Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 1 (2024)

"Innovations in Functionally Graded Materials for Advanced Engineering Applications"

**Saurabh Kumar Sahu[1], Ramit Chugh[1], Devendra Sahu[1*],
Rajiv Khatri[2], Shubhrata Nagpal[3], Shiena Shekhar[3]**

[1] *Research Scholar, Department of Mechanical Engineering, University Teaching Department, CSVTU, Bhilai, Chhattisgarh, India.*

[2]*Professor, Department of Civil Engineering, Global Institute of Engineering & Management, Jabalpur, M.P., India.*

[3]*Professor, Department of Mechanical Engineering, Bhilai Institute of Technology, Durg, Chhattisgarh, India.*

Abstract: - Functionally graded materials (FGMs) merits remarkable attention in the various science and engineering societies over composite and laminates. It is a unique concept that can be used to form various types of material by altering their microstructure by help of a specific gradient. The overall properties of FGM acquire uniqueness and variation from the properties of materials it is made from. Many a technique have been developed to manufacture FGMs, some conventional and some advanced. Each technique has its own merit and demerits. The unique physical, manufacture and structural characteristics make FGMs application popular and desirable. The paper enumerates the details of FGM manufacturing process, with their pros and cons. It discusses the application of the FGMs in the fields of engineering and industry on the basis their parent materials. This paper would serve as a guiding catalogue for researchers, designers and manufacture to comprehend the FGM production and application.

Keywords*: Functionally graded materials, Composite, Laminates.*

1. Introduction

Material and science play an essential role in the social and cultural development of a society. The usage of the material in a scientific manner followed by its conversion and arrangement in a specific way, results in different types of alloys, composites, etc. [1] As the name suggests, Functionally Graded Materials are two or more material brought together in a various specific ways that the material properties gradually starts varying on one or all directions. The material properties also gradually vary either fundamentally or functionally. For instances, when metal and ceramics combine, metal provides magnificent fracture strength and ceramic gives thermal resistivity [2, 3].

FGMs offers high durability and it outreaches its performance of the composite materials when compared to the normal reinforced composites; reason being the real convergence avoiding the sharp regions of the composite. The continuous gradient is achieved by altering the density distribution of the constituent over matrix [4].

The assimilation of different materials results in a mixture also known as composite that aims to provide a number advanced and useful properties, namely:

1. The thermal stress magnitude at critical location is controllable.
2. The Material Properties of the FGMs are gradually distributed.
3. Thermal Stress can be reduced by approximately 30% in FGMs, which in turn prevents the destruction of the interface.
4. Surface de-lamination is reduced as well.

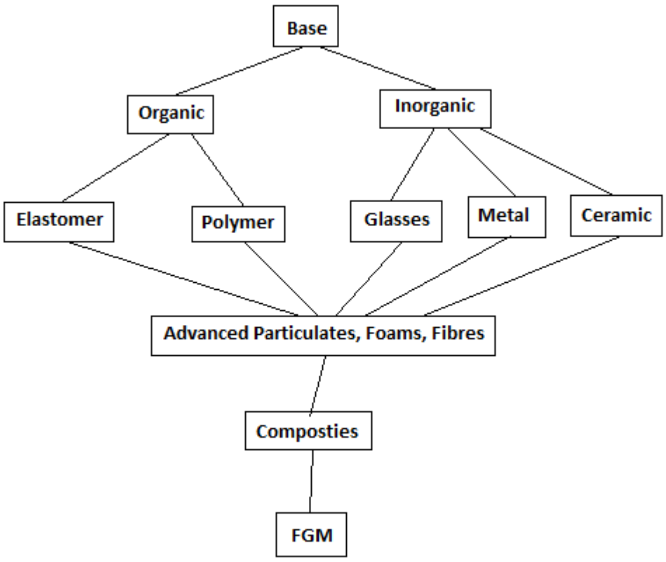

Figure1. Representation of Material Hierarchy

The concept of FGMs can, very well, be said to have been derived from the Nature's concept of structures, such as human skin, bamboo trees, etc. The aforementioned flow chart figure 1 [5] depicts the evaluation periods and the journey of FGMs thus far. The process of fabrication of FGMs is about mixing the two discreet materials phase, for instance, any specific mixture of metal and ceramic. Generally, the precise data about the distribution of the constituent particles and the shape of the particles are unavailable. Hence the effective material properties like shear moduli, elasticity, moduli, density, etc; of the graded composites have to been analyzed on the basis of the approximation of the shape of dispersed phase and volume fraction. FGMs may be a heterogenous mixture, but its material properties are considered homogenous for the sake of conduction or comprehension.

