Synthesis Techniques of Functionally Graded Materials - A Review

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Abstract: Functionally Graded materials (FGMs) are the combination of two or more material which changing composition, micro-structure and porosity across the volume of the material, it is used to enhance the mechanical, thermal and electrical properties. The properties of FGM are unique and different from another composite material. In FGMs the property of material are not uniform across the material, its property varies point to point. In the modern era, these materials are at the forefront of material research. We can do many processing techniques to make FGMs. There are many types of processing techniques which has own characteristics according to the production of the gradation phenomena. The paper exhibit the review study on fabrication methods of FGMs synthesis in the last ten years. There are wide ranges of application of FGMs, which are facing innovations. Some applications of functionally graded material have also been presented in this paper. It has been concluded that the centrifugal casting technique is the cheapest and easy to handle.

Keywords: FGMs, Composite Material, Centrifugal Casting.

1. INTRODUCTION

There are so many materials available in the earth crust, and their properties exhibit various applications. Nowadays, due to technological advancements, it is necessary to develop hybrid mixing materials, so that the characteristics of materials enhanced. Functionally Graded Materials (FGMs) are the composition of two or more materials which have been applied to produce components with superior physical properties of metals, ceramics, and organic composites [1]. FGMs are unique concepts, which were first attempted by the Japanese in 1984 in the Sendai region of Japan. They have used this technique for specific intention to increase a thermal barrier in aerospace [2]. It is a homogeneous material, which is changing the composition, microstructure and porosity of material across the volume. In FGM the property of material are not uniform across the volume of material, its property varies point to point. Material variation can modify according to the design and the desired functionality to the application's requirement. [3].

Initially, some methods such as chemical vapor deposition / physical vapor deposition (CVD / PVD), powder metallurgy were available, but now there are many fabrication techniques available for making FGM. However, in 1995, Kawasaki et al. gave up on a comprehensive review of powder metallurgy based fabrication technique, which are comfortable, cheaper and fewer steps gradients are required [4]. In the last decades, many fabrication techniques were developed. Through all these techniques, we can reproduce the FGM in less time and in a better way [5]. All fabrication methods are classified into four categories such as powder technology methods, in-situ processing methods, deposition methods and rapid prototyping process [6].

The manufacturing process of FGM is divided into two steps. The initial stage, called gradation is typically built-up of homogeneous structure and final step, which is called consolidation, transforms the structure into a bulk material. Further gradation process can be classified into three processes constitutive, homogenizing and segregating processes. Continuous and stepwise are the types of Graded structure. In the continuous type graded structure, changes in composition and microstructure are consistent with position and in stepwise graded structure the changes in the microstructure change in the manner of interfaces between discrete layers. Powder metallurgical processed FGMs follows the stepwise graded structure and centrifugal casting follows a continuous graded structure [7].

In this review, has been focused on some significant manufacturing techniques so far. Also, some applications of FGMs are presented.

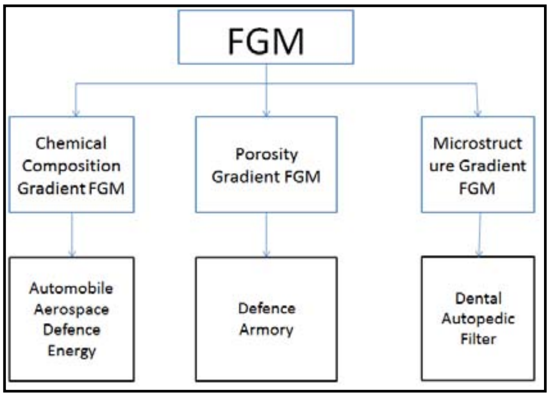

Figure 1 : Flow diagram of an application of FGM [8]

2. FABRICATION TECHNIQUES OF FUNCTIONALLY GRADED MATERIAL

In the present day, there are more than forty fabrication techniques are available for fabrication of FGM. In the beginning, these fabrication techniques have been classified according to material phases such as solid, liquid and gas [9]. In recent days rapidly uses of these techniques we cannot classify old way because today more than one phases are involved. This paper summarizes various processing techniques for the production of FGM.

