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Functionally Graded Materials: Processing Techniques and Applications

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Abstract

Functionally graded materials (FGMs) revealed an immense growth with worldwide demand. This paper describes a brief review of the feasibility of production methods (solid, liquid, and gaseous methods) chosen for FGMs, with the aid of schematic diagrams. Advanced FGM fabrication techniques such as additive manufacturing and laser deposition, which have been gaining importance are also explored. The evolution of fabrication techniques is correlated to the industrial requirements along with their merits and limitations. This review article also highlights some advanced engineering applications observed for FGMs. Comparing various fabrication technologies employed for FGMs, centrifugal casting was the most established and economically feasible method that met vast industrial product demands like hybrid and double-graded FGMs. Powder metallurgy was preferred for bulk gradation in spite of their sharp transitions across layers. Advanced FGM fabrication techniques like additive manufacturing, electrochemical gradation, and laser deposition techniques improved critical production parameters like precision, gradation control, etc. Thermal spraying successfully improved the heat insulation performance of FGMs.

Keywords: Functionally Graded Materials, Processing Techniques, Additive Manufacturing, Laser Cladding.

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1. Introduction

The scientific use of the raw materials available in various inorganic and organic compounds has led to the development of advanced polymers, engineering alloys, structural ceramics, etc. Growing demand and optimization of industrial applications have revealed the limitations of conventional materials and promoted the development of advanced materials. Evolution of Functionally Graded Composites (FGCs) have addressed these limitations to a great extent by integrating customized mutually exclusive properties [1,2]. FGCs periodically gained widespread attention and were extensively researched to replace metals and their alloys, thus providing superior mechanical properties aside from being light-weight [3]. Functionally graded material (FGM), an advanced class of composite material developed by Japanese in 1984, displayed a localized property dependency against the spatial distribution of its constituent phases. Koizumi [4] and Knoppers et al. [5] recommends these potential materials for specific industrial applications as they gave the designer, the ability to tailor the required morphologies and properties. This made FGCs superior and more appealing than conventional composite materials, as it eliminates the limitations like sharp changes along the composite boundaries with smooth, continuous and gradient transition in mechanical properties of FGM [6,7]. Interests in Functionally graded material (FGMs) have increased exponentially with its diverse potential to manufacture customized products that are ideal candidates for unique variants of hightech applications, such as aerospace, automobile, bioengineering and nuclear industries.

A mono reinforced FGM is produced from a single constituent/phase unevenly distributed within the matrix relative to standard composites, whereas more than one constituent/phases are observed in case of double FGMs. A continuous gradient is obtained in the both cases, based on the continually varying distribution density of constituents/phases over the matrix. FGMs typically are classified based on the combination of constituents such as, ceramic/metal, ceramic/ceramic, metal/metal and ceramic/polymer where, ceramic/metal being the most commonly used material combination (Fig. 1). Ceramic/metal FGMs, which contain metal alloys (matrix) and secondary phases (ceramics) are compositionally graded from a ceramic phase to a metal phase.

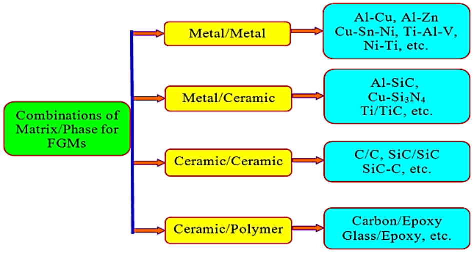

Fig. 1. Preferable matrix-particle combinations used in FGMs [8].

These FGMs gained widespread importance owing to its capability to take advantage of improved mechanical properties such as hardness, strength, machinability, toughness and enhance thermal, wear and corrosion resistances.

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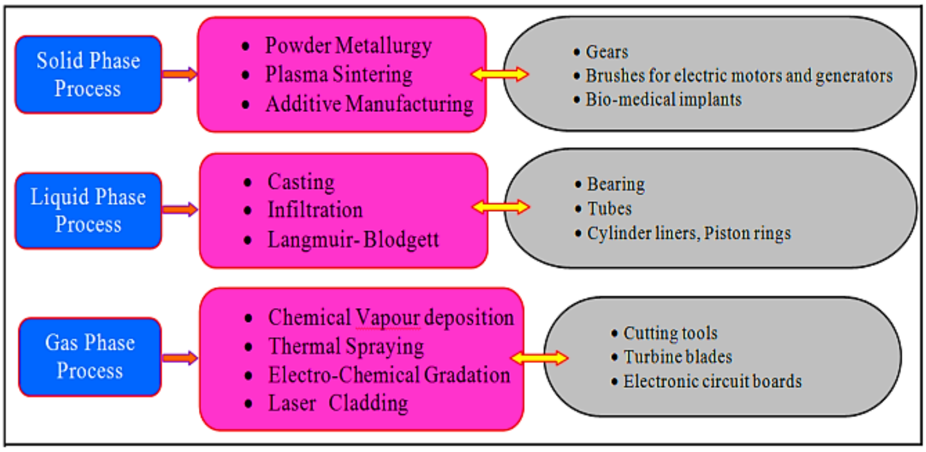

Fig. 2. Classification of established fabrication techniques for FGM applications [13].

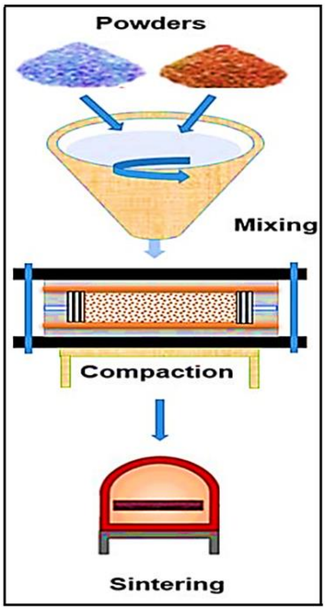

Fig. 3. Fabrication stages of powder metallurgy [14].

