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A Review on Functionally Graded Materials and Their Applications in the Field of Prosthetics

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ABSTRACT
Functionally graded materials (FGMs) are special types of advanced composites with peculiar features and advantages. The main characteristic of an FGM is the gradual variation in composition and microstructure across its dimensions, resulting in enhanced properties. FGMs are consisting of two or more materials in order to achieve the desired properties according to the application where an FGM is used. As a result FGMs are of great interest for numerous applications. This paper reviews various fabrication techniques, classification and its applications in the field of prosthetics.

Keywords: *Functionally graded materials (FGMs); processing techniques; classification; application; prosthetics.*

1. Introduction

Throughout history, materials have been playing an important role in the life of human beings from the first man until now. In different eras, man has used different materials obtained from nature or prepared by man for the sake of their ease in numerous applications.

Although the properties of materials are inherent to them but they can be changed in a variety of ways. For example, by combining materials or changing the material’s underlying structure. Since early times materials have been processed to change their properties.

Alloying is a combination in molten state of one metal with other metals or non-metals which gives a property that is different from the parent materials. The first alloy that appears in human history was Bronze which is actually an alloy of copper and tin. Bronze was first invented in 3500 BC, so this era called the Bronze Age [1]. However, this method has limitations, which are the amount of material that can be dissolved in a solution of another material because of thermodynamic equilibrium limit [2] and the prohibition of alloying two dissimilar materials with wide apart melting temperatures. To overcome this, powdered metallurgy (PM) method was used in which alloys are produced in powdered form. This method gives excellent properties, but it has some limitations such as the difficulty of producing complex shapes and features by PM process, in addition to porosity and poor strength of parts.

Composite is another method of producing materials with combination of properties by combining materials in solid state. Composite material are a class of advanced material which made up of two or more materials that results in better properties than those of the individual components used. Although composite materials are stronger, lighter and they provide design flexibility, resistance to corrosion as well as wear, they have a disadvantage of sharp transition of properties at the junction of materials which resulted in component failure by the process called delamination.

Another method to achieve changed and tailored material properties is the use of Functionally Graded Materials (FGM) which was first applied in Japan in 1984 for the core purpose of their aerospace project [2]. Functionally graded material removes the sharp interfaces existing in composite material [3] by replacing the sharp interface with a gradient interface which produces smooth transition from one material to the next [4, 5]. In addition it can tailor a material for specific application [6]. Historical progress from pure metal to functionally graded metals is indicated in Figure 1.

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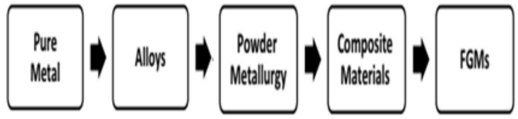

Figure 1 - Material development towards FGM

2. FGM Classification

FGMs replace the sharp transition of properties with smooth and continuous varying properties such as Shear Modulus, Poisson's ratio, Young's Modulus, density, and coefficient of thermal expansion in a desired spatial direction [7–10], in addition to, the continuous graded properties like thermal conductivity, corrosion resistivity, specific heat, hardness, and stiffness ratio [11]. Due to distinguished characteristics of FGMs, several efforts have been made by researchers to enhance the properties of FGMs. Several types of FGMs have been introduced up till now based on size and structure. FGMs can be classified to a variety of classifications [12, 13] as follows;

- According to the material combinations FGMs were classified such as; metal / ceramic, ceramic / ceramic, ceramic / plastic and many other combinations of materials.
- According to their compositions, FGMs are classified to functionally gradient type, functionally gradient coating type and functional gradient Connection
- According to its density gradient, FGMs can be divided into the changing nature of FGM, composition FGM, optical FGM, fine FGM, etc. [14].
- According to application areas can be divided into heat-resisting FGM, biology FGM, chemical engineering FGM, Electronic engineering FGM, etc. [15].
- According to its structure, FGMs are sub divided to continuously structured FGM and discontinues (Layard) FGM as in Figure 2.
- According to industrial point of view [17], FGMs are classified as follows:
  - According to conventional classifications of FGMs, six conventional classification criteria were presented to classify the FGMs based upon: state during processing, FGM structure, FGM type, nature of FGM gradient, main dimensions, and field of FGM application.
  - According to processing methods, five classification criteria were presented to classify the FGMs based upon: achievable complexity of shape, degree of gradient control, effect of residual stresses, energy consumption and environmental impact and total process cost.