1.1 History of FGMs

FGMs are produced by engineering techniques and many an engineering concepts are developed under its realms. The concept of this, however, can be found in nature's lap itself. For example, the bones and skin combined together gives phenomenally graded properties like toughness, elasticity and tactile strength. In the field of engineering, metals, isotropic materials, chemicals, alloys of copper, steel, titanium, magnesium, aluminum, etc; and also alumina, zirconia, silicon-carbide and tungsten-carbide, that are structural ceramics, (fig.2) depicts gradual development of FGMs.

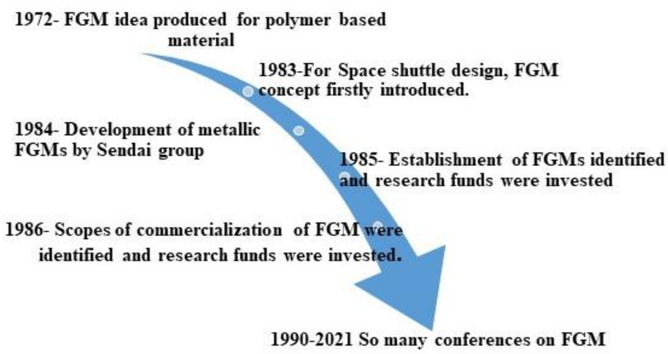

Figure 2. Development of FGMs

1.2 Material Combination and application:

Earlier FGMs were covered under conventional composite materials based on the constituents of combination materials. [6] Material combination can be, ceramic-polymer , ceramic-ceramic ,metal-ceramic, or, metal-metal [7] as shown in the fig (2). FGMs are either used or found in extreme conditions or areas of highly sensitive applied usage. For instance, heat transfers and elements that can resist heat are found in nuclear reactors, space crafts, and biomedical plants. In FGMs, various combination of generally incompatible functions to form new materials to be used in fields like aerospace, nuclear reactors, turbine blades, defense, sports equipment etc. Researchers so far have been concentrated on experimentation, physical characterization as well as the micro structural characteristics of the FGMs. However, mathematical modeling and numerical stimulation of these structures have not been the priority as they have complex micro structural arrangement and highly intricate structures.

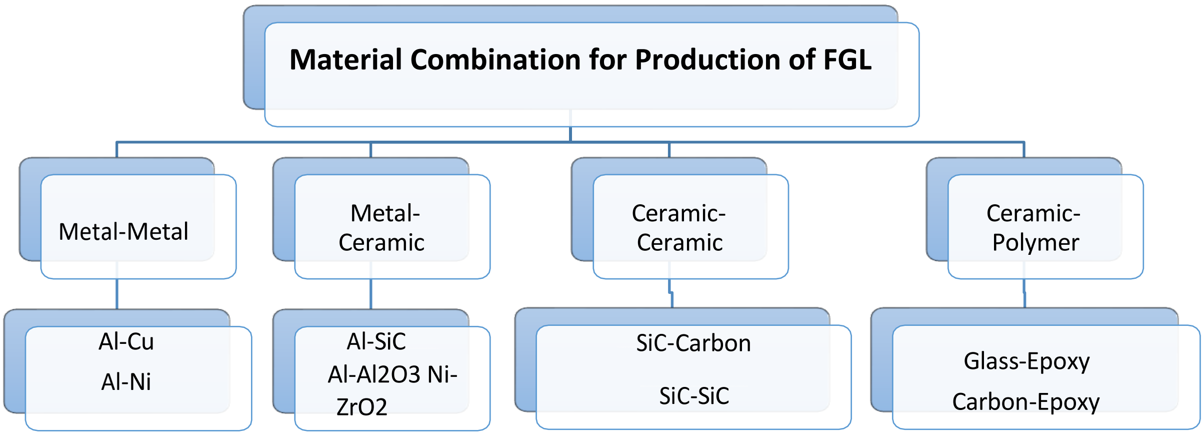

Figure3. Material combination for production of FGM

FGM offers many advantages over composites and laminates. FGLs allows the researches to control the magnitude of normal and shear stress at critical locations whereas the composites delaminate very easily. Material Property Distribution in FGL occurs very gradually, whereas laminates fractures abruptly or suffers a deformation. A FGL allows the reduction of thermal stress by 30% which is impossible in either laminate or composites. Figure 4 shows these differences quite clearly.