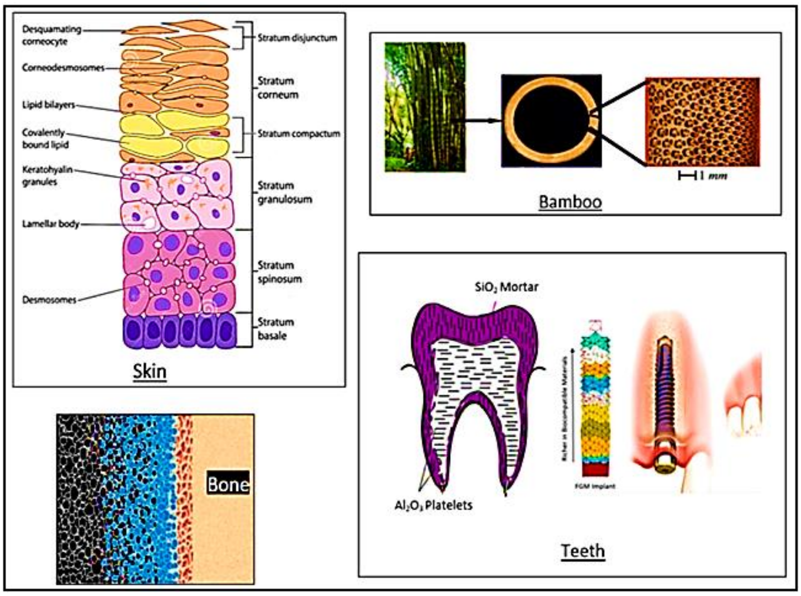

Fig. 4. Natural FGMs and FGCs employed for bio-medical applications [19].

FGMs also reduce the thermal stresses developed and display enhanced bonding between the phases, thus producing improved fracture resistance and toughness along the graded volume [8].

The properties of FGMs are largely dependent on the method of processing and thus the selection of the manufacturing process plays an important role in fulfilling the industrial needs and having functional properties [9]. There are two crucial steps to develop the compositional gradient [10]. They are spatially heterogeneous structure gradation and settling of this structure on substrate [11]. These vary from old and basic to sophisticated and complex methods, covering a large range of physical and chemical concepts, which are classified as gaseous, liquid and solid phase methods. Gaseous-based methods generally involve obtaining a gradient composition on the deposited product, depending on the reaction ratio of the phases in the mixture and the production control method. Some methods commonly employed to fabricate FGM involve vapour deposition techniques such as Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD), plasma spraying and ion mixing. Liquid phase methods gained importance as these processes provided manufacturing stability and high deposition rate as well as ease of coating over complicated geometry. Some commonly used liquid phase processes are centrifugal casting, laser deposition, electrochemical gradation etc.

2. FGM Fabrication Techniques

The suitability and feasibility of production methods were determined based on material composition, transition functionality, component geometry [12,13]. Fig. 2. clasifies the different fabrication techniques employed for processing FGMs.

2.1. Solid Phase Processes

2.1.1. Powder Metallurgy

Powder metallurgy as an FGM fabrication method, had undergone evolution and was followed by various stacking techniques like powder stacking, wet filtration, vibrational stacking process, centrifugal process, wet powder spray forming process, sequential slip casting, slurry dip casting etc. Fig. 3. schematically represents the different fabrication stages of powder metallurgy. The FGM properties were experimentally proven, to be significantly influenced by process parameters such as temperature, time and pressure [14,15]. Critical challenges such as warping, frustum formation, pin crack initiation and propagation, delamination etc., were addressed during the stacking process [16]. Uncontrolled particle distribution significantly influenced the component failure [17].

The imbalance of sintering developed during powder metallurgy was prevented through an intermediate process called hot pressing [18]. Customized chemical composition and microstructural formation coined powder metallurgyas a prime FGM production technique. Fig. 4. displays few natural FGMs and FGCs employed for biomedical applications of powder metallurgy method [19].

2.1.2. Plasma Sintering

Conventional sintering process underwent evolution and brought out an advanced and successful production technique called Spark Plasma Sintering (SPS) process to produce high quality FGMs. Electric mode of ion activation promoted swift migration and improved the diffusion process [20]. Ionic discharge stimulated localized high temperature spots, which softened or melted the composition to fill the gap between the particles [21]. Fig. 5. schematically represents the SPS fabrication process. Dwell duration, rate of heating, temperature and pressure variations were the most influential parameters, which directly impacted the diffusion mechanics of sintering [22,23]. Studies on diffusion modes helped to classify them as surficial, bulk volume and grain boundary diffusion.

This method was widely preferred to manufacture enhanced tribo-resistant and tough materials, which were conventionally produced through complex production techniques [24]. Such materials produced through sintering were widely used for cutting lens mold, nozzles and machinery screws. SPS systems had achieved several advancements in the form of swift sintering, utility of limited additives, uniform sintering, economic optimization and feasibility, when compared to conventional methodology. This was achieved through modern techniques like hot pressing and hot isostatic sintering to develop advanced materials like FGMs, amorphous and target materials.