2.1 Powder metallurgy (P/M) based method

Regarding powder metallurgy, we can say that this is the most simple, fast, cheap and elegant technique for manufacturing FGM. This technique is capable of both types continuous and stepwise classified structure [10], and it gives rise to a stepwise structure. It is capable of producing medium and large layer thickness (medium layer thickness - 100 to 1000 µm, large layer thickness - 1mm) [11]. In FGM metal-ceramic and glass-ceramic can be fabricated by powder metallurgy [12]. In the powder metallurgy process firstly chooses an appropriate material as per design. Then selected material is formed in powder form. Powder form material is stacking layer by layer to form at low pressure. After formation of the layer, these are compressed by the hydraulic press at room temperature. A pressure less sintering process is applied to the compressed material. After the sintering process, a functionally graded material is formed. A Aluminum/Steel Functionally Graded Material by PM processing, in which 100% steel was replaced by one side, and another side was 100% aluminium. Steel/aluminium FGM fabricated by PM, should not exceed its sintering temperature above 600°C. Due to the increase in the number of layers in steel/aluminum, FGM reduces the sharp interface between the layers. [13]. Functionally Graded Material of Al-SiC Composites fabricated by PM processing technique. The results show that with the increase in the composition of SiC, there is an increase in hardness, impact strength and normalized displacement. The author has obtained the best results on the weight of 25% of 320 grit size SiC particles. Along with that, the author has obtained maximum hardness=44.8 BHN and maximum fracture strength=37 N-m. FGM exhibited the ability to take some load after the initial crack propagation phase [14]. Powder metallurgy fabricated functionally graded lithium ferrite and barium ferrite specimens show that the constant dielectric increases with the increasing number of layer and magnetic properties were also increased with the increasing the number of the layer due to the increase in the average grain size [15].

2.1 Slip Casting

Slip casting is a powder-based shape method, which is used for mass production. Traditionally the ceramic industry has been used this process. This technique is suited for complex shapes especially for relief decoration and thin walls. It is capable of producing intricate shapes not obtainable by pressing. Slip Casting is relatively inexpensive since no expensive tooling or equipment is needed.

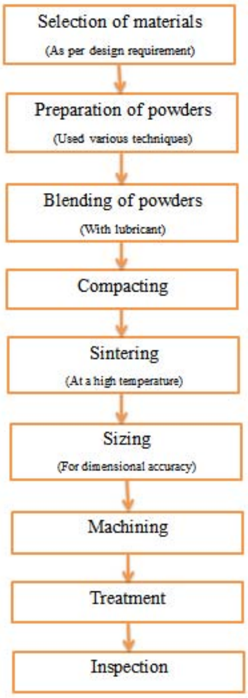

Figure 2 : Processing steps of powder metallurgy [16]

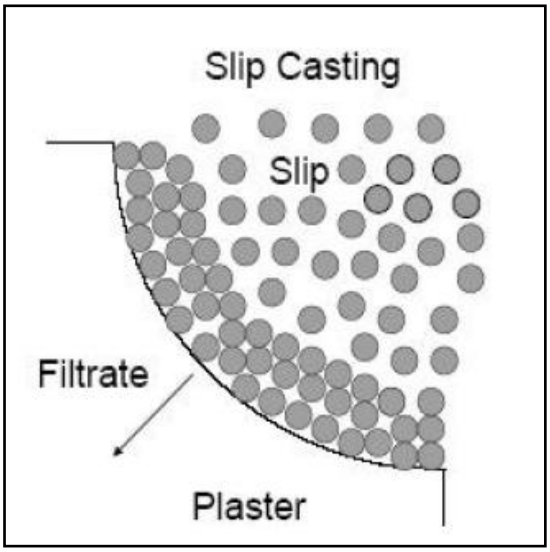

Figure 3 : Slip phenomena in Slip Casting [17]

The Al_2O_3-W (tungsten Powder) FGM was fabricated by using the slip-casting. There was an additional improvement in the scattering of Al_2O_3 particles and W particles in aqueous solution demonstrated a continuously graded composition from Al_2O_3 to W [18]. A sequential slip casting method has designed with microarchitecture to make laminated ceramics relatively easy, in which an accurate control of each layer's structure and thickness can be obtained [19]. A titanium foam to stabilised emulsions was fabricated by slip casting method [20]. Step-graded ceramic composite samples were also fabricated by ZTA core with the use of sequential slip-casting [21].

