Chapter 8
Development of FGM and FGAM

Eujin Pei and Israt Kabir

8.1 Functionally Graded Material (FGM)

FGM is a special class of composite material that was first developed in Japan around 1984 for the propulsion system and airframe of space planes. The challenge was to create a thermal barrier that would be capable of withstanding a temperature of 1000 °C over a cross-section of 10 mm. A sharp interface between the matrix and the reinforcement in a traditional composite material would cause cracking in high temperatures. The cracks occur due to the generation of interfacial stress induced by the mismatch of thermal expansion between two different materials. FGM introduces a smooth gradual transition at the interface of two different materials, thereby avoiding sharp interfaces. They are characterised by spatially varying the composition or micro-structures across the volume of a material, contributing to corresponding changes in material properties in line with its functional performance. For example, a metal-ceramic reinforced FGM can withstand high temperature environments by combining the best properties of both materials. The thermal stress at the critical locations can be controlled.

Composites Versus FGM

Traditional composite materials are a homogeneous mixture of two different materials. The final properties of the composites are derived from the properties of the separate materials. However, the two materials experience sharp changes as evident in the coated or laminated composites. Whereas in FGM, the actual properties of different materials can be retained and the change in properties is gradual at the gradient zones or interface, as illustrated in Fig. 8.1.

E. Pei (✉) · I. Kabir
Brunel University London (UBRUN), London, UK
e-mail: Eujin.Pei@brunel.ac.uk

© The Author(s) 2022

D. Godec et al. (eds.), *A Guide to Additive Manufacturing*, Springer Tracts in Additive Manufacturing, https://doi.org/10.1007/978-3-031-05863-9_8

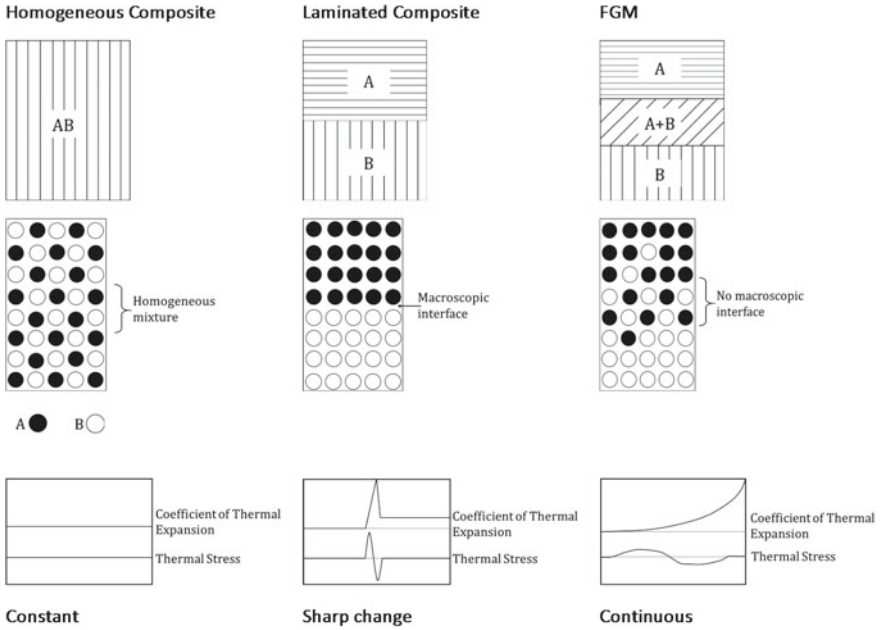

Fig. 8.1 Difference among traditional composites and two component FGM (Reproduced from Loh et al. [2])

8.1.1 Benefits of FGM

The use of FGM is significant as it combines multiple properties in a single part, eliminating sharp interfaces among gradient zones, thus increasing the interfacial strength. This also provides capabilities for part integration and increasing the part lifetime. The use of FGM can also lead to improved material properties and efficiency compared to alloys and metals. The use of FGM parts allows properties such as weight, modulus of elasticity, fracture toughness, wear resistant and hardness of materials within a component to be precisely controlled. As a result, various combinations of incompatible substances can be joined to create new materials for applications. Such materials can also be selectively reinforced in regions that require special properties.

