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Review **JoPC**

A Mini Review of Synthesis and Applications of Functionally Graded Materials

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Abstract

Material composition or microstructure varies gradually along the thickness over a specific volume in functionally graded material (FGM) that results in spatial change in properties like thermal conductivity, strength, stiffness, electrical, magnetic, and light properties, etc. Application of the concept of FGM leads to a single product that has multiple properties in it as demanded by the operational or functional requirements of the product under service conditions. It also allows the designer to tailor make or customize the properties of the component meant for a specific application. FGMs can be thin or thick. Thin FGMs (coatings) are fabricated by physical and chemical vapor deposition techniques whereas thick FGMs are fabricated by powder metallurgy, centrifugal casting and solid free form (SFF) routes. Out of these methods, SFF, that is the additive manufacturing (AM) technique, is versatile and is rapidly gaining the popularity and importance. Besides, SFF appears to be the promising method to undertake the fabrication of FGMs at large scale due to its high manufacturing flexibility and suitability for achieving high production rates. FGMs are finding increasing applications in various fields namely aerospace, defense, energy, electronic, medical etc. This paper reviews various techniques of synthesis of FGMs and touches upon their application areas.

Keywords: Applications, coatings, functionally graded material, property gradient, solid free form, synthesis

INTRODUCTION

A mechanical equipment or a component operating simultaneously under various types of loads and environments, each one dominant at a definite location in the component, is quite common. Finding a single homogeneous and isotropic metal that possesses all the desired properties which can fulfill every stated operational requirement at a time is virtually impossible [1]. As such, under application of multiple and different types of loads, conventional practice of design with a single metal calls for higher factor of safety to cater for material inadequacy against some of the loads that results in increased body mass which is undesirable. A bimetallic or a multi-metallic configuration shows a lot of promise in dealing with such cases wherein different metals having distinct properties or same metals with different microstructure and properties are bonded to each other so that each metal performs the assigned role. Introduction of new welding technologies namely diffusion bonding, friction stir welding, explosive welding, laser, and electron beam welding etc., that are capable of joining dissimilar metals at molecular levels, have made the fabrication of bimetallic bodies possible in a big way. Positive reports about successful testing and implementation of bimetallic systems have paved the way for a new class of materials known as functionally graded materials (FGMs).

The FGM is a non-homogeneous composite in which the material composition or microstructure varies gradually over the volume resulting in continuous and gradual spatial change in material properties along the thickness namely stiffness, thermal conductivity, strength, stiffness, toughness, electrical, magnetic, and light properties etc. Another unique characteristic of the FGM is the ability to tailor make or customize the stated

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properties of the product for a specific application. Importantly, FGMs usually are marked by the absence of distinct or abrupt interfaces in contrary to what is found in a bimetallic configuration and even in conventional fiber-resin composites (FRPs) with discrete and distinguishable interfaces between resin and fibers. Use of different materials in the form of particulates, fibers, whiskers or platelets are conducive to the fabrication and development of FGMs. Engineering alloys of steel, titanium, tungsten, aluminum, magnesium etc. and ceramics such as zirconia, alumina, silicon carbide, tungsten carbide etc. are the most preferred constituents of a FGM. The first FGM [2] was developed in Japan in mid 1980s for use in hypersonic space plane that required a thermal barrier across 10 mm thickness with outside surface temperature of 2000 K and inside body temperature of 1000 K. The outer exposed surface of the plane had to be heat resistant while the inner core had to be both strong and tough. One of the attractive choices among FGMs is a metal-ceramic composite in which metal takes care of strength and toughness in inner core whereas ceramic fulfills the requirement of withstanding high surface temperature. A typical ceramic-metal composite is shown in Figure 1. There is a gradual change in composition (volume fraction) of metal and ceramic with no visible or distinct interfaces. Currently, FGMs have gained world wide importance with the intention to make the suitable use of all the properties of available materials in the best possible manner.

LITERATURE REVIEW

Numerous studies have been reported in the field of FGMs till date. Most of the studies pertain to the review work. Off late, Zhang et al[3]. reviewed additive manufacturing methods of functionally graded materials. Majid et al[4]. presented a review of classification, fabrication methods and the applications of FGMs. Galy et al[5]. discussed FGMs classifications and developmental trends from industrial point of view. Li et al[6]. reviewed FGMs and related structures fabricated via additive manufacturing. Pasha et al[7]. investigated fabrication of FGMs and their potential challenges and applications. Birman et al[8]. touched upon diverse areas relevant to various aspects of theory and applications of FGMs. Their study included homogenization, heat transfer issues, stress, stability, and dynamic analysis, testing, manufacturing, design, and applications and fracture of FGMs. Zhang et al[9]. reviewed additive manufacturing techniques for large scale metallic FGMs. Zhang et al[10]. presented an overview on stability, buckling, and free vibration analysis of FGMs. Quite recently, Hayashi et al[11]. fabricated the FGM consisting of AG nanoparticles and silicone rubber using a sustainable sonochemical approach. Gupta et al[12]. carried out the sustainability and life cycle assessment of FGM. Keeping the above in view, this paper is another step forward towards a succinct and comprehensible review of the synthesis and applications of FGMs.

SYNTHESIS

Manufacturing methods of FGM play a pivotal role in meeting the design requirements of a graded structure in terms of geometric features, composition, microstructure etc. In addition, choosing the right manufacturing method that takes care of economic and time aspects and also fulfills the environmental considerations like low energy consumption and control over pollution is equally important.

