ISSN 2310-4090

International Journal of Scientific Footprints Open Access

Functionally Graded Materials: A Critical Review

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Keywords:
Graded Materials; FGM's.

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Funding Information:
No funding information provided.

Received:
July 2014; Accepted: August 2014

International Journal of Scientific Footprints 2014; 2(4): 18-29

Abstract

With the development of new industries and modern processes, many structures serve in thermal environments, resulting in a new class of composite materials called functionally graded materials (FGMs). FGMs were initially designed as thermal barrier materials for aerospace structural applications and fusion reactors. They are now developed for general use as structural components in extremely high-temperature environments. FGMs are now recognized as important composite materials throughout the world. Utilization of FGMs appears to be one of the most efficient and effective materials in achieving sustainable development in Industries. This paper presents a critical review of the existing literature of FGMs. This paper explores following review strands:

1. Introduction.
2. Historical background.
3. Application Areas.
4. Processing techniques of FGMs.
5. Conclusion and Future Scope.

The paper will focus light on above issues and each plays an important role within the FGMs literature and ultimately influences on planning and development practices. It is expected that this comprehensive contribution will be very beneficial to everyone involved or interested in FGMs.

Introduction

Functionally graded materials (FGMs) exhibit a continuous variation of material properties which result from the non-homogenous microstructure. Due to the unique graded materials properties, FGMs have attracted a great amount of attention from researchers in many fields, including aerospace, biomaterials and engineering among others in the past decades. Functionally graded materials (FGMs) possess a position dependent microstructure, chemical composition or atomic order, which may result in the continuous variation of material properties with position such as mechanical, electrical and thermal properties.

Composite material are a class of advanced material, made up of one or more materials combined in solid states with distinct physical and chemical properties. Composite material offers an excellent combination of properties which are different from the individual parent materials and are also lighter in weight. Wood is a composite material from nature which consists of cellulose in a matrix of lignin [1].Composite materials will fail under extreme working conditions through a process called delamination (separation of fibers from the matrix) [2]. This can happen for example, in high temperature application where two metals with different coefficient of expansion are used. To solve this problem, researchers in Japan in the mid-1980s,confronted with this challenge in an hypersonic space plane project requiring a thermal barrier (with outside temperature of 2000K and inside temperature of 1000K across less than 10 mm thickness), came up with a novel material called Functionally Graded Material (FGM) [3,4].

Functionally Graded Material (FGM), a revolutionary material, belongs to a class of advanced materials with varying properties over a changing dimension [5,6]. Functionally graded materials occur in nature as bones, teeth etc. [7], nature designed this materials to meet their expected service requirements. This idea is emulated from nature to solve engineering problem the same way artificial neural network is used to emulate human brain. Functionally graded material, eliminates the sharp interfaces existing in composite material which is where failure is initiated [2]. It replaces this sharp interface with a gradient interface which produces smooth transition from one material to the next [3,4]. One unique characteristics of FGM is the ability to tailor a material for specific application [5].