8.1.2 Classifications of FGM

There are generally two categories of FGM, comprising of homogeneous and heterogeneous FGM as presented in Fig. 8.2. Homogeneous FGM are made up of a single material. Heterogeneous FGM are composed of two or more materials. The

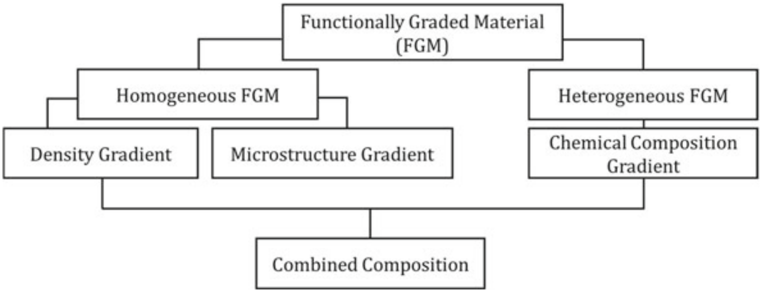

Fig. 8.2 Categories of FGMs (*Source* UBRUN)

components can be either graded with varying chemical compositions, densities or microstructures, or as a combined form. In homogeneous FGM, variable functionality is mainly achieved through the density gradient or by changing the microstructure. Both homogeneous and heterogenous FGM are explained in the following sections.

Homogeneous Composition

Density gradient

In homogeneous FGM, the density gradient is achieved based on the degree of porosity that is spatially distributed across the material. There are two ways of altering the density gradient in the FGM material, which is by changing either the pore size and/or the pore density. The shape and size of the pores can be designed and varied, according to the required properties of the component. Figure 8.3 illustrates both pore size and pore density gradation of a homogeneous FGM material.

The gradation of pore size can be achieved by varying the powder particle sizes during the gradation process or by optimising the processing and sintering parameters. The density of the porosity can be altered by varying the number of porosities distributed throughout the structure as shown in Fig. 8.4. Density variation in a monolithic structure helps to reduce the overall weight and the density of the part. As a result, this may influence the tensile strength and Young's modulus of the material.

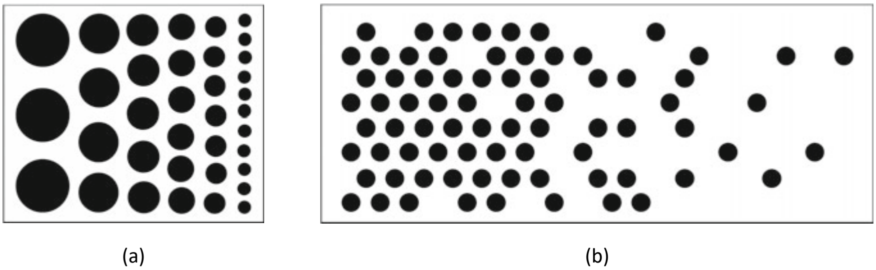

Fig. 8.3 Two types of density gradient, by regulating the **a** pore size and **b** pore density (*Source* UBRUN)

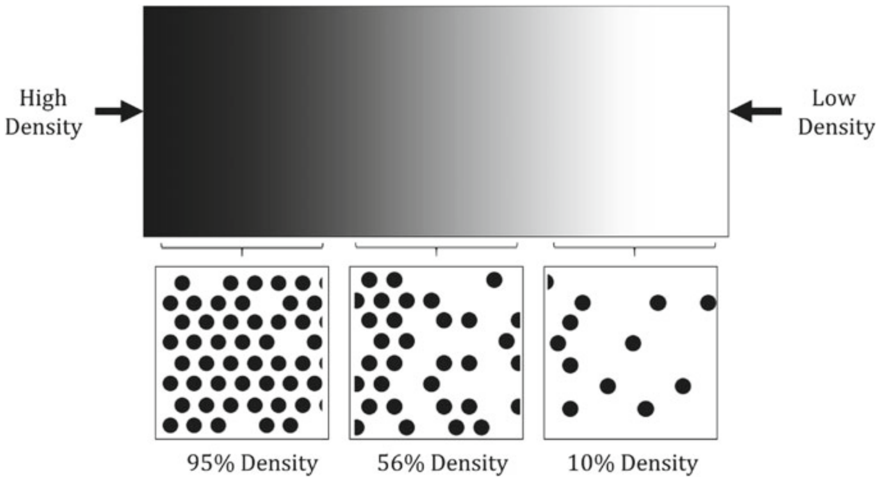

Fig. 8.4 Density variation is achieved by controlling the percentage of porosity distribution (Reprinted from Additive Manufacturing, Volume 23, 2018, [2], Copyright 2021, with permission from Elsevier)