Thin FGMs (thin films and surface coatings)

Introduction of advanced and sophisticated metal deposition techniques has opened a lot of possibilities for producing different types of coatings or thin films over the parent bodies. The use of surface coatings to enhance the life of the parent body is gaining enormous commercial significance [13]. For example, coatings in the form of thin surface films of materials, that are chosen for their chemical inertness, stability at elevated temperature and low thermal conductivity, have been introduced to improve the turbine engine efficiency and to extend the life of the engine components. Similarly, surface coatings are found to enhance useful lifetimes of the parts operating under the conditions of high friction and wear arising due to consistent contact between two or various parts. The components that require thin film coatings to reduce friction and wear are found in internal combustion engines, artificial hip and knee transplants, computer hard disks for magnetic data storage etc. The idea of thermal barrier coating (TBC) to thermally insulate parent metallic structure from high temperature environment has also been attempted with promising results. This technology is based upon the principle of multi layers. For instance, the TBC system for a gas turbine blade constitutes four different layers. They are in the form of a metallic substrate that is the turbine blade itself, a metallic interlayer or bond coat (100um), thermally grown oxide like zirconium oxide (100–400um) and finally a ceramic outer layer or top coat. Great strides have also been made in thin film technology to promote development of miniature and highly integrated electronic circuits. In such devices, confinement of electric charge relies largely on interfaces between materials with different electronic properties. Similarly, thin film coatings are of prime importance in many micro-electro-mechanical systems that serve as sensors or actuators. A silicon membrane coated with piezoelectric or piezoresistive thin film is used to electronically detect the membrane deflection upon application of the pressure or by acceleration of the supports. Moreover, as titanium alloys have poor high temperature properties besides being prone to fire hazards, a thin layer of heat resistant stainless steel is reported to be cladded over titanium alloy. Near future applications of coatings are foreseen in titanium nozzles, exhaust structures, gas turbine blades and other parts operating in high temperature areas. The thickness of coatings usually ranges from nanometers to micrometers. Notable methods of applying coatings over the parent or substrate surfaces are elucidated as follows:

Physical Vapor Deposition (PVD)

Refer Figure 2. It is the process in which the coating material (target) is transferred in the vapor form through vacuum to the substrate (parent body to be coated). The vapor is then condensed to settle on the substrate thereby resulting in a thin, solid coat or film on the surface. The techniques used to convert the coat material to vapor form are thermal evaporation, electron beam evaporation, sputtering, pulsed laser deposition arc etc. The chamber vacuum level maintained during transportation of vapor is 10–2 to 10–6 Torr. The substrate temperature rises to several hundred K during the process. The deposition rate of the vapor on the substrate is of the order of 0.1–10 nanometers per second. PVD results in a uniform and adherent coating with high purity and controlled thickness. Complex shapes can be easily coated by PVD. But PVD necessitates requirement of vacuum that is costly. Moreover, it cannot be applied to coat deep holes. Also, some materials like polymer may not sustain high temperatures and can melt before vaporization. The various sub-processes based on the principle of PVD are briefly discussed as under:

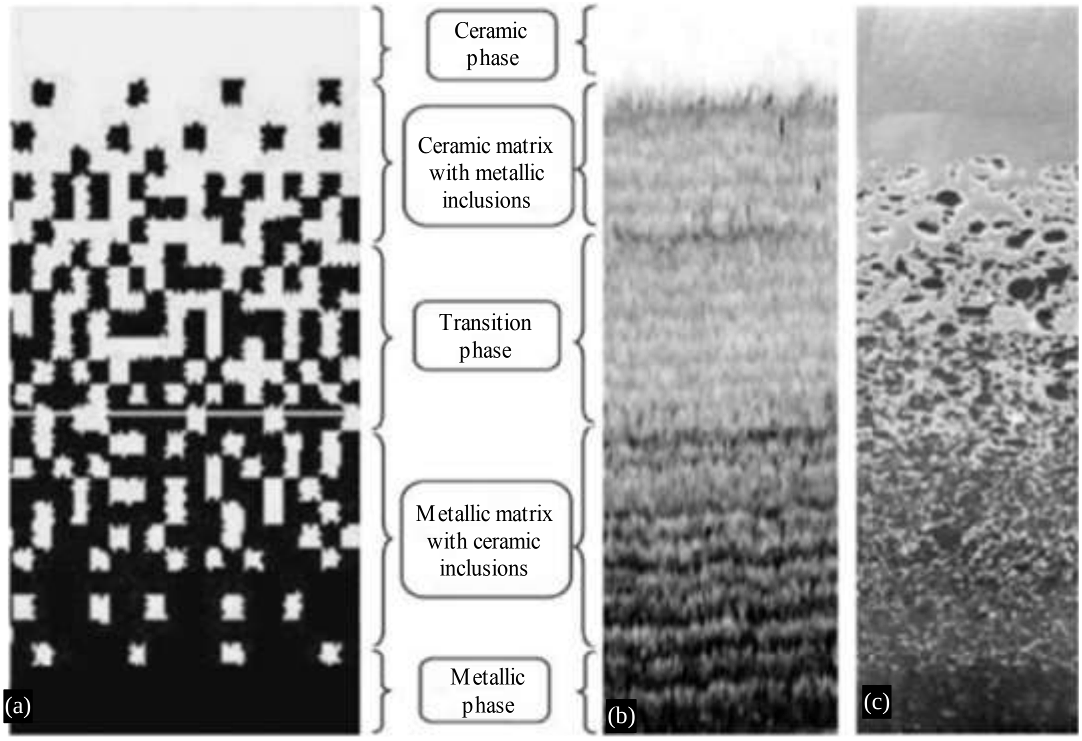

Figure 1. Schematic of continuously graded microstructure with metal-ceramic constituents in a FGM a) Smooth graded microstructure b) Enlarged view c) Metal-ceramic FGM.

