A Review on Functionally Gradient Materials (FGMs) and Their Applications

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Abstract. Functionally gradient materials (FGM) are innovative materials in which final properties varies gradually with dimensions. It is the recent development in traditional composite materials which retains their strengths and eliminates their weaknesses. It can be formed by varying chemical composition, microstructure or design attributes from one end to other as per requirement. This feature allows FGM to have best material properties in required quantities only where it is needed. Though there are several methods available for manufacturing FGMs, additive based metal deposition (by laser, electron beam, plasma etc.) technologies are reaping particular interest owing to their recent developments. This paper presents evolution, current status and challenges of functionally gradient materials (FGMs). Various manufacturing processes of different types of FGMs are also presented. In addition, applications of FGMs in various fields including aerospace, defence, mining, power and tools manufacturing sectors are discussed in detail.

1. Introduction

Materials are continuously developed from iron, pure metals to composite materials which are in use today. Continuous material development from Bronze Age to present and future scenario is presented in figure 1 [1]. Pure metals have very limited use, since actual application may require contrary property requirement which cannot provide by using single metal. As compared to pure metals, alloys can be stronger and more versatile. Bronze which is alloy of copper and tin was the first alloy that was developed in 4000 BC (Bronze age). Since then, different mixtures of metals and non-metals were tried to combine strengths of multiple materials as per functional requirement.

Figure 1. Continuous material development from bronze to FGMs

Composite materials are most advanced form of materials which are made from two or more constituents with significantly different physical and chemical properties from the individual materials. Composite materials allow distinct combinations giving hard, wear resistant surface and soft core as
per functional requirement of application. Heterogeneity, anisotropy, symmetry and hierarchy are the main characteristics of composite materials reaping particular interest for various applications. High strength to stiffness ratio, greater resistance to fatigue, wear and corrosion, high reliability etc. are the advantages of composites over pure or alloyed metals. In spite of all these advantages, composite materials are subjected to sharp transition of properties at the interface which can result in component failure (by delamination) at extreme working conditions.

This drawback of conventional composites eliminated by modified form of composites called functionally gradient materials (FGMs). These materials replace sharp interface with gradient interface which results in smooth transition of properties from one material to the other. These advanced materials with engineered gradients of composition, structure and specific properties in the preferred direction are superior to homogeneous material composed of similar constituents [1]. The mechanical properties such as Young’s modulus of elasticity, Poisson’s ratio, shear modulus of elasticity, material density and coefficient of thermal expansion vary smoothly and continuously in preferred directions in FGMs. Bone, teeth, skin and bamboo tree are some examples of naturally occurring functionally gradient materials. The concept functionally gradient material (FGM) was first developed by researchers from Japan in 1984. They designed functionally gradient thermal barrier with outside temperature of 2000 K and inside temperature of 1000K across 10 mm thickness. Since then, use of functionally gradient materials has increased in various fields including aerospace, mining, power and medical. FGMs have numerous advantages that make them suitable in these applications. It includes high fracture toughness, reduction in plane and through the thickness transverse stresses, enhance performance of thermal barrier systems etc. Due to this prominence of FGM, lots of efforts were made to improve FGM manufacturing process and properties of the FGM. There are several manufacturing methods are available for manufacturing FGMs depending on the type of FGM required. These include powder metallurgy, vapour deposition, centrifugal method and solid free form techniques. Out of all these methods, solid free form techniques by using laser, plasma or electron beam as energy source are becoming very popular in the recent years.

This paper presents describes functionally gradient materials (FGMs), their types and methods of manufacturing. Solid free form manufacturing (SFF) techniques of FGMs are also discussed in detail. Finally, few applications of FGMs along with recent research work and challenges of FGMs are presented.

2. Types of Functionally gradient materials (FGMs)

![Classification of Functionally gradient materials](image)

**Figure 2.** Classification of Functionally gradient materials [2]

Two different criteria’s are used to classify functionally graded materials. One is based on structure of material and the other is based on size of functionally graded materials. As shown in figure 2, functionally graded materials can be further divided into two major groups based on structure of materials: Continuously structured and discontinuously structured FGM. In continuous FGM, there is continuous gradient present from one material to the other material. However in case of discontinuous FGM, material gradient is provided in layered fashion. Based on size of materials, FGM’s are
classified into two major types: Thin FGM and bulk FGM. Thin FGM are having relatively thin sections like surface coating, whereas the bulk FGM’s are complete volume of materials. Manufacturing processes like physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD) and Self propagating High temperature Synthesis (SHS) method are used to manufacture thin FGM. Whereas, bulk FGM’s are manufactured by using methods such as powder metallurgy, centrifugal casting and solid freeform/additive manufacturing techniques.