Microstructure gradient

In a microstructure graded FGM, the microstructure is tailored for a gradual change of the material properties. This can be achieved during the solidification process, whereby the surface of the material is quenched. The core of the material cools down slowly, which further produces a different microstructure from those on the surface of the part.

Heterogeneous Composition

In heterogeneous FGM, two or more materials are present. As the composition of multi-materials is varied from one material into the other, it results in different phases with different compositions. The different phases are dependent on the compositional quantity and manufacturing conditions of the reinforcing material. For example, a binary heterogeneous FGM system contains two components A and B. The concentration of A varies along the length from 100 to 0% leading to the formation of different phases in the material. Theoretically, there are three zones with different phases. In the first zone, the concentration of A is more than B. In the second zone, the concentration of B is more than A. Lastly, the mixed zone has a combined composition of A and B in which the gradual transition of microstructure and composition is present.

Combined Composition

Another class of FGM that brings together both homogeneous and heterogeneous categories is known as combined composition. This is where a combination of variable density, chemical composition and microstructure exists within the FGM.

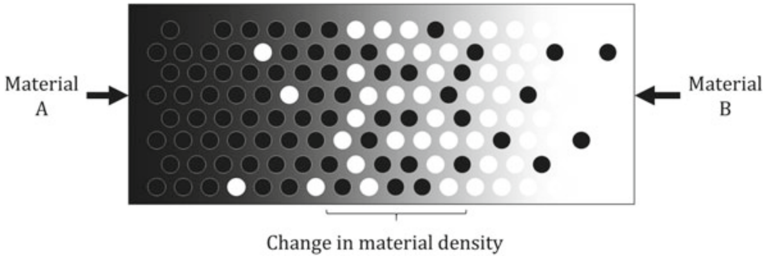

Fig. 8.5 Combined composition heterogenous FGM with two material components (Reprinted from Additive Manufacturing, Volume 23, 2018, [2], Copyright 2021, with permission from Elsevier)

Figure 8.5 shows a heterogeneous FGM with both variable density and chemical compositions, known as combined composition FGM.

8.1.3 Manufacturing Methods for FGM

Different fabrication methods of FGM are available for thin or bulk types of products. Thin-film FGM is used in some applications that require different surface properties as opposed to bulk materials. Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) processes are principal methods used to produce FGM coatings. In some applications, bulk FGM is required where the material is exposed to extreme working environments. The FGM manufacturing techniques are divided into 3 groups: gas, liquid, and solid phase processes. The common fabrication methods in a gaseous phase include PVD and CVD. Liquid phase methods include Centrifugal Casting and Tape Casting. Solid phase methods include the use of Powder Metallurgy. In addition, Additive Manufacturing (AM) techniques can be used for both liquid and solid phases, in which this process is known as Functionally Graded Additive Manufacturing (FGAM). The following sections describe the manufacturing methods for FGM in detail.

Gas-Assisted FGM Production by Physical Vapour Deposition (PVD)

PVD is a vaporisation-based vacuum deposition method in which the solid material is evaporated and deposited as a thin film through means of condensation. PVD is used for high melting point and low vapour pressure materials. High temperature is also required to vaporise the material in which specific techniques include sputtering, evaporation, and plasma-spray. The thickness of the thin film on the surface ranges from nanometers to micrometers. Parts produced by PVD is often used in mechanical, optical, chemical, or electronic applications, especially for automotive, aerospace, biomedical, defence, die and moulding industries.

Gas-Assisted FGM Production by Chemical Vapour Deposition (CVD)

CVD is a process where a gaseous precursor reacts to form a solid coating on a heated substrate. The reactions of by-products are removed from the chamber with unused precursor gases. The process is carried out in hot-wall reactors and cold-wall reactors.