Sputter deposition

It is a PVD technique meant for depositing thin film over the substrate. Inert gas is filled in a chamber containing positive charged substrate and negative charged coating material. High voltage is applied to generate a plasma. The resulting ions are made to move that strike the coating material with high energy in order to eject the molecules from the material. The ejected coat molecules are then diverted towards the substrate to settle on it thereby leading to the formation of a thin film.

Plasma spraying

It is a thermal spray coating technique wherein a plasma torch is ignited that produces plasma jet with temperature of the order of 15000 deg C by ionizing the gas namely argon, hydrogen or nitrogen etc. The solid coat material most likely metal, ceramic alloys etc is introduced in the plasma jet. This results in tiny particles of the coat accelerating at high velocities towards the substrate. These particles subsequently flatten and solidify over the substrate leading to the desired film of high quality and properties.

Ion beam assisted deposition

This method involves the combination of PVD and simultaneous bombardment of ions on already growing film on the substrate by focusing high energy ion beam (Typically Ar+, N+, O+ ions) towards the substrate. These ions have energy ranging from tens to hundreds of electron-volts. These ions on bombarding the already coated substrate by PVD lead to a substantial enhancement in film properties such as adhesion, density, and crystallinity.

Chemical vapor deposition (CVD)

Refer Figure 3. It is the process in which the coat material, in the form of vapor or gas, is generated by chemical reaction that takes place on or near the heated substrate surface. The flow of precursors (reactants) is arranged in a reaction chamber. Chemical reaction is initiated at the hot substrate surface that results in deposition of solid material on the substrate as a thin film. The gaseous by-products are suitably exhausted from the chamber.

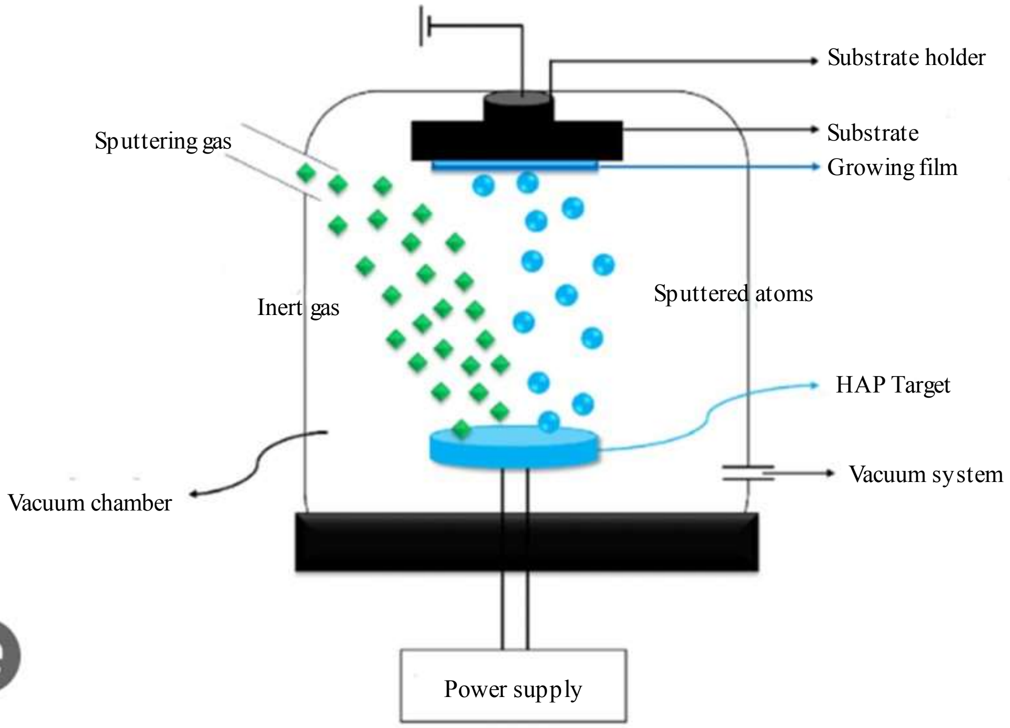

Figure 2. Schematic of PVD process.