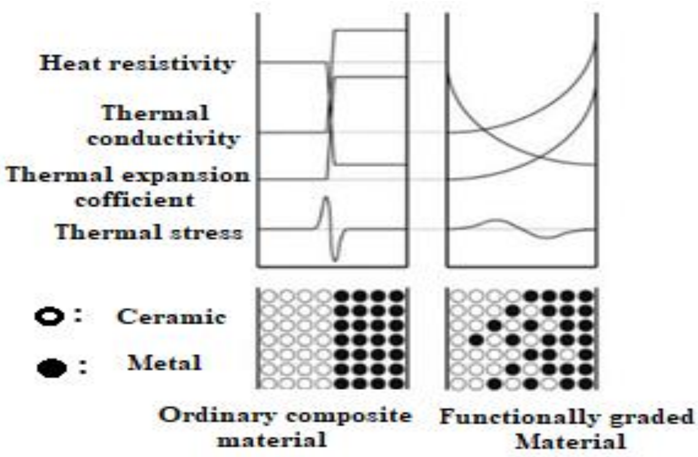

Figure 4. Material Structure and properties of composite and FG

2. Manufacturing Techniques

Manufacturing and Fabrication Techniques are two very highly sophisticated methods in the FGMs' research and development. The most effective production technology in FGMS goes through various stages of evolutions from deposition and casting depending upon its suitability and feasibility of the method, which is decided by the constituent materials' composition, component geometry and functionality [8, 9].

FGM processing methods are often considered by their operating principles, advantages and disadvantages. A number of renowned techniques and fabrication routes are used in FGMs production covering different aspects of it mechanical and chemical characteristics. There are various process of FGM production like, chemical and physical vapor deposition (CVD/PVD), centrifugal casting, powder metallurgy, centrifugal casting, plasma spraying, infiltration method etc. Many scholars have worked upon the subject and outlined different method of production and described in detail their scopes and limitation and few also talked about their technicality and research trends [11].

2.1 Gas phase methods

The Gas phase (vapor deposition) method uses productive process to produce graded layer that is very thin of approximately nm to sub-nm.

2.1.1 Vapour deposition methods

Vapour deposition method talks about a process in which the vapour cycle procedure is used and materials are compressed and condensed into solid [12]. It make coatings which dictates the underlying features of substrates of the graded layer like mechanical wear, tear, corrosion etc. [13] Two different types of vapour deposition methods are: Physical vapour deposition (PVD) and chemical vapour deposition (CVD)

2.1.2 Physical vapour deposition method

In this method, condensed solid state material transforms into vapour state and in turn forms a thin condensed and coated film. PVD is used in making of substantially a thin layer of environmental-friendly coating material that is very unique to the PVD method. [15]

PVD is the most effective vacuum deposition method to develop thin coating/films. There are various PVD methods that are applicable in manufacturing of a smooth as well as thin films that carries graded properties like; sputter deposition ,electron beam deposition, sublimation sandwich method, close-space sublimation, pulsed laser deposition, , cathodic arc deposition, pulsed electron deposition, evaporative deposition and [16]. The coatings graded by PVD show extraordinary resistance to ear and tear and improved mechanical properties. PVD method is used in fields like aerospace and automotive.

2.1.3 Chemical vapour deposition method

Chemical vapour deposition is the method used in manufacturing solid materials of supreme quality via vacuum deposition system. The smooth film produced by CVD possesses properties like; ultrahigh vacuum, atmospheric pressure, laser-assisted, low pressure, electron assisted, hot filament and direct liquid injection [17]. CVD method is widely used in semiconductor production and has excellent wear and tear resistance and corrosion resistance accompanied with improved mechanical properties [18, 19].

FGM manufactured using SiC coating via CVD process demonstrates increased thermal fatigues, where deposition occurred at 1673-1773K temperature and a maximum gas pressure of 1.3kPa [20]. The FG composites developed by CVD can be effectively used as thermal barrier. The decomposition of SiC layers to understand the microstructure behavior has been the center of many research works [21, 22]. WC/Co/diamond nano composites on FGMs by infiltration of chemical vapour are studied in order to enhance the mechanical and physical properties.