2.1.3. Additive Manufacturing

Additive manufacturing had evolved as an effective production technique for manufacturing FGMs where the challenges of commercialization still prevailed. These limitations were overruled using hybrid methods like Friction Stir Additive Manufacturing (FSAM) and wire and arc additive manufacturing route (WAAM) [25].It was inferred that FSAM follows a layered mode of manufacturing technique that facilitates excellent scalability for fabricating functionally graded bulk-scale materials [26]. Intensive interfacial frictional heat generated by pin sliding over metal substrate led to plastic mode of deformation, which completed the weld. Multi-layered final component was fabricated through effective stacking of compositional layers along the welded layer [27]. FSAM offered a novel approach for creating heterogeneous and hierarchical layered functionally graded material structures, which resulted in modified microstructure and phase formations. Considering the process parameters, it was proposed that effective control on strain rate and peak temperature improves the performance by limiting material deformation, interfacial rub, and heat generation [28]. Applications of FSAM are not just restricted to metal additive manufacturing, but extended to metal-metallic hybrid coats on metallic substrates [29].

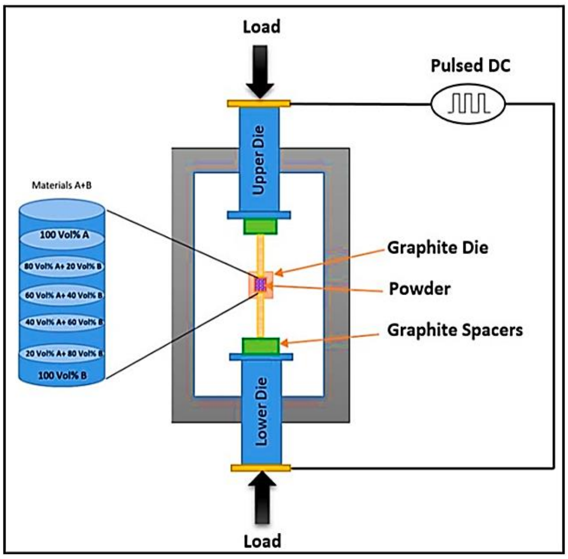

Fig. 5. Fabrication process of Spark Plasma Sintering [23].

They are specially utilized for niche engineering applications like structural repair and joining operations for a wide range of materials like aluminum, titanium, magnesium, steel and nickel-based alloys. These operations were locally confined to smaller regions to eliminate surficial damage, cracks and wear. The physics underlying material flow and deformation, heat generation, temperature evolution, and thermal coupling were unexplored. However, the excellent capabilities for rendering physical properties, suggested them as an emerging trend for aerospace, automotive, and defense industries where lightweight metals, nanostructured materials, high entropy alloys and heterogeneous materials with load-bearing capacity are crucial. Fig. 6a represents the schematic illustration of FSAM process.WAAM was successful in designing complex parts for graded structures with enhanced properties along specific directions. These were experimentally confirmed through optimal selection of processes conditions using multiple feed mechanisms [30]. Fig. 7. displays the various FGM components manufactured using solid phase processes. Study on process parameters of WAAM process like current, wire speed and torch speed revealed that optimization of torch speed ensured supreme mechanical strength at the graded zone [31]. The fame and acceptance of WAAM process in industries was the ability to develop large metallic FGCs with low production period [32]. The sub-processes, which worked hand-in-hand with advanced additive manufacturing technique, include Plasma Transferred Arc, Plasma Arc Welding, Tungsten Inert Gas and Metal Inert Gas [33,34].

2.2. Liquid Phase Process

2.2.1. Centrifugal Casting

Casting being one among the primitive and established FGM manufacturing technique, evolved drastically to meet the higher growth of diverse industrial demands. Casting technology periodically underwent modifications and evolved as wide variants of production methods like gravity casting, centrifugal casting, squeeze casting, vacuum die-casting, compo casting, recasting etc. Versatility and commercial feasibility established centrifugal casting as the most effective FGM casting technique. The properties of composites were effectively regulated by controlling the composition and microstructure. For FGMs with cylindrical structures, centrifugal casting is mainly preferred. This casting process can be classified into two categories based on the rotating axis - horizontal and vertical centrifugal casting. Applications of materials developed using centrifugal casting include tubular pipes, washers, sleeve bushes, cylindrical inner liners, shell casts etc. For fabricating MMCs using horizontal centrifugal casting process, the reinforcement phase (either particle or fiber) is mixed in a molten metal matrix to attain required composition (Fig. 8). Effective mixing is ensured with appropriate mechanical set-up like mechanical stirrer [35].The desirable gradation is achieved within the composite specimen at the required location through effective distribution of the functional reinforcements or particles at the required zones. Segregation of ceramics or particles was achieved within the matrix, through gravitational or centrifugal forces [36]. Another tactic used to achieve the same, is through suitable material selections - choosing the reinforcement of appropriate size and density [39]. This plays a key role in association with the centrifugal forces involved during hybrid composite castings or double FGM production, to achieve advantageous gradation and controlled solidification. In-depth studies on FGM fabrication using centrifugal castings focused on advanced numerical modelling of particle motion within the molten mixture and axial-rotating solid particles within the mould [38]. Influence of viscosity of molten matrix on gradation of ceramics or reinforcement particles under centrifugal force were also studied [39].Centrifugal cast technique was influenced by production parameters like matrix-particle density variance, wall thickness, solidification time, size, texture and volume of reinforcements [40].