Table1 : Material combination via Powder Metallurgy

S. No.	Author	Material combination of FGM	Range of Content Variation	The range of hardness variation	Sintering conditions	Year
1	C.-Y. Lin et al.	SiCp/Al 2124	Al 2124 and Al 2124/40 vol.-% SiC	143 HV to 163 HV	Not reported	1999
2	Mahmoud M. Nemat-Alla et al.	Aluminum/ steel	Steel and aluminium (100%)	Not reported	800˚C to 600˚C for 2 hr	2011
3	A. Shahrjerdi et al.	Titanium (Ti) and Hydroxyapatite (HA)	At the Topside 100% HA & at the Bottom side 100% Ti	285 HV to 450 HV	1200°C during 8 h	2011
4	A. B. Sanuddin et al.	Al/Al_2O_3	At the Inner disc 90% Al & 10% Al_2O_3 and at the outer disc 70% Al & 30% Al_2O_3	Not reported	640°C for 2 hr	2012
5	R Kumar and Dr C N Chandrappa	Al-Mg-SiC	SiC up to 10 vol. %	Maximum hardness=44.8 BHN	600˚C for 3 hours	2014
6	Akram R. Jabur et al.	LiM and BaM	At Top 100% BaM & at the Bottom 100% LiM	Not reported	1100˚C for 2 hr	2017

2.3 Centrifugal Casting

The centrifugal casting or rot casting technique which is used to cast thin-walled cylinders also used to cast metal, glass and concrete. It gives good quality results, which is why it is used more and more. The centrifugal casting technique is the mainly used to manufacture stock materials in standard size. Typical materials such as iron, steel, stainless steel, glass, and aluminium alloy (copper and nickel) are cast by this process. Most typical parts like pipes, flywheels, cylinder liners and other parts which are axis-symmetric are made by this process. The process deliver sound casting of very high content, and used for many applications like jet engine compressor cases, petrochemical furnace tubes, many military products and other high reliability applications. The functionally graded metal matrix composites made of pure aluminum reinforced with SiCp has been fabricated through horizontal centrifugal casting technique [22].

Author had used Al-SiC FGM to investigate solidification process in centrifugal casting in cylindrical mold [23]. The influence of the vertical centrifugal casting technique on the mechanical and metallurgical properties of a hyper-eutectic Al–18Si alloy was studied [24]. Stochastic model have been developed for the prediction of solidification grain structures in centrifugal casting [25]. Centrifugal speed of centrifuged Al alloy and Al–SiCp FGMMC's, in which ball-on-ring tests were studied using high-carbon chromium steel (AISI52100) as counter body [26].

Centrifugal casting is also used to produce the structural component of Al-Si alloys and functionally graded aluminium matrix composite components [27, 28].

2.4 Laser Cladding

Laser cladding technique is considered to be the relevant technique in all laser-supported technologies, which is also known as commercial hard facing method [29]. The Laser cladding technique can be classified into two categories – (1) Pre-placed powder Technique and (2) Blown powder Technique. Author had fabricated Al-SiC FGM composite with laser cladding technique with laser on nickel alloy substrate and produced a functionally gradient region on the substrate with many lasers processed tracks [30]. Laser cladding Technique is also used to fabricate AISI 316 L and cobalt-based super alloy powders, obtaining homogeneous and stable powder flows. Functionally graded three-dimensional structures were produced with this technique, changing the mixture of precursor materials during the processing time.

