Chapter 2
Types of Functionally Graded Materials and Their Areas of Application

2.1 Introduction

Materials with changing composition, microstructure, or porosity across the volume of the material are referred to as the functionally graded material (FGM) [1]. Functionally graded materials (FGMs) are designed with changing properties over the volume of the bulk material, with the aim of performing a set of specified functions [2]. The properties of material in FGMs are not uniform across the entire material, and the properties depend on the spatial position of the material in the bulk structure of the material. Functionally graded materials are designed with varying properties that include changing chemical properties, changing mechanical, magnetic, thermal, and electrical properties. There are FGMs that are designed as stepwise-graded structures, and some are designed to be continuous-graded structures, depending on the areas of application [3–6].

There are different types of areas, in which FGMs are now being used that are different from the initial area of application, for which the material was invented [7].

In this chapter, the different types of FGMs and their areas of application are presented. The different types of FGMs include porosity and pore size gradient-structured FGMs, chemical gradient-structured FGMs, and microstructural gradient-structured FGMs. These different types of functionally graded materials are presented in the next sections.

2.2 Types of Functionally Graded Materials

At the inception of the development of the Functionally graded materials, the concept was to remove the sharp interface that existed in the traditional composite material, and to replace it with the gradually changing interface, which was translated into the changing chemical composition of this composite at this interface

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region. The growing interest in this type of material has resulted in different types of FGMs being developed. The type of intended application usually determines the type of FGM to be used. In the biomedical application, for instance, some implants need to really mimic the human organ that they intend to replace or repair, for them to be able to function properly without destroying the surrounding tissues. They also need to be able to last longer in service. In Chap. 1, it was seen that most of the human body is made up of FGMs, because of the functionality requirement. This is one of the reasons why the implants should also be made of FGMs, in order to match the part being replaced or being repaired. The different types of FGMs that are being produced now include the chemical composition gradient FGM, the porosity gradient FGM, and the microstructural gradient FGM. Each of these types of FGMs is discussed in detail in the following sections.

2.2.1 Chemical Composition Gradient Functionally Gradient Materials

This is the type of Functionally graded materials, where the chemical composition is gradually varied, according to the spatial position in the material. This could be in the form of a single phase, or in a multiphased material. A single-phase FGM is produced when the composite is produced from a single phase, as a result of the solubility of the chemical elements of one phase in the other phase. This usually occurs during the sintering process [8]. The gradual change in the distribution of the chemical elements in the single phase results in the formation of the Functionally graded material. According to the phase diagram and thermodynamic limitations, when some materials are added to another material, the material that was added to the other material would be soluble in that material over a range of composition and mixing conditions. Such material would become what is called a single-phase material—but with a varying chemical composition—because of the solubility.

This type of FGM is less common. The most commonly designed and most commonly used Functionally graded materials are the ones with a multiphase chemical composition [9, 10]. The phases and chemical composition are made to vary across the bulk volume of the material. As the composition of material is varied from one material into the other, it will result in different phases with different chemical compositions that would help to achieve the intended application, for which the FGM has been designed. The different phases that are produced are dependent on the compositional quantity of the reinforcing material and the manufacturing conditions—such as the cooling rate and the heat treatment conducted on such material.

In powder metallurgy, the method of producing FGM is by putting the required powder composition layer-by-layer, and this is then followed by powder compaction and thereafter sintering. During the sintering process, some of metallic powders will react to form different chemical compounds and phases. These would vary, according to the spatial position in the Functionally graded material.

2.2.2 Porosity Gradient Functionally Gradient Materials

The porosity gradient functionally graded material is another type of FGM, in which the porosity in the material is made to change with the change in the spatial position in the bulk material. The shape and size of the pore are designed and varied, according to the required properties of the Functionally graded material. The schematic diagram of a typical porosity gradient functionally graded material is shown in Fig. 2.1.

This type of functionally graded material is very important for the biomedical applications, because the natural material they intend to replace consists of functionally graded porosity, and the graded porosity would also help in the integration of the implant and the surrounding tissues. The porosity is important for the healing process of this implant, and it also helps in the blood circulation to the integrated tissues. The graded porosity also helps to reduce the overall weight of the implant and to improve the modulus of elasticity of the implant material to match that of the human tissue. The graded porosity helps to reduce the density of the bio-implant. This is necessary to prevent stress shielding that occurs when the modulus of elasticity of the implant is greater than that of the human bone. Porosity gradient materials are produced by the deposition of powder with a varying mixture of different particle shapes and sizes that would help to produce the needed varying porosity with the changing pore shapes and sizes.