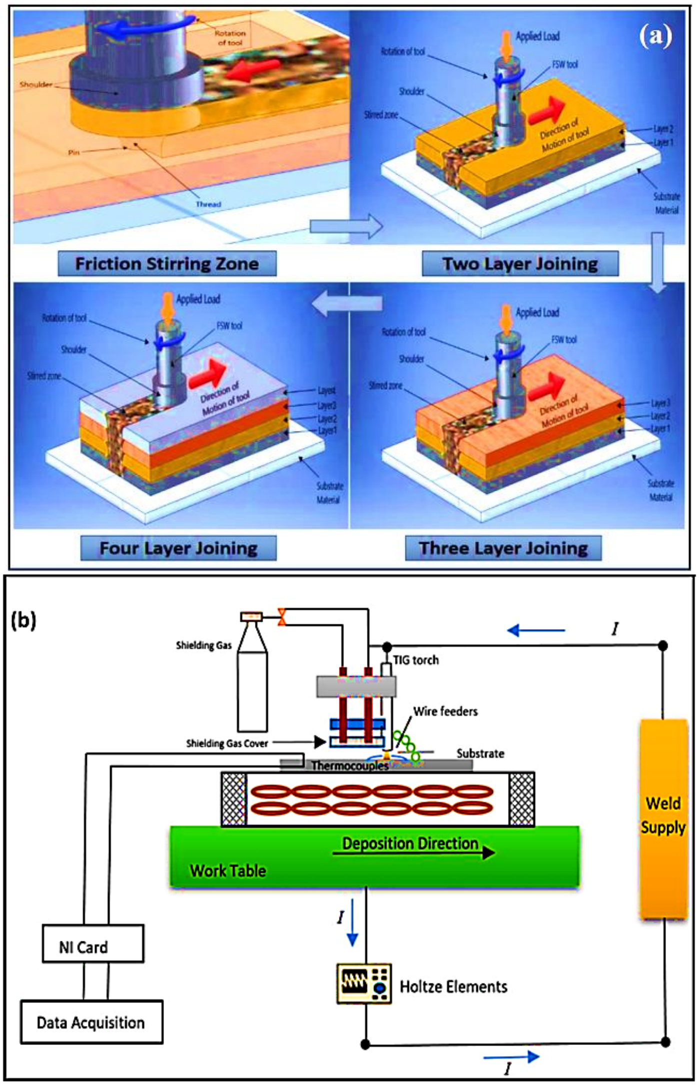

Fig. 6. Fabrication process of (a) FSAM [29] and (b) WAAM [30].

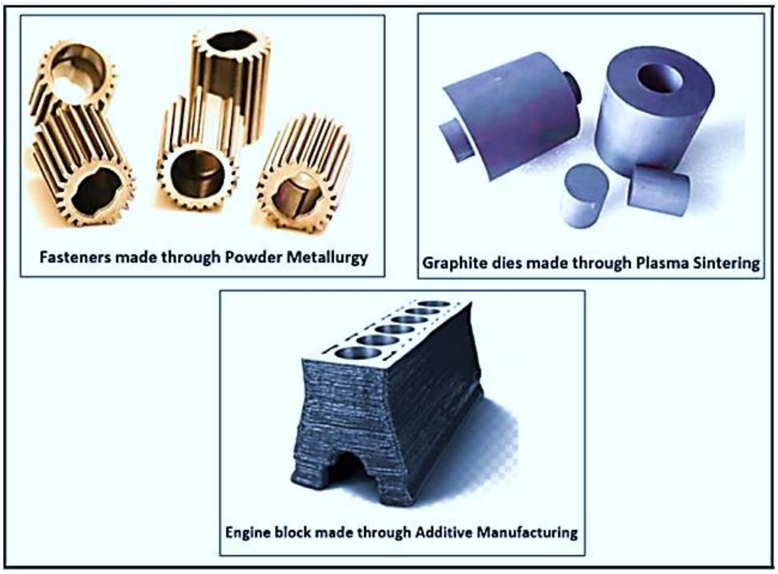

Fig. 7. Various FGM components manufactured using solid phase processes [31].

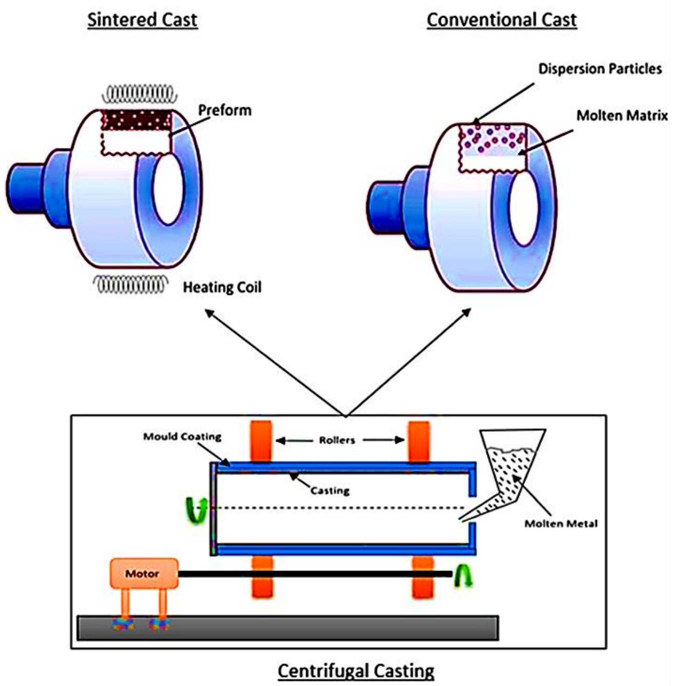

Fig. 8. Sintered and conventional centrifugal casting for FGMs [41].

Optimization of these production parameters enhance tribological as well as mechanical performance of FGM composites irrespective of its matrix and particle composition [41].

Limitations and drawbacks of fabricating nano-particle reinforced FGM composites using conventional centrifugal castings were overruled through the introduction of an advanced production technique called centrifugal mixed-powder method [42]. This can be described as a combination of powder metallurgy and simple centrifugal casting where the mixed powder is pre-set in rotating mould before pouring the molten metal.