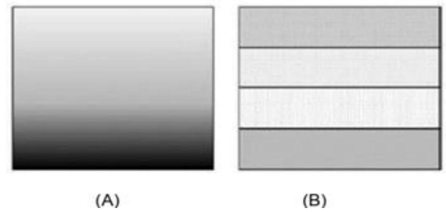

Figure 2 - Continuously (A) and layered (B) type FGM

3. Manufacturing Techniques

Most of the researches on FGMs have been dedicated to processing resulting in development of various production methods of FGM. The choice of the production method depends mainly on the material combination, type of transition function required, and geometry of the desired component [18]. Functionally graded materials can be classified as thin FGM which are relatively thin sections or thin surface coating and bulk FGM which are volume of materials that require more labour intensive processes [19].

3.1. Thin functionally graded materials.

This type of functionally graded materials is usually in the form of surface coatings, the selection of surface deposition processes depended on the service requirement from the process [20]. They are produced by Vapors Deposition, Plasma Spraying, Self-propagating High temperature Synthesis (SHS) etc. The most important methods for producing thin FGMs for coating applications are the deposition based methods such as vapor deposition methods, thermal spray methods and electrophoretic deposition method [21]. The most important method for producing a thin graded layer is *vapour deposition method* in which materials are condensed into a solid material during the vapour cycle [22]. This method has different techniques such as Chemical Vapour Deposition (CVD), Physical Vapour Deposition, (PVD) and sputter deposit. These techniques are used to deposit functionally graded surface coatings [23]. Although these techniques provide an excellent coatings microstructure, they are energy intensive and generate poisonous gases [24].

3.2. Bulk functionally graded materials

Bulk FGM cannot be produced by the previous techniques because they are not economic as they are slow and required intensive energy. The most promising methods of the production of these materials are powder metallurgy; additive manufacturing and friction stir additive manufacturing process. By using these methods the graded can be controlled to a high degree to make them available to various industrial applications [25]. Some of bulk functionally graded materials fabrications are as follows:

3.2.1. Powder metallurgy method

Although powder metallurgy (PM) method is one of the oldest methods used in producing components , it is used for producing FGMs [26] that is because its wide range control on microstructure, composition and shape forming capability [27]. It has the advantages of lower costs, lower energy consumption, shorter processing times, higher raw materials availability and simpler processing equipment. This method is generally consisting of four steps as following: mixing, stacking, pressing and sintering, as illustrated in Figure 3. PM technique gives rise to discontinuous gradient structure [28]. If continuous structure is desired, then centrifugal method is used.

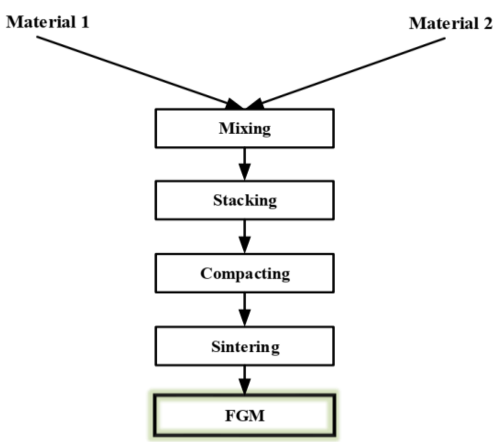

Figure 3 - Processes involved in powder metallurgy

3.2.2. Centrifugal casting

This method for producing a bulk functionally graded materials is same as centrifugal casting where in both of them the molten metal is discharged into a rotation mould and by using the force of gravity through the rotation of the mould, bulk functionally graded material is formed [29] as in Figure4. The graded material is produced in this way due to the difference in material densities and the mould rotation [30]. Although it has a wide range of control on microstructure and composition [31], it has some limitations such as the shape that produces is just cylinder and the product gradient type due to the gradient is produced by a natural process [32]. To overcome these problems, another manufacturing process called solid freeform is used [33].

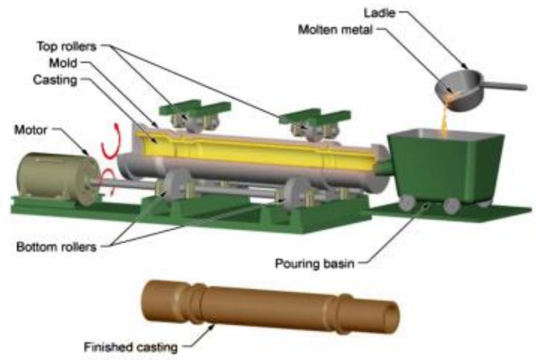

Figure 4 - Centrifugal casting process

3.2.3. Solid Freeform (SFF) Fabrication Method

Solid freeform is a type of additive manufacturing processes which has lots of advantages such as higher speed of production, less energy intensive, maximum material utilization, ability to produce complex shapes and design freedom as parts are produced directly from CAD (e.g. AutoCAD) data [34]. SFF consists of five steps as following:

- Generation of CAD data from the software like AutoCAD, Solid edge etc.
- Conversion of the CAD data to Standard Triangulation Language (STL) file
- slicing of the STL into two dimensional cross-section profiles
- building of the component layer by layer
- Removal and finishing.