In accordance with the microstructural behavioral study, these formed graded layer are very impertinent in enhancing the thermal properties of FG coatings and prove to be useful in the process which requires exposure to extreme high temperature of the surface. Films produced by FG TiO_2 and Ti–O–Si with the help of CVD, increases the thermal resistance of the smooth layering up to 1000 degree centigrade.

2.2 Electro deposition methods

FGMs are produced by electrophoretic deposition (EPD) method- the simple method used in gradations production based on electrophoresis principle [23]. Under chemical treatment and electrolysis, different particles that are active, they chemically react and sits on the hot filament surface substrate and deposit on the surface [24]. The combination of solvent and additives gets the particles charged. These charged particles are passed through controlled electric field, in turn these particles from expanded form of accumulated deposition at the electrode. The arrangement and the entire method of EPD is very simple and easy to apply in various set ups. The process equipment is easily operable, accurate, and low costing. It is used in making of thin foil like FGM body only. The electrophoretic deposition process is of great significance in variety of areas like; laminates, Infiltration and textured materials, coatings (nm-mm), graded materials [25].Alloys and composites like Al_2O_3-YSZ produced by EPD are studied to understand their particle distribution and mechanical properties as FGM

[26]. It is observed that particle distribution effect and controls such mechanical and physical properties. The study outlined many premises and it points out that when sintering temperature is adjusted to 1400 ◦C, the graded characteristics varies by using different alloy oxide layering. Similarly, when titanium dioxide (TiO2) nanocomposite gradient coatings (0, 10 and 20 wt% of TiO2) on Ti–6Al–4V substrate synthesis by the use of EPD, it has been observed that there is vast change in the bending properties and its ability to withstand resistance, these two mechanical properties have been supremely enhanced and improved. The TiO2 nanoparticles reduces the porosity content of the graded layer by improving the wettability of the substrate and grade layer [27].

2.3 Thermal Spray Method

Thermal Spray Method is used in protecting materials against the corrosive action, thermal damages and electrical isolation. In this manufacturing process, raw material for the coating will be first melted which can be effectively done by the use of heat and then it will be sprayed on any particular base material with the help of gas treatment. ZrO2/NiCoCrAlY is used to coat materials by the effective use of thermal spray which will impact the thermal characteristics of the materials [28]. By increasing ZrO2 coating, the thermal property of FG composite is also increased. Another study highlights that increased weight ration of the FGMs, the residual stress is decreased [29, 30].

2.4 Solid State Method

Solid state methods involves various techniques and process like; additive manufacturing, powder metallurgy and friction stir additive manufacturing process, and are preferred means and techniques of producing varied materials. These processes help in forming irregular gradient but these grades are controlled even at higher degree which makes them useful to several industrial applications [31].

2.4.1 Powder metallurgy Method

Powder metallurgy method involves the technique that blends the fine powdered material and then by pressing and compacting it to develop different forms and then applying heat to effectively bond the material. It consists of:

- Powder manufacture
- Powder blending
- Compacting
- Sintering.

Powder forging, hot iso-static pressing, metal injection molding, electric current assisted sintering, additive manufacturing are some of the techniques developed over the period of time. Powder metallurgy has evolved over the years and then by the evolution of stacking techniques like powder stacking, sequential slip casting, vibration stacking process, wet filtration, centrifugal process, etc. it has been observed the FGM properties are altered via temperature, time, and pressure [32,33]. In Powder metallurgy, controlled particle distribution is very important otherwise it causes component failure [34]. Hot pressing is used to balance the imbalance sintering during powder metallurgy.[35]. Controlled particle distribution is very important otherwise it cause component failure. [34]. Two type layer variation of FGCs, in which aluminum was reinforced and four layer (0%, 3%, 7%, 10%) and five layer (10%, 20%, 30%, 40%, 50%) volumetric composition variation is constructed to achieve better mechanical property [36]. Powder metallurgy also reduces crack deflection and increases fatigue resistance property [37]. Study on Zirconia shows a higher resistance to fractures, along with enhanced binding strength and high durability which is very widely used in biomedical engineering.

2.4.2 Plasma sintering

Plasma Sintering (SPS) is an advanced version of conventional sintering process used in manufacturing of supreme quality of FGMs. E When put under the electric mode, the migration of ion starts taking place because of an active stimulation given by electric mode and it enhances process of diffusion [38]. The discharged ions elevate the localized high temperatures that supports in melting the composition which helps to fill particle gaps [39]. The diffusion mechanics of sintering is directly affected by Dwell duration, heating rate and any change in the pressure or the temperature [40]. When sintered under 100 MPa, Aluminum matrix reinforced with zirconia exhibits superior hardness, and fracture toughness as the zirconia stops aluminum grain growth [41].