2.2.2. Infiltration

Infiltration technique is a liquid phase process chosen for fabricating FGM components that are less complex, in terms of size and features. Effective soaking of dispersed phase-ceramics in molten matrix, during the fabrication process results in minimum porosity [43]. The reaction of preform with the substrate medium causes interfacial chemical effect, in addition to pressure due to capillary/mechanical/gaseous actions. This resulted in an FGM structure with minimal preparation and formulation of sizes [44]. Fig. 9. displays the fabrication process of pressure die infiltration and gas pressure infiltration techniques. Microstructural analysis of graded layers revealed improvement in the electrical properties across rise in gradient. Customization of localized properties was easily achieved through slight modifications in fabrication setup and punch-die orientations [45].

2.2.3. Langmuir-Blodgett film

Langmuir-Blodgett (LB) film method is one among the latest production techniques preferred for FGM development. This technique facilitated advanced high precision FGM layering through depositions of uniform film up to single molecular thickness [46]. Fig. 10. schematic illustrates the LB film method. The graded films developed are utilized for electronic applications like active layers or passive insulators. Highlight of this method is that the film thickness is precisely controlled at molecular level [47]. This involves handling ofa wide variety of materials in a multi-layered architecture.

Design of layered structure is customized as per demand and requirements of specific functionalities. At primary stage, a monomolecular coating of amphiphilic material is prepared over the water surface and then moved on to the solid substrate as a secondary process. During aqueous state, amphiphilic molecules are spread across the air-water interface and the surface layer is compressed by a special membrane to develop a mono-molecular surficial layer. This sequential isothermal compression modifies the monomolecular film structure [48]. Immersion of flat substrate in the solution and subsequent draining are repeated during multiple cycles to accomplish a desired multi-molecular layered structure. Selection of substrate and solute, their proportion of dissolution, temperature, chronological sequence of immersion etc., are yet to be explored. Addressing these research gaps widen its scope of implementation for commercial production of FGMs.

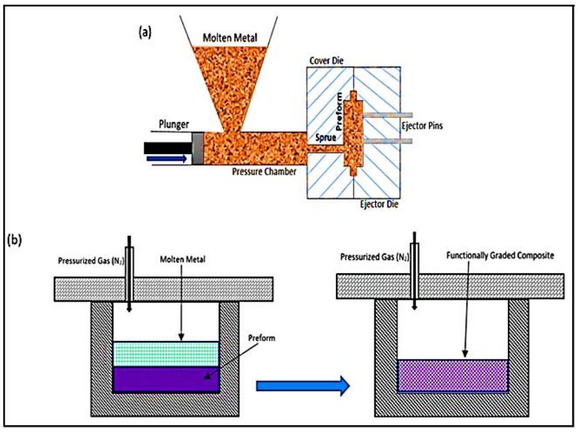

Fig. 9. Schematic representation of (a) pressure die infiltration and (b) gas pressure infiltration process [44].

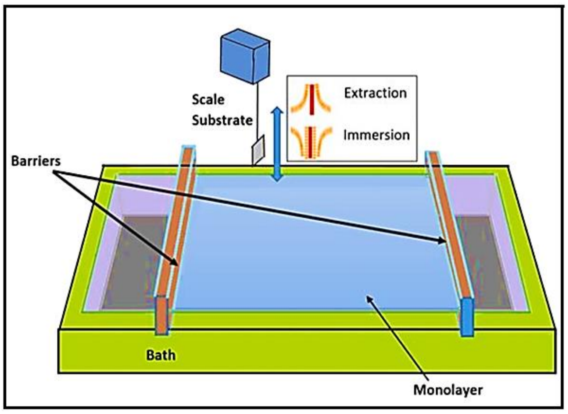

Fig. 10. Illustration of Langmuir-Blodgett film method [46].

2.3. Gas Phase Processes

2.3.1. Vapour Deposition

FGMs fabricated through vapour deposition technique primarily explores the interaction of ceramic-ceramic or ceramic carbon coats with metallic substrates, producing metal-ceramic graded structures.

PVD and CVD are the pre-dominant variants of vapor deposition techniques used in FGMs, which utilizes deposition of coating material over the material substrate. This ensures excellent microstructure refinement and effective graded properties [49]. PVD is recommended mostly for applications that demand thin surface coat as this fabrication route is energy intensive and costly, considering commercialization [50]. Metal-ceramic graded FGM was fabricated through reactive PVD technique by promoting combined deposition of more than one vaporized metallic gaseous substituents like carbon or nitrogen. These gaseous atomic substituents reacted with depositing metal substrate, which resulted in a controlled association of metals with carbides or nitrides [51].

Fig. 11.a schematically illustrates the PVD process. Adjusting the gradient layered structures by effectively varying the timely introduction and concentration of reactive constituent gases, facilitated effective customization of metallic FGMs. Thin films made with PVD display high-temperature tolerance, superior ablation resistance and is environment-friendly [52].

