Review Paper

Functionally graded materials classifications and development trends from industrial point of view

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Abstract

Over the last few years, many classifications have been proposed for functionally graded materials (FGMs). In this Paper, critical review of different available classifications for FGM based on their physical, structural and manufacturing characteristics are presented. Advantages and limitations of each fabrication method for use in a given application is correspondingly considered. In addition, new classifications based on gradation control and accuracy, residual stresses, specific energy consumption, environmental impact evaluated throughout the complete life cycle and manufacturing costs are proposed. These classifications mainly reflect the needs of both FGM designers and industrial manufacturers. Based upon the presented classifications and the recent advances in analysis and production techniques, new major directions for FGMs research are proposed.

Keywords Functionally graded materials (FGMs) · Processing techniques · Classification · Advantages · Limitations · New trends · Industrial application

1 Introduction

Many applications such as aerospace, automotive, power generation, microelectronics, structural and bioengineering demand properties that are unobtainable in conventional engineering materials [1, 2]. These applications require mutually exclusive properties to have resistance against thermo-mechanical stresses as well as chemical stability. The need for property distributions are found in a variety of common products that must have multiple functions, such as gears, which must be tough enough inside to withstand the fracture but must also be hard on the outside to prevent wear [3]. Similarly, a turbine blade should also possess a property distribution. The blade must be tough to withstand the loading, but it must also have a high melting point to withstand high temperatures on the outer surface [4].

Conventionally, surface treatment or hardening techniques were used to reach the required properties. However, there were always concerns about the properties at the interface or the adhesion of the surface layer to the substrate materials [5]. In addition, the treated surface layer may not be sufficient to achieve the required product life [6]. Although alloying can be used to partially improve the performance in such cases, there is a lot of limitations related to material solubility due to thermodynamic equilibrium. Likewise, alloying of two materials with wide apart melting temperatures is difficult or even impossible. Powder metallurgy represents an excellent method of producing parts with conflicting properties than conventional alloying [7]. Another method to achieve tailored material properties is the use of composite materials. Both matrix and reinforcing materials possess distinct physical and chemical properties. Composite materials offer excellent combinations of conflicting properties. Unless the material is laminated, the properties of composites are equally distributed over the entire material giving a homogeneous behaviour on the product level. This cannot be used to achieve the required gradient in

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the applications mentioned above [8]. Although laminated composites can produce very narrow but discrete change of properties across the thickness, they suffer from interlaminar shear stresses and discontinuity at the interface.

In 1972 the general idea of structural gradients Functionally Graded Materials (FGM) was initially proposed for composites and polymeric materials [9] to imitate the structure and behavior of natural materials like bones, teeth [10] and Bamboo trees [11] etc. The concept of FGM was first applied in Japan in 1984 during the design of a space shuttle [12]. The objective was to manufacture the body from a material with an improved thermal resistance and mechanical properties by gradually changing compositions to withstand severe temperature difference of 1000 °C. Figure 1 illustrates the historical progress from pure metal to functionally graded metals.

FGMs exhibit many advantages compared to conventional alloys and composite materials. FGMs introduce means for controlling material response to deformation, dynamic loading as well as to corrosion and wear [13], etc. Furthermore, they give the opportunity to take the benefits of different material systems e.g. ceramics and metals [14]. In addition, biocompatibility of some FGMs increase their suitability as bone replacement. FGMs can also provide a thermal barrier and can be used as high scratch resistance and reduced residual stress coating [15]. Similarly, FGMs can be used as a high strength bonding interface to connect two incompatible materials [16]. Figure 2 illustrates the possible variation of properties in conventional composites compared to FGMs. A single FGM can be obtained by a single dispersed constituent/phase that is not uniformly distributed within the matrix compared to conventional composites, while more than one constituent/phase in the case of double FGM. The continuous gradient is obtained in all cases, depending on the change distribution density among the used constituents/phases and the matrix.

FGMs were initially classified by researchers under conventional composite materials depending upon the used combinations of constituents [17]. There exist many possible material combinations that can be used to produce FGMs. Metal–metal, metal–ceramic, ceramic–ceramic or ceramic–polymer [18] are the most common as shown in Fig. 3 [17, 19]. Over time, and because of the development of more applications and technologies to produce FGMs at different scales, different classifications appeared. In the third section of this paper, six conventional classification criteria were presented to classify the FGMs based upon: state during processing, FGM structure, FGM type, nature of FGM gradient, main dimensions, and field of FGM application [20, 21]. With the help of these aspects or classifications, the fabricated FGM can be always described. However, these classifications are of little help to FGM industrial producer in the selecting the appropriate fabrication technique that fulfills both the technical requirements of the designer (e.g. shape complexity, accuracy, minimum residual stress), and the economic requirements of the industry (e.g. productivity, minimum energy, minimum cost, lower environmental

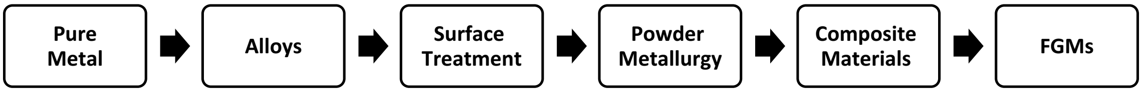


Fig. 1 Material development towards FGM [5]

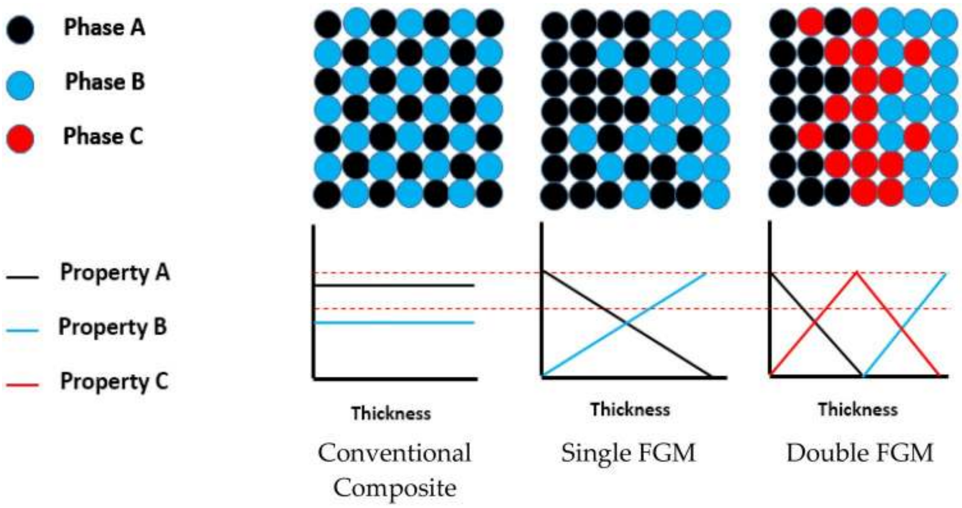


Fig. 2 Variation of properties in conventional composites and FGMs [22]

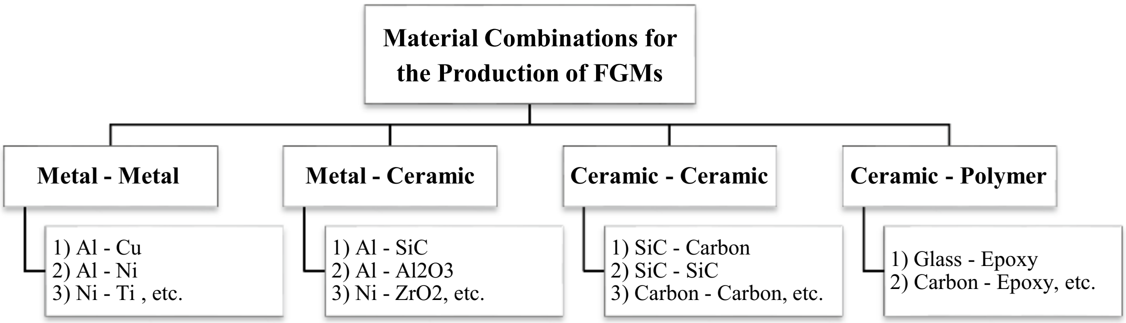


Fig. 3 Examples of possible material combinations used in FGMs (after [19] with modification)

impact). The classifications that will be introduced in this paper aims at providing some guidelines for the industrial manufacturer to find the proper fabrication technique that meets both the technical and economic aspects.