Fig. 1.1 Traditional Composite Materials

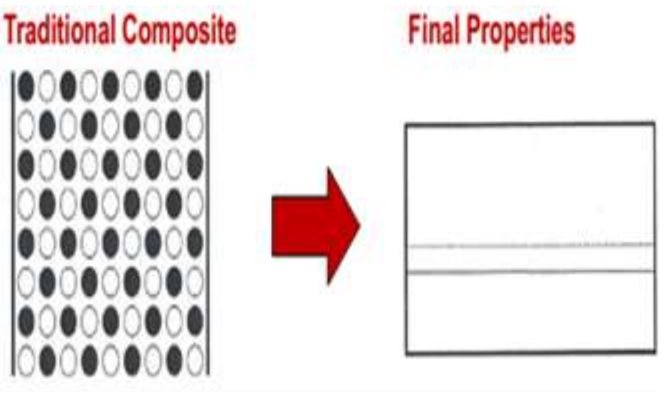


Fig. 1.2 Functionally Graded Materials

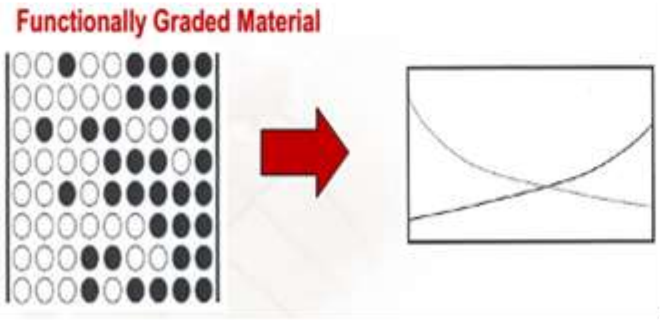
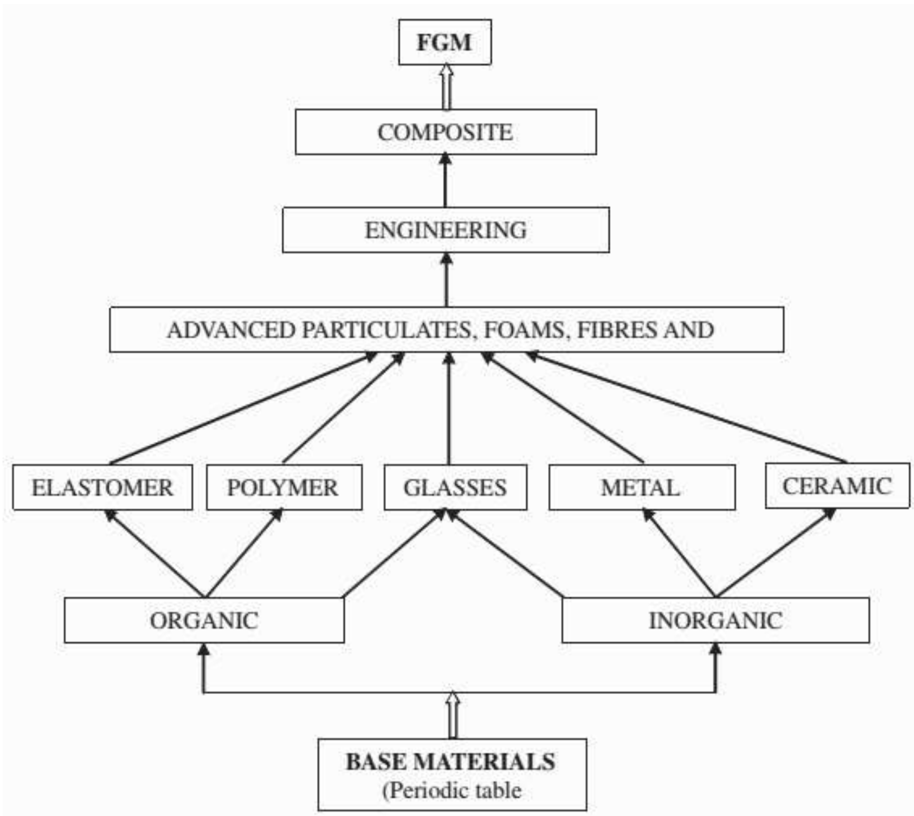


Fig.1.3 Representation of Modern material Hierarchy



In the development of our society and culture, materials have played an essential role. The scientific use of available base materials into various inorganic and organic compounds has made the path for developing the advanced polymers, engineering alloys, structural ceramics, etc. The structure of development of modern material is illustrated in Fig. 1.3. These materials possess numerous advantages that make them appropriate in potential applications. It includes a potential reduction of in-plane and through-the thickness transverse stresses, improved thermal properties, high toughness, etc. [8]

2. Historical Background:

The original idea of compositional and structural gradient in material microstructure was first proposed for composites and polymeric materials in1972.Bever in 1972 studied various gradient composites, investigated the global material properties and reviewed potential applications of graded composites. Shen in 1972 reported that the gradation of polymeric material might be induced by the variation of the chemical nature of the monomers, the molecular constitution of the polymers and the supramolecular structure or morphology of the polymers [9]. The effective properties, such as chemical, mechanical, biomedical and transport properties and possible applications, including gasoline tank and damping materials were considered. However, the design, fabrication and evaluation of this gradient structure was not studied.