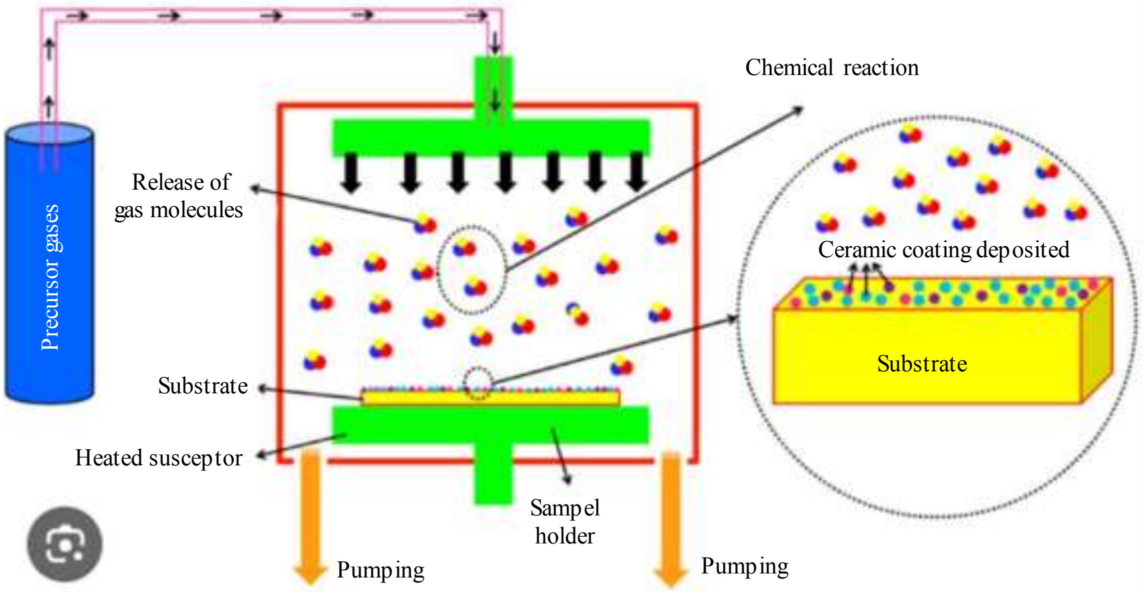

Figure 3. Schematic of CVD process.

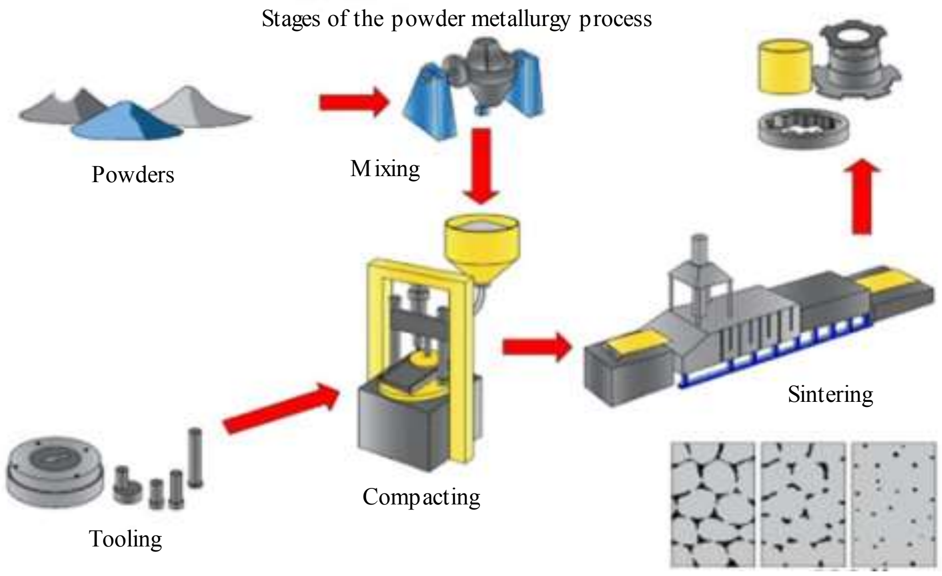

Figure 4. Schematic of powder metallurgy process.

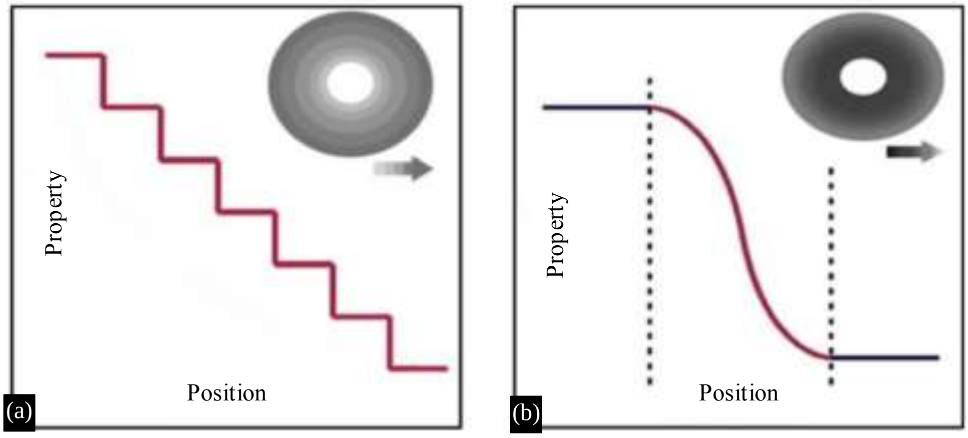

Figure 5. a) Discontinuous FGM b) Continuous FGM.