2 FGM production methods

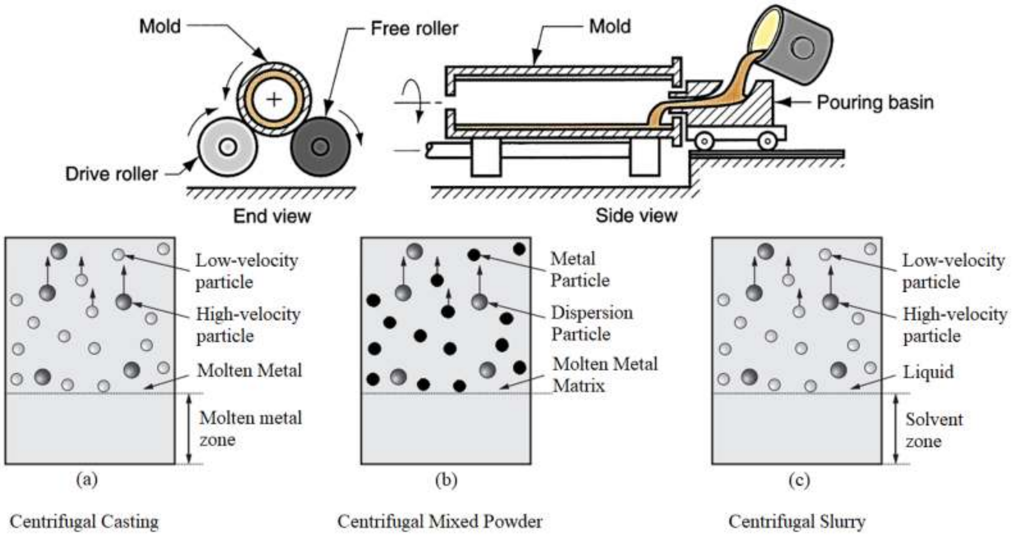
Quite a large number of well-known techniques and fabrication routes are widely used for the production of FGMs as summarized in Fig. 4. These ranges from old and simple to advanced and complex techniques and covers various physical and chemical principles. FGM production techniques include centrifugal casting, powder metallurgy, plasma spraying, chemical and physical vapor deposition (CVD/PVD), lamination and infiltration methods, in addition to the family of solid freeform fabrication (SFF) or additive manufacturing (AM) with its subcategories. Nowadays, various kinds of materials can be used in AM processes, including metallic material in LENS and DMD, polymer material in FDM and SLA, and biological material in inkjet printing and micro extrusion [23]. Many publications which focus on the description of the details of the different production methods and discuss their technicalities, advantages, limitations, applications and research trends are found in literature [3, 24–32]. It is clear that most research work focused on experimental mechanical characterization (esp. tensile and hardness) [33], wear rate prediction [34] or thermal properties evaluation [35]. Very few research groups are considering numerical simulation of FGMs. This may be due to the high degree of complexity related to the modelling of the different constituents and their properties, modeling of interfaces and the gradual change of structure. Description of FGMs production techniques is not within the scope of the current work. However, the main characteristics, advantages and limitations of available manufacturing families and processes are of great interest for the purpose of process classifications.

Table 1 summarizes these aspects and lists a number of recent publications which were mostly concerned with the optimization of FGM production parameters or aimed at the achievement of specific properties. The number of publications reflects the trends of scientific concern and the market importance of some manufacturing techniques. These cover a wide range of product sizes, complexity, durability, productivity and cost. Centrifugal casting technique that suits more bulky and simple products is still in competition with high quality powder metallurgy processes used for manufacturing of special moderate complexity parts, and with advanced additive manufacturing techniques (AM|) which proved to excel in producing relatively small complex prototypes. The information extracted from the listed sources is used to introduce the main technical features of each of the available manufacturing process to the reader. This gives a different perspective that helps in understanding the reason behind the need for new classifications that differs from the conventional classifications presented in the next section.

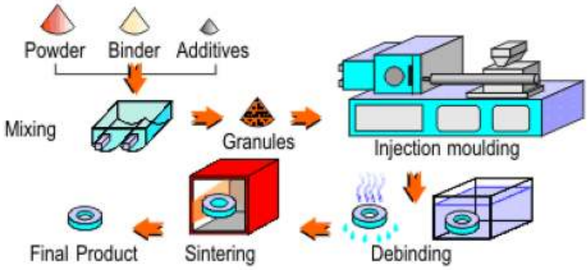
3 Conventional classifications of FGMs

3.1 According to the state during FGM processing

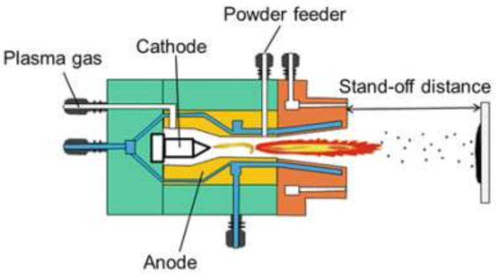
Based on the state of FGM processing, methods can be broadly classified into solid state processes, liquid state processes and deposition processes. Figure 5 lists the different processing methods falling under these categories [36]. There exists a large number of research work covering all processing states within different FGM production techniques. Deposition methods represent highly advanced technologies that are used for high accuracy and small products. Liquid-state processes are usually used for large products of relatively lower property control, while solid-state-based FGMS are utilized for highly stressed thermo-mechanical components [37]. The production of FGM by different routes and in different states affects the



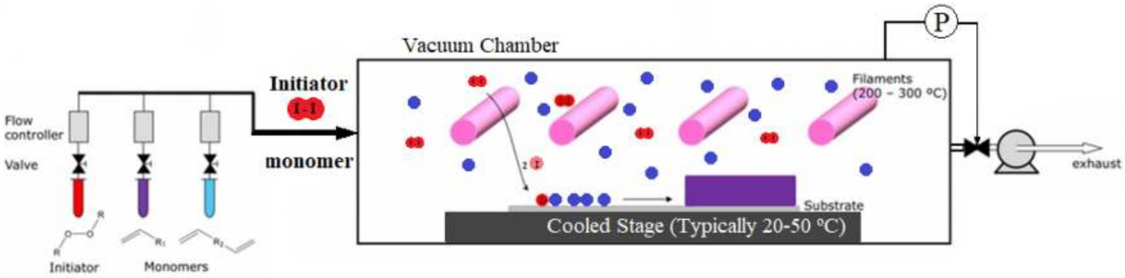
Centrifugal Casting Methods [39, 40]



Powder Metallurgy (PM) [41]



Plasma Spray Forming (PSF) [42]



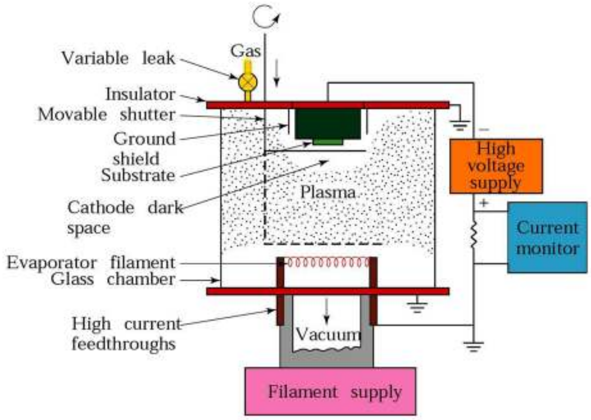
Chemical Vapor Deposition (CVD) [43]

Fig. 4 Commonly used processing techniques for production of FGMs

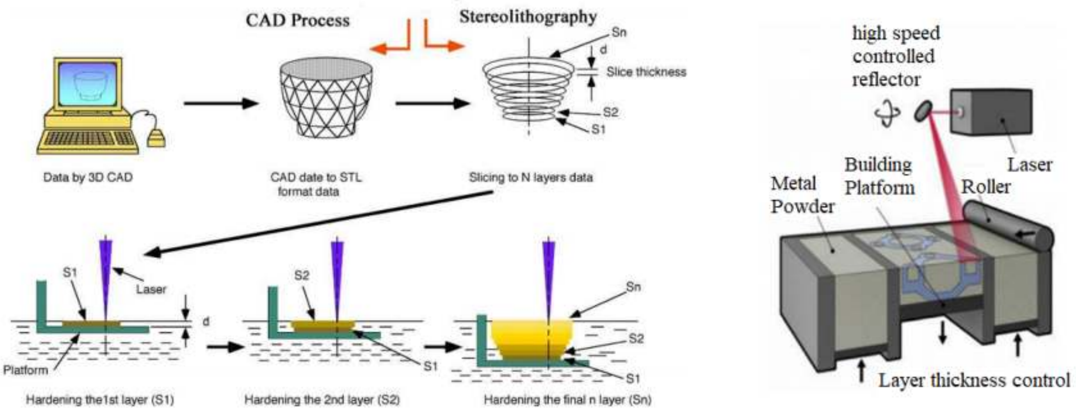
characteristics of the final product according to the thermal influences, mechanical loading, pressure and inertia forces taking place during manufacturing.