Until 1985, the use of continuous texture control was presented to improve the adhesion strength and minimize the thermal stress in the ceramic coatings and joints being developed for a reusable rocket engine (Niino et.al., 1986).More general concepts applied to impart new properties and functions of materials were proposed by continuous control of the microstructure, also the design of such materials was initially introduced. The term of functionally graded materials was coined for these gradient composites and materials for more accurate description and grammar in 1986.In 1987,the famous research plan of FGMs, fundamental studies on the relaxation of Thermal stress by Tailoring Graded Structures" was pioneered in the thermal barrier for a space plane in Japan. The capabilities of withstanding a surface temperature of 17000C and a temperature gradient of 10000C across only a 10mm section were achieved by FGMs as a thermal barrier. The results and development of this research project were spread worldwide via papers, media and international conferences.

Due to their unique graded material properties, FGMs attracted great amounts of researcher interest, FGMs are potentially widely applicable in numerous fields. In addition to the aforementioned thermal barriers, coatings and joints in aerospace, FGMs have also been developed for other novel applications. In the field of biomaterials, biomedical implants such as artificial bones and dental implants are classic examples. Tampieri et al. in 2011 attempted to produce the porosity graded hydroxyapatite (HAP) ceramics, which not only good and fast bone in growth but also withstand early physiological stress as an implant to replace natural bone. Many other researchers agreed and reported that FGMs could provide the implant a suitable stiffness to endure the physiological loading and that the graded porosity structure could enhance the mechanical property of the implant to optimize the materials response to external loading (backer and Bolton, 1997, Pompe et.al. 2003, Wang et.al. 2012).

3. Processing Techniques of FGMs:

The manufacturing process of a FGM can usually be divided in building the spatially inhomogeneous structure ("gradation") and transformation of this structure into a bulk material ("consolidation"). Gradation processes can be classified into constitutive, homogenizing and segregating processes. Constitutive processes are based on a stepwise build-up of the graded structure from precursor materials or powders. Advances in automation technology during the last decades have rendered constitutive gradation processes technologically and economically viable. In homogenizing processes a sharp interface between two materials is converted into a gradient by material transport. Segregating processes start with a macroscopically homogeneous material which is converted into a graded material by material transport caused by an external field (for example a gravitational or electric field). Homogenizing and segregating processes produce continuous gradients, but have limitations concerning the types of gradients which can be produced. Usually drying and sintering or solidification follows the gradation step. These consolidation processes need to be adapted to FGMs: processing conditions should be chosen in such a way that the gradient is not destroyed or altered in an uncontrolled fashion. Attention also has to be paid to uneven shrinkage of FGMs during free sintering. Since the sintering behaviour is influenced by porosity, particle size and shape and composition of the powder mixture, these problems must be handled for each materials combination and type of gradient individually referring to the existing knowledge about the sintering mechanisms [10]. Thin functionally graded materials are usually in the form of surface coatings, there are a wide range of surface deposition processes to choose from depending on the service requirement from the process.

