Building a conceptual understanding of Functionally Graded Additive Manufacturing (FGAM) and its limitations

G.H. LOH and E. PEI
College of Engineering, Design and Physical Sciences, Brunel University London, UK
[1]Hsiang.loh@burnel.ac.uk , [2]Eujin.Pei@brunel.ac.uk

Abstract

Technological progress in Additive Manufacturing (AM) hardware, software, as well as the opening of new markets and applications has encouraged research into novel materials with functionally graded and high performance capabilities. Functionally Graded Additive Manufacturing (FGAM) is a layer-by-layer fabrication technique that gradationally varies the ratio of the material organization within a component to achieve an intended function. As research in this field has gained worldwide interest, the interpretations of the FGAM concept requires greater clarification. The objective of this paper is to present a conceptual understanding of FGAM by clarifying key terms associated with FGAM. The current state-of-the-art and capabilities of FGAM technology are reviewed alongside with current technological obstacles and limitations, followed by recommendations on possible strategies to overcome those barriers for FGAM to take off.

Keywords: Functionally Graded Materials, Variable-Property 3D Printing, Functionally Gradient Design Fabrication, Functional Performance, Functionally Graded Composite Materials

1 Introduction

Functionally Graded Materials (FGMs) are inhomogeneous materials developed in 1984 for an aerospace research project built to sustain high thermal resistance to overcome the shortcomings of traditional composite materials (AZO Materials, 2002). FGMs are a class of advanced materials with spatially varying composition over a changing dimension, with corresponding changes in material properties built-in (Oxman, 2011a). Their multifunctional status is attained by mapping performance requirements through material structuring and allocation (Oxman, 2011a). Conventional manufacturing methods of FGMs include shot peening, ion implantation, thermal spraying, electrophoretic deposition and chemical vapour deposition. The differences of a traditional composite compared to an FGM composite is shown in Figure 1a and 1b.

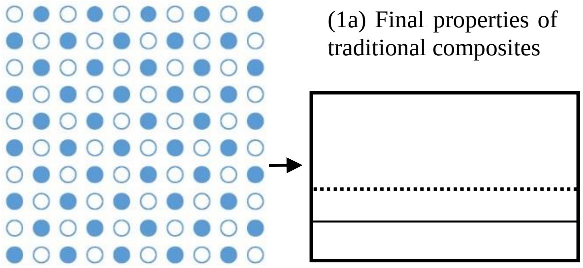


Figure 1a: Traditional Composite

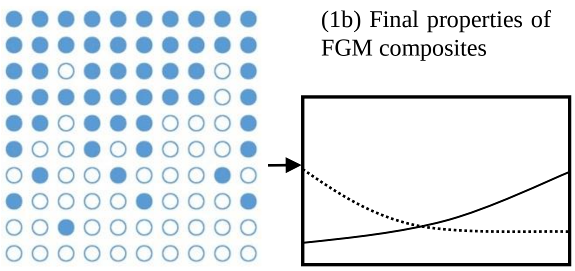


Figure 1b: FGM Composite

2 The concept of Functionally Graded Additive Manufacturing (FGAM)

Additive Manufacturing (AM) is a solid freeform manufacturing technology that involves a "process of joining materials to make objects from 3D model data" (ASTM International, 2012), depositing material by layer upon layer, as opposed to subtractive or formative manufacturing methodologies (e.g. moulded) (ASTM International, 2012). Today, the use of Additive Manufacturing has given added potential to produce FGM parts, through a process known as Functionally Graded Additive Manufacturing (FGAM). Functionally Graded Additive Manufacturing (FGAM) is a layer-by-layer fabrication technique that intentionally modifies the process parameters and gradationally varies the spatial of material(s) organization within one component to meet the intended function. As this area of work is relatively new and lack of available standardisation, there have been various given terms such as functionally graded rapid prototyping (FGRP) (Oxman, 2011a), varied property rapid prototyping (VPRP) (Oxman, 2011b) and site-specific properties additive manufacturing (T-Williams, 2016). The purpose of this paper is to present a conceptual understanding of FGAM by clarifying key terms associated with FGAM.