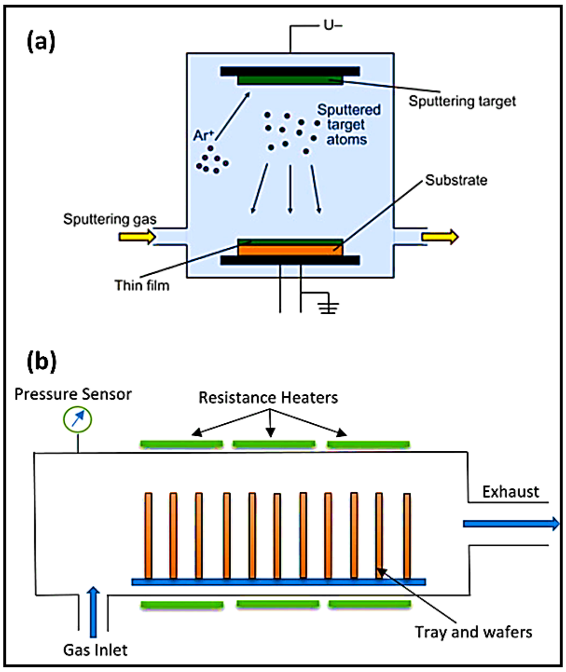

Fig. 11. Illustration of (a) physical vapour deposition technique and (b) chemical vapour deposition technique [52].

Another advanced vapor deposition approach - CVD, deposits uniform films on metal/alloy surfaces with complex topologies making it a right choice for fabrication of FGMs. CVD was first industrialized through the deposition of tungsten onto carbon filaments used in lamps. By 1970s, CVD became the popular fabrication technique for semiconductors and coating of electric circuit boards. However, this method utilized expensive and highly toxic precursor gases. Therefore, this method was adopted for fabricating advanced FGCs for turbine blades, solar cells etc., where enhancement of mechanical and tribological properties were vital [53]. Fig. 11.b schematically illustrates the CVD process. Heat, plasma and light were the driving source of energies during material deposition process using CVD. Bromides, hydrides and chlorides were the popular gaseous sources. It was observed that optimization of gas ratio, temperature of deposition, gaseous pressure, rate of flow and type of gas helped in achieving the desired chemical compositional gradient [54]. Fabrication of FGM components through CVD facilitated production flexibility through continuous or controlled change in composition, minimal temperature fabrication process, accuracy in component shape etc. [55].

CVD processes were utilized irrespective of industrial discipline. This process has developed a technological capability to coat even a small area.

PVD is the preferred technique for depositing thin layer of material using physical means to produce an extremely tough, anti-corroding coating through sequential steps at high-thermal-vacuum conditions whereas, CVD is preferred for coating thin irregular surfaces like screw threads and recesses with high purity and density. CVD is promoted and commercialized due to their versatility in range of elements and compounds used for coating, and their economic feasibility for bulk batch production. Vapour deposition techniques are applied across wide variant industries to apply thermal and wear resistant coatings.

These include semiconductors produced for electronic devices and fabrication of structuraldense components which replaced the expensive conventional techniques.

2.3.2. Thermal Spraying

Thermal spraying has advanced as a production technique for fabricating MMCs with FGM coatings as this fabrication route offered a possibility to combine phases with low refractory metals at high melting temperatures. Deposition droplets underwent surficial spreading and swift solidification to form adherent coats. Properties are largely defined by the interaction of feedstock with the plasma jet at the substrate interface [56]. It is largely dependent on many technological parameters like type of deposition particles, composition of plasma gas, rate of flow, rate of quenching, plasma torch off-set distance, input energy etc. Plasma Spray and High-Velocity Oxy Fuel (HVOF) are the mostly preferred thermal spraying techniques. Fig. 12. displays the fabrication process of thermal spraying technique. The feasibility of deposition processes and their flexibility are the key promoters of coating deposition on diverse materials [57].

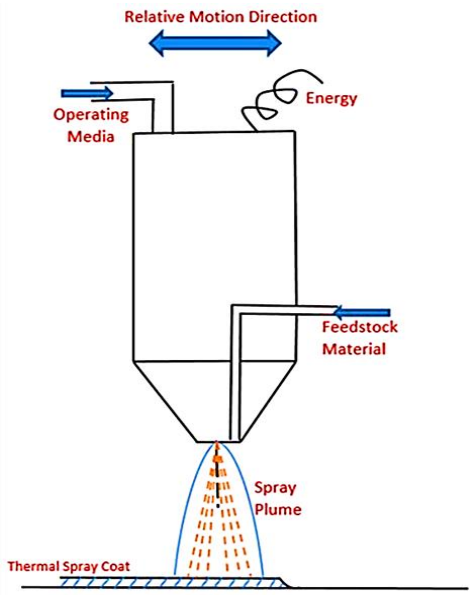

Fig. 12. Fabrication process of thermal spray technique [57].

Fig. 13 displays the various energy level classifications of thermal spray technique. The HVOF, plasma spray process in inert atmosphere and novel powder compositions are the processing advancements that widened the scope of implementing thermal-spraying process to both monolithic and composite materials.

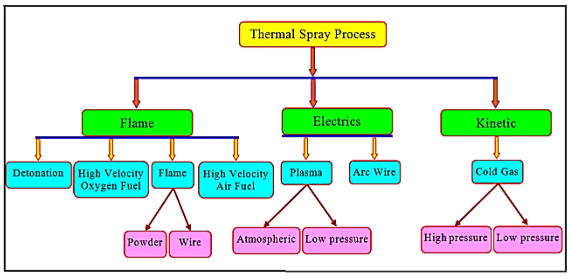

Fig. 13. Energy level classification of thermal spray process.