3.2 According to FGM structure

FGMs can be generally classified into two main groups: continuous and discontinuous graded material as shown

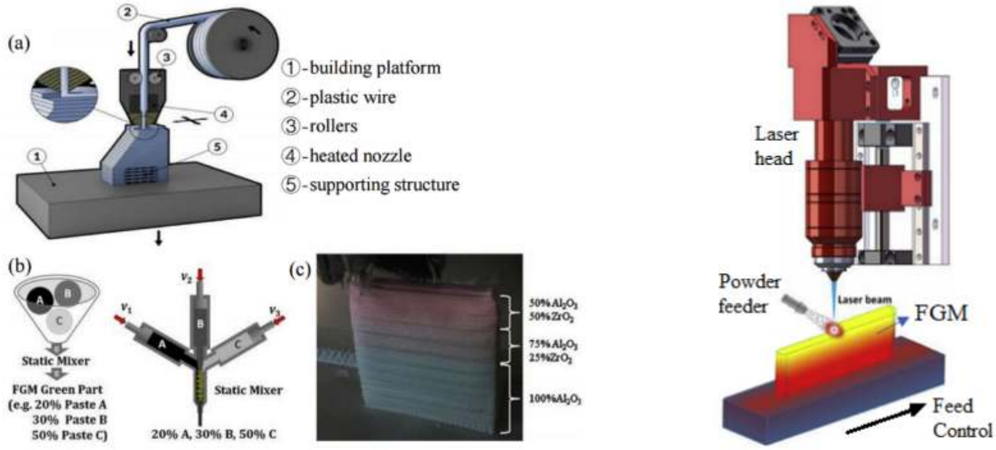


Physical Vapor Deposition (CVD) [44]



Solid Freeform Fabrication (SFF) [45]

Selective Laser Sintering/Melting (SLS/SLM) [46]



Fused deposition modelling (FDM) with triple-wire-extruder and sample FGM consisting of Al_2O_3 and ZrO_2 [47]

Laser engineered net shaping (LENS) based on powder deposition [46]

Additive Manufacturing Techniques used for the production of FGMs

Fig. 4 (continued)

Table 1 FGM production techniques with advantages and limitations

Processing technology	Advantages	Limitations	Publications
Powder metallurgy (PM)	Different layers/constituents possible Produced layers can be of different thickness (nano to mm range) Low stresses during sintering High productivity	Non-continuous structure Wall thickness > 2 mm, height/diam. < 7 Undercuts and threads should be machined in following process Economic feasibility > 100,000 products	[47–55]
Centrifugal casting method	Continuous Grading can be achieved using centrifugal casting method Suitable for bulky/large products	Only cylindrical shapes possible Graded structure difficult to control due to melting problems	[56–97]
Centrifugal slurry method	Continuous grading More rapid densification kinetics than the solid phase sintering Very high fraction of refractory phase can be used	Only cylindrical shapes possible Solvent is needed to obtain good distribution Cannot form Nanoparticles	[39, 98, 99]
Centrifugal mixed-powder	Similar to centrifugal slurry method, but can form nano-particles	Only cylindrical shapes can be formed	[38, 100–102]
Gravity settling	Continuous Grading can be achieved using this method A range of particle sizes can be used	Tendency to produce separate zones of relatively constant volume fraction. Not suitable for all materials	[36]
Additive manufacturing (AM) and solid freeform fabrication (SFF)	Complex shapes are possible Low cost for prototyping From art to part directly (min. tooling) High accuracy High repeatability	Secondary finishing operation is required Mainly produce discrete structure Very high specific energy consumption Huge equipment costs in case of metal products Lower productivity rates	[37, 103–105]
Plasma spray forming	Simultaneous melting of metallic and highly refractory phases, blending the two in ratios that can be present by control of the feeding rates of the powders of the two materials	Optimization of processing parameters (such as distance between gun and substrate, feed-rate, carrier gas composition) can differ between the two components of the FGM structure	[41, 106–108]
Laser deposition	High accuracy due to laser control Selectively deposited material reduce the post-process machining/finishing	Uneconomical for bulk FGM Only produce discrete structures Relatively high residual stresses requires post heat treatment	[109–114]
Vapour deposition processes	Layers can be in nano/micro range Graded structure easy to control simply by varying the composition of the gas phase	Attention must be paid to subsequent heat treatments to avoid inter diffusion between the substrate and the graded film	[115, 116]
Infiltration	Layers produced can be very thin Structure has a good mechanical strength Suitable method for FGMs containing phases of very different melting points	Difficult to control process Graded preform should have sufficient porosity for the liquid metal to penetrate and get solidified	[117–120]

in Fig. 6 [121]. In the first group, no clear zones or separation cut lines can be observed inside the material to distinguish the properties of each zone. In the second group, the material ingredients change in a discontinuous stepwise gradation which is known as layered or discrete FGM. Continuous and discrete can further be classified into three types: composition gradient (Fig. 6c, f), orientation gradient (Fig. 6d, g), fraction gradient (Fig. 6e, h). A further subgroup can be obtained by considering size change in any of the cases (e.g. grain size coarsening or different particle sizes) [45].

Fraction gradient type can be obtained by utilizing centrifugal force through the use of centrifugal casting process [63]. Centrifugal and repulsive forces act on the particles [27], which are dispersed into the melt. There is also the gravitational force, but in almost all cases, gravity is very small with respect to the centrifugal force and can be neglected [32]. Theoretically, shape gradient can introduce a well-tailored property distribution. However, the process of fabricating the reinforcing/dispersed phase with the necessary accuracy and the placement of the shaped constituent is very sophisticated and cost intensive from manufacturing point of view. Powder metallurgy represents one of the important method of producing FGMs containing shape gradient [121].

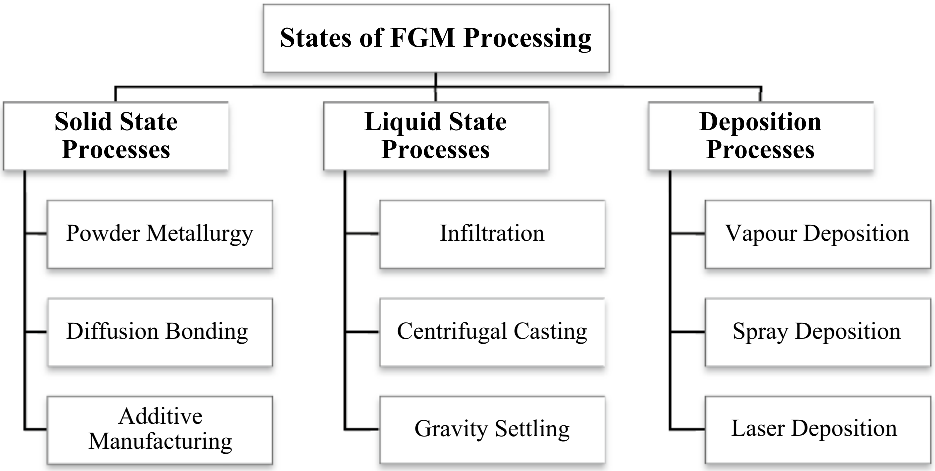


Fig. 5 Classification of FGMs according to state during manufacturing (after [36] with modification)

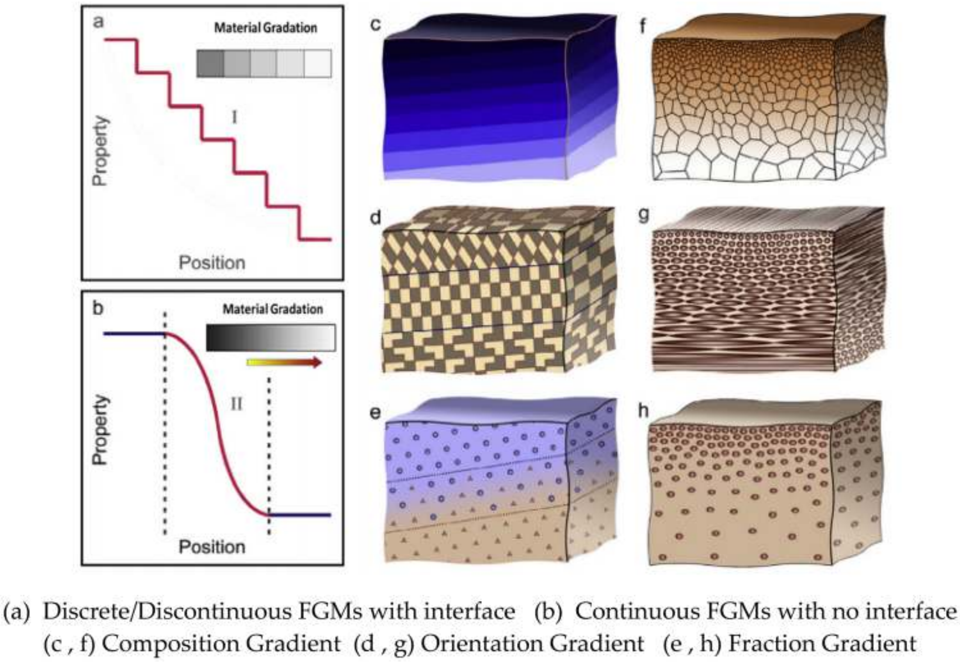


Fig. 6 Functionally graded materials with different forms of gradient [45]. **a** Discrete/discontinuous FGMs with interface. **b** Continuous FGMs with no interface. **c**, **f** Composition gradient. **d**, **g** Orientation gradient. **e**, **h** Fraction gradient

The properties of FGMs containing orientation gradient change as a result of a change in particles orientation, not due to a phase ratio or size change. There are different methods that can be used to achieve orientation gradient in FGMs. Subjecting the molten metal to strong electromagnetic fields can help in reorientation of the reinforcing particles in the molten metal slurry. The electromagnetic forces have different roles depending on the type of the produced functionally graded (FG) composite. In the production of reinforced ceramics by liquid routines [122], they may be used to drive the ferromagnetic particles to the required position and with required orientation. On the other hand, electromagnetic forces are used to affect the solidification of the liquid matrix in MMC [32]. An appropriate thermal control of die cooling with the aid of electromagnetic fields governs the magnitude and direction of the solidification velocity [123] and help in obtaining the graded structures in MMCs [124].