The emergence of FGAM has the potential to achieve more efficiently engineered structures. An example includes highly customizable internal features with integrated functionalities that would be impossible to produce using conventional manufacturing (AM Platform, 2014). The amount, volume, shape and location of the reinforcement in the material matrix can be precisely controlled to achieve the desired mechanical properties for a specific application (Dalal, 2016). FGAM optimises the exploitation of materials in the manufacturing process with excellent freedom of geometry with no tooling costs (Pei et al., 2017). The process also advances the process-ability and improves the material usage. By simplifying the assembly of complex part using dynamic gradients, some disadvantages of traditional composites can be avoided such as reduced in-plane and transverse stresses at critical locations and improving the distribution of residual stress (Chauhan, 2016; Birman, 2007). The amount of support material can be potentially reduced as FGAM components can be designed to self-stabilize in the build process with minimum support structures. FGMs also offers variable property supports where sacrificial areas could be designed to break away.

The aim of using FGAM is to fabricate performance-based freeform components driven by their graduated material(s) behaviour. In contrast to conventional single-material and multi-material AM which focuses mainly on shape-centric prototyping, FGAM is a material-centric fabrication process that can establishes a radical shift from contour modelling to performance modelling. Having the performance-driven functionality built-in directly into the material is a fundamental advantage and significant improvement to AM technologies. Oxman (2011b) describes the concept of FGAM as a Variable Property Rapid Prototyping (VPRP) method with the ability to strategically control the density and directionality of material substance in a complex 3D distribution to produce a high level of seamless integration of monolithic structure using the same machine. The material characteristics and properties are altered by changing the composition, phases or microstructure with pre-determined location. The potential material composition achievable by FGAM can be characterised into 3 types: (a) variable densification within a *homogeneous* composition; (b) *heterogeneous* composition through simultaneously combining two or more materials through gradual transition; and (c) using a combination of variable densification within a heterogeneous composition. These three types of characteristics are described in the next section in detail.

2.1 Homogeneous composition

Single- Material FGAM

Oxman (2011a) proposed FGAM as a biological inspired rapid fabrication process that mimics FGM occurring in nature such as tissue variation in muscle (variable elasticity) or changes in bone density. The use of FGAM has the potential to achieve a more efficient engineering structure by altering the density and morphology of lattice structures (T-Williams, 2016).

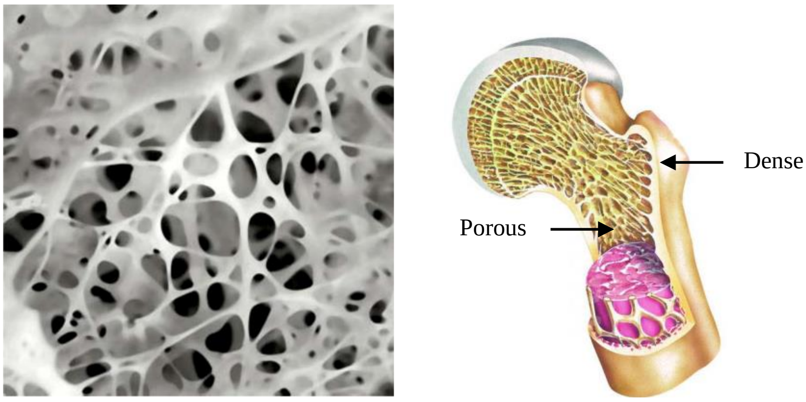


Figure 2 (Left) and (Right): Variable density in bone structure.