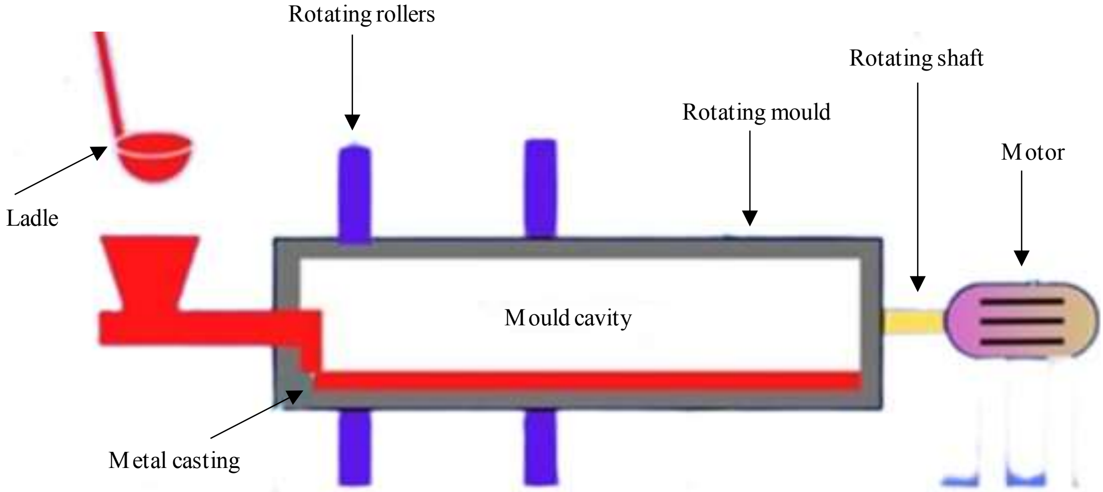

Figure 6. Schematic of centrifugal casting.

Thick/Bulk FGMs

The processes explained so far for producing thin films and coatings cannot be used to produce thick FGMs because these processes are energy intensive and are very slow. Thus, they are not suitable and economical for thick FGMs. The techniques used for producing thick FGMs are as follows:

Powder Metallurgy

Refer Figure 4 and Figure 5a). This method [14] produces a discontinuous FGM with discrete interfaces. The process involves the following major steps:

1. Crushing of parent material to powder form by a suitable method like ball milling etc.
2. Weighing and mixing of powder to achieve the desired density as demanded by the functional requirements of FGM
3. Removal of volatile contaminants like water vapor and gases from the powder
4. Ramming of the powder to achieve a homogeneous blend. This is followed by cold pressing of the blend that results in a green part which can easily be handled for further processing.
5. Preparation of various green blends with different powder densities to achieve spatial property distribution corresponding to the requirements of FGM.
6. All the green blends are stacked over one another and the final assembly is sintered to produce the desired FGM. Sintering is the process of heating the green parts in a furnace that causes some of the constituent materials of FGM to melt. Sintering temperature is usually below the highest melting point of the constituents. Atoms move through the microstructure during sintering thereby migrating from the area of higher chemical potential to the zone of lower potential. Six common mechanisms of sintering are (1) Surface diffusion, (2) Vapor transport, (3) Lattice diffusion from surface, (4) Lattice diffusion from grain boundary and, (5) Grain boundary diffusion

Centrifugal Casting

Refer Figure 5b) and Figure 6. This method produces a continuous FGM with no distinguishable or discrete interfaces [15,16]. It is the most versatile and economical technique to produce FGM. Centrifugal action is responsible for achieving the continuous variation of the composition and therefore the gradient in properties across the volume of the product. In other words, variation in centrifugal force due to the difference in density between molten metal and solid particles results in the desired material gradient. Many parameters are instrumental in controlling the gradient segregation such as matrix type, reinforcement size and type, weight fraction, rotational speed, pouring temperature, solidification rate, mold preheat etc. For instance, if the processing temperature is lower than the liquidus temperature of master alloy, the dispersed phase remains solid in the liquid matrix. This situation is same as that of ceramic-dispersed FGMs and this method is known as centrifugal solid-particle method. On the other hand, if the processing temperature is higher than the liquidus temperature of master alloy, the centrifugal force is directly applied during solidification of both the dispersed phase and the matrix. This solidification is named as centrifugal in-situ method.

Solid free form (SFF) method

Inability of powder metallurgy and centrifugal casting methods, discussed previously, to comply with geometric complexities and density limitations coupled with high energy consumption and environmental pollution has given rise to the need for alternative methods of the development of thick FGMs. Solid Free Form (SFF) technique [17] is one such method that pertains to additive manufacturing technology (AM). The shape of the product is generated by adding materials layer by layer over each other. Due to this reason, AM is also called as the layer manufacturing technology. Complex and complicated shaped parts can conveniently be produced in one go by AM. Raw material in powder form is commonly used in two sub processes namely powder bed fusion and directed energy deposition systems. The main difference between the two is that in the latter, instead of the powder bed, a coaxial powder or wire feeding system with a laser or electron beam is used on the substrate. Solid free form method involves the following steps:

1. Development of CAD model of the product by the use of softwares like AutoCAD, SolidWorks etc.
2. Transformation of CAD data to Standard Triangulation Language (STL) file
3. Slicing of STL file into two dimensional cross section profiles
4. Building of component layer by layer
5. Final removal and finishing

Laser based technology is mostly used in fabrication of FGM by SFF method. Laser based SFF processes include a) Laser cladding b) Selective laser sintering and c) Selective laser melting. Laser cladding and selective laser melting possess the capability of producing fully dense components.

Although SFF technology offers high manufacturing flexibility and sustainability, it produces poor surface finish of the final product thereby necessitating secondary finishing operations before the product can practically be pressed into service.