Size gradient FGMs are easily achievable based on the fundamental phenomena of flotation and sedimentation. Gravity and squeeze casting processes make use of these phenomena along with gravitational forces for the production of particle reinforced composites. Through manipulation of particles' sizes/masses and surface properties, particles can be distributed in the molten metal/alloy according to the magnitude and the direction of the resultant force [3]. Centrifugal and repulsive forces acting on the dispersed constituent also have an effect on the resulting FGM structure.

3.3 According to the type of FGM gradient

FGMs can be generally classified into three different groups of gradient: composition, microstructure, and porosity as shown in Fig. 7 [125]. The composition type of FGM gradient depends on the composition of the material, which varies from one substance to another, leading to different phases with different chemical structures. These different phases of production depend on the synthetic quantity and the conditions under which the reinforced materials are produced [41]. During the solidification process, the microstructure type of the FGM gradient can be achieved so that the surface of the material is extinguished. In this type, the core of the same material can cool slowly, helping generate different microstructures from the surface to the inside of the material [126, 127]. With the changes in the spatial location in the bulk material, the porosity type of FGM gradient in the material changes [128]. Powder particle sizes can be measured by varying the pore particle sizes used during gradation at different positions in the bulk material [129].

3.4 According to the FGM scale and dimensions

“Thin FGMs” are manufactured by different methods like physical vapor deposition (PVD) [109], chemical vapor deposition (CVD) [130, 131], thermal spray deposition [132] and self-propagating high temperature synthesis (SHS) techniques like laser cladding (Fig. 8) [133–135], while “Bulk FGMs” are manufactured by powder metallurgy [136, 137], centrifugal casting [138, 139], solid freeform techniques [140], gravity settling. Thin FGMs ranges between 5 nm and 500 nm [141, 142] and may be extended to the micro-meter range (e.g. 1–120 µm thick deposited layers [130, 143]. In thick FGMs, gradients can cover 5–350 mm [26, 56, 144]. Also, the gradient of FGM can developed along one, two or even three different directions.

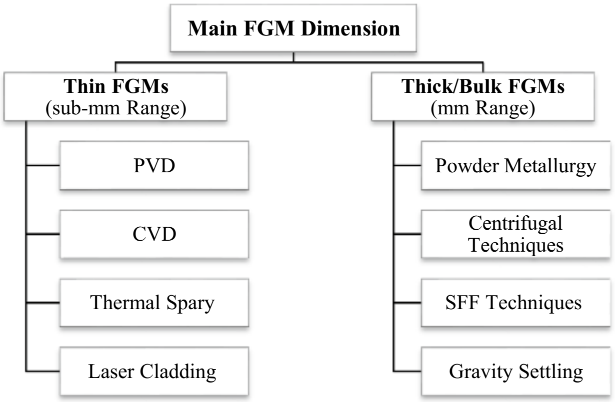


Fig. 8 FGMs classification based on the main FGM dimension (after [32] with modification)

3.5 According to the nature of FGM gradation process

Another classification of the gradation process divide the FGM production to constructive and transport processing [145]. The first category assumes a layer by-layer construction starting with an opposite distribution in which the consecutive gradients are exactly constructed [146]. While in the second category, gradients within the structures are dependent on the physics of transport method (e.g. fluid flow, diffusion or heat conduction) [69, 147]. The advantage of constructive methods is the ability to fabricate unrestricted number of gradients. Advances in additive manufacturing during the last two decades have proved that constructive gradation processes are technologically and economically feasible, especially

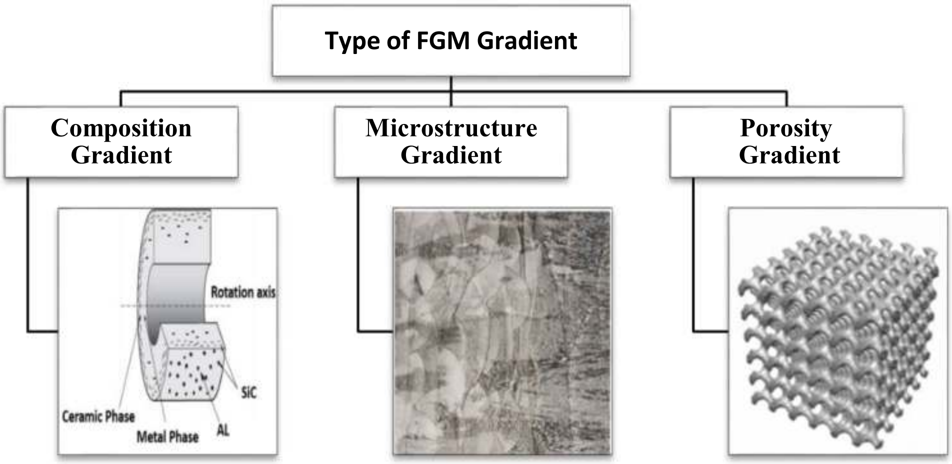


Fig. 7 Typical example of three different types of FGM gradient [125]

for prototypes and small batch production (Fig. 9), even with constituents that are not entirely compatible or homogeneous in nature [36]. Additive manufacturing (AM) techniques, offer additional advantages in form of accuracy and repeatability to reproduce the designed gradients and properties [148].

3.6 According to the field of application

As described in the introduction section, FGMs were found and used in either severe operating conditions or very sensitive application. Examples include heat exchangers, heat resisting elements in space crafts or fusion reactors as well as for biomedical implants. [28, 149, 150]. Various combinations of the ordinarily incompatible functions can be implemented to create new materials for aerospace, chemical plants, nuclear energy reactors, etc. [22, 151, 152]. According to area of application, FGMs can be classified into biomaterial [125, 153–155], aerospace [156–158], automotive [159, 160], defense [161, 162], cutting tools [163], nuclear reactor [164], smart structure [165], turbine blades [166] and sports equipment [167]. Figure 10 represent an overview of the classification according to the major fields of applications.

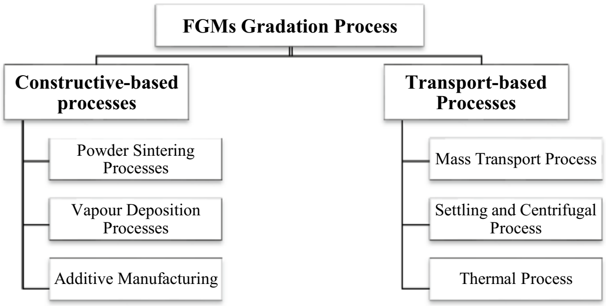


Fig. 9 Classification of FGMs according to gradation method [36]

4 Proposed classifications for FGM processing methods

The classifications which have been introduced in previous sections are mainly based on the nature of the constituents and their physical characteristics (size, relative positioning and density) to suit a specific application. However, in most fabrication processes, there is no concrete design methods that can be followed to realize a specific property gradient. In the following subsections, widely used FGM production techniques will be classified from designer or manufacturer point of view. The classifications will consider some technical aspects such as the realizable the complexity of product form and wall thickness, the degree of control on gradient, the developed residual stresses due to the FGM production method, the specific energy consumption and the related environmental impact, in addition to the economic aspects which will be represented in form of evaluation of the equipment and total production costs. These classifications aim at providing guidelines for the manufacturer to help them selecting the FGM manufacturing process which almost meets their technical requirements and provide answers to their economic-related questions.

4.1 Classification according to the achievable complexity of shape

Complexity of shape plays a vital role in the selection of the FGM manufacturing process [168, 169]. The complexity of shape may be quantified or classified by the ability of the manufacturing method to create a complicated geometries in distinct directions or by the possible achievable directions of gradients in the space [169–172]. A perspective for classification according to complexity of product shape is represented in Fig. 11.