2.3.3. Electro-Chemical Gradation

Electro-chemical gradation is an advanced processing route that facilitates adjustable modifications of chemical gradients with efficient control of experimental reactions and concentration to produce a functionally graded component. Appropriate electrode design optimizes the ionic-kinetics at a macroscopic level and helps in developing the FGM component model. Electro-chemical gradation happens on a system with unequal potential concentration [58]. Direct diffusion of electric charge ions, through a permeable membrane created an electric potential, which forced the ion diffusion for ionic balance. Optimizing the production factors like composition of electrolyte, charge or current density, material properties like electro-conductivity etc., contributed towards the development of gradient profiles within the component [59]. By using modified electrodes, a functionally graded component with required shape and symmetry was successfully produced. This technique overcame the challenging era of heterogeneous coating. As a modern approach to produce gradient materials based on infiltration of refractory porous pre-forms with a molten metal (tungsten or copper), an electrochemical potential gradient was set up inside the porous pre-form. This produced a gradient rate of electrochemical dissolution or deposition of the pre-form material and resulted in gradient porosity (Fig. 14). A macroscopic model was developed to study the influence of experimental parameters like current density, electrode and electrolyte resistivity along with geometrical factors, over the gradation profiles [60].

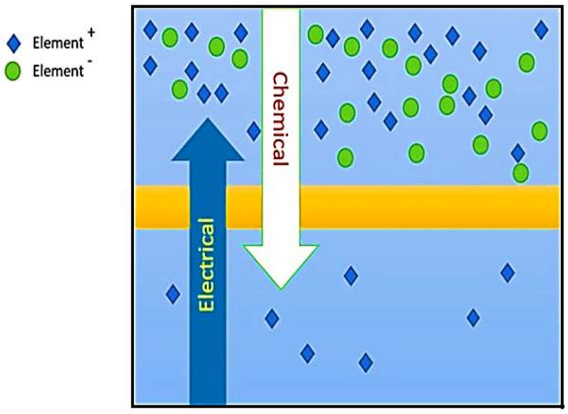

Fig. 14. Electro-chemical gradation in FGMs [60].

2.3.4. Laser cladding

Laser cladding is a modern technique employed for fabricating FGMs where dissimilar materials are merged through laser intercession (Fig. 15). Structures that demand extra-challenging mechanical properties, prefer laser deposition fabrication technique for thick and dense cladding over complex structures [61]. This method is effective whenever there is a considerable difference in melting temperatures of matrix and reinforcement materials.

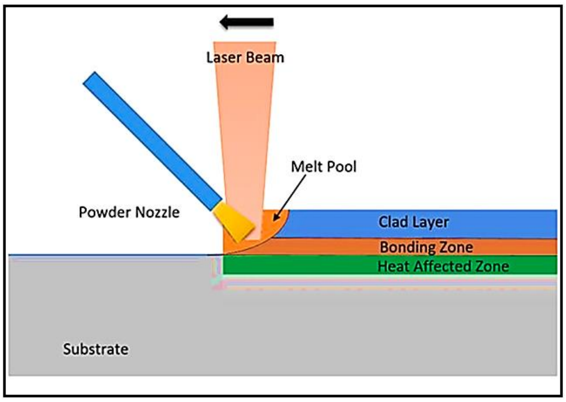

Fig. 15. Illustration of laser cladding process [61].

This technique was preferred for providing graded coating over complex shapes and structures. Layer over-layer processing technique has its own limits due to the expensive production set up and initial cost [62]. This keeps it away from mass production and makes it less popular within industry. Current advancements in laser metal deposition technique includes efficient control of chemical composition at graded layers and optimizing fabricating parameters like flow rate, laser intensity etc. FGMs fabricated through laser metal deposition technique has widened their applicability in nuclear and aerospace fields [63]. This was mainly due to their superior elasticity, low density and challenging mechanical properties attained at higher temperatures.

3. Engineering applications of FGMs

FGMs through effective combination of material composition and fabrication route widens their possibilities for commercialization. Currently, FGMs are predominantly preferred for engineering applications from automotive, aerospace, bio-engineering and electronic sectors as shown in Fig. 16. They possess unique capabilities to customize and limit their undesirable properties and accommodate advantageous properties within the same component. Engineering applications of FGMs are classified as below:

1) Military service: exceptional capability of FGMs to integrate light weightiness along with crack resistance and penetration-resistance made it suitable for amour plates and bullet-proof jackets. Al FGMs produced by CVD process [64] and Al_2O_3–ZrO_2 FGCs produced by powder metallurgy [65] are highly utilized for heavy performance bearings, nuclear reactor components and cutting tools due to their exceptional hardness, heat conductivity, chemical resistance and electrical conductivity.

2) Medical industry: dental and orthopedic application demands are met to a great extend through concept of FGM [66]. The ability to tailor bio-compatibility along with mechanical and tribology performance made it popular for cartilage repairs, prosthesis fixture, dental screws etc. Titanium/Zirconia based FGCs fabricated using two-stage powder metallurgy method has gained wide acceptance in bio-medical industry as a permanent alternative to the skeletal cultivation [67].

3) Optoelectronics: Al6091/6092 FGCs reinforced with 40–44%SiC are preferred for electric sliding applications where electric conductivity and tribology resistance are incorporated within the same component [68]. Other aluminum grades like Al7075 are preferred along with significant ratio of copper for semiconductors, electronic displays etc. Advanced FGM manufacturing techniques like laser deposition techniques are preferred for electronic applications [69].