Table 2 : Material combinations via Slip Casting Method

S. No.	Author	Material combination of FGM	Sintering conditions	Year
1	A.J. SaÂnchez-Herencia et al.	zirconia/ alumina	1550˚C for 2 hours	2000
2	A. Ozieblo et al.	Al_2O_3-Fe	1470˚C for 1 hour	2005
3	B. Neirinck et al.	Ceramic-Titanium	950˚C for 2 hours	2009
4	Tomoyuki Katayama	Al_2O_3-W	1600 °C for 3 hours	2011
5	JustynaZygmuntowicz et al.	Al_2O_3/ Ni	Not reported	2017

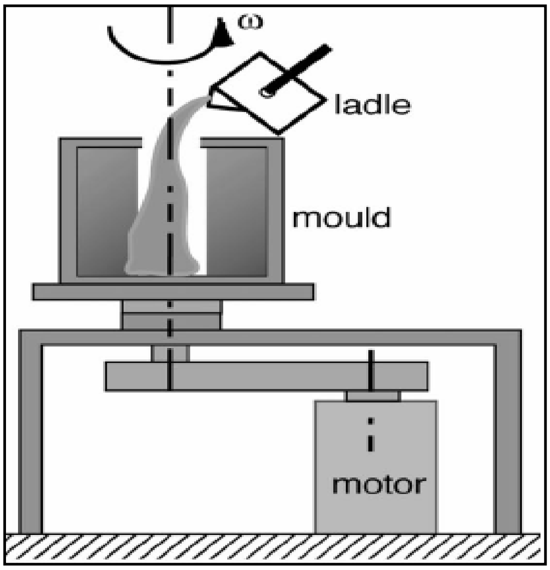

Figure 4 : Vertical Centrifugal Casting setup [23]

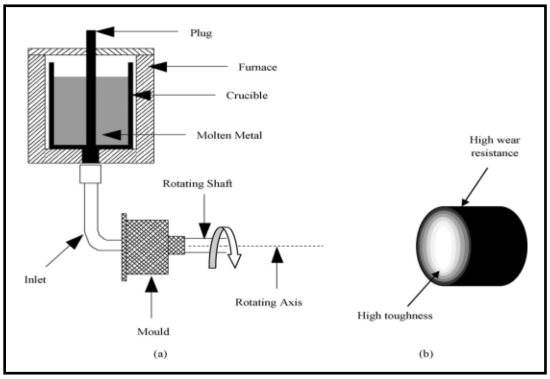

Figure 5 : Schematic representation of (a) the Horizontal centrifugal casting process and (b) final product [26]

The walls obtained present a smooth gradient of the precursor materials. The base of the wall has virtually identical characteristics to the real steel walls: similar values of micro hardness (175-245 HV), and similar austenitic microstructure. On the other hand, the top of the wall has virtually the same values of hardness (600 – 700 HV) and dendrite microstructure than the pure cobalt base super alloy walls [31]. Laser powder cladding process is also used to fabricate AlSi40 as functionally graded material, where the Si particles exhibit a continuous increase in both size and volume fraction of the FGM tracks bottom to the top [32]. In the extension of this work, five-fold twinning and growth features of silicon particles were also studied [33].

2.5 Selective laser sintering (SLS)

SLA part is fabricated by laser spot instead of continues scanning on the resin which forms a thin solid layer on the surface of the liquid resin through the photo polymerization. The powders used in this technique bounded with the focused energy source. The powder of materials should be in uniform texture [34]. In this technique, there are two types of binding mechanism namely melting and sintering. In the consolidation approach, after the above stage of the phase of the material requires some sophisticated powder feed and control system. There are two established techniques in the sintering approach: liquid phase sintering (LPS) and the second are called solid phase sintering (SPS). As we know liquid phase sintering is a very fast technique [35]. LPS was used for the synthesis of tungsten carbide and cobalt with the continuous gradient in cobalt content [36]. This technique is good extent for FGM synthesis.