Porosity gradient materials could be porosity density gradation or pore size gradation. The porosity density is produced with the density of porosity changing with respect to the spatial position across the volume of the material. The pore size

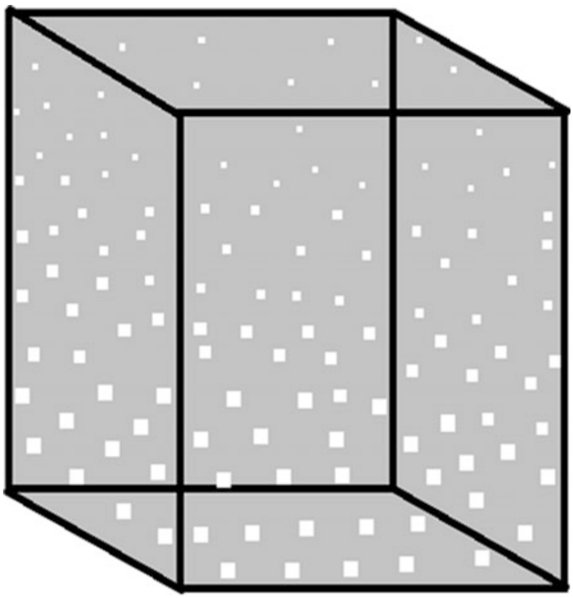

Fig. 2.1 Schematic diagram of porosity-graded FGM

gradient of the FGM, on the other hand, is produced by varying the pore sizes or the pore shape, or both.

The pore size gradation can be achieved by varying the powder particle sizes that are used at different locations in the bulk material during the gradation process. It can also be produced by varying the production processing parameters, or through the use of different sintering parameters to produce the required porosity gradient [11, 12].

The function of pore size gradation is seen in bone implants, where the larger pore sizes in the porosity functionally graded implants are to be implanted in the bone, in order to aid the bone ingrowth, while the smaller pores are useful for the cartilage growth [12]. The function of porosity-graded FGM includes the gradual change in the pore distribution in a porosity-graded FGM that helps in absorbing the shock from one face to the other. It also helps to provide thermal insulation; it helps to aid the catalytic efficiency; and it also helps to relax the electrical and the thermal stresses.

The porosity gradient in a FGM also has an effect on the tensile strength and the Young's modulus of the material. A number of porosity gradient FGMs have been reported in the literature for biomedical application [12–33].

2.2.3 Microstructure Gradient Functionally Gradient Materials

Microstructural gradient functionally graded material is another type of FGM, where the microstructure is tailored so that different microstructures are produced in the material, which is made to change gradually, so as to achieve the required properties from the material. Microstructural gradation can be achieved during the solidification process, such that the surface of the material is quenched, for example, when producing a very hard surface property of the material. The core of the same material is allowed to cool down slowly, which would help to produce different microstructures from those on the surface of the material to the innermost part. Also, the microstructural gradation can be achieved through a controlled heat treatment process. For example, a varying microstructure can be produced by a controlled heat treatment of a titanium-alloy cylindrical part, as shown by the schematic diagram in Fig. 2.2.

A functionally graded microstructure can be achieved by first allowing a liquid metal, whose melting temperature is lower than the melting temperature of the titanium alloy, and such that the recrystallization temperature of the titanium alloy would be reached when this molten metal is run in a kind of heat exchanger setup, as shown in Fig. 2.2a. The liquid metal is allowed to run for a certain period of time, and subsequently withdrawn, and then the part is allowed to cool down. The heat is transferred from the inner part of the cylinder to the external part. It is expected that the temperature of the innermost part of the cylinder is much higher than that of the outermost temperature.