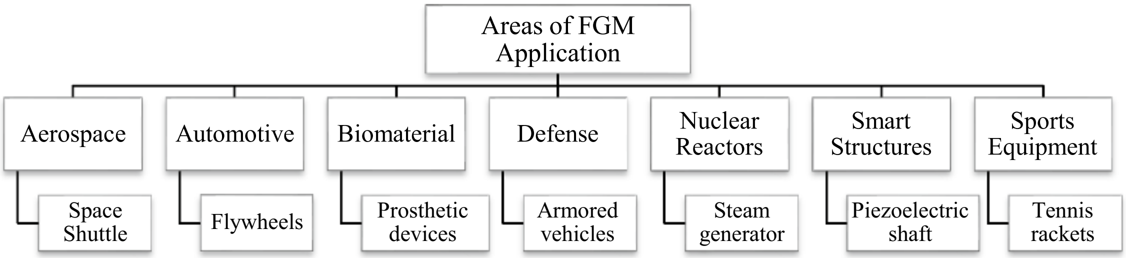


Fig. 10 Functionally graded materials: fields of application and examples

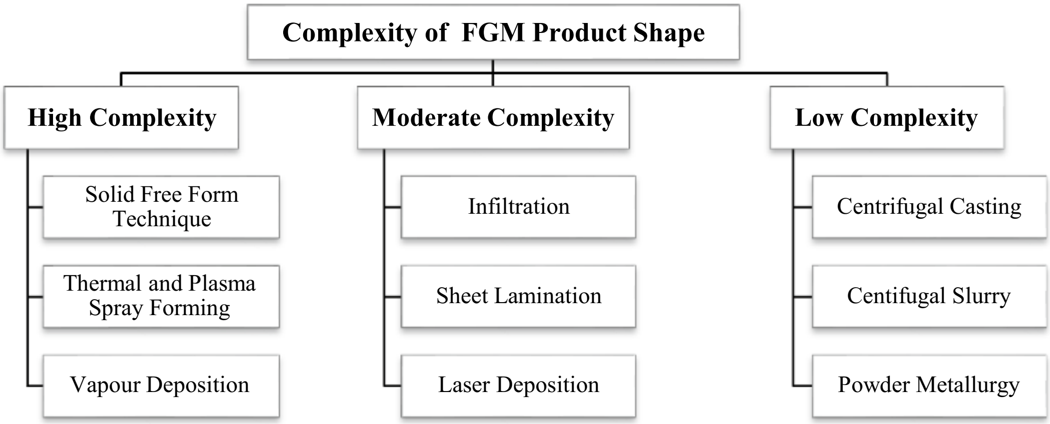


Fig. 11 Classification of FGMs according to product complexity

4.2 Classification according to the degree of gradient control

FGMs can be classified according to the degree of control on gradient or the accuracy of reinforcing phase distribution into three main categories: high degree of process control, moderate degree of process control and low degree of process control, as shown in Fig. 12 [100]. Gradient control is defined as the degree by which the predesigned property change governed by the particle or reinforcement concentration along the direction of gradient is achievable. High control methods can realize the predesigned property gradient with an accuracy of more than 90%, as shown in Fig. 13 [173]. The high grade of control is mainly achieved by the capability of the process to place the reinforcing constituents. This is more realizable in solid state processes than in liquid state ones. Although low control techniques provide smoother variation of properties compared to moderate control methods, the control of production parameters in the first group is much more complex due to the considerable number of involved parameters as well as their interactions. For example, the range of particle size in powder to be used for powder metallurgy should vary from 4 microns to 200 µm [174]. In addition, there is a wide range for the variability of each parameter such as grain size of particles or the viscosity of matrix material at different points inside the FGM during solidification [175]. Moderate and low control methods are not normally predesigned to achieve a specific property gradient and depends mainly on experience of the manufacturer or trial and error. The variation in the resulting gradient range between 50 and 60% in the low accuracy group and increase to 80% in the moderate accuracy group. Some examples of realizable gradients which can be achieved using both groups are represented in Figs. 13 and 14.

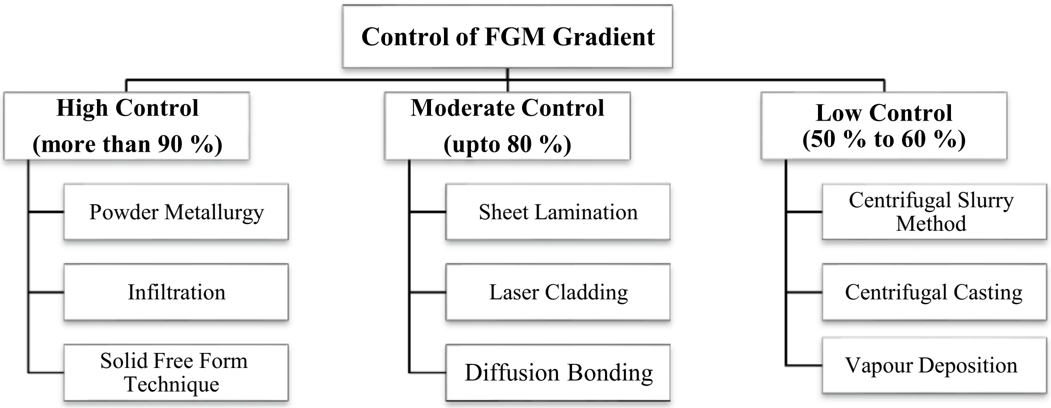


Fig. 12 Classification of FGMs according to control of property gradient

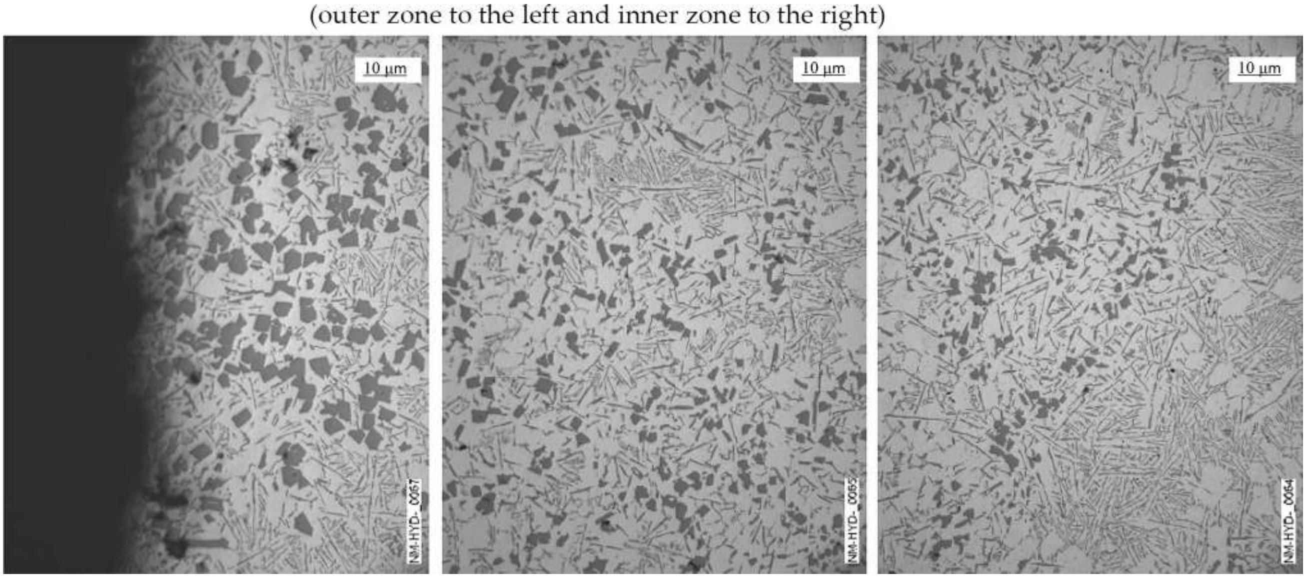


Fig. 13 Low degree of control on property gradient using centrifugal casting technique [36]

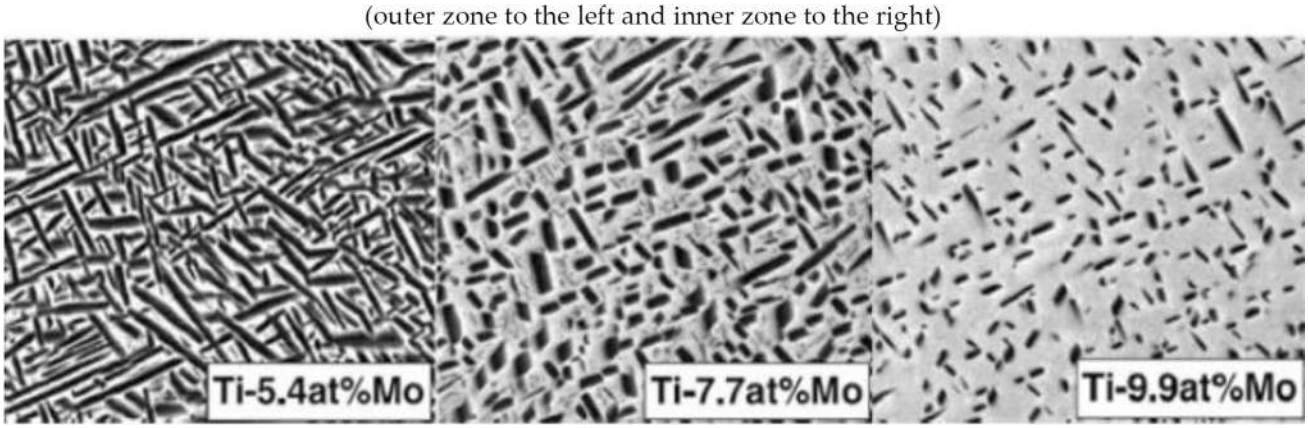


Fig. 14 Example of the high degree of control on property gradient using solid freeform technique [173]

Table 2 Residual stress for common FGMs manufacturing processes

Process	Residual stress (MPa)		References
	From	To	
Centrifugal casting	− 50	+ 35	[181–183]
Powder metallurgy	− 40	+ 100	[184–186]
Vapour deposition	− 150	+ 200	[176]
Electrophoretic deposition	− 200	+ 250	[177]
Laser cladding	− 50	+ 300	[178, 179]
Thermal and plasma spray forming	− 100	+ 200	[180]
Infiltration	Up to + 80 MPa		[150]

4.3 Classification according to the effect of residual stresses

Different FGM production techniques result in various levels of residual stresses that develop during manufacturing. Table 2 shows the residual stress value in the different production processes for thermal expansion (CTE) coefficients and large changes in production temperature. Figure 15 represents a perspective for classification FGM production methods according to the level of residual stresses. Although stress relief heat treatment is commonly advised to remove or reduce the influence of residual stresses, there are no investigations which are concerned with the post-treatment of FGM products to optimize the amount of residual stresses [176–180].