2.4.3 Additive Manufacturing Methods

Additive manufacturing methods involves creation of an object following the phased building of one layer at a time. It uses layer-by-layer mechanism in metal production, instead of using simple molds. Fields like architecture, medical, robots, space, energy, etc uses this AM method for FGM production [42]. Different product designs and technology are used in this method for enhanced quality, composition and performance. These methods vary fundamentally depending upon different design and shape along with graded properties for the same materials [43].

2.4.3.1 Laser-based methods

Laser-based methods, such as Selective laser sintering/melting (SLS/SLM) [44] and laser engineered net shaping (LENS) [45] are used to deal with powder material [46]. When the laser energy produces powder, it creates 3-D CAD on component geometry from which 2D layering part is extracted [47]. Under the laser energy the particles get sintered/fused together into a solid. SLM is a manufacturing process that is powder bed-based, incapable of doing real time composition control. This makes it incapable of fabricating FGMs with graded chemical compositions.

Laser metal deposition (LMD) is a direct deposition technology of metal used in producing FGMs that carries gradient which is discrete. In this method, both the energy and the specific material are integrated into DED process simultaneously and the energy source is utilized at the decomposition site to heat the material directly, Stereo litho graphic process.

2.4.3.2 Material Jetting Process

In material jetting process, the material is delivered from the base and model is constructed part by part [48]. The method is restricted to wax and polymers only and is used in medical field applications [49, 50]. According to different researches, FG TiC/Steel parts are acquired after free filtration of the graded properties in the materials like ferrite and pearlite microstructure.

2.4.3.3 Hybrid Methods with Additive Manufacturing

Arc welding method in additive manufacturing has been developed by researches to reduce the production time and cost of FGM production [51]. It helps produce FGC at low cost [52]. Other method introduced in AM are tungsten inert gas (TIG), plasma transferred arc (PTA), Metal inert gas (MIG) and plasma arc welding (PAW) [53]. The method uses wire feed material hence it is also called wire and arc additive manufacturing (WAAM) [54]. The wire acts as powder and the arc acts as power source, and is very useful in developing micro structural bonding in FGM. The FGM have mechanical property at every direction and WAAM aids it in doing the same [55]. It is observed that gas and arc welding techniques improves the mechanical properties of the material. Another AM technique is Friction Stir Additive manufacturing (FSAM) which results in more manageable FGMs and Friction stir welding (FSW) likewise based on same principle of solid-state welding. [56].

3 Liquid state methods

The liquid state concept results in FGMs having gradient features using techniques like centrifugal techniques slip casting, infiltration and tape casting [57]. They improve material quality and are more affordable [58].

3.1 Centrifugal force methods

Centrifugal force is detrimental in FGMs production, and in combination with a continuous graded with certain properties, it becomes highly useful in various industrial application [59]. Due to mould rotation, the centrifugal forces result in unequal distribution of ingredients [60].

3.1.1 Centrifugal casting method

Centrifugal casting is a process that gives effective shaping and feeding by the application of liquid state approach. It considers process variable like rotating speed, feed speed, mould preheat, and coating and works on the principle of unequal distribution of base material densities.

3.1.2 Centrifugal slurry pouring method

Researcher combined the powder metallurgy process with centrifuge method to create the method of centrifugal slurry pouring. In this process, two different types of particles of different densities are placed in revolving mould that has suspended liquid. The variation in centrifugal course caused by different masses of the particles result in continual modifications of characteristics [62].

3.1.3 Centrifugal pressurization methods

In centrifugal pressurization methods, necessary gradient is created before using the centrifugal force. The figure 5 depicts a simple pressure being applied in centrifuge method. Three different types of pressurization techniques are the centrifugal sintered casting technique, the mixed centrifugal powder technique and the reactive centrifugal casting technique [63].