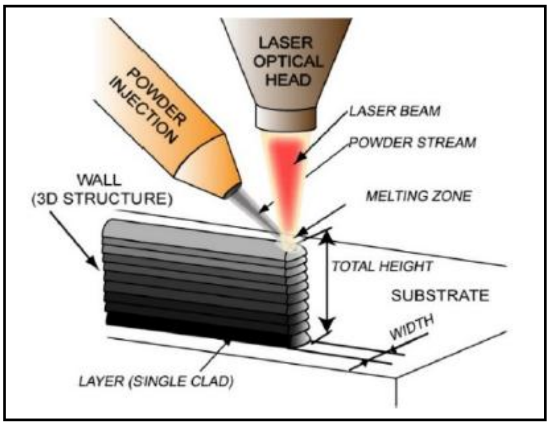

Figure 6 : Laser cladding process [31]

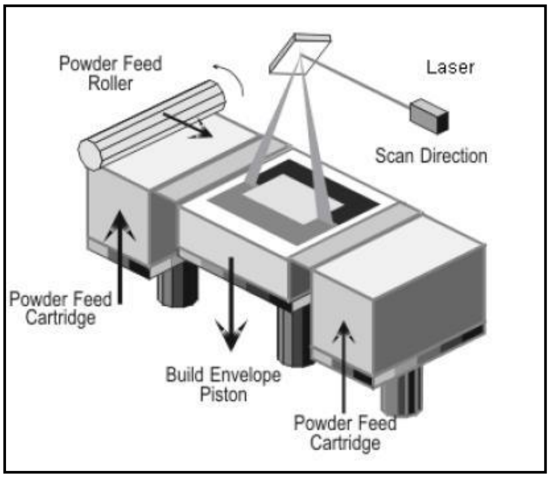

Figure 7 : Selective Laser Sintering [37]

Functionally graded Nylon-11 composites were fabricated by varying volume fraction of glass beads [38]. A functionally graded porous polymer structures were also fabricated using thermal bonding lamination techniques. The phenomenon of polymer inter diffusion was shown to be adequate for the intended application. It is shown that with a compressive load, two 3-D printed thin polymer sheets can be brought into close contact [39].

2.6 Spark Plasma Sintering

Spark Plasma Sintering is the propelled technique for sintering, which is otherwise called Pulse Electric Current Sintering (PECS). This technique produces high minimized material at low temperatures in less time [40]. In this procedure, DC is gone through the kick the bucket, in which the powder is stacked. This procedure depends on electrical start release wonders, which have high vitality, low voltage start beat flow and from a few to ten thousand between the particles. The schematic portrayal of the SPS framework has been sketched out in figure 8. This innovation is equipped with different materials, continuous holding and material surface treatment with sintering process. This innovation does not require green state, folios or pre-sintering stage. It is equipped to create net and close shape from powder. After the amalgamation and union, the electric field and weight are given somewhere else on definite material shaped [41].

Spark plasma sintering process is also used to obtain silicon carbide ceramic; which has excellent mechanical properties [43]. Aluminium and pure WC powders are ruptured by the spark plasma [44]. Sodium potassium niobate ceramics were successfully fabricated using SPS at a low temperature with the nominal composition of Na0.5K0.5NbO3 [45].

2.7 Physical Vapour Deposition (PVD)

For thermal barrier coating, PVD is the most promising technique. This technique has provided excellent thermal shock resistance, erosion resistance and does not require additional polishing [46]. The vaporization depends upon vapour pressure of the material; in that technique, due to coating, it becomes challenging to evaporate materials that why it have the significant difference in their vapour pressure. This technique is environmentally friendly vacuum deposition techniques. Partially reactive physical vapor deposition, magnetron sputtering, resistance heating, high energy-ionized gas bombing and electron beam are variations of PVD, which are currently available. All the variations of PVD are used for functionally graded coating on various substrate materials. Electron beam PVD technique is used to produce a functionally graded coating of NiCOCrAlY on the substrates of super alloy [47]. This technique is also suitable for components with close tolerance [48]. Inhomogeneous material were prepared by CVD or PVD in control phase distribution [49]. Thermal barrier coatings (TBC) fabricate from ZrO28wt%Y2O3 (8YSZ) was applied to turbine components by Electron Beam-Physical Vapor Deposition (EB-PVD) [50]. ZnO nanowires were produced using a physical vapour deposition approach [51].