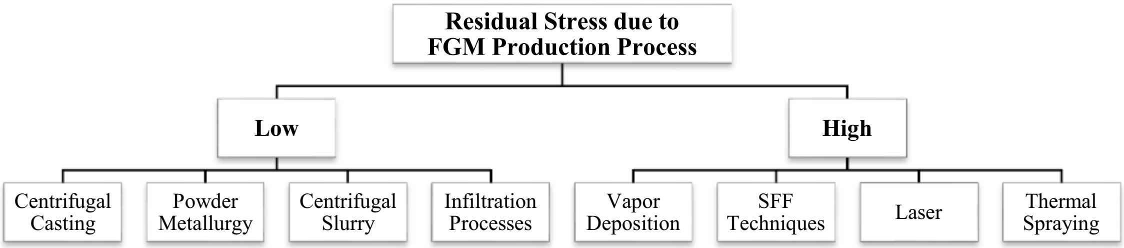


Fig. 15 Classification of FGMs according to residual stress

Table 3 Energy consumption throughout the life cycle [23]

Process	Machining	EBM
Final part (kg)	1.09	0.38
Ingot/material consumed (kg)	8.72	0.57
Raw material (MJ)	8003	525
Manufacturing (MJ)	952	115
Transport (MJ)	41	14
During service (MJ)	217,949	76,282
Total energy	226,945	76,937

4.4 Classification according to the energy consumption and environmental impact

Energy consumption has become a very critical factor while selecting a manufacturing technology. Detailed analysis of energy consumption distribution over the process stages (e.g. heating, feeding, pressing, removal, etc.) in addition to the energy needed for preprocessing of input materials and post-processing of products have been studied by many research groups [23, 187–190]. Specific energy consumption (SEC) is widely used for the comparison of different processes or process stages with respect to the produced mass (or volume in some cases). The evaluation of energy consumption has been extended in some studies to include the energy consumption estimate during the product life. An example of comparing the energy consumption of electron beam melting (EBM) technique to conventional machining is given in Table 3. This type of life cycle analysis (LCA) is used to evaluate the Global Warming Potential (GWP) and hence the environmental impact of the production process. Some investigations and industrial studies considered the comparison of some manufacturing processes that suits FGM production with conventional forming and machining processes and evaluated SEC and GWP for studied groups and processes.

Due to the difficulty to establish a general evaluation formula, models with different variables and weights were usually formulated and evaluated with the help of some case studies. For example, [191] compared SEC of various conventional forming techniques (casting, injection molding) and machining processes (milling, turning, drilling, grinding) to six different additive manufacturing techniques. An example of the presented series of SEC charts is shown in Fig. 16. The study also presented some beneficial pie charts showing the energy consumption distribution over the stages of each process.

Based upon the presented results, attention should be paid to the use of AM techniques as a powerful FGM production technique due to its very high SEC. In a recent study, Azevedo et al. [192] stated that “Additive

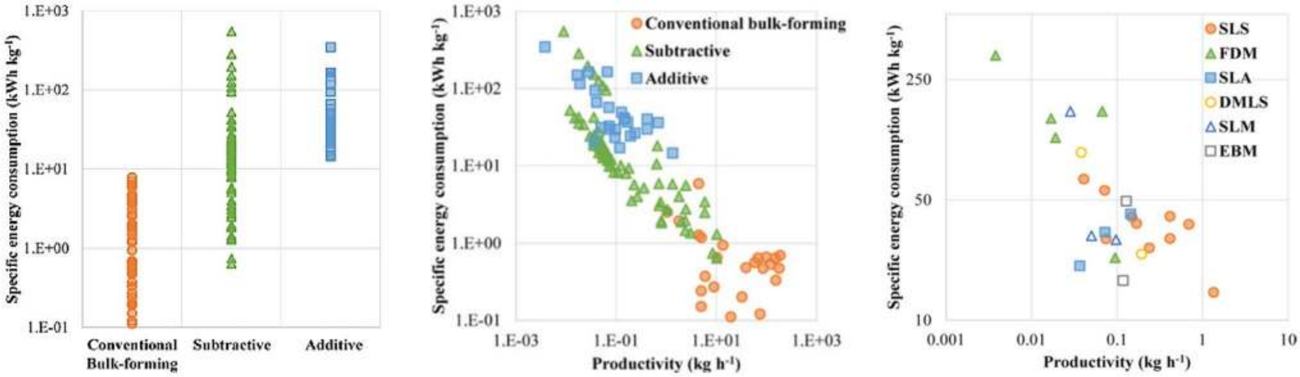


Fig. 16 SEC for different manufacturing processes and relation to productivity rates [191]

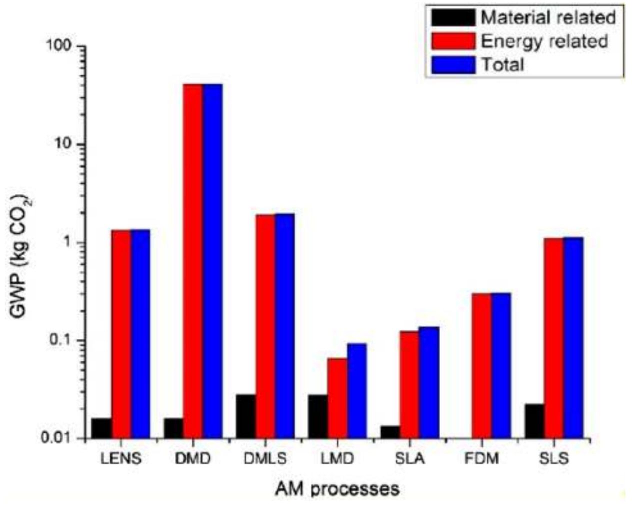


Fig. 17 GWP impact results of different AM processes [194]

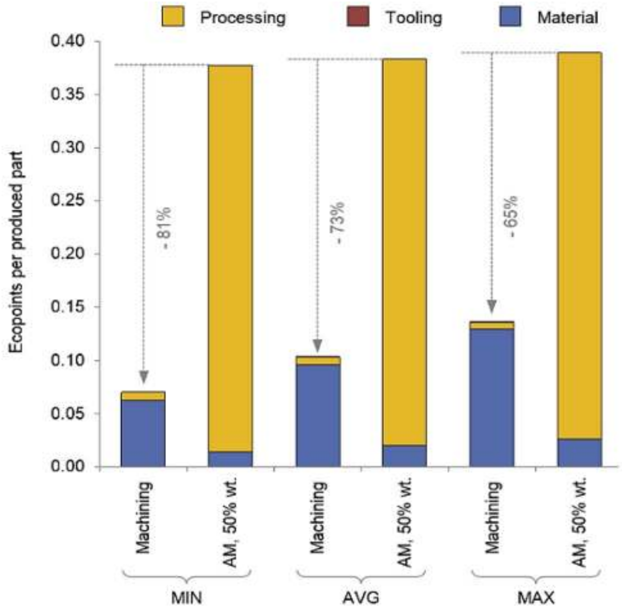


Fig. 18 Ecopoints comparison between AM and conventional machining with three geographically-dependent estimates of aluminum production [191]

manufacturing is the only process besides press and sintering whose environmental impact has been studied in the literature". In a recent publication, Liu et al. have evaluated the GWP impact of AM techniques as shown in Fig. 17 and proved that the optimization of process parameters can result in an improved GWP.

Ingarao et al. [193] investigated the environmental impact of AM techniques in comparison to conventional forming and machining techniques. The in-depth investigation included pre- and post-manufacturing stages in a detailed LCA analysis. Ecopoint is selected as single point indicator for environmental impact quantification, while $CO_{2\text{-eq}}$ was also selected as a single indicator for Global Warming Potential (GWP). Results revealed that AM could not be identified as an environmentally friendly solution. Even with scenarios assuming 50% weight reduction, conventional methods are still preferable. The change of "breakeven ecopoint" with the geographically-dependent variability of aluminum production is always in favor of forming processes for quantities more than 137 products. A case study of car component with AM optimized geometry showed that AM still does not result in more green choice. The breakeven Ecopoint is reached after about 2 millions of km drive distance! Figure 18 shows the high environmental impact of AM compared to conventional machining. It should be also noticed that processing cost is the decisive factor in AM processes due to the high energy demand.