APPLICATIONS

The concept of FGM, as discussed earlier in Introduction, is applicable to numerous fields and is described as a systematic process of bringing all incompatible properties and functions such as thermal, strength, wear, and corrosion resistance, toughness etc. into a single part or a product. This possibility has considerably augmented the application potential of FGMs in many crucial sectors like aerospace, defense, energy, electronic, medical sectors etc. These applications are discussed one by one as follows:

Aerospace

A copper liner assembly in the liquid rocket combustion engine that requires considerable cooling during operation in an extreme hot gas environment [1] is shown in Figure 7. To fulfill the requirement of protection from very high temperatures, thin flat panels of copper platelets are fabricated by diffusion bonding. Internal channels are introduced in the panels for flow of liquid hydrogen to provide adequate cooling. Hot diffusion bonding is used to join the panels with each other. The whole liner assembly of copper is finally bonded to the structural support jacket of cast alloy steel, having high strength and reasonable toughness, resulting in a sturdy, two-material, bimetallic FGM configuration.

Platelets of same or different metals are laser cut to the designed channel configuration in the development of panels for liquid or gas flow devices [1]. Refer Figure 8. The etched channels are subsequently arranged properly, stacked, and diffusion bonded. The obtained product is finally machined to the required hardware configuration. Diffusion bonding has been successfully applied to a wide range of engineering materials such as stainless steel, copper, aluminum, titanium alloys and refractory materials. The process offers a significant cost reduction in the production of fluid or gas flow devices required in aerospace applications.

Titanium alloy due to its low density and reasonably good properties related to strength, workability and weldability is finding a lot of use in the aerospace industry. Also over the years, new intermetallic single phase titanium alloys namely Ti3Al and TiAl ( ) have been developed to withstand higher temperatures than the conventional titanium alloy. But these alloys are found to be brittle that has adversely affected their use. Properties of titanium alloys at ambient temperature are as follows [18]:

Ti Alloy
- *Yield strength*: 380-1150 MPa
- *% elongation:* 10-25
- *Fracture toughness*: 12-50
- *Creep limit*: 600 deg. C

Ti3Al Alloy (Alpha Phase)
- *Yield strength*: 700-990 MPa
- *% elongation*: 2-10
- *Fracture toughness*: 13-30
- *Creep limit*: 750 deg. C

TiAl alloy (Gamma Phase)
- *Yield strength*: 350-600 MPa
- *% elongation*: 1-4
- *Fracture toughness*: 12-35
- *Creep limit:* 750-950 deg. C

Titanium based metal-matrix composites represent one of the most significant developments in the field of advanced aerospace materials [1]. The key factors governing the introduction of these composites into aerospace field are their high performance with low weight characteristics, feasibility of mass production and reasonable cost in comparison with other metal matrix composites and functionally graded materials. A typical laminated composite is meant to take advantage of high temperature properties of Ti-22Al-25Nb alloy and excellent toughness of Ti-10V-5.5Fe-1.5Al alloy. This FGM is produced by hot pressing and rolling of the layers of individual alloys. Another useful metal matrix FGM is Ti-22Al-25Nb/SiC that is produced by foil-fibre method which involves laying up of foil and fibre in well defined arrangements followed by vacuum hot pressing. The possibilities of fabricating and tailor making of such laminates with desired properties in this manner are limitless.

Space vehicles flying at hyper-sonic speeds experience extremely high temperatures due to aerodynamic heating caused by friction between the vehicle surface and the atmosphere [19]. During re-entry of the vehicle, at altitudes between 50 km and 120 km above earth, velocity is greater than escape velocity that leads to rapid heating of the leading edge where the heat protection shield is located. Maximum temperature that develops during the process is of the order of 2500 deg. C. All structural components of the vehicle that experience the maximum exposure to heat such as the nose cone, the leading edge, the rudder and flapperons are made of non-metallic FGM's of carbon-carbon composite coupled with the use of adequate oxidation protection coatings.

FGM's also find utility in related aerospace equipment namely solar panels and solar cells. Gallium arsenide is emerging as the market leader for solar cells developed for extra-terrestrial applications.

The creep and impact properties of Ti3Al and TiAl alloys are therefore optimized by creating a two phase mixture alloy known as titanium (Alpha and Gamma) phase alloy. Besides application in airframe, this new alloy has potential for use in gas turbine engines and the valves of internal combustion engines.

Defense

Cooling of the sapphire window frame in the forebody of a missile is needed to protect the electronic sensors underneath from severe hypersonic flight environment [1]. Ref. Figure 9. Over heating of the sensor can blur or distort the target signal. Extremely small and complicated cooling channels of same or different metals are therefore diffusion bonded to fabricate the window frame of the forebody.

Stealthiness is a major requirement of the modern weapons. Parts of specific materials are used in a stealth missile to absorb the emitted electro-magnetic energy to minimize the waves reflecting into the direction of enemy radar receiver. Also, in many applications e.g. high velocity missiles, the materials are subjected to high thermo-mechanical stress. For these applications, the most promising material is ceramic-ceramic FGM reinforced with ceramic woven fabric.

FGMs demonstrate excellent ability to inhibit crack propagation [2]. This property makes them useful as penetration resistant materials that are meant for armor plates and bullet proof vests in defense applications. FGMs increase the level of ballistics protection, up to 10–20 folds vis-a-vis the conventional materials, and that too at reduced weights. FGM for such an application comprises an extremely hard surface layer to absorb the impact energy followed by a multi layered graded interface inside that is reinforced with a tough backing metallic material to neutralize the deformations post ballistic impact.