SFF fabrication has various types of methods technologies such as laser process which are mainly used to produce the functionally graded materials. This technology is consists of the laser cladding based method، Selective Laser Sintering (SLS), 3D Printing (3DP), and Selective Laser Melting (SLM). Although Solid freeform provide manufacturing flexibility compared with other processes, but the surface finish is poor so that it is necessary to carry out a secondary finishing operation. Many research efforts in this direction to improve surface finish, dimensional accuracy etc.; [35].

4. Areas of Application of Functionally Graded Materials

In general, the gradient properties of the FGMs have made them the best choice in nearly all the human areas of applications such as aerospace, automotive, coating, electronics, and biomaterials, building and cutting tools [36], as shown in Figure 5. These application are described as follows:

Figure 5 - Various fields of application of FGM

4.1. Aerospace applications

FGMs find wide applications in aerospace industries due to its ability to withstand extremely high thermal gradient. Most parts of spacecraft and aircraft now used FGMs such as a rocket engine; spacecraft gear structure, heat exchange plates, and some structures, such as reflectors, solar panels, camera bunks, turbine wheels, turbine blade coating, nose covers, and the front edge of the missiles, and space shuttles [37].

4.2. Manufacturing

The FGMs are widely used in various industries such as cutting tools, forming molds and machine engine blocks beside many sports equipment such as golf clubs, tennis rackets, and skis [38].

4.3. Automotive applications

FGMs have been used for automobile parts such as engine cylinder liners for diesel engine pistons, spark plugs, leaf springs, combustion chambers, drive shafts, shock absorbers, flywheels, some car body parts, window glass, and racing car brakes. Also, they are used in enhanced body coatings for cars [39].

4.4. Defence applications

It is used in defence application due to its ability to inhibit crack propagation and reduce the weight of vehicles. They are used as Penetration-Resistant materials in the defence industry in applications, such as armour plates and bulletproof vests, in addition to the manufacture of defensive parts such as guide rods, precision rollers, shafts, tubes, latches, axle's housings and firing pins [40, 41].

4.5. Energy

Functionally graded materials find wide applications in the field of energy industries to improve the efficiency of some of their equipment. Some of the applications of the functionally graded materials in the energy industry include the solar panel, the solar cells, the inner of nuclear reactors, the thermo-electric converter for energy conversion, the tubes and pressure vessels, the graded electrode for the production of solid oxide fuel, the piezoelectric functionally graded materials for the ultrasonic transducer, the dielectric, the fuel cell, the turbine blade coatings, and for thermal barrier coatings.

4.6. Electrical / Electronics Applications

The FGMs have also been used in electrical and electronic industries such as the relaxation of the field stress in the electrode and the field–spacer interface [43, 44], in the diodes, in the semiconductors, for insulators, and for the production of sensors [45].

4.7. Biomedical applications

The idea of graded structure is not new. Gradual variations in the microstructure of materials have been existed for millions of years by the living organisms such as bio tissues of plants, bamboos, shells, coconut leaves, and are even found in our bodies such as in bones and teeth [46]. As a result of damage, natural ageing process to human body parts, these parts must be replaced during the time. The engineering materials that are biocompatible are used for their replacements. Biomaterials should simultaneously provide many qualifications and possess characteristics such as nontoxicity, corrosion resistance, thermal conductivity, strength, fatigue durability, biocompatibility and seldom aesthetics [47]. The main reason that the majority of functionally graded materials used in the biomedical industry are used for implants is that natural parts that these materials replace are functionally graded materials in nature. Many researches have been conducted to improve the properties of biocompatible material in the human body using FGMs [48, 49]. They are now widely used in prosthetic devices and artificial teeth components because they give the medicinal components corrosion and abrasion resistance in one side and strength of bonding in the other side.