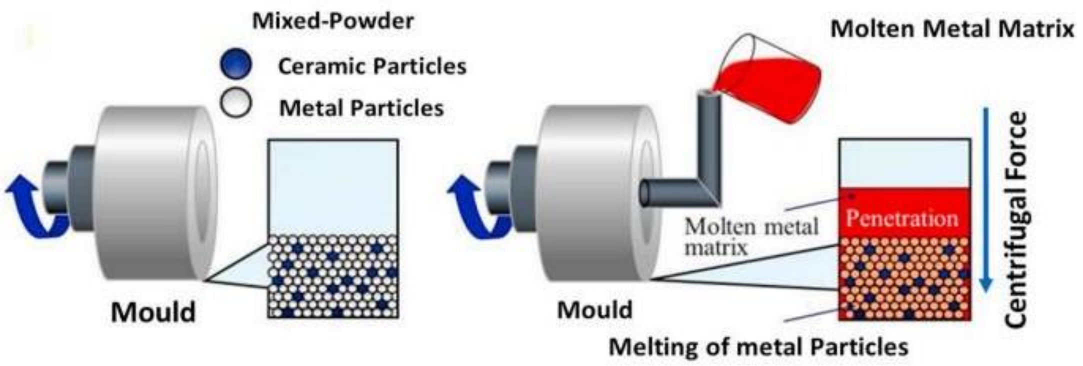

Fig.5.Concept of centrifugal pressurization methods during FGMs production [63]

3.2 Slip Casting Method

Slip casting are made by suspending granules into matrix made of liquid that has fine grain size. The surface is drained from the slip by capillary action into a porous mould. A clay slip coating covers the mould's interior walls. Once the thickness of the wall of desired size is obtained, then the remaining fluid is freely drained out from the casting mould. Once it has dried, the cast is taken out of the mould. Intricate shapes and creation of continuous grades are few of the advantages of this method [64].

3.3 Tape casting method

Tape casting method produces FGMs with gradient layers from 50 to 1000m. it began with a traditional process and developed to a high level of contemporary ceramic intricacy [65]. It is used to create multi-layer particles and embedded system for substrates the multi-layer condensers. A typical method of tape casting is doctor blading [66].

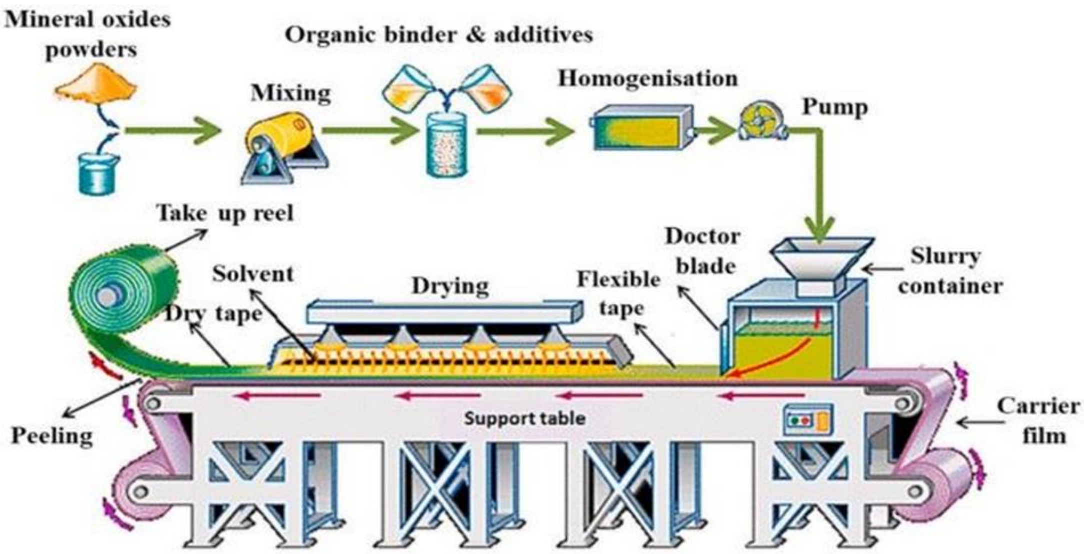

Fig.6 .Schematic illustration of tape casting process

3.4 Infiltration method

A molten matrices space that fills and occupies the gap that exist in between the dispersed stage and the prepared dispersed phase (ceramic particles) is used to produce FGMs by an infiltration procedure in a liquid state [67]. As demonstrated in Fig.6, infiltration with metal at liquid state is accomplished without pressure (capillary action) or under pressure (gaseous or mechanical action).

3.5 Langmuir-Blodgett method

In this method, homogenous film materials can precisely be deposited up to a single molecule layer thickness [68].ThefilmscreatedusingtheLBtechniquecanbeappliedtoelectronicsaslayers that are active or insulators that are passive.