The changes of density contribute to property and functional deviations. This change of density is demonstrated through Steven Keating’s work on 3D printed concrete being fabricated by a MakerBot 3D Printer with a modified extruder (Next Big Future, 2011). It shows a functional gradient of density in the concrete piece, from a solid exterior to a porous core (Figure 3). The density gradient in concrete has an excellent strength-to-weight ratio, making it lighter yet more efficient and stronger than a solid piece of concrete (Shapeways, 2011).

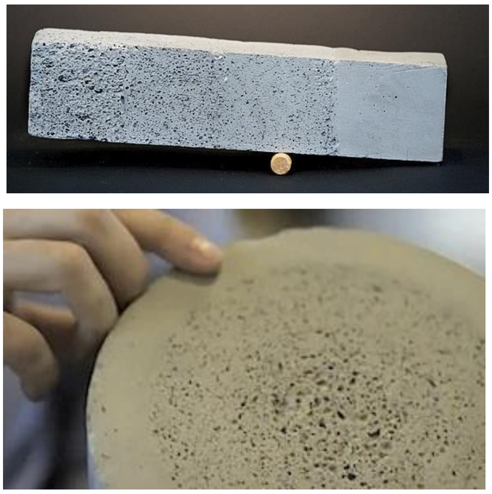


Figure 3: AM variable densities concrete (Steven Keating, MIT Media Lab)

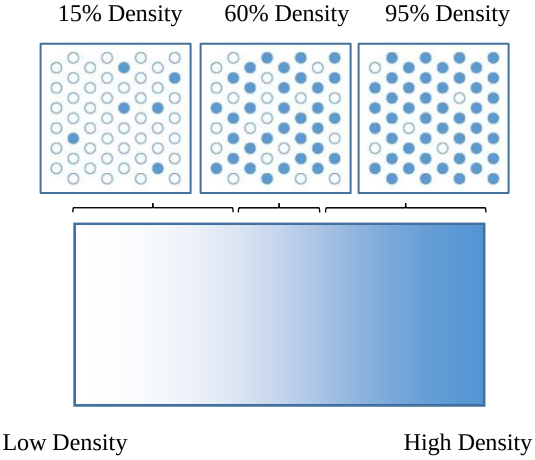


Figure 4: Densification of homogeneous composition

2.2 Heterogeneous compositions

Multi-material FGAM

More recent 3D Printers are equipped with multiple nozzles which can extrude different materials known as Multi-Material Additive Manufacturing (MMAM). However, most of these are only able to achieve a sharp interface between the two materials and this phase results in parts that are brittle (T-Williams, 2016). Issues include surface delamination and cracks caused by the tension between the two materials (Sirris, 2012; Choi, 2011). Heterogeneous FGAM improves the bond between materials by removing distinct boundaries between dissimilar or incompatible matter. The mechanical and thermal stress concentrations caused by different expansion coefficients of multi-materials can be reduced (T- Williams, 2016).

Birman (2007) addressed the coupling effect of materials through sandwich configurations to achieve an optimum combination of component properties such as weight, surface hardness, wear resistance, impact resistance or toughness; or to produce material gradients to change the physical, chemical, biochemical or mechanical properties through complex morphology (Kieback, 2003; Hascoet, 2011). The geometric arrangement of the two phases controls the overall material properties and the tolerance in the design and the accuracy of manufacturing needs to be properly managed to ensure that the final component fulfils the expected requirement (T-Williams, 2016).