Liquid-Assisted FGM Production by Centrifugal Casting

To produce FGM by centrifugal casting, a molten material containing another reinforcing material is poured into a rotating mould. A centrifugal force is created that helps to draw the molten material towards the mould and create a separation in the suspended solid powder material. The graded distribution of the FGM formed by centrifugal casting method is influenced by the processing parameters such as the density variation between the reinforcing and the molten material, the particle size, particle distribution, viscosity of the molten material and the solidification time.

Liquid-Assisted FGM Production by Tape Casting

Tape casting is achieved by spreading a slurry mixture onto a moving belt and passing the belt under the blade edge to shape the slurry into a tape form of a constant thickness. Thin sheets of ceramic are cast as a flexible tape with a thickness of several μm to mm. The slurry consists of suspended ceramic particles and organic liquid that contains binder and plasticiser materials. Stepped gradients of FGM are produced by stacking those tapes made from different compositions.

Solid-State FGM Production by Powder Metallurgy

The Powder Metallurgy (PM) process is an old manufacturing technique for producing engineering components. The steps involved in the production of FGM using this method include preparation of the powder material, processing of the powder, the forming operation, and sintering or other pressure-assisted hot consolidation processes.

Table 8.1 presents an overview of common FGM manufacturing methods. Different applications may utilise one approach over another. However, when creating extremely complex end-use products that contain lattice structures, none of these manufacturing technologies are suitable. The use of Functionally Graded Additive Manufacturing (FGAM) is one such method to construct complex geometries and being able to achieve combined FGM compositions.

8.2 Functionally Graded Additive Manufacturing (FGAM)

FGAM is a layer-by-layer fabrication process that involves gradationally varying the material organisation within a component to achieve an intended function. FGAM can produce engineered freeform structures with customisable site-specific properties, tailored at small sections or at a strategic location that would be impossible

Table 8.1 Overview of conventional processing methods for FGM (Reprinted from Materials Science and Engineering: A, Volume 362, Issues 1–2, 2003, [1], Copyright 2021, with permission from Elsevier)

Process	Layer thickness[a]	Type of FGM	Versatility in phase content	Versatility in component geometry
PVD	C	Coating	Very good	Moderate
CVD	C	Coating	Very good	Moderate
Centrifugal casting	C	Bulk	Very good	Poor
Tape casting	M	Bulk[b]	Very good	Poor
Powder metallurgy	M, L	Bulk	Very good	Moderate

[a] L: large (>1 mm); M: medium (100–1000 μm); C: continuous
[b] Maximum thickness is limited

using traditional production methods. The advancement of AM technologies makes it possible to strategically control the density and directionality of material deposition within a complex 3D distribution. The amount, volume, shape and location of the reinforcement in the material matrix can be precisely controlled to achieve the desired properties for a specific application. The merits of FGAM stem from the use of Additive Manufacturing (AM) technologies to enable design freedom, for custom-made production, increasing the speed to cost ratio, providing easy accessibility with a single-step manufacturing process, reducing risks and addressing sustainability.

8.2.1 The FGAM Process Chain

A typical FGAM process chain is presented in Fig. 8.6 which presents the five steps involved in the manufacturing workflow of FGAM which are described as follows.

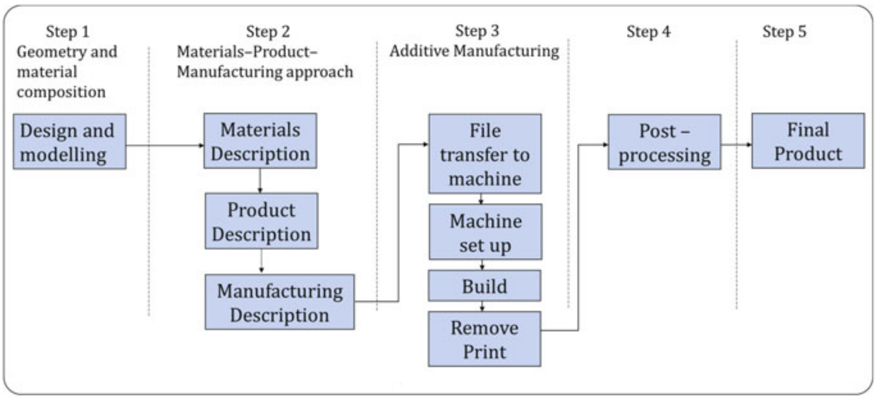

Fig. 8.6 The FGAM process flow from design to manufacturing (Adapted from Muller et al. [3])