4. Applications

1. **Aerospace applications:** The aircraft engine parts and the space shuttle requires a heat resistance surface, the functionally graded materials with properties of high resistance against temperature, thermal shocks and thermal fatigue become ideal material. The chamber wall of spacecraft engine combustion requires material with effective heat insulation properties as the wall needs to withstand the thermal erosion of 2000k. The aircraft engines also require high precision, resistant from the corrosion and lesser coefficient of thermal expansion which is less dense but hard enough to wear high resistance. It is, therefore, determined that FGMs has enhanced physical and chemical properties that normal used materials are inefficient to acquire.[69- 70]
2. **Biomedical applications**: In the biomedical area the presence of gradient material is quite rampant and usual in nature as it is most likely to be found in layered components like, animal skeleton, layered human skin, layered shell of animals etc. The FMG help in making artificial joints, heart, teeth, bones, artificial prosthesis. FGM is also desirable because of its property biocompatibility which helps in self-healing and regaining regenerative power.[71,72]
3. **Defense applications/Military services**: Military service FMG has exceptional capacity of penetration-resistance and crack resistance along with being light weighted. These features make it ideal for making jackets that are bullet proof and amour shields plates. Most of the FGMs produced by the method of CVD [302] while Al_2O_3–ZrO_2 FGMs produced by powder metallurgy have shown brilliant results with nuclear reactor component, heavy performance bearing and cutting tools. They additionally provide hardness, thermal conductivity and chemical resistance to components.[73]
4. **Energy applications**: Energy Sector 23 The high heat resistance and thermal shock property of FGM makes it most suitable material to be used in power generation system. It prevents any cracks and

damages to the emitter that has working environment of1860 degrees Celsius and it is very effective in reduction of stress formed by thermal energy.

5. **Opto-electronics**: In electric sliding applications, Al6091/6092 FGCs reinforced with 40–44%SiC are most desirable materials as electrical conductivity and tribology resistance is applied on same material. FGM manufacturing techniques makes complex process like laser decomposition easier and effective.[74]
6. **Marine Application**: Al/Steel FGMs are most preferred in manufacturing of components like deep water riser, pipe system, dive cylinders etc. because of its ability of mechanical strength and resistance to corrosion. WAAM technique makes it possible for suitable materials to withstand corrosive marine environment for instance, the use of duplex stainless steel alloy that is resistive to corrosion along with normal steel and carbon .[75]
7. **Commercial applications**: The functionally graded material has wide commercial user aging from laptop covers, elevators to musical instruments. Tungsten-carbide or Titanium carbon nitride when reinforced with cobalt makes instruments of high strength like, turning tools, drills, milling cutters etc.[76]
8. **Optical field**: The glass is hard but brittle in normal conditions. However, its external environment is not always same and it is this uncertainty that impacts its life and work. Functionally graded material when added with rare earth element and material that has different refractive indices can alter the optical properties of glass with respect to its corresponding environment. Such optical glasses are highly desirable for making materials of glass lasers, optical fiber lenses, discolored glass and anti-reflection films.
9. **Electromagnetic Field**: Functionally graded material has piezoelectric gradient function in the field of electromagnetic as it bears a gradient structure. This enables it in manufacturing of various items like, ceramic filters, ultrasonic oscillators, shield material of electromagnetic properties etc. The use of FMG can also help to enhance the performance by substantial reduction in size as well as the mass of the material.
10. **Nuclear Energy Field:** The evolution of next generation nuclear industry depends highly on FGM that can give high strength and heat resistance along with low corrosive tendency to the infrastructure. The reactors that involve fusion of nuclear materials needs relaxation effect caused due to creation of thermal stress which is possible only by the use of functionally graded materials. [77].

Conclusion:

FGMs are one among the most evolved and emerging engineering technologies which can be used in wide range of fields like, engineering, defense, biomedical, and petro-chemical etc. The paper highlights the importance of FMGs and discusses the manufacturing methods of it. The paper presents list of challenges and opportunities in this field which will provide slight direction to the researcher in the field. This critical review paper will help academician and researchers to have basic concept of the FGMs and its process of manufacture and the challenges associated with it along with the most effective method to get smooth graded properties. It also presents wide range of suggestions for new scholars in the field. This will help in saving time and human effort to understand the complexities of functionally graded materials, thereby, helping researchers to have proper understanding and possibilities outlined in the paper.

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