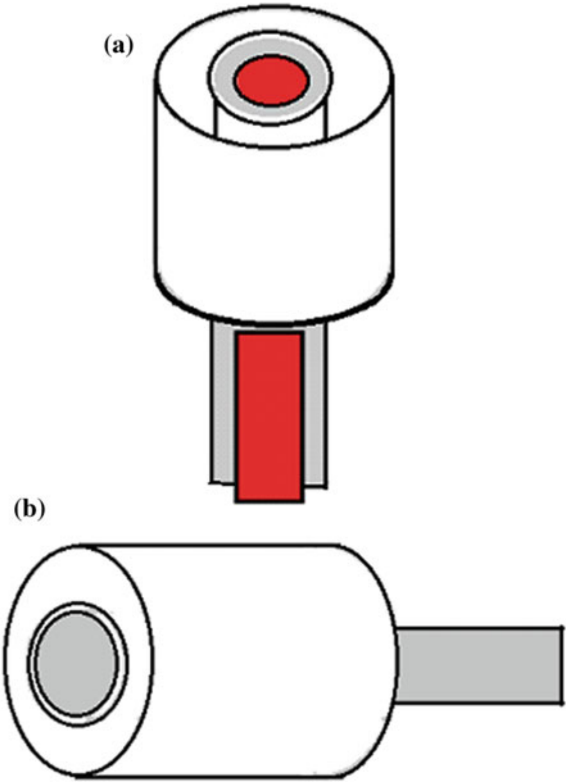

Fig. 2.2 Schematic diagram of cylindrical part subjected to a flow of **a** liquid metal and **b** cooling water

This would result in a varying microstructure, as the part is allowed to cool down. The outer part would behave like a heat sink, and the microstructure of this area would be larger because of the grain growth, while the innermost microstructure would be smaller and equiaxed, because of the refined microstructure during the recrystallization process and the slow cooling rate. In another type of microstructural gradation process, the cylinder could be heated to a certain temperature, and then cooling water could be run through the inner part of the cylinder —also in a heat exchanger setup, as shown in Fig. 2.2b. The inner part of the cylinder would be subjected to rapid cooling, thereby causing the formation of a non-equilibrium microstructure at this face. The innermost microstructure would consist of a martensitic microstructure that is harder, while the microstructure of the cylinder far away from the innermost part would be completely different from the microstructure on the outer part of the cylinder.

A schematic diagram of a typically graded microstructure is shown in Fig. 2.3. This is because, the outermost part of the cylinder would cool down more slowly, and this would favour the formation of a more equilibrium microstructure, and a largely equiaxed microstructure would be produced. The gradients in the microstructure due to the heat treatment could also cause some changes in the

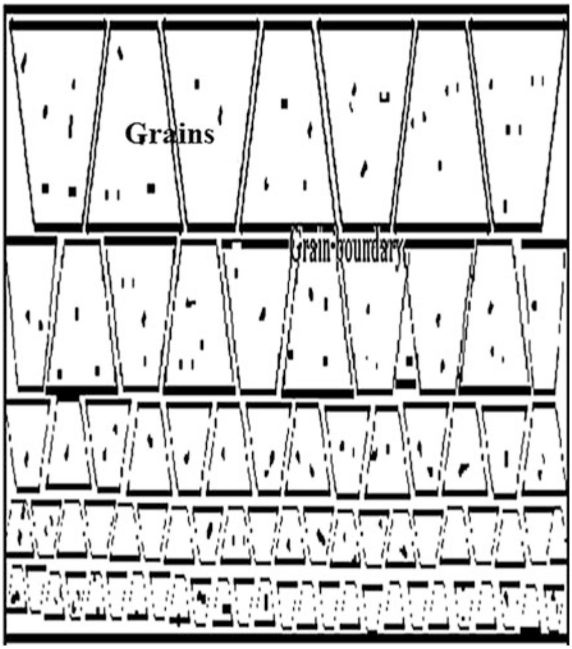

Fig. 2.3 Schematic diagram of graded microstructure

elemental composition, and in some cases, the intermetallic phase could be produced in the graded microstructure.

The graded microstructure would result in a gradual change of the material properties with respect to position, since the microstructure is dependent on the position in the FGM, and because the microstructure is directly related to the properties of the material.

The microstructural gradient FGMs find their application in components that must have a very hard surface to resist wear, and a tough core to resist the high impact that occurs during the operation. An example of this type of Functionally graded material includes case-hardened steel, cams or ring gear, bearings or shafts, and turbine applications [34, 35]. The areas of application of the different types of FGMs are presented in the next section.