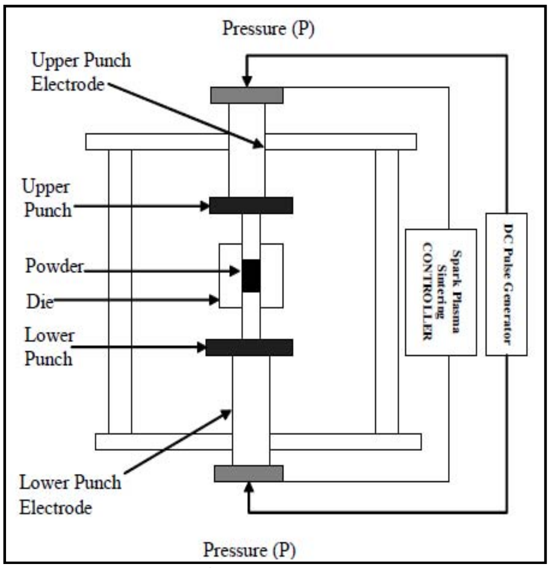

Figure 8 : Setup of Spark Plasma Sintering process [42]

2.8 Chemical Vapour Deposition (CVD)

Chemical Vapour Deposition is a concoction procedure that is utilized to create excellent, elite strong materials. This is antiquated innovation for FGM generation. This procedure is utilized in the semiconductor business to create thin movies. In this procedure where a reactant gas blend is permitted to go through a high-temperature reactor in which to shape a thin layer on the surface of the substrate, commonly 1-2 meter length has a glass tube. The normal temperature scope of CVD is between 800˚C to 1200˚C. The practically reviewed covering is roughly 5-10 pm/hour by changing the proportion of the gas mixture [52]. A comparison of both PVD/CVD techniques in Table 3 has been presented.

2.9 The electrophoresis-based route to manufacture FGM

This is the developing innovation for the arrangement of FGM. Because of its effortlessness and low consumptions, in the present situation is by and large broadly used to fabricate FGM. As we realize that electrophoretic statement is a notable electro-active wonder dependent on the guideline of electrophoresis and as of late, FGM has pulled in consideration as a basic and exquisite strategy for blend. It was first found in the eighteenth century when an Indian analyst G.M Bose was considering the utilization of fluid siphon, later Reuss (1870) talked about the points of interest of the episode in the popular two fold layer hypothesis [53]. The particular part of this marvel is that it has been executed effectively, there are a few standards identified with this wonder, for example, molecule charge balance, electrochemical coagulation of particles which was an augmentation of DLVO hypothesis and molecule collection. A steady suspension is required with Electrophoretic Deposition (EPD), in spite of the fact that the molecule ought to be charged so a connected power field can be reacted [54].

The flow diagram of an EPD process is shown in figure 9. A review of various FGM fabricated through EPD with significant results has been given in Table 5.

3. APPLICATION OF FUNCTIONALLY GRADED MATERIALS

3.1 In the Aerospace Industry

The practically evaluated materials were utilized to build up the space plane bodies. The utilization of this material has been expanding step by step in the aeronautic trade. Today the vast majority of the hardware and structures are made by this material. Through this procedure, we make the rocket motor parts, the shuttle bracket structure, and the warmth trade boards[57].

Some structures such as Reflector, Sun Oriented Board, Camera Lodging, Turbine Wheels, Turbine Sharp Edge Coatings, nose tops, the main edge of the rocket and Space Transport are manufactured by this material. These materials are additionally utilized for the structure dividers.

3.2. The Automobile Industry

The automobile is another industry, where the use of this material is very high. However, due to high production costs, it is used only in a limited area. This material is used in critical places in the automobile, due to which the cost does not matter. We use this material to make car body parts, make engine cylinder liners, to make leaf springs, to make spark plugs, to make combustion chamber, to make drive shaft, to make shock absorber and for making a flywheel. FGM is enhancing the body coating of the car with the help of particles such as dioxide/ mica.