According to the available information, models and discussion, FGM production methods can be broadly classified into low SEC, moderate SEC and high SEC processes. The different processing methods falling under these three categories are listed in Fig. 19. The data used for this classifications is collected from [190–192, 195]. The power ranges for some industrial equipment available on market is summarized in Table 4.

4.5 Classification according to the total process cost

Cost plays a significant factor in the selection of FGM manufacturing process. Cost factors include both fixed costs (which depends mainly on the used technique, required equipment and tooling as needed automation) and variable costs (which varies with many technical aspects including the used materials and processing parameters which greatly influence the energy consumption). The feasibility of a given production process should be always evaluated according to the planned production quantity or the breakeven volume. A number of research work and industrial reports considered the comparison of cost for different techniques which are suitable for FGM manufacturing, or compared them to conventional forming and machining processes. For example, a comprehensive study of costs and cost effectiveness of additive manufacturing was published by National Institute of Standards and Technology [190, 196, 197]. The study showed that the greatest AM cost driver is the initial investment in equipment. Initial machine costs account for 45–74%, while tooling account for only 5% of the total production cost, as shown in Fig. 20. In comparison, injection molding dies accounts for more than 90% of the manufacturing costs. According to a 2015 study published by the International Cost Estimating and Analysis Association, the AM materials' costs

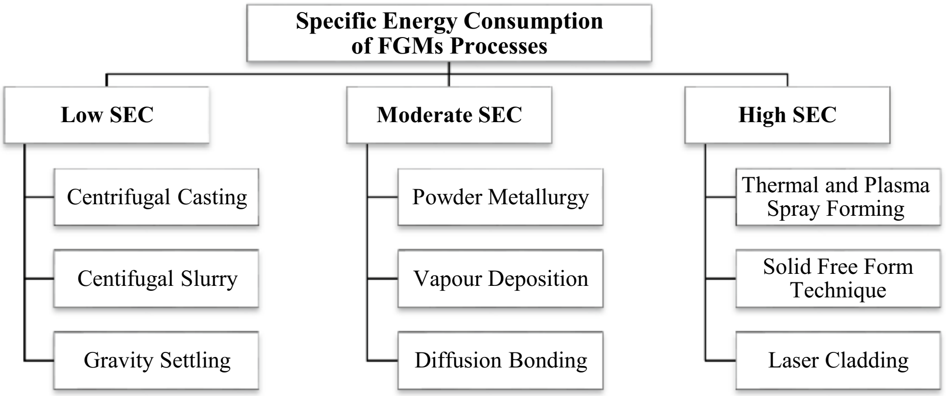


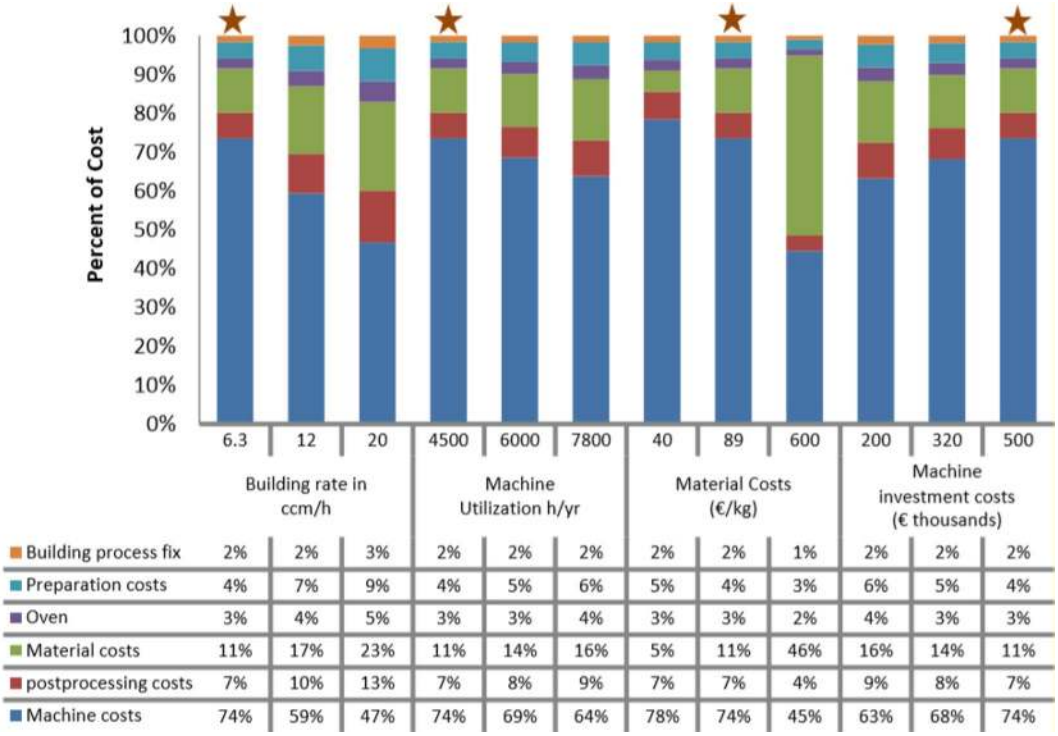
Fig. 19 Classification of FGMs according to energy consumption

Table 4 Energy consumption for some FGM manufacturing equipment (by UltraFlex Power Technologies)

Machine/process	Energy consumption (kW)	
	Small Part	Large Part
Centrifugal casting	2–3 kW	6–10 kW
Powder metallurgy	1–2 kW	4–7 kW
Vapour deposition	1–3 kW	5–8 kW
Laser cladding	50–70 W	200–500 W
Thermal and plasma spray forming	26–120 W	200–420 W

are nearly 8 folds of those used in conventional forming and machining on a per-weight basis. However, the lower material consumption in case of AM compensate the high material costs so that the materials cost accounts for 18–30% of the total production cost.

Experience of the manufacturer plays an important role at this point, where some rule of thumb exists for different processes. For example, PM products are economically feasible only for small parts with weights between 20 and 200 g produced in mass production in order of 10^4–10^5 products. This is due to the high tooling costs and the



	Building rate in ccm/h			Machine Utilization h/yr			Material Costs (€/kg)			Machine investment costs (€ thousands)		
	6.3	12	20	4500	6000	7800	40	89	600	200	320	500
🟧 Building process fix	2%	2%	3%	2%	2%	2%	2%	2%	1%	2%	2%	2%
🟦 Preparation costs	4%	7%	9%	4%	5%	6%	5%	4%	3%	6%	5%	4%
🟪 Oven	3%	4%	5%	3%	3%	4%	3%	3%	2%	4%	3%	3%
🟩 Material costs	11%	17%	23%	11%	14%	16%	5%	11%	46%	16%	14%	11%
🟥 postprocessing costs	7%	10%	13%	7%	8%	9%	7%	7%	4%	9%	8%	7%
🟦 Machine costs	74%	59%	47%	74%	69%	64%	78%	74%	45%	63%	68%	74%

Fig. 20 Parameters influencing the distribution of production cost drivers [197]

maximum achievable pressures [174, 198]. In some highly stressed automotive parts which are produced in high volumes, PM can provide cost saving between 20 and 50% when compared to conventional forging or die casting processes by eliminating preassembly machining steps and reducing material losses [199].

The total cost of some manufacturing methods can vary tremendously according to the product size, material and manufacturing temperature. For example, centrifugal casting of Ti–ZrO_2 of large FGM tubes that requires a high temperature resistant ceramic mould can shift the process fixed cost from a low cost to a high cost process [27].

Production volume is also decisive factor when considering economical aspects. For example, studies showed that AM can be more economically feasible for very small number of products as shown in Figs. 16 and 21. However, the smaller the product size and the material melting temperature, the more efficient and economical the process will be. For example, using smaller powder size and higher density as well as a smaller layer thickness and higher energy density in LENS process will cause a higher specific energy consumption and hence the total manufacturing costs. By controlling the processing condition, higher energy efficiency can be reached without affecting the product quality. For example, [23] give some recommendations for selecting laser power, scanning speeds, powder feed rates which are suitable for different materials (Inconel 718, Triboloy 800 and Stellite-1, AISI 4140) and comparing them to other materials available in literature.

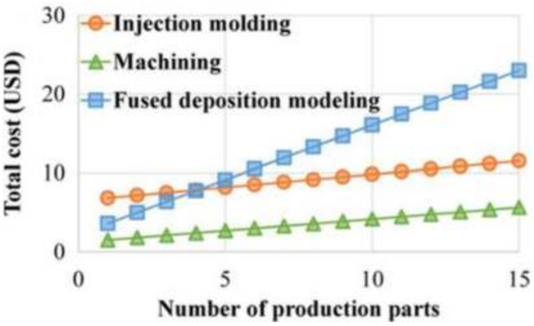


Fig. 21 Production cost as a function of production volume for different manufacturing methods [191]

Table 5 Capital cost for some FGMs manufacturing equipment (according to direct-industry website)

Machine/process	Estimated cost ($)	
	Small part	Large part
Centrifugal casting	400–1000	8000–13,000
Powder metallurgy	5000–6000	20,000–25,000
Vapour deposition	13,000–15,000	53,000–55,000
3D printing machine	350–900	37,000–50,000

For the purpose of classification, we assumed a medium sized product (in the mm-cm range) made of high melting point metallic material. Figure 22 represents a perspective for classification according to manufacturing costs, while Table 5 gives a range of capital cost for different FGM manufacturing equipment.