3. Methods of manufacturing FGMs
Several techniques are available to produce functionally graded materials (FGMs). Few of them are described below in detail.

3.1 Vapour deposition technique
Vapor deposition techniques describe a variety of vacuum deposition methods which can be used to produce thin films on the base materials. All these techniques can be used to produce thin FGMs only. Different types of vapour deposition techniques include physical vapour deposition (PVD) and Chemical vapour deposition (CVD). These are energy intensive and produce poisonous gages as their by-products [3]. Other deposition based techniques which can deposit thin functionally gradient coatings are electron beam deposition (EBD), Ion beam deposition (IBD) and Self propagating high temperature synthesis (SHS) [4]. All above mentioned methods are uneconomical to produce bulk type FGMs.

3.2 Powder metallurgy
Powder metallurgy based technique can be used to produce bulk type FGMs with discontinuous (stepwise) structure. The process is carried out by using steps including weighing and mixing of powder according to the pre-designed spatial distribution as per functional requirement, stacking and ramming of the premixed-powders, and finally sintering [5].

3.3 Centrifugal method
Centrifugal method is capable to produce continuously structured bulk type FGMs. It uses force of gravity through spinning of mould to produce functionally graded materials [6]. Difference in material densities and spinning of mould produces FGMs. There are two disadvantages of this method are this method can produce only cylindrical shaped FGMs and there is limit to which type of gradient can be produced.

3.4 Solid free form fabrication/additive manufacturing (AM) techniques
Solid freeform fabrication (SFF)/Additive manufacturing (AM), also known as 3D printing, is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technology [7]. This tool-less manufacturing method can produce fully dense metallic parts in short time, with high precision. Metal AM processes can be broadly classified into two major groups, - Powder Bed Fusion based technologies (PBF) and Directed Energy Deposition (DED) based technologies. Both of these technologies can be further classified based on the type of energy source used. In PBF based technologies, thermal energy selectively fuses regions of powder bed. Selective laser sintering/melting (SLS/SLM) and electron beam melting (EBM) are main representative processes of PBF based technologies. In DED based technologies focused thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited. Laser Engineered Net Shaping (LENS)/Direct Metal Deposition (DMD), Electron Beam Free Form Fabrication (EBFFF) and are based AM are some of the popular DED based technologies.

Most of above mentioned SFF/AM methods are capable to produce functionally gradient materials (FGMs) from thick coatings to complicated FGM bulk parts.
Advantages offered by AM techniques like higher material utilization, speed of production, design freedom, capability to produce complicated parts and less energy intensiveness are garnering particular interest in manufacturing FGMs for different applications.

Powder bed fusion (PBF) based AM technologies like Selective laser melting (SLM) and Electron beam melting (EBM) are very popular methods for producing complicated parts owing to their high accuracy and surface finish as compared to directed energy deposition (DED) based technologies. However, PBF based technologies are less flexible than DED based technologies as far as functionally gradient material manufacturing are concerned. It is due to fact that material gradient by varying chemical composition of powder is not possible. However these methods can produce bulk FGMs by controlling porosity or by introducing different types of lattice structures in parts to be manufactured.

Directed energy deposition (DED) based AM techniques are most convenient methods to produce FGMs since these methods can produce FGM from thick coatings to bulk parts having continuous or discontinuous gradient. These methods can produce FGMs with better adhesion and mechanical properties than powder bed technologies. Laser metal deposition (LMD) and Electron beam free form deposition (EBFF)/ Electron beam additive manufacturing (EBAM) are popular methods based on DED based AM systems which can be used to manufacture different kinds of FGMs.