1. Geometry and Material Composition: This first step involves the design and modelling process that consists of the development of the product using Computer-Aided-Design (CAD) for manufacturing, simulation, topology or infill optimisation. The mechanical function of the part is defined by describing the fundamental attributes before developing a modelling scheme. The factors considered at this stage include part geometry, material composition, optimisation, gradient vector dimension, geometry or surfaces attributed to the composition, property, material characteristics or other mechanical parameters.

2. Materials-Product-Manufacturing: There are three aspects considered in this step. In the materials description stage, it includes the material selection and microstructure allocation, defining the optimal material properties, the gradient and analysis of the void density. The data that concerns the chemical composition and characteristics of the part is modelled and analysed. Digital simulation is used to represent the materials, so as to formulate a matching epistemology for the material selection, gradient discretisation, volume of support, residual stresses, etc. Next, in the product description stage, the geometry and material composition with mathematical data is used to identify an appropriate manufacturing strategy and process control. Finally, in the manufacturing description stage, the build orientation of the part is determined, and the geometry is sliced. The manufacturing strategy is determined according to a triptych approach of material-product-manufacturing process. The mathematical data from product and material description is used to define the slicing orientation, categorised as either planar or complex slices.

3. Additive Manufacturing: The process consists of file transfer to the machine, the machine set-up, and the build process. While transferring the CAD file to the machine, the machine toolpath is defined and evaluated. Numerical Control (NC) programming is involved in the generation of paths and modification of process parameters using but not limited to G-code programming. The G-code or an appropriate data file is sent to the AM machine for the production sequence to commence.

4. Post-Processing: Post-processing ensures that the quality aspects such as surface characteristics, geometric accuracy, aesthetics and mechanical properties of the printed part meet its operating requirements or build specifications. AM post-processing methods include, but are not limited to tumbling, machining, hand-finishing, micromachining, chemical post-processing, electroplating and laser micromachining.

5. Final Product: After post-processing treatment, the final product is sent for quality assurance and validation. Experimental analysis such as non-destructive testing, stress analysis or microscopic imaging is carried out to validate the final product and its desired properties.

8.2.2 Design and Modelling of FGAM Parts

The design phase for FGAM is a critical and crucial step to ensure that accurate and high-quality parts are achieved. The design software for FGAM requires features that are able to model and simulate multi-materials and the composition for each material. The CAD software should be able to define the graded material in the 3D CAD file and using Computer-Aided-Engineering (CAE) for Finite Element Analysis (FEA) and calculations. Some CAD tools adopt a voxel-based approach to design FGAM models. The material values are assigned across a pixel grid on each geometry slice before converting them as a toolpath for manufacturing. These voxels are made up of different materials. The composition for hybrid materials has multiple elements with a weighted percentage. VoxCAD is an open source voxel-based digital materials simulator. This software can design FGM parts using voxel modelling and integrated with FEA features. It can perform 3D static and dynamic analysis including large deformations, collision detection and non-linear material models such as plastic deformation. It also supports parts with multi-materials, and with variable properties to simulate FGM characteristics.

Most AM software export the data in a mesh-based STL file format that is insufficient to retain the information for FGM parts. Design for FGAM requires file formats that can feature external and internal information, material specifications, mixed and graded materials and substructures, characteristics for materials and porous structures. Some potentially suitable file formats for FGAM include AMF (Additive Manufacturing Format), FAV (Fabricable Voxel) and 3MF (3D Manufacturing Format). AMF is an Extensible Markup Language (XML) file format capable of storing colours, materials, lattices, duplicates, and constellations of the volumes that make up the object. The AMF file format is supported by SolidWorks, Inventor, Rhino and Mesh Mixer CAD software. The file can contain functional representations, 3D texturing or volume texturing and voxel representation. FAV a voxel-based data format proposed by Fuji Xerox in collaboration with Keio University, Japan. Each voxel can be expressed with various attributes values, including colour (RGB, CMYK, etc.) and material information. The file format allows the user to design (CAD), analyse (CAE) and inspect 3D model data using Computed Tomography in an integrated process without having to convert the data. 3MF is another XML-based open format developed by the 3D Consortium that allows AM design applications to send “full-fidelity” 3D models to a mix of other applications, platforms, services and printers.