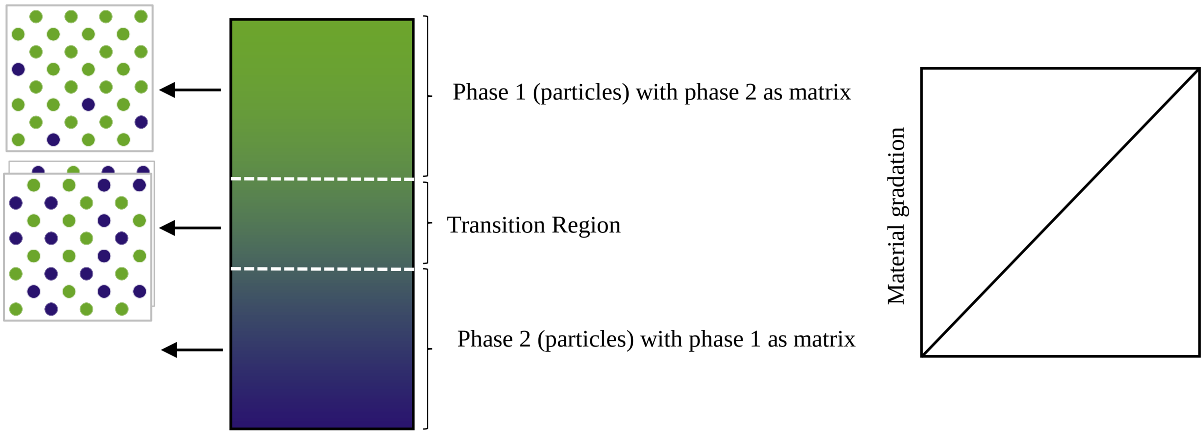
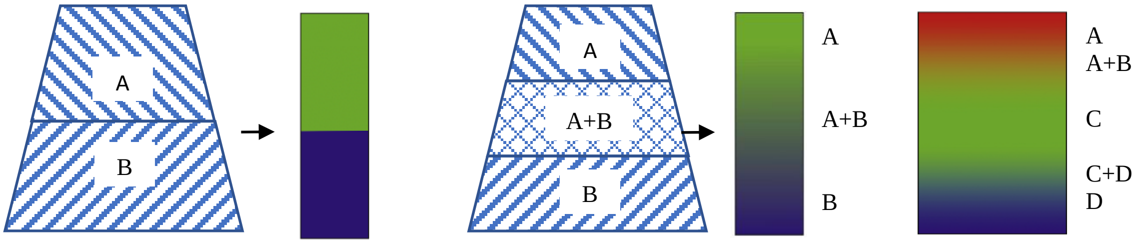


Figure 5: Continuous graded microstructure of FGMs – 2 materials (Fig. b)

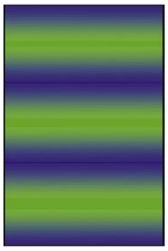
Figure 5 demonstrates a continuously varying volume fractions of the FGMs transition from 0% at 1 end to 100% to the other end. The use of heterogeneous compositions can result in a smooth and seamless integration and FGAM multi-layer composite plate can be divided into 4 types: transition between 2 materials (Fig. 6b), 3 materials or above (Fig. 6c), switched composition between different locations (Fig. 6d) and heterogeneous compositions with density variation (Fig. 6e). The continuous variation within the 3D space can be produced by controlling the ratios in which two or more materials that are mixed prior to the deposition and curing of the substances (Mahamood, 2012). According to Vaezi (2013), the compositional variation must be controlled by computer and program to be considered as FGAM. Raw materials that are pre-mixed or composed prior to deposition or solidification is not considered to be FGAM.



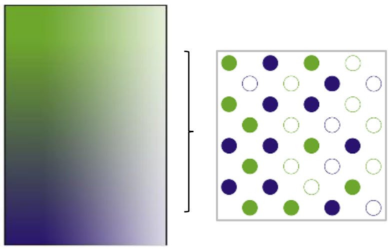
(6a) Conventional MMAM

(6b) MM FGAM (2 materials)

(6c) MM FGAM (3 materials or above)



(6d) Switched composition



(6e) Varied density heterogeneous composition

The variation of material within a heterogeneous component can be classed as 1D, 2D and 3D gradient (Muller, 2012). Key parameters include the dimension of the gradient vector, the geometric shape and the repartition of the equipotential surfaces. Figure 9 shows a diagram that classes how the gradient of FGAM parts can be assigned.