3.4.1. Laser metal deposition (LMD). Laser engineered net shaping (LENS) and direct metal deposition (DMD) are main processes based on DED technology which uses laser beam as power source and raw material in the form of powder. LENS process was originally developed by Sandia national laboratories in 1997 and then licensed to Optomec (USA), whereas DMD process was jointly developed by POM group and University of Michigan [8, 9]. In these process, high power laser beam is used to create a molten pool on base material and then powder material is injected into the molten pool by using nozzles. Delivered powder at laser beam spot is absorbed into the melt pool and creates deposit. As shown in figure 3, the work table can move in x - y direction to obtain desired cross section of sliced model and then subsequent layers can be deposited by incrementing deposition head in z direction to complete the object. Deposition of layers is repeated until the desired three-dimensional component has been additively formed. Metal powder is delivered through nozzles and distributed around the circumference of deposition head either by gravity, or by using inert carrier gas. The entire process is conducted under controlled argon atmosphere where oxygen levels are maintained below 10 ppm.
FGMs can be fabricated into complex shapes as the rate of elemental powder deposition can be controlled for each feeder during the fabrication for each layer and the final product can be achieved within hours [11].

3.4.2. Electron beam direct manufacturing. Electron Beam Direct Deposition (EBDM) is another technology based on directed energy deposition (DED) which uses electron beam as power source and raw material in the form of wire. This technology was developed by Sciaky (Chicago, USA) and also known as Electron beam additive manufacturing (EBAM). This process can produce medium to large sized near net shaped components inside vacuum chamber directly from digital model. After manufacturing, component requires finishing operations such as heat treatment and machining. Maximum size of component to be manufactured by EBAM is restricted by vacuums chamber size of the machine. Commercially available welding wires are used as the deposition material. The standard electron beam system is a Sciaky 60 kW / 60 kV welder. The electron beam is electronically focusable and the output power is scalable over a very wide range. This enables a very wide range of deposition rates to be achieved using the same system. Typical deposition rates of EBAM systems are from 3 to 9 Kgs/hrs depending on the material used and part complexity. Additionally, the EBAM system has closed loop control system in which melt pool size is continuously monitored and parameters are adjusted to keep the size constant. This ensures consistent part geometry, uniform microstructure and mechanical properties.

![Figure 4](image-url)

**Figure 4.** Electron beam additive manufacturing by twin wire deposition [12]

EBAM technology can also produce various types of functionally graded materials (FGMs) by using multiple wire feed nozzles as shown in figure 4 to single EB gun. Two or more wires of different metal alloys can be independently controlled and simultaneously feed to single molten pool to form graded materials. Both coating and bulk type of FGMs can be formed in continuous or discontinuous manner.

3.4.3. FGMs by Arc deposition technologies. Wide ranges of arc based additive manufacturing processes are available where arc (plasma, TIG, MIG) is used as power source and material is used in the form of powder or wire. Plasma transferred arc (PTA) and plasma arc welding (PAW) are free form AM processes which uses plasma arc as power source and raw material in the form of powder and wire respectively. Shaped metal deposition (SMD) is another AM technique which uses tungsten inert gas (TIG) or Metal inert gas (MIG) welding with material in the form of wires for free form fabrications. Since most of such systems are wire feed type, these are also known as Wire assisted additive manufacturing (WAAM) systems. Large number of system configurations can be achieved by integrating conventional welding systems with robots, manipulators or gantries for automation. All of these processes with proper inert gas shielding have strong potential to produce near net shaped medium to large sized parts at much lower cost as compared to laser and electron beam based processes.
Few welding based AM systems has been developed which can deposit functionally gradient materials. In this case, two filler wires are controlled separately and supplied to the arc (TIG or MIG) for deposition. Several studies have been carried out to demonstrate effectiveness of arc based AM configurations to produce FGMs. Sajan Kapil et. al [13] successfully fabricated Al-Si alloy having gradient in thermal conductivity. It was fabricated by using Hybrid layered manufacturing machine (HLM) which combines 3 axis CNC and gas metal arc welding (GMAW) deposition system. S. Suryakumar et al. [14] demonstrated two different ways to fabricate functionally gradient materials by using weld deposition. FGMs can be produced by varying process parameters or by using double wire feeder which can be guided and controlled separately.

4. Applications

In the recent years, there has been growing interest in the use of functionally gradient materials (FGMs) due to their numerous advantages over composite materials. Owing to graded variation in the composition, the properties of FGMs changes significantly and continuously from one surface to another, thus eliminating interface problems like stress concentrations and poor adhesion [15]. Use of FGMs is increasing in aerospace, defense, nuclear industry, biomedical and electronics sectors.