3.2 Biomedical

In the human body, there are such a large number of practically reviewed materials like bones and teeth [58]. These parts are supplanted at whatever point these parts are harmed. Practically evaluated materials are utilized instead of that harmed parts. That is the reason these materials are utilized in the biomedical business for inserts. It has the full scope of utilization in dental.

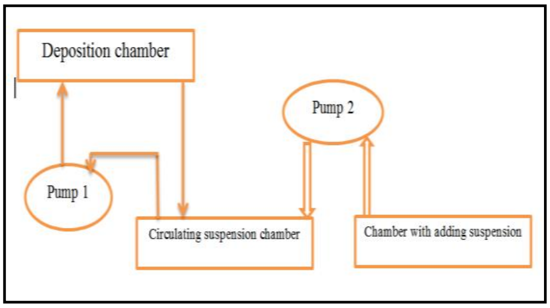

Figure 9 : Flow diagram of an EPD process [55]

3.3 Energy

There is much equipment in the energy industry energy industry there are so many which are made up of FGM. It is commonly used to improve the efficiency of the part. It is used in energy conversion devices. We use it to provide thermal barrier and for protective coating on the turbine blade in the gas turbine engine.

4. CONCLUSION

Functionally graded materials are vital material in today's scenario. It has tremendous application in the engineering field. In that paper, we have discussed so many processing routes for the preparation of FGM. Centrifugal casting technique is the most cheaper and accessible to handle the fabrication of FGM. The different application areas have also presented in this review and how the application can be made with many different materials. This review shows that due to the high cost we cannot use it in many different areas. However, we can use it in some places to enhance the efficiency.

Table 3 : Comparison of PVD & CVD

Technique	Deposition rate	Deposition temperature range	Atmosphere	Oxide coating formation	Structure of coating& thickness range	Various variants of PVD/CVD
PVD	Faster	100˚C to 600˚C	Vacuum	Difficult	Crystalline as well as amorphous; 2-5 µm	Thermal evaporation, EB-PVD, magnetron sputtering, ion plating, low ion pressure
CVD	Slow to moderate	800˚C to 1200˚C	Controlled atmosphere	Can be produced	Crystalline as well as amorphous; 6-10 µm	CVD, plasma enhanced, photochemical & aerosol assisted

Table 4: Materials Combination via EPD

S.No.	Author	Material combination of FGM	The range of hardness variation	Nature of gradient attained	Sintering conditions	Year
1	P. Sarkar	Al2O3-YSZ	24 to 13 Gpa	Step	Not reported	1996
2	C. Zhao et al.	Al2O3/Ce-ZrO2	1000 and 1100 kg/mm^2	Continuous	1600˚C for 1 hour	1999
3	S. Put et al.	ZrO2-WC	900 to 1800 kg/mm^2	Continuous	1450˚C at 28 Mpa	2002
4	S. Put et al.	WC- Co	21 to 9 Gpa	Continuous	1290˚C for 1 h	2003
5	JefVleugels et al.	Al2O3/ZrO2	Not reported	Continuous	2 hours at 1480°C in air	2003
6	Guy Anné et. Al	Al2O3/ZrO2	Not reported	Step	1 hour at 1550°C	2005
7	B. Ferrari et al.	Ni/Al2O3	Not reported	Continuous	1450˚C (5–20µm)	2006
8	E. Askari et al.	Al2O3/SiC/ZrO2	20.8 ± 0.3 GPa	Continuous	2 hours at1800˚C	2012

Table 5 : Overview of processing methods for FGM [56]

S No.	Process	Variability of Transition Function	Variability of Phase Content	Types of FGM	Versatility In Component Geometry
1	Powder Stacking	Very Good	Very Good	Bulk	Moderate
2	Slip Casting	Very Good	Very Good	Bulk	Good
3	Centrifuging	Good	Very Good	Bulk	Poor
4	Laser Cladding	Very Good	Very Good	Bulk, Coating	Very Good
5	PVD,CVD	Very Good	Very Good	Coating	Moderate

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