Energy

In order to increase the efficiency and performance of turbo engines, gas inlet temperatures in the high pressure zones must be increased and component cooling needs to be decreased. To withstand high heat environment in the process, ceramic thermal barrier coatings with low thermal conductivity applied on vulnerable parts like turbine blades play a key role. Ceramic coated parts are connected to the parent bodies by thin metallic bond coats which also protect the assembly from hot corrosion and oxidation.

The gas turbine disk is one of the highly stressed rotating parts in a gas turbine. It is simultaneously subjected to high temperature and high stresses. Cast and wrought Unimet 720 is reported to be bonded with Udimet 720 produced by powder metallurgy to fabricate the disk [1]. Although both of them are nickel based super alloys, their properties are different due to different microstructure. Unimet 720, being creep resistant due to coarse grain and less grain boundaries, is used in the rim of the gas turbine disk which is exposed to high temperature gases. Udimet 720, being a high strength alloy due to small grain size, is devoted to the hub where the operational stresses are high.

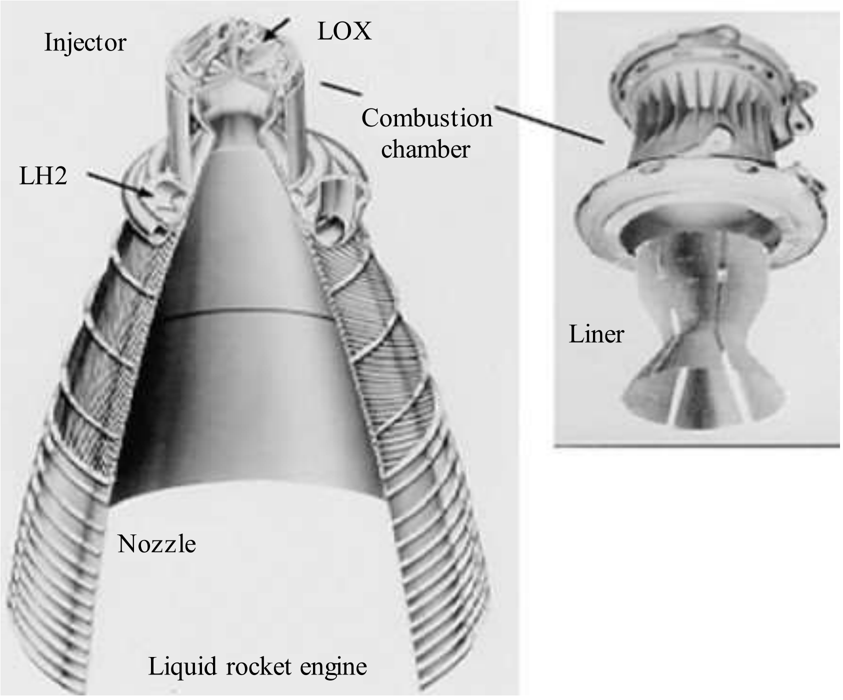

Figure 7. A copper liner assembly in rocket combustion engine.

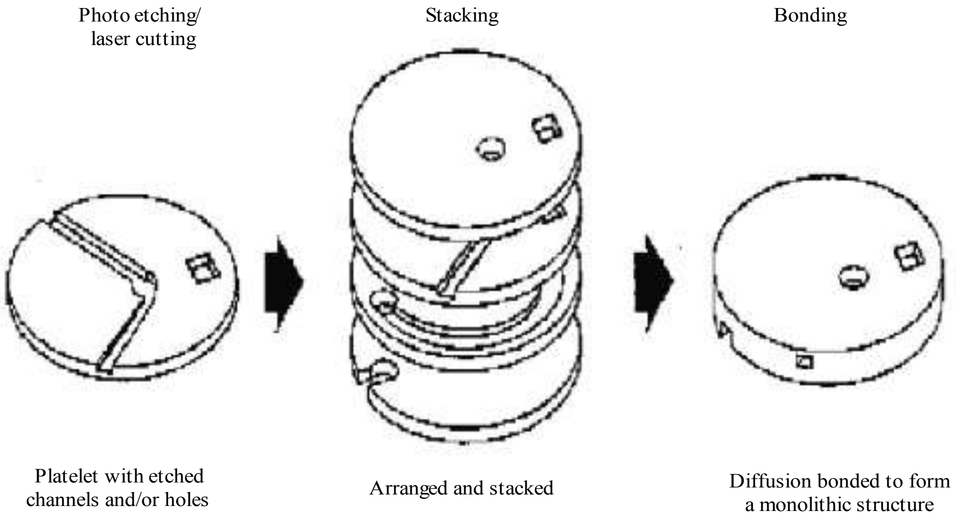

Figure 8. Platelet panels.