3.1. Vapour Deposition Technique:

There are different types of vapour deposition techniques, they include: sputter deposition, Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD). These vapour deposition methods are used to deposit functionally graded surface coatings and they give excellent microstructure, but they can only be used for depositing thin surface coating. They are energy intensive and produce poisonous gases as their by-products [12]. Other methods used in producing functionally graded coating include: plasma spraying, electrode position, electrophoretic, Ion Beam Assisted Deposition (IBAD), Self-Propagating High-temperature Synthesis (SHS), etc. [11]. All the above mentioned processes cannot be used to produce bulk FGM because they are generally slow and energy intensive, therefore they are uneconomical to be used in producing bulk FGM. Some of the fabrication methods for producing bulk functionally graded materials are as follows:

3.2 Powder Metallurgy (PM)

Powder metallurgy (PM) technique is used to produce functionally graded material [13, 14] through three basic steps namely: weighing and mixing of powder according to the pre-designed spatial distribution as dictated by the functional requirement, stacking and ramming of the premixed-powders, and finally sintering [15]. PM technique gives rise to a stepwise structure. If continuous structure is desired, then centrifugal method is used.

3.3 Centrifugal Method

Centrifugal method is similar to centrifugal casting where the force of gravity is used through spinning of the mould to form bulk functionally graded material [16]. The graded material is produced in this way because of the difference in material densities and the spinning of the mould. There are other similar processes like centrifugal method in the literature (e.g. Gravity method etc.). Although continuous grading can be achieved using centrifugal method but only cylindrical shapes can be formed. Another problem of centrifugal method is that there is limit to which type of gradient can be produced [17] because the gradient is formed through natural process (centrifugal force and density difference). To solve these problems, researchers are using alternative manufacturing method known as solid freeform.

3.4 Solid Freeform (SFF) Fabrication Method

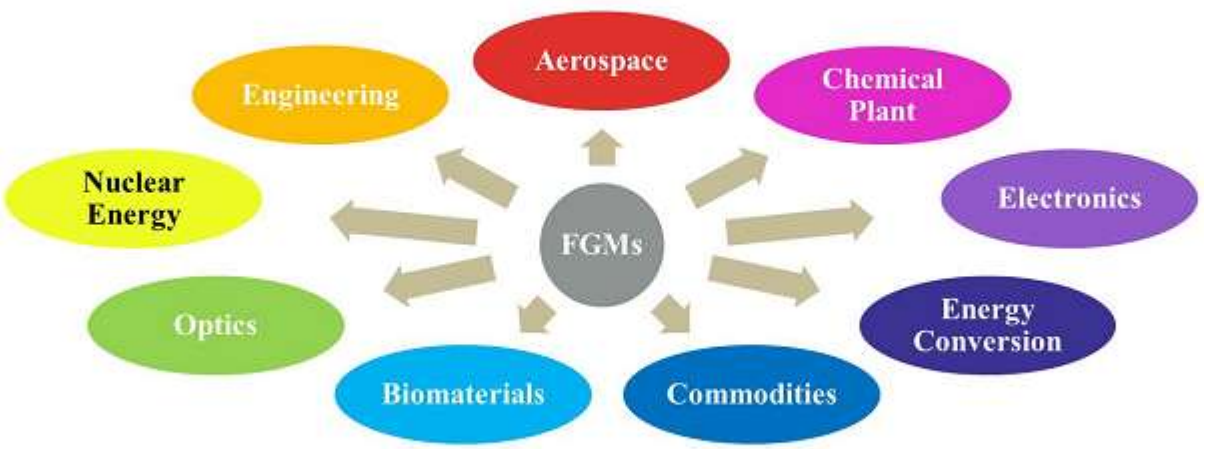
Solid freeform is an additive manufacturing process that offers lots of advantages that include: higher speed of production, less energy intensive, maximum material utilization, ability to produce complex shapes and design freedom as parts are produced directly from CAD (e.g. AutoCAD) data [18]. SFF involves five basic steps [19]: 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, and lastly removal and finishing. There are various types of SFF technologies, laser based processes are mostly employed in fabrication of functionally graded materials [20]. Laser based SFF process for FGM [21,22] include: laser cladding based method [21, 23-28], Selective Laser Sintering (SLS) [31, 32], 3-DPrinting (3-DP) [25, 27], and Selective Laser Melting (SLM) [24, 26].