8.2.3 FGAM Technologies

There are six types of AM technologies used to produce FGAM parts. This includes Material Extrusion (MEX), Vat Photopolymerisation (VPP), Powder Bed Fusion

(PBF), Material Jetting (MJT), Sheet Lamination (SHL) and Directed Energy Deposition (DED).

Material Extrusion (MEX)

This process builds FGM parts layer-by-layer through computer-based controlled extrusion and deposition. This method has the potential to produce parts with locally-controlled properties by changing the deposition density and the deposition orientation, resulting in anisotropy in the properties along the horizontal axis. Li et al. found out that deposition directions in layers and gap sizes between the filaments are the most important parameters to control the mechanical properties. Other ME based methods use the mixing of paste or slurries such as ceramic slurries and metal pastes. In this process, it is important to control the paste mixing sequence and the extrusion parameters to achieve correct gradation in density.

Vat Photopolymerization (VPP)

Vat Photopolymerization (VP) can be used as an FGAM technique. A variant known as Direct Light Processing (DLP) is a mask-image projection method that was developed to overcome the shortcomings of a single-vat VP technique. The system comprises of switchable resin vats and micro-mirror devices. Instead of a laser heat source, it uses a Digital Micromirror Device (DMD) in which the sliced CAD models are converted into a 2D mask image. DLP systems project the mask images layer-by-layer to build a multi-material component systematically through a single build process. It is faster than conventional VP systems as it can form the whole layer simultaneously.

Powder Bed Fusion (PBF)

PBF involves the spreading and sintering of typically 0.1 mm thick of powder material layer-by-layer with a roller between the layers, then selectively fusing or melting either by laser or electron beam. The PBF technique can be classified into several types depending on the heat source and fusion process. Table 8.2 lists the PBF categories and the materials that have been successfully used to manufacture FGAM parts.

PBF-LB/P (SLS) can produce complex components of polymers with spatially varying mechanical properties using suitable means of powder delivery. It can fuse

Table 8.2 Different kinds of PBF technique used for FGAM

PBF techniques	Materials
Selective Laser Sintering (PBF-LB/P-SLS)	Nylon
Direct Metal Laser Sintering (DMLS) Selective Laser Melting (PBF-LB/M-SLM) Selective Mask Sintering (SMS)	Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel
Electron Beam Melting (PBF-EB/M-EBM)	Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel, Copper

thin sections from 0.02 mm to 0.06 mm together and create very complex geometries. Chung and Das studied the production of FGAM polymer nanocomposites of Nylon-11 and silica with various volume fractions of 15 nm glass beads (0–30%). On the contrary, PBF-LB/M (SLM), DMLS and PBF-EM/M (EBM) are generally used to process metallic FGAM parts. PBF-LB/M can produce metallic FGAM where metal powders are deposited co-axially with a high-power laser beam. Two or more multiple feeders of powder are used to continuously modify the composition of the deposited metal. In previous studies, PBF-LB/M was used to produce FGM metallic parts and a periodic lattice structure of Al-Si10-Mg composite.

Material Jetting (MJT)

MJT, which is also known as PolyJet trademarked by Stratasys, can achieve the widest range of digital materials with varying physical properties in a single print using the Objet Studio and Polyjet Studio software. FGAM parts produced by MJT can have up to 82 different material properties including shore hardness, transparency, colour, unique properties, biocompatibility, etc. An example is a chair called the Gemini Acoustic Chaise designed by Neri Oxman from MIT. The chaise was designed to study vocal vibrations and the relationships between sounds and human physiology. The inner lining was printed using 44 composite materials with the Polyjet system.

Sheet Lamination (SHL)

SHL including Ultrasonic Consolidation (UC), can be used to produce FGM components. Examples of parts have been produced by joining 3 different metallic foils made up of stainless steel, aluminium, and copper together through ultrasonic welding using a UC machine that mechanically vibrates the welding head (the sonotrode) at 20 kHz. FGAM could be produced by adopting this machining strategy or by using an intermediate glue layer.