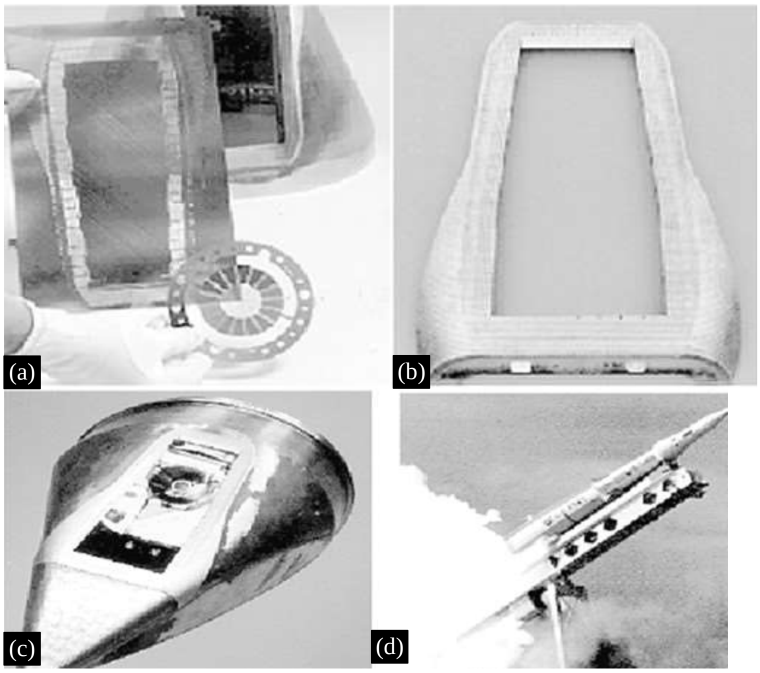

Figure 9. (a) to (d). Missile forebody. (a) etched platelets, (b), bonded and formed window frame (c) forebody, and (d)

Electronic

Recent trend has been towards the design and manufacture of piezoelectric transducers based on the concept of FGM [20]. In such a case, the conventional single piezoelectric material is replaced by a graded piezoelectric material and consequently some or all the properties namely elastic, piezoelectric, and dielectric may change along one specific direction in which several functions or laws of gradation can be used. The main advantages of using FGM are the drop in mechanical stress, improved stress redistribution, optimization of output displacement and increased bonding strength and fatigue life. In other applications of piezoelectric materials, the FGM concept allows reduction in intensity of reflected waves inside piezoelectric and ultrasonic transducers that in turn produces acoustic responses with smaller time waveform (larger bandwidth) than nano-graded piezoelectric transducers. These features are required to improve the axial resolution in medical imaging and are useful in non-destructive testing of products.

Shape Memory Alloys (SMA) [21] are smart materials known for super elasticity and shape memory effect. But the SMA layer is sensitive to temperature variations wherein changes in temperature can result in phase transformation that alters the stiffness and shape of SMA. Use of FGM concept in shape memory alloys finds applications in light weight shielding media that take advantage of the recoverability of potentially large strains offered by super elastic SMAs and of higher ratio of strength and stiffness to density with improved wear and fatigue resistance offered by FGM in comparison with the matrix material. Thus FGM-SMA results in a smart and active composite allowing light weight integrated temperature driven actuation and tunable stiffness.

FGM concepts [22] are tried in MEMS, sensors, actuators, photodetectors, and bio-medical devices. In these components, volume fraction of constituents changes continuously along a spatial material direction. Novel non-homogeneous and functionally graded Polycrystalline-SiGe layers are used in MEMS structures to control the thermal effects and pull in voltage and temperature that cause instability in response of micro-beam. FGMs have also been tried and tested in micro-switches, poly size micro-beams and micro-resonators.

Concept of FGM is implemented in optical fibers meant for high wave speed transmission. The FGM based optical fiber geometry analyzer is a new product that has been introduced to accurately measure the geometry of optical fibers including the core diameter, cladding diameter and other parameters. FGMs also find application in computer printed circuit boards (PCBs) and cellular phones.

Medical

FGMs can be designed and developed to imitate or mimic the natural material heterogeneity found in tissues of the body [23]. Bone is one such prominent example that has natural functional gradient in both radial and longitudinal directions. In the radial direction, bone has a denser outer structure that changes to a softer and more porous internal material. Longitudinally, the bone is composed of specifically aligned fibers that are meant to bear the necessary compressive and torsional forces to enable movement, sustain mechanical stresses and to protect the internal organs. FGMs have the capability to recreate the biological features of the bone. The methods that have been developed for generating gradients in bio-materials are light based methods, 3D printing, micro-fluidics, electro-spinning, freeze drying, solvent casting and particulate leaching.

Natural tooth has hard and wear-resistant outer surface with tough core inside. The advantages of using FGMs [24] as dental implants are the reduced stress effect on surrounding bones, improvement in bio-compatibility, prevention of thermo-mechanical failure at the bone-implant interface and achievement of bio-mechanical requirements of the tooth while maintaining the overall tooth health. Ceramic-metal is one of the ideal choices to create the functionally graded bio-material tooth. Ceramic coat on the exposed or outer surface of the tooth is conducive to high wear resistance whereas the metal core inside the tooth ensures strength with reasonable toughness.

CONCLUSION

Background of Functional Graded Materials (FGMs) is explained in a simple and comprehensible manner in the paper. The techniques for synthesis of thin and thick FGMs are reviewed. Thin FGM (coatings) are produced by vapor deposition processes while thick and bulk FGMs are manufactured by powder metallurgy, centrifugal casting and solid free form (SFF) methods. Application aspects of FGMs in diverse sectors namely aerospace, defense, energy, electronics, and medical are concisely touched upon.

It is inferred from the review that SFF, the additive manufacturing (AM) technique, appears to be the most promising method to undertake the fabrication of large scale and thick FGMs due to its high manufacturing flexibility and suitability for high production rate without any compromise on sustainability and environmental aspects. FGMs are also found to exhibit high utility potential in numerous fields other than those reviewed in the paper.

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