2.3 Areas of Application of Functionally Graded Materials

The important characteristics of the FGM have made them to be favoured in almost all the human areas of endeavour. Functionally graded materials are currently being applied in a number of industries, with a huge potential to be used in other applications in the future. The current applications and futuristic application of the FGM are presented in this section. The current areas of applications include

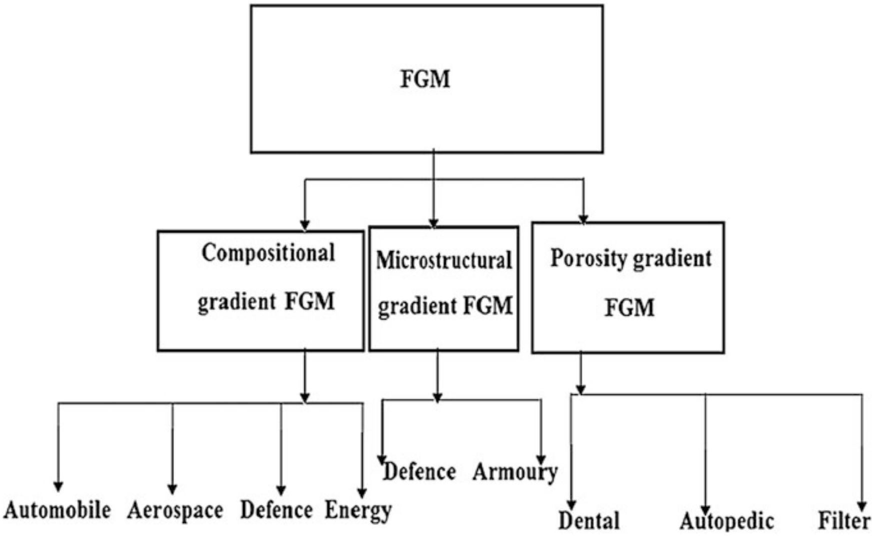

Fig. 2.4 Areas of applications for the three types of functionally graded materials

aerospace, automobile, biomedical, defence, electrical/electronic, energy, marine, opto-electronics, and thermoelectronics. Figure 2.4 shows the different types of FGMs and their application areas. FGM offers great promise in applications with harsh operating conditions, or example, for wear-resistant linings for handling large heavy abrasive ore particles in the mining industry, for the rocket heat shields, for the heat engine components, for heat exchanger tubes, for the plasma facings for fusion reactors in nuclear reactor plant, for thermo-electric generators, and in the electrical insulating applications.

Functionally graded materials are also ideal for reducing the mismatch in the thermo-mechanical properties in metal–ceramic bonding that help to prevent debonding. The future demands for functionally graded materials are in such applications, where extraordinary mechanical, thermal, and chemical properties are required, and which must be able to sustain severe working environments. These potential future application areas include applications, where the structural and the engineering uses require a combination of incompatible functions, such as hardness and toughness.

The future application areas of functionally graded materials will also expand, when the production costs of these important engineering materials are reduced. The fabrication processes of functionally graded materials are explained in detail in Chap. 3 and the use of additive manufacturing technologies for the production of FGMs is presented in Chap. 4.

Although some applications are more interested in the reliability of the FGM, rather than the cost of such materials, such niche industries include aerospace and nuclear energy. On the other hand, the cost of production of functionally graded materials is important in some applications such as the cutting tools, machine parts, and engine components. The use of functionally graded materials is now seen as one of the most important, effective, and efficient materials for promoting sustainable development in industries. Some of these applications, such as aerospace, automobile, biomedical, defence, energy, and the marine industry, are presented and explained in the following subsections.

2.3.1 The Aerospace Industry

The initial application where functionally graded materials were developed was for space plane bodies. The application of this novel material is increased over the years in the aerospace industry. Most aerospace equipment and structures are now made of functionally graded materials. These include the rocket engine components, the spacecraft truss structure, the heat exchange panels, and some structures, such as the reflectors, the solar panels, the camera housing, the turbine wheels, the turbine blade coatings, the nose caps, the leading edge of missiles, and space shuttles. Functionally graded materials are also used for the structural walls that combine thermal and sound insulation properties. Automobiles are another industry, in which functionally graded materials have been used. These will be presented in the next subsection.

2.3.2 The Automobile Industry

The use of functionally graded materials in the automobile industry is still limited at the moment, because of the high cost of production of functionally graded materials. However, the material is being used in very important parts of the automobile, where the present high cost justifies its use. The present applications include the engine cylinder liners for diesel engine pistons, for the leaf springs, for the spark plugs, the combustion chambers, the drive shafts, the shock absorbers, the flywheels, some car body parts, the window glass, and racing car brakes. Also, functionally graded materials are used in enhanced body coatings for cars, and that includes the graded coatings with particles, such as dioxide/mica.