The classifications of available processing methods used to produce FG components are summarized in Table 6. Those classifications represent two groups of classifications. The first group is primarily dependent upon the physical characteristics of the FGMs and is obtained from literary information, while the second proposed group of classifications represents the proposed guidelines for designers and manufacturers.

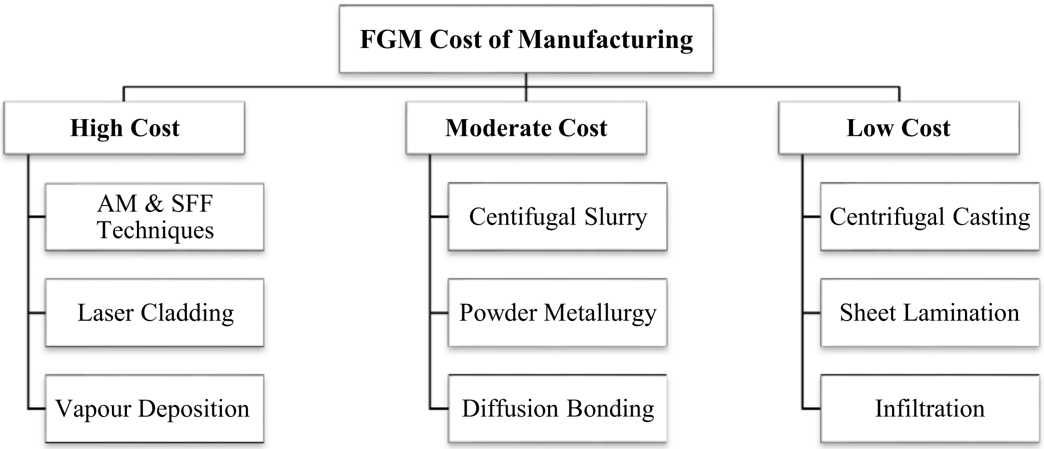


Fig. 22 Classification of FGMs according to process cost

Table 6 Summary of available and proposed classifications for FGM production methods

Processing technology	Structure	Process state	Gradation process	Dimension	Product scale range	Control of gradient	Complexity	Specific energy consumption	Fixed cost
Powder metallurgy (PM)	Discontinuous or stepwise structure	Solid state process	Constructive processing	Thick	Millimetre range to centimetre	High	Low	Moderate	Moderate
Centrifugal casting method	Continuous structure	Liquid state process	Natural transport phenomenon		Centimetre range to metre	Low	Low	Low	Low
Centrifugal slurry method	Continuous structure	Liquid state process with solid state	Natural transport phenomenon		Millimetre range to centimetre	Low	Low	Moderate	Low
Centrifugal mixed-powder method	Continuous structure	Liquid state process with solid state	Natural transport phenomenon		Nanometre to millimetre range	Moderate	Low	Moderate	Low
Gravity settling	Discontinuous or stepwise structure	Liquid state process	Natural transport phenomenon		Centimetre range to metre	Moderate	Moderate	Low	Low
Solid freeform fabrication (SFF)	Discontinuous structure	Solid State process	Constructive processing		Millimetre range to centimetre range	High	High	Very high	High for metals
Thermal and plasma spray forming	Continuous structure	Deposition state process	Natural transport phenomenon	Thin	Nanometre range	Moderate	High	Very high	Moderate
Laser deposition	Discontinuous structure	Deposition state process	Constructive processing		Nanometre range to millimetre range	Moderate	Moderate	Very high	High
Vapour deposition process	Continuous structure	Deposition state process	Constructive processing		Nanometre to millimetre range	Low	High	Moderate	High
Infiltration	Continuous structure	Liquid state process	Natural transport phenomenon		Millimetre range	High	Moderate	Low	Low

5 FGMs challenges and new frontier

There are some issues that need further investigations and research efforts to make use of FGMs on industrial scale. The following points summarizes the main research directions that should be followed [123, 200]:

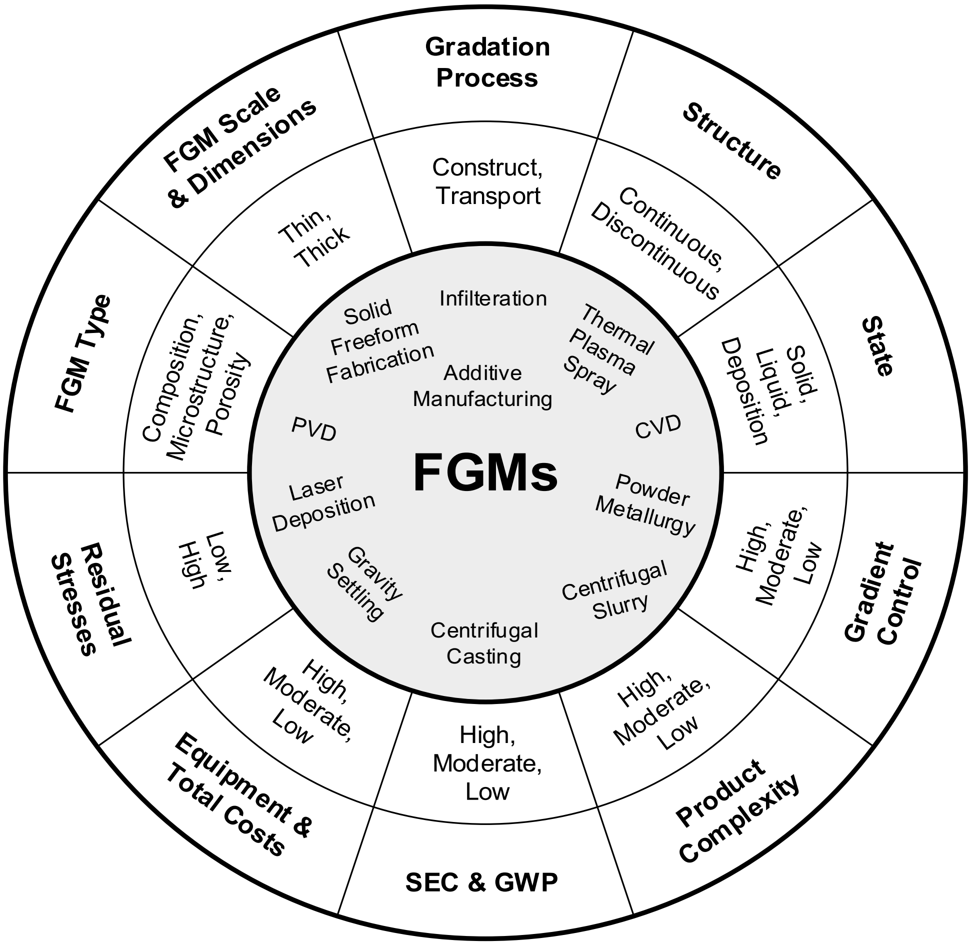
1. Building adequate material models that describe the physical properties of FGMs.
2. Developing a proper database for FGMs (including material systems, parameters, material preparation, performance evaluation and long-term reliability).
3. Improving the continuum theory, quantum (discrete) theory, percolation theory and micro-structure models.
4. Building computer simulation models for FGMs.
5. Investigating the performance of different FGMs in wear, fatigue, corrosion, residual stresses, semi-conductivity, etc. and optimizing the production parameters.
6. Developing a systematic methodology for selection of most adequate FGM production technique according to the required component's characteristics.
7. Developing a systematic methodology for designing components made of FGMs according to the selected production technique.
8. Analyzing the economic aspects of the production processes aiming at integration into the mainstream of industry.

6 Summary and concluding remarks

Functionally graded materials have proven their position among modern advanced materials. They became a hard competitor in wide cluster of applications, especially in energy, defense, aviation and medicinal areas. The increasing interest of FGMs in research and industrial communities makes the introduction of several classifications with different points of view necessary. These allow more insight into the relationship among FGM properties, processing techniques, degree of control and cost.

This paper introduced a critical review of different classification methods used in the field of FGMs. These

Fig. 23 Possible classifications of FGMs' production methods



compared the advantages and limitations of the classified groups from different engineering points of view.

From designer and manufacturer point of view, new classifications of FGM production methods were proposed according to the complexity of product form and wall thickness, the realizable degree of control on properties gradient, the developed residual stresses due to the FGM production method, the equipment and manufacturing costs, the specific energy consumption and the environmental impact evaluated throughout the complete life cycle (Fig. 23). Some aspects were highlighted as challenges for FGMs on the industrial scale such as material modelling, numerical simulation, systematic selection and design methodologies as well as databank for FGMs. The adaptability for mass production, process repeatability, reliability and cost effectiveness are among the future frontier for FGMs.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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