4) Aerospace: ability of certain FGMs to perform at high temperature without compromising its mechanical strength, made it feasible for structural applications like turbine blades, space jets, aerospace body sheets etc. Al reinforced with oxide based ceramics like Al_2O_3 revealed excellent thermal and corrosion resistance and are used to produce engine parts and rocket nozzles [70]. 304L stainless steel incrementally graded to Inconel 625 using additive manufacturing produced high-end

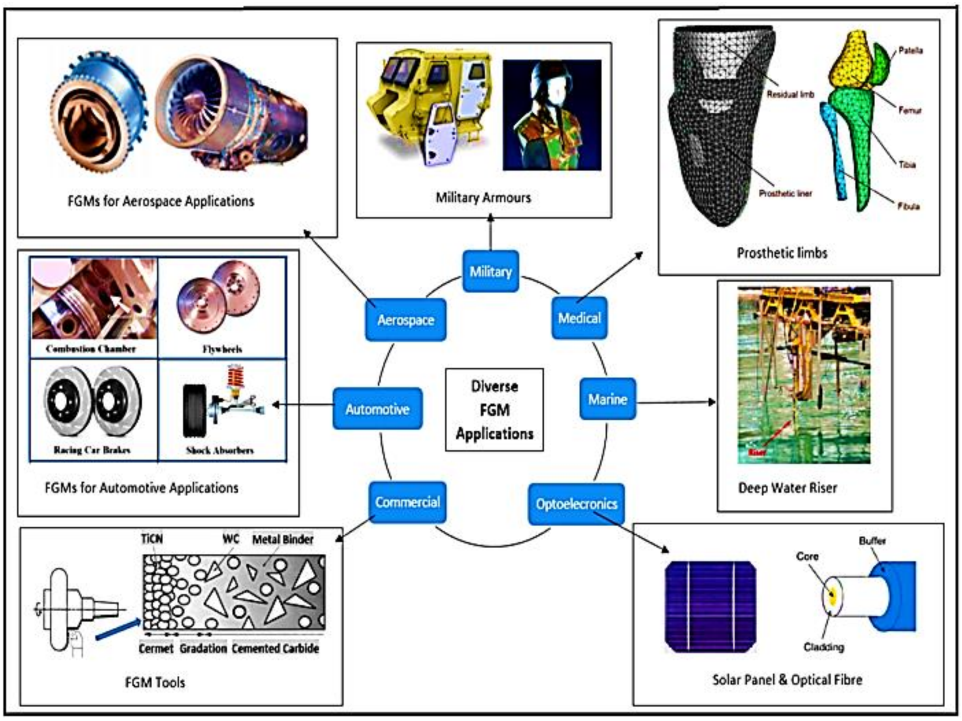

Fig. 16. Classification of engineering applications of FGM [66, 73-75].

corrosion resistant automobile engine valve stems [71]. Laser cladded Stainless Steel 316L and Inconel 718 FGMs are best suitable for thin thermo-wear resistant aircraft structures [72]. Other aerospace structures like heat exchange plates, reflectors, panels, bunks, turbine wheels and blades, nose covers, missile front edge and space shuttles widely prefer graded FGM structures.

5) Automobile industry: Some industrial Companies prefer carbide ceramic (SiC, TiC, B_4C) reinforced Al/FGMs for engine components and other automotive parts, which includes braking systems, shock absorbers etc., due to their excellent endurance and wear resistance [73]. Centrifugal casting technique is preferred in association with thermal treatment to enhance tribo-mechanical properties of copper based graded composites for heavy-duty bearing applications, as directional distribution and grain refinement is achieved through centrifugal/gravity forces.

6) Marine applications: Al/Steel FGMs with supreme mechanical strength and corrosion resistance are preferred for marine components like pipe system, deep water riser, dive cylinders, etc. [74].Anti-Corroding duplex stainless steel alloy reinforced with carbon manganese steel using WAAM technique produced graded composites for corrosive marine environment.

7) Commercial applications: apart from the industrial applications, FGMs produced via diverse fabrication routes are used for manufacturing tool inserts, laptop cover, elevators, music instrumentsetc. Tungsten-carbide or Titanium carbon nitride when reinforced with cobalt produces graded structures to manufacture cutting tools like turning tools, drills, grinding and milling cutters [75]. This is due to their enhanced tool life, feed rate and low machining time achieved through improving surficial wear resistance and mechanical strength.

4.Conclusion

Selection of manufacturing technique is highly scrutinized based on functionality, geometry, applicability, material composition, work environment and surface texture. Various fabrication techniques are classified based on three phases - solid, liquid and gas and the influential parameters and processing techniques are compared.

Powder metallurgy being the primitive solid phase technique for FGMs, is highly recommended for ballistic-military operations with effective stacking of distinct layers. The limitation of sharp layer boundaries periodically evolved with the introduction of sintering, to facilitate complex and precise structures like screws and lens molds.

Additive manufacturing techniques like FSAM and WAAM promotes scalability of commercial FGM production that facilitates oriented gradation for complex parts.

Among liquid phase techniques, infiltration is less preferred for complex structures whereas, Langmuir-Blodgett (LB) film method has emerged as an advanced technique for precise FGM layering for electronic applications. Among liquid phase techniques, infiltration is not suggested for complex structures whereas,

Langmuir Blodgett (LB) film method has emerged as an advanced technique for precise FGM layering for electronic applications.

Centrifugal casting is the most established production technique among other FGM manufacturing techniques as it facilitates versatility and commercial feasibility. Extensive flexibility to produce hybrid composite castings and double FGMs has sustained its popularity in this current era.

Gaseous phase FGM techniques like vapour deposition techniques have limited scope for graded thin coatings. However, thermal spraying improves the heat insulation performance of FGMs by eliminating the risk of coating heterogeneous materials.

Nowadays, FGMs are gaining a vast acceptance among the electronic industry where advanced processing techniques like electro-chemical gradation and laser deposition provides graded coatings over complex shapes and structures. However, when compared among FGM manufacturing techniques, horizontal centrifugal casting is widely being subjected to bulk FGM research since years and still in demand. This is due to its ability to accommodate growing industrial demands with minor variations in mass production parameters or material composition with low economic burden.

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