Directed Energy Deposition (DED)

DED systems consist of a nozzle mounted on a multi-axis arm, which deposits molten material in either wire or powder form onto a specified surface at an angle. Energy from laser, electron beam or plasma arc is used to create beads, tracks and layers of solid materials upon solidification of the melt pool on the substrate. The metallic powder is located coaxially with the energy source and delivered into the melt pool. Laser Metal Deposition (LMD) is a laser-based DED process which can fabricate metallic parts with a graded composition by adjusting the volume of metallic powders delivered to the melt pool. LMD has been used to produce FGM parts using 304L Stainless Steel and Inconel 625 with a 910 W Yttrium Aluminium Garnet (YAG) laser and hatch angle of 60°. Thermodynamic computational modelling is often used for optimising the process parameters to produce FGAM parts.

Table 8.3 The potential engineering applications of FGAM parts

FGAM parts	Applications
Rocket engine components, heat exchange panels, reflectors, turbine wheels, turbine blades, nose caps, etc	Aerospace sector
Dental implants, Skeletal implants, etc	Biomedical sector
Engine cylinder liners, leaf springs, spark plugs, driveshafts, car body parts, racing car brakes, etc	Automotive sector
Inner wall of nuclear reactors, solar cells, piezo-electric ultrasonic transducers, flywheels, etc	Energy sector
Bullet-proof vests, armoured components, etc	Defence sector
Cutting tools, blades, etc	Other sectors

8.2.4 FGAM Applications

FGAM technologies show huge potential for novel and existing applications. Table 8.3 presents a list of major FGAM applications including aerospace, biomedical, automobiles, and other industries.

8.3 Conclusion

The use of FGM as well as FGAM have a great potential to revolutionise the manufacturing world. Considerable progress has been made since the earliest discovery of FGM. Some of the major challenges in the use of FGAM include having a better understanding of materials, CAD tools and AM technologies. In terms of our knowledge of materials, current applications lack a broad understanding of the "processing-structure–property" relationship of FGAM components, especially for heterogeneous FGAM parts. Therefore, the behaviour of the manufactured part may deviate from the predicted properties. In addition, the availability of suitable materials for FGAM is still limited and variability in material interaction may occur at different operating conditions. Material data such as chemical composition, manufacturing constraints and build parameters are required. Suitable measurement and characterisation techniques to modify the microstructure, material arrangement, compatibility, mixing range, property distribution, etc. need to be established. A "function-behaviour-structure" ontology could be applied to model, calculate and predict the behaviour of a FGAM component. There is also lack of advanced CAD software to describe and translate the material properties and behaviours to design FGAM parts. The limited number of the voxel-based modelling engine and available features can sometimes lead to poor representation and managing of data. There is a need to develop new CAD/CAE software to specify, model and manage the material information for Local Composition Control (LCC). Furthermore, new AM slicing software is required to slice, analyse and prepare parts for FGAM fabrication. Lastly, conventional AM technologies still operate dominantly on isotropic materials, focusing on surface modelling. Most AM processes are also limited to in-situ mixing. Industrial-grade materials cannot be reliably blended or graded to form novel materials with the desired composition ratio. FGAM components are still prone to internal and external defects. Therefore, FGAM processes require a very high level of precise deposition with a reliable and predictable outcome. These are the current challenges facing the use of FGAM in which over time with more research and knowledge being generated, newer applications will emerge.

References

1. Kieback, B., Neubrand, A., Riedel, H.: Processing techniques for functionally graded materials. Mater. Sci. Eng. A **362**, 81–105 (2001)
2. Loh, G., Pei, E., Harrison, D., Monzón, M.: An overview of functionally graded additive manufacturing. Addit. Manuf. **23**, 34–44 (2018)
3. Muller, P., Mognol, P. and Hascoet, J.-Y.: Functionally Graded Material (FGM) parts: from design to the manufacturing simulation. In: Advanced Manufacturing Processes; biomedical Engineering; Multiscale Mechanics of Biological Tissues; Sciences, Engineering and Education; Multiphysics; Emerging Technologies for Inspection. ASME, p. 123 (2012). https://doi.org/10.1115/ESDA2012-82586

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.