Laser cladding based system and selective laser melting are capable of producing fully dense components. Solid freeform provide manufacturing flexibility amongst other advantages but the technology is characterized by poor surface finish making it necessary to carry out a secondary finishing operation. There are lots of research efforts in this direction to improve surface finish, dimensional accuracy etc. There are other fabrication methods for functionally graded materials; readers can refer to the review studies by Kieback and Neubrand and Gasik, [17, 31]. These authors presented comprehensive processing techniques of functionally graded materials.

4. Application Area:

FGMs have great potential in applications where the operating conditions are severe, including spacecraft heat shields, heat exchanger tubes, biomedical implants, flywheels, and plasma facings for fusion reactors, etc. Various combinations of the ordinarily incompatible functions can be implemented to create new materials for aerospace, chemical plants, nuclear energy reactors, etc. For example, a discrete layer of ceramic material is bonded to a metallic structure in a conventional thermal barrier coating for high temperature applications.

Fig.1.4 Various fields of Application of FGMs



Typical applications of FGMs are as follows:

*** Smart Structures**

Functionally graded piezoelectric materials.

Shape memory alloys.

*** MEMS and sensors**

*** Electronics and optoelectronics**

Optical fibres for wave high speed transmission.

Computer circuit boards (PCB)

Cellular phone.

*** Medicine:**

Living tissues like bones and teeth are characterized as functionally graded materials from nature, to replace these tissues, a compatible material is needed that will serve the purpose of the original bio-tissue. The ideal candidate for this application is functionally graded material. FGM has found wide range of application in dental and orthopaedic applications for teeth and bone replacement.

*** Biomaterials**

Artificial bones joist.

Teeth

Cancer prevention.

*** Others**

Baseballs cleats.

Razor blades.

Titanium watches.

*** Power plant**

Thermal barrier coatings.

Heat Exchanger tubes.

*** Manufacturing**

Machine Tools

Forming and cutting tools.

Metal casting and forging processes.

*** Aerospace and Aeronautics**

Exhaust wash structure that separates exhaust gas from aircraft structure for vehicles which have internally exhausted engines, i.e., stealth aircraft and UAVs with engines that don’t exhaust directly to atmosphere. Hot, high speed engine exhaust flows over the top surface of exhaust wash structures which, in turn, causes large deflections. An FGM patch applied to the underside of the exhaust wash structure can be designed such that thermally induced deflection of the FGM patch is in a direction opposite to the exhaust wash structure deflection. Ceramic metal FGMs are particularly suited for thermal barriers in Space vehicles. FGMs have the added advantage that the metal side can be bolted onto the airframe rather than bonded as are the ceramic tiles used in the orbiter. Other possible uses include combustion chamber insulation in ramjet or scramjet engines.

*** Applications of FGM as Thermal barrier**

Coating

One of the salient applications of FGM is in thermal Barrier Coatings. Thermal barrier coatings find their widespread applications in automotive and aircraft industries. They are specifically designed to reduce heat loss from engine exhaust system components including exhaust manifolds, turbocharger casings, exhaust headers, down pipes and tail pipes.

*** Defence:**

One of the most important characteristics of functionally graded material is the ability to inhibit crack propagation. This property makes it useful in defines application as a penetration resistant materials used for armour plates and bullet-proof vests.

*** Energy:**

FGM are used in energy conversion devices. They also provide thermal barrier and used as protective coating on turbine blades in gas turbine engines.

5. Conclusion and Future Scope:

Functionally graded material is an excellent advanced material that will revolutionize the manufacturing world. There are a number of hurdles for realizing this objective. Cost is one of them, with substantial part of the cost expended on powder processing and fabrication method. Lots of studies have been conducted on behaviour of functionally graded materials and the literature is very rich on this because of the wide areas of application of this novel material. 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 historical background, various fabrication methods and its wide application areas.

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