2.3.3 Biomedical

The human body is made up of a number of functionally graded materials, which includes the bones and the teeth. These are the most replaced human body parts, as a result of damage to these parts, or as a result of the natural ageing process. The engineering materials that are biocompatible are used for their replacements. The natural parts that these materials replace are functionally graded materials in nature. This is why the majority of functionally graded materials used in the biomedical industry are used for implants. The porosity gradient functionally graded materials are most commonly used in this industry, because their properties are very close to those of the parts they intend to replace. Examples of where the porosity gradient FGM is used in the biomedical industry include the following: In the permanent skeletal replacement implants, graded porosity helps to minimize the stress shielding [13]. The gradient porous titanium dental implants also help to improve the osseo-integration properties of the implant [14]. The graded porous hydroxyapatite (HA) mimics the bimodal structure of the human bone (cortical and cancellous), which helps to promote the new tissue growth, and also with the desired mechanical properties [17–19].

2.3.4 Defence

The ability of the FGM to offer penetration-resistant properties by inhibiting crack propagation is an attractive property that makes the material favoured in the defence industry. The functionally graded materials are used in the defence industry in applications, such as bullet-proof vests, the traditional Japanese sword, and in armour plates. Another key area of application of functionally graded materials is in the body of bullet-proof vehicles.

2.3.5 Energy

The energy industries are constantly in need of different types of functionally graded materials, in order to improve the efficiency of some of their equipment. Some of the applications of the functionally graded materials in the energy industry include the inner wall of nuclear reactors, the thermo-electric converter for energy conversion, the solar panel, the solar cells, the tubes and pressure vessels, the graded electrode for the production of solid oxide fuel, the piezo-electric functionally graded materials for the ultrasonic transducer, the dielectric, the fuel cell, the turbine blade coatings, and for thermal barrier coatings.

2.3.6 Electrical/Electronics

Functionally graded materials are used in the electrical and the electronic industries in a number of ways. These include in the relaxation of the field stress in the electrode and the field–spacer interface [36, 37], in the diodes, in the semiconductors, for insulators, and for the production of sensors. The thermal-shielding elements in the micro-electronics are also made from the carbon nanotube functionally graded materials.

2.3.7 Marine

Functionally graded materials also find their application in the marine industry. The applications of functionally graded materials in the marine and sub-marine industry include in the propeller shaft, the diving cylinders, the sonar domes, the composite piping system, and in the cylindrical pressure hull.

2.3.8 Opto-Electronics

Functionally graded materials find their application in the opto-electronic industry for the production of such parts as those that are made with the optical fibre materials, the lens, the GRINSH lasers, the highly efficient photo dectectors, the solar cells, the tunable photodetector, the magnetic storage media, and in the production of semiconductors—with a varying refractive index.

2.3.9 Sport

Functionally graded materials are used in a number of sporting equipment, such as the golf clubs, tennis rackets, and skis. These are all made of functionally graded materials.

2.3.10 Others

The application of functionally graded materials also includes, but is not limited to, the cutting tools and dies to improve the thermal strength of the cutting tool and die, razor blades of iron-aluminide/stainless steel [38], in the safety equipment, such as Firefighting air bottles, the fire-retardant doors, the eyeglass frames, and the helmets. Others include the MRI scanner cryogenic tubes, the pressure vessels, the fuel tanks, the laptop cases, the musical instruments, and the X-ray tables. The applications of FGMs in Japan have also been presented by Miyamoto [39]. Readers can consult the material for further readings. The area of application of functionally graded materials is expected to increase, if the cost of production of this material is reduced in the future.

2.4 Summary

The different types of functionally graded materials and their application areas have been presented in this chapter. The functionally graded materials that were initially developed were chemical compositional gradient functionally graded materials, and it was developed for thermal bearer application. The high interest in the functionally graded materials in the research community has made this novel material to evolve into different types, while the areas of application have also expanded greatly. The three main types of functionally graded materials presented in this chapter are the chemical composition gradient functionally graded materials, the microstructure gradient functionally graded materials, and the porosity gradient functionally graded materials. The porosity gradient functionally graded materials are widely used in the biomedical application as medical implants, because they are designed to mimic the human organs, which are functionally graded materials in nature.

Different areas of application of this type of functionally graded material and other types of functionally graded materials have also been presented in this chapter. The areas of application of functionally graded materials are also expected to increase, if the cost of producing functionally graded materials is reduced.

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