past three decades, the application of centrifugal force has been used with a variety of reinforcement materials.

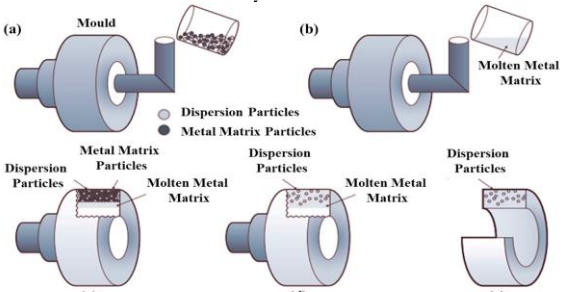

Figure (11): Steps of Centrifugal force for FGMs production method [42].

2.3.2 Method of Slip Casting

The slip-casting process, ceramic particles are suspended in a liquid matrix with very small particle sizes. When the matrix is removed from the slip, capillary action causes the surface to collapse into a porous mould. Mold walls [43]. on the other hand, will remain stacked in the form of a clay slip. The remaining fluid is drained from the mould once the desired thickness of the wall has been achieved. It will be ready to be popped out of the mould when it's completely dry [44]. Slip casting was used extensively in the production of FGMs because of its ability to provide continuous graded characteristics and complex shapes. For the FG metal/oxide ceramic composites, FG zone microstructure and mechanical characteristics were studied [45]. The FG Al_2O_3/W particle distribution was also explored. the slip-casting method calls for the use of FG Using the slip-casting method under magnetic fields, the graded structure of the Ni/ZrO_2 composites has been studied concerning the nickel concentration in the composites [46]. FG Al_2O_3/Fe composites' microstructure behaviour and particle dispersion were studied about the influence of magnetic fields on FG samples' smooth gradation of characteristics. The mechanical and microstructural features of the FG SS304/ZrO_2 composites formed by slip casting have been studied to determine the effect of the discrete gradient. As a result of the particle distribution being more diverse. It has also been discovered that the mechanical behaviour and microstructure of FG Ni/Al_2O_3 composites made by centrifugal slip casting process influence the size of Ni particle sizes [47]. There were significant effects on graded zone formation due to the size of Ni particles; however, a smoother distribution of particles was observed for the higher Ni particle sizes [48].

2.3.3 Tape Casting Method

Tape casting manufacturing method for thin FGM products (with layer thicknesses ranging from 50 to 1000 nm) that was originally a normal ceramics process but has subsequently evolved into a high-tech ceramics process. This approach was used to produce thin FGM products as shown in Fig. 13 [49]. The procedure of doctor blading, which is a classic kind of tape casting, has been adapted to specific substrates to create multi-layered structures and integrated circuits [50]. FG Ceramics composed of the material sialon (Si–Al–O–N) have been designed and manufactured with the tape casting and lamination method to evaluate the sialon (Si–Al–O–N) ceramics' effects on the mechanical properties and microstructure of the generated graded layers. In addition, samples of FG-SiAlON with a variety of microstructures were investigated for potential usage in several different applications [51]. FG Nb-doped PZT/carbon black piezoelectric ceramics have been designed and produced using the tape-casting process to investigate the thermal properties and microstructure of graded layers. This was done to better understand the piezoelectric properties of the ceramics. According to the data, the results show that utilizing the tape-casting technique results in an increase in both the gradation and thermal characteristics of the material [52].

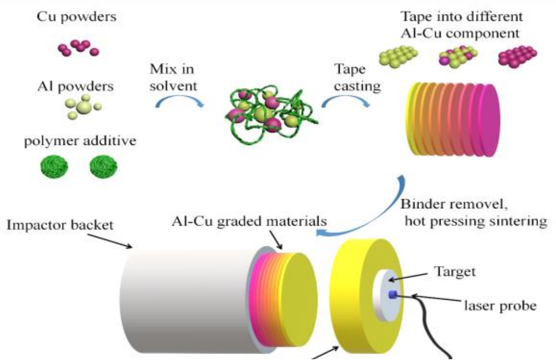

Figure (12): Schematic shown of tape casting manufacturing process [53]

2.3.4 Infiltration Method

The process of fabricating FGMs, and infiltrating is a crucial step that takes place in a liquid state. This process involves filling the gaps between distributed components and moltenly soaking the matrix space (ceramic particles) [53]. Capillary action or gaseous or mechanical pressure can produce an infiltration method with a condition of liquid metal, as depicted in Fig.14. The FG structure was created at the chemical interaction contact, which was prepared of material [54]. The approach has the advantages of a fast preparation time and the formation of regular sizes. that which is known as the FG The electrical properties and microstructural characteristics of the graded layers of Cu–W Composites have been studied and manufactured by employing the infiltration production method to examine the graded layers. The infiltration process produced graded material with improved electrical properties, as predicted by the study's findings. By employing the infiltration approach, FG AlN/Cu composites were created and fabricated to explore the microstructure and electrical characteristics of the inorganic salt concentration [55] to increase the wettability between dissimilar material The results showed that the infiltration process improved the electrical properties of the material's characteristic gradation [56].

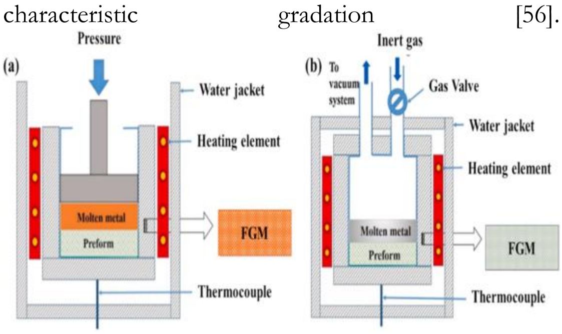

Figure (13): Schematic show the infiltration process (a) method of, (b) method of pressure [4].

2.3.5 Method of Langmuir-Blodgett

LB film method is believed to be one of the most modern attentional production methods now being studied by engineering experts to produce graded structures. The method allowed for the deposition of a thin, homogeneous film of materials up to a molecular layer thickness [57]. The basic idea behind the LB approach was to create a monomolecular coating of an amphiphilic substance on the water's surface, and then transport it to a solid substrate. Aqueous stage: At the air-water interface, the amphiphilic molecular structure will be arranged. Fig. 15 shows the monosyllabic monomolecular surface layer created by compressing the surface layer using a specific membrane (a). This isothermal compression has an impact on the monomolecular film structure, which has been transmitted via a set of two-dimensional states conventionally referred to as water, solid crystal, and ice. Fig.18 shows this effect (b). It's possible to determine a film's physical, chemical, and structural features by studying the film phase diagram. The film is transferred to a solid support by flooding a flat substrate with the solution and then draining the solution with the adsorbed surface. It is one of the technique's flexibility aspects [57]. that the monomolecular film transfer procedure can be replicated several times to achieve multiple multi-molecular layers. Active layers or passive insulators in electronic applications could be made utilizing the LB approach, which has the advantage of allowing for molecular-level control over the interior structure and precise thickness control. We were also given the ability to work with different materials with very specialized functions, and we were able to prepare the architectural layer with organic thin-film systems that are constructed of molecules [58].

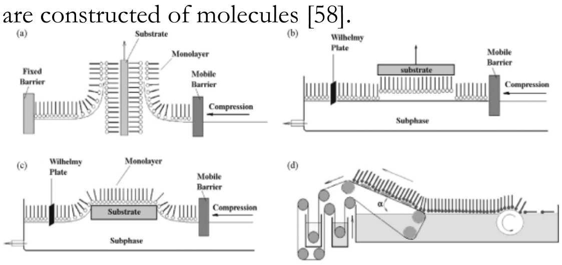

Figure (14): Schematic define the Langmuir-Blodgett method [57].

3. The Functional Design of FGM in Biomedical Sector

As a general rule, metallic implants were designed to be utilized as long-term implants and not for short-term use. Generally speaking, in other circumstances, the corrosion rate of magnesium-based implants was critical for specific applications, hence metallic implants were preferred [59]. The Young's modulus of metallic implants is significantly bigger than the Young's modulus of human bone. This results in stress-buffering effect concerns and early implant breakdown even though they have ideal uniaxial tensile and compression strength and mechanical strength [60]. The value of Young's modulus for human bone ranges from 5 to 23 metallic implants like Ti-6Al-4V and 316L stainless steel, on the other hand, have a Young's modulus of around 114 and 190, respectively, for The FGM design is regarded as a good solution for metallic implants due to the issue of large YM differences. The design and management of variants based on FGM results in components with good mechanical properties at various grades. With the use of an intelligent and effective hierarchical surface design and the production of chemical/biomechanical bonding in FGMs bone tissue around the implants may be stimulated and good attachments can be achieved [61]. In nature, several instances of FGM structures can resist impact and contact forces, such as shark teeth and fish scales. There are numerous applications for the microstructural and microhardness gradation changes that may be achieved using AM techniques in metallic objects to increase mechanical strength and resist damage from contact [62].

3.1 FGM Dental Implants

Since dental implants can be customized to match the unique biomechanical properties of the host bone, a primary goal of employing FGMs in this application is creating a replica of the host bone's peripheral tissue. As a result, the use of FGM dental implants is quite beneficial because they may be stabilized and placed [63]. The elimination of the need for stress shielding is one of the most significant advantages offered by the utilization of FGM components in dental applications [64]. The mechanical problem of characteristic mismatches between native biomaterials and implants could reduce the Osseointegration process and lead to bone re-modelling if these new FGM implants are used [65]. To simulate the biomechanical qualities of a certain implant portion region, the properties of dental FGM implants are typically developed in a precise pattern. Generally speaking, HA-based dental FGM implants are regarded as a composite fundamental for the human bone constitution. The biocompatibility of this substance and other tissues can be improved. Under harmonic and static occlusal stresses, the biomechanical response of dental FGM implants has been studied in 3-D FEM The implant's substance is a blend of biometal and bioceramics with a smooth longitudinal gradient in characteristics and composition [66]. Ti and HAP component ratios were varied in the longitudinal direction (from pure Ti to 100 per cent HAP) One of the dental implants, as seen in Fig.16, has been paired with a supporting bone system. The occlusal process generates direct forces on the upper portion of an implant, which will be transmitted by a screw-fixing connection to the implant itself Because it maintains a load-bearing capacity and effectively reduces the mismatch of material between an implant and the bone tissues that surround it, a high volume of Ti and a large percentage of HAP concentration in the upper region of an implant are typically preferred. This is because they are located in the upper region of an implant [67].

Figure (15): biomechanical reaction in FGM dental implant with the surrounding bone was modeled using three-dimensional (FEM) [67].

The amounts of stress that are caused by the FGM are lower in the lower sections and in the middle of the implant. the FGM scheme is a useful technique for enhancing the biomechanical response of dental implants [68]. In recent studies, researchers have analyzed and contrasted three distinct models of dental implants: a homogenous dental implant with a homogenous coating, a homogenous dental implant with a graded FGM coating, and a functionally graded (FGM) implant with a homogenous coating material. Each of these models has its own set of advantages and disadvantages [69]. According to the findings, the third model with the FGM structure and the homogeneous coating is the one that is the most successful at lowering the stress-shielding effect. Despite this, porous FGM frameworks have the potential to be utilized in maxillofacial or orthodontic implants [70]. Porosity levels of Ti-6Al-4V, Co-29Cr-6Mo, and 316L stainless-steel alloys have been investigated and shown to be appropriate for use in medical applications [71]. It has been demonstrated that the best range of pore size for fibroblast ingrowth is 5–15 m, that the optimal range for chondrocyte ingrowth is 70–120 m, and that the optimal range for bone regeneration acres is 100–400 m [72]. This topic has been investigated under a variety of operational circumstances in vitro as well as in vivo [72].

3.2 FGM Orthopedic Implants

Furthermore, In the treatment of bone-related disorders, such as orthopaedic implants, the utilization of FGM pieces appears to be completely appropriate. Bone tissue is believed to be a realistic natural FGM structure. For implant applications, FGM designs are a viable option. For instance, Bio FITM arthroplasty mimics the structure of a human bone [73]. An accurate simulation of the role that connective tissue plays in the functioning of the intervertebral disk [74]. By utilizing AM technology, a variety of orthopaedic implants may be fabricated from FGMs as well as lattice structures [75]. FGM portions are designed to mimic the characteristics of the desired region and retain the region's importance, such as limiting the stress-shielding effect and inhibiting the damaging shear stresses that could be produced in the interface regions of bone and implant [76]. In addition, FGM portions are designed to mimic the characteristics of the desired region [76]. Altering the chemical makeup of individual layers allowed for the production of a Ti/HA-based implant utilizing powder metallurgy. When the amount of HA in a material rises, its elastic modulus and compressive strength both drop [77] The electrochemical and bioactivity characteristics of a range of FGMs produced from HA-reinforced stainless steel 316L were investigated using powder metallurgy (SS). To change the concentration of HA from 0 to 20 per cent, an increase of 5 weight per cent in each layer was used. Fig.19 is an animation of the mix-FGM micrograph in the untick condition, which demonstrates that the HA particles have a regular and uniform distribution throughout the mix-FGM. There were no visible cracks at the layer interfaces or within the layers, and the HA increases clearly from top to bottom [78]. the rational design proposes radial gradient porous architecture that can replicate the gradient structure of bone. A linear variation in porosity in the radial direction with two porous zones is found in SLM-produced samples. It has a high-porosity region in the inner section that promotes cell regeneration and proliferation and a low-porosity region in the outer part that provides a high load-bearing capacity. Young's modulus and yield strength are in the range of real human bone as a result of this design. Compressive strength and toughness, as well as the suitable elastic modulus, can be significantly improved and preserved by adding structural support

[79]. The scaffold's stability and energy absorption capacity can be improved as a result In terms of biological FGM production, AM techniques are among the most promising [80]. the most effective method would be to use a FGM-based cemented stem with Ti and collagen gradation. This means that the uppermost layer of the stem would be made of titanium, while the lowermost layers of the stem would be formed of a collagen-based material. Cemented stems, like the one you see here, have a greater chance of removing the stress-shielding issues that occur in the medial portion of the femur [81].

3.3 Metallic FGMs for Biomedical Applications

The major and wide-ranging uses of FGM Ti alloys, particularly those produced by additive manufacturing, are covered in earlier sections. This section examines several metallic and multi-metallic systems' FGM production processes [82]. Composites made of metal and metal-ceramic are one of the most significant forms of metallic FGMs. The vast majority of these composites are designed expressly for use in the biomedical industry [83]. The gradient porosities were created using the powder metallurgy technique on titanium/zirconium materials for biological applications in one study [84]. FGM Diffusion along the transition area is observed to have occurred during the sintering process, resulting in the creation of a non-stoichiometric Zr (Ti) phase [85]. In addition, as a consequence of the transition zones' microhardness values, the transition zones' microstructures improved over time and underwent incremental transformations. In addition, the findings of the Rietveld refinement show that the pressure that was applied during the cold isostatic pressing did not have a substantial impact on the unit cells [86]. Development of the functional gradient bio-coating employing ceramic material ranging from 0 to 100 per cent on Ti-6Al-4V substrate. This is accomplished through the use of laser depositing material does an excellent job of limiting the influence of thermal expansion changes between two biomaterials thanks to the insolation cover it provides [87]. The use of co-sedimentation technique and the samples have been deposited following the layer-by-layer settling of the suitable powders. After the pure Ti layer had been established, the next layer to be laid down was the Ti-Mo graded layer, then the Mo-W graded layer, and finally, the pure W layer. In addition, a minute amount of nickel and copper powders were employed here as sintering activators. After the powder was processed, several different suspensions were created and then placed in order into a container designed for sedimentation. After reaching full particle sedimentation, the deposit body was compacted and sintered in a vacuum furnace at a temperature of Celsius and a pressure of 30 megapascals; electron micrograph shows as well as the linear distributions of the elements along the cross-section of W-Mo-Ti FGM [88]. They investigated the structural, physical, and mechanical properties of the stainless steel (SS-316L)/hydroxyapatite (HA) and SS-316L/calcium silicate (CS) FGMs that were created using powder metallurgy solid-state sintering. It has been discovered that the compressive mechanical characteristics of the SS-316L/CS composites and their FGMs are noticeably superior to those of the SS-316L/HA composites and their FGMs. This is the conclusion that was reached. In addition, the SS-316L/CS FGMs with enhanced mechanical and gradation in physical and structural qualities are ideal candidates for prospective usage in load-bearing applications [89]. These FGMs are among the suitable candidates for prospective usage. The SPS technology was used to develop a novel kind of fused zirconia material (FGM) with the addition of aluminium oxide and a cushion layer formed of yttria-stabilized zirconia (YSZ), which has the potential to be used in bone implants [90]. The provision of a smooth gradient of functionality was the primary objective of this FGM design. This included improved bulk toughness as well as surface biocompatibility that was maintained. In this regard, HA and YSZ with respective fracture toughness of 1.5 and 6.2 MPa.m1/2 were bonded to an Al2O3 transition layer, which resulted in the smallest gradient of mechanical characteristics with a fracture toughness of 3.5 MPa.m1/2 [91]. The fact that the effective FGM structure was built without the usage of composites or extra materials is an extremely exciting element of this research. This is so since it completely solved the bonding and layer separation concerns that were previously present. Because of its exceptional biodegradation behaviour and mechanical properties that are comparable to those of natural bone, the SPS approach was used to develop a magnesium-based FGM composite for temporary orthopaedic implant applications [92]. synopsis of the review of biomedical implantation of commonly used biomedical metal material found in Table 1.

Table (1): DH Parameters of the Robot Manipulator.

Method	Material	Mechanical properties	Biological properties	Application	References
EPD	Ti-6Al-4V	The torque and contact angle measurements to evaluate the osteointegration level between the implants and the bond tissue	Porosity different percentage and optimization the osteointegration level	Orthodontic	[93]
EPD	Zr-Alo3	Porosity variation and FGM layer thickness	Best osteointegration between the implants surface and the bone tissue	Orthodontic	[94]
EPD	NiTi	Different FGM coating materials and different coating layers thickness has been tested	Biocompatibility of different coating layers gas been measured	Orthodontic	[95]
EPD	Ti-6Al-4V ELI	Different FGM coating particle size has been studied to optimizing the best results	Study the health problems that appeared after a long period of using titanium implants and the ability of solutions	Orthopedic	[96]
EPD	Ti-12Cr	Different FGM coating particle size has been studied to optimizing the best results	Study the bioactivity for the sounding tissue with various coated particle sizes	Orthodontic	[97]
SLM	Ti6Al4V	The value of Young's modulus within the cortical bone range structures with Honeycomb shape supporting the structure depending on in the outer layer have the best strength and toughness of any other structure.	–	Orthopedic	[98]

SLM	Ti6Al4V	By using a variation of porosity approach (structures with diamond lattice shapes), one may produce elastic modules range and that range of the corresponding mechanical characteristics of cortical bone and cancellous bone.	–	Bone scaffolds	[99]
SLM	Pure Ti	FGM scaffold with porous Diamond manufacturing is achieved by a combination of accurate geometric replication and a comprehensive spectrum of graded fractions volume. The modulus of elasticity, which is comparable with cancellous bone, may has been the user's tailored preferences by modifying the graded Volume component.	–	Bone implant	[100]
SLM	CoCr	Pillar-octahedral-shape Indicated here are the bending stiffness, tensile strength, and energy absorption capabilities of cellular CoCr structures with range of porosity from 41 to 67 percent. values that are analogous to those that are seen in genuine bone	–	Metallic orthopedic implants	[101]
SLM	CoCrMo	Both the weight and the rigidity of the FGM design (square pore cellular structures), as compared to the usual completely dense stem, are reduced by up to 48 percent.	–	Femoral stem implant	[102]
EBM	Ti6Al4V	Seeks to lower the elastic modulus mismatch between the titanium alloy and bone tissue implant by suppressing the stress-shielding action. This will allow for the mismatch between the two to be reduced.	Seeks to lower the elastic modulus dissimilar between the titanium alloy and the bone tissue and implant by suppressing the stress-shielding action. This will allow for the mismatch between the two to be reduced. Supported by 3-D printed linked porous FGM include the calcium deposition, synthesis of proteins, and adhesions of proliferation such as vinculin, fibronectin, and actin. Other proteins that are supported include fibronectin.	Bone implants	[103]
EBM	Ti6Al4V	In comparison to a sharp interface, the FGM porous body (cubic structure with open-cell) possesses a huge compressive strength with a transition area that ranges from 4 to 8 mm.	–	Biomedical implants	[104]
SLM	stainless steel 316L	It is the grate density of dislocations and subdrain boundaries that are responsible for the material's excellent flexibility; yet, the significant number of voids is what causes the material to fracture prematurely.	Higher biocompatibility and better biological performance	Medical implant applications	[105]
Laser metal deposition	HS6-5-2 Stainless steel,	There was very little porosity, and there was no evidence of any delamination. Based on the results of microhardness testing, gradient materials that have been sintered in an environment containing N2-10 percent H2 and reinforced by using of VC carbide have the highest possibility of hardness.	–	Possible biomedical application	[106]
Laser cladding	Dissimilar zirconium (Zr)-stainless steel (SS)	Functionally graded deposition in materials that aren't compatible with one another led to the formation of a structure that was disintegrated and had a lot of cracks running in different directions. During the layer-by-layer AM process, there may have been a significant accumulation of thermal stress, which might have led to the formation of microcracks.	–	–	[107]

3.4 Metals and Alloys with Gradient Nanostructured (GNS)

One of the most important FGMs categories is referred to as gradient nanostructures (GNS). This category includes gradient nanograined, nano-twinned, and nano-laminated metals and alloys. Sometimes, these GNS materials can have amazing mechanical properties that are hard to find in materials with random or homogeneous patterns, such as wear resistance, considerable corrosion, improved fracture, strength-ductility synergy and fatigue resistance, and strain hardening. Other times, these GNS materials can have amazing chemical properties that are difficult to find in materials with random or homogeneous patterns as shown in Fig.20 [108].

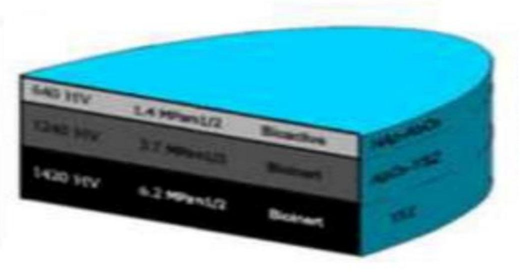

Figure (16): The FGM sample manufactured by using spark plasma sintering (SPS) [15]

One of the examples of a suitable GNS material is the nano-twin structure. Evident is the surface mechanical grinding procedure that was utilized to develop an architectural surface layer in a Fe-Mn austenitic steel that had a gradient drop in twin density. In the lowest layer, there is clear evidence of a heterogeneous microstructure consisting of nanoscale twin bundles [109]. It is then made abundantly evident that, as we get closer and closer to the depths of the sample, the twin density and nano-twin bundle volume fraction steadily increase, whilst the volume fraction of nanograins gradually decreases. Another example of GNS is the graded nano-grained (GND) copper that was produced by using the SMGT technique. It has about twice the yield stress of typical Cu samples, in addition to significant strain softening and outstanding plasticity This material was created using the SMGT technique [110]. The SMGT process to build a nano-laminated structure in nickel in a subsurface layer that was approximately 10-80 nm deep from the surface; 2-D laminated structures with low angle boundaries and strong deformation textures were observed, and their average thickness was about 20 nm. It was demonstrated that these nano-laminated structures underwent deformation as a result of dislocation slip and deformation twinning at the nanoscale. This, in turn, led to the production of a nano-sized equiaxed grain structure [111]. It was discovered that the structure has numerous nanometer-scale twin boundaries that are preferentially orientated and that these boundaries are housed within micrometer-scale columnar-shaped grains [112].

3.5 THE 4-Dimensional Printing in Metallic FGMs

The manufacture of smart materials in a layer-by-layer fashion, which provides the material with an additional dimension, is the primary distinction that can be drawn between techniques for printing in three dimensions (3D) and techniques for printing in four dimensions (4D). Because of this, several different physical and chemical properties, such as temperature, pressure, humidity, light, magnetic and electric fields, and even the passage of time, may all play a role in assisting the 4-D printed item in changing its shape [113]. These four-dimensionally printed components may be readily managed and form bimetallic structures by the selective deposition of various metals. As a consequence of this, a temperature-responsive response can be programmed into the metallic four-dimensionally printed components. This is a very valuable quality to possess. It would appear that the creation of smart metallic biomaterials would considerably benefit from the beneficial and controlled properties of technologies associated with 4-D printing, despite the limited number of research that has been conducted on this subject [114].

4 Conclusions

FGMs are considered the recent theory of substance which entices much concern from the medical field, academicians, and manufacturers. the utilization of the FGMs in the biomedicine field reinforces the total performance of implantation on both biological and biomechanical due to the classified nature of the bone and other physical systems. the design standard, methods, implementation, advantages, and disadvantages of FGM, are comprehensively discussed in this review paper, especially in biomaterials. we have studied in this case several FGM production methods, mainly additive manufacturing methods which are known for their capability to produce complicated FGM structures with multifunctional characteristics and high determination. In addition to the above we have another method, for example, methods based on powder metallurgy, as well as gas, liquid, and solid phases of matter, are described. A deep explanation has been made in biomedical applications for the functional design of FGMs and the biological concept of FGM design. The FEM-based designs are used in the simulation of natural tissues specifically in dental and orthopedic implants with the utilization of FGM design. the objective of this research is to improve the characteristics of the FEM design in biomechanical and biological make an action on the plant's performance. also, the applications of FGM and its limitations that should be overcome in future have been mentioned briefly. The newest ideas that can support the fast growth of FGM and its applications have been introduced, with bioprinting, metamaterials, 4-D designs, etc. In the end, the future of biomedicine and its applications could be improved by the utilization of the FGMs if kept developed in future from both a technological position and scientific perspective, as it is far away from achieving the optimum situation and variety industrialization. as the aim of our research is to focus on how the properties of up-to-date, intelligent, and useful FGM biomaterials.

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