The use of functionally graded biomaterials in medical prosthetics has been considered in recent researches as Hedia and Fouda [50] focused on the tibial component of TKR implants. They implemented a two-dimensional axisymmetric FE model including both the surviving tibia and the tibial prosthesis to define the best FGM components and the best direction of the gradient profile in order to control the stress distribution. The results indicated that the optimal design required to grade the composition vertically, from HA at the end of the tibial stem to collagen at the upper layers of the tibia plate. This induced a sensible reduction of the stress shielding effect. The same result achieved by Enab and Bondok [51]. They developed two dimensional finite element models to study bone and interface stresses for six different tibial prosthesis (titanium, CoCrMo and four functional graded materials ‘‘FGM’’ models). They revealed that the FGM tibia tray will reduce the stress shielding in the surrounding bones of the artificial knee which will increase the life of the total knee prosthesis. Gong et al. [52] study the remodelling behaviours of a two-dimensional simplified model of cementless hip prosthesis with stiff stem, flexible ‘isoelastic’ stem, one-dimensional Functionally Graded Material (FGM) stem and two-dimensional FGM stem for the period of four years after prosthesis replacement were quantified by incorporating the bone remodelling algorithm with finite element analysis. Their results show that two-dimensional FGM stem may produce more mechanical stimuli and more uniform interface shear stress compared with the stems made of other materials. While Oshkour et al. [53] develop a three-dimensional finite element model of a functionally graded femoral prosthesis. The model consisted of a femoral prosthesis created from functionally graded materials (FGMs), cement, and femur. The hip prosthesis was composed of FGMs made of titanium alloy, chrome–cobalt, and hydroxyapatite. The results indicated that FGMs have the potential to be effective biomaterial substitutes in producing a new generation of hip prosthetic parts that are capable of reducing stress shielding, thus increasing the longevity of the replacement and preventing the loosening of the prosthesis. Ghazianiet al., [54] propose several FGM implants and compare their bone remodelling results with the conventionally used Titanium implants by linking an FE analysis to a bone remodelling algorithm. They utilize Titanium/Hydroxyapatite (Ti/HAP) FGM implants in their study with different gradation directions and compositions. The analyses revealed evident advantages for the FGM fixtures over the conventionally used Titanium fixtures. They concluded that the gradation direction considerably affects the bone adaptation procedure. The results showed that using a radial FGM with low-stiffness material in the outer layer and less metal composition significantly improves the bone remodelling behaviour., Ayatollahi et al., [55] improve the performance of the bone prosthesis system and prevent the aseptic loosening in a total knee replacement surgery using two types of ceramic based functionally graded biomaterials, alumina based and zirconia based FG biomaterials. Both the alumina based and zirconia based FG biomaterials showed significantly better performance compared to commonly used Cr.Co prosthesis. They can both reduce the effect of shielding stress, while the zirconia based one shows better performance in this respect. Tharaknath et al., [56] investigate the functionally graded material properties of the hip prosthesis using static and dynamic loading condition and also finding out the deformation of the material are analysed. Zaier and Resan [57] designed the shank and analysed in the Solid Work program using a 3D printer for manufacturing. Two types of materials are used to construct the shanks PLA, ABS. Then they design a special device to examine the life of the new shank by alternating load. The results showed that the mechanical characteristics of the new shank were good, corresponding to the specifications of the qualities of prosthetic limbs, after the practical and numerical examination of the shank. Xiao et al. [58], designed and manufactured the FG mandibular prosthesis using the 3D printing with metallic coating in order to explore the graded lattice prosthesis applications. They used the SLA and PVD to produce FG from titanium Ti-coated polymer lattices with gradient Porosities. The results revealed that the Ti-coated lattices were capable of withstanding compressive strains above 20% with a compressive strength increase of 2–3 times, while the porosity of the lattices that correspond to the highest and lowest stress regions of the human mandible (68.3% and 86.3%, respectively), thus the produced graded lattices produced can be used potential prosthesis design and other biomedical components. Mishina et al. [59], study the fabrication of $ZrO2$/AISI316L functionally graded materials (FGMs) for use in joint prostheses and evaluate their mechanical and bio-tribological properties through fracture toughness, bending strength, and wear resistance studies. They found that fabricated FGMs showed a higher fracture toughness and wear resistance than a monolithic ZrO2 when the thickness of the layers was greater than 2.0 mm. FGMs with a layer thickness of more than 2 mm therefore have mechanical and biotribological properties and are suitable for use in joint prostheses.

5. Conclusions

- Functionally graded material at the fore in the field advanced materials science and proven their position among them due to their superior mechanical and physical features, with a wide range of applications, so Lots of studies have been conducted on behaviour of functionally graded materials and the literature is very rich on this.
- Functionally graded materials are very important in engineering and other applications

but the cost of producing these materials makes it prohibitive in some applications. This study presents an overview on FGM, its classifications, its various fabrication methods and its wide applications especially in the field of prosthetics.

- Based on these criteria, this study concluded that functionally graded materials find wide application in field of biomedical such as implants and prosthetics and they provide excellent mechanical and biotribological properties when compared to conventional materials.

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