FGMs are mainly used in those applications where combinations of two extreme properties are required in single component for example hardness and toughness [16]. For example, in case of turbine blade, thermal resistance and anti-oxidation properties are required at high temperature side and mechanical strength and toughness are required at low temperature side. To tackle these requirements turbine blades were used to manufacture by using metal-ceramic composites [17]. However, the property difference between two materials created residual stresses and adhesion issues at interface which may lead to failure. Turbine blade made by using FGM possesses smooth property change from ceramic to metal and diminishes interface problems [18]. Figure 5 shows turbine blade made by using FGM where properties like thermal conductivity and mechanical strength are continuously graded from metal to ceramic region.

The applications like cutting tools and machine parts require heat, wear, mechanical shock and corrosion resistance. Reliability and cost/performance ratio plays major role in these applications [16]. Figure 6 shows composite and FGM cutting tools with metal shank and ceramic tip. Composite tool suffers from sharp transition of properties from metal to ceramic which may result in residual stresses and tool failure. However FGM cutting tool where FGM material used in between metal and ceramic increases thermal strength and tool expected to have long life.

![Figure 5. Turbine blade material properties containing FGM](image)

![Figure 6. Conventional and FGM metal cutting tool](image)

Metal-ceramic FGM is also used in armors, [21,22] Where hard ceramic front surface blunts the projectile, whereas metallic back surface catches fragments and prevents penetration [23]. Similar FGMs also finds applications as heat resistant valves of internal combustion engines [17]. Functionally graded thermal barrier coatings (FTBC) by using various spraying techniques are popular methods of producing such FGMs [24, 25].
Another emerging area for FGM application is biomedical sector where functionally graded prosthesis joint can increase adhesive strength and reduce pain [26].

Performance of metal prosthesis joint can be enhanced by using functionally gradient material having high biocompatibility at surface. As shown in figure 7, biocompatibility property increases and mechanical strength decreases as we move from metal to bone.

Number of diffusion and deposition based technologies are used to enhance surface properties of components. However, recently it is observed that their performance can be further increased by combining diffusion with deposition processes. Combination of diffusion processes like nitriding, nitro-carburizing etc. with deposition processes like PVD,CVD type coatings of hard material provides functionally gradient effect which improves properties [28]. These treatments are well known as duplex surface treatments where diffusion process (nitriding, boriding etc) are combined with coating processes (like PVD, CVD or TRD- thermo reactive diffusion). Deposition technologies can produce hard, wear resistant layer on metal surface. However, thickness of this coating is very small and there is sudden change in properties between coating and the substrate material. It can result in premature failure of coating during service conditions by delamination of coating. Thermo chemical diffusion treatment like nitro-carburizing prior to deposition of hard coating can form graded structure from surface to substrate and provides tough and supportive sub-surface for hard coating [29]. It is also observed that such a graded structure can shift failure mechanism from Thus, Duplex surface treatment involving nitro-carburizing and thermo reactive deposition can retain beneficial effects of both treatments and eliminates drawbacks of them by forming graded structure from surface to base. Along with all these applications, FGMs are also used in piezoelectric actuators [30], functionally graded thermal protection system for hypersonic and supersonic planes [pap-modelling and analysis-206] and functionally graded heated floor systems [31].

5. Recent developments and challenges of FGMs
In case of most of the FGMs, a material property varies in thickness direction [32]. However, modern applications may demand FG materials in which material properties in both thickness and axial directions [33]. Recently, a gradient material in which properties varies in both directions are also developed and extensively studied [34, 35].Such smart materials are known as bidirectional functionally gradient (BDFGMs) materials. Laser metal deposition based AM technique is most suitable to produce such BDFGMs [11].

Though substantial technology advancement has been made in the field of FGMs, few critical issues still need to be addressed. A proper database of FGMs in terms of parameters and testing is still not available. Conventional testing and measurement method may not suitable to evaluate performance of modern FGMs, so developments of advanced testing methods are required [36]. Most of the processing techniques of FGMs are very costly, so low cost processing technique which can mass produce large sized, complex shape FGMs is still remain as a challenge. The selection of proper material suitable for intended application is the immediate and direct challenge for future technology development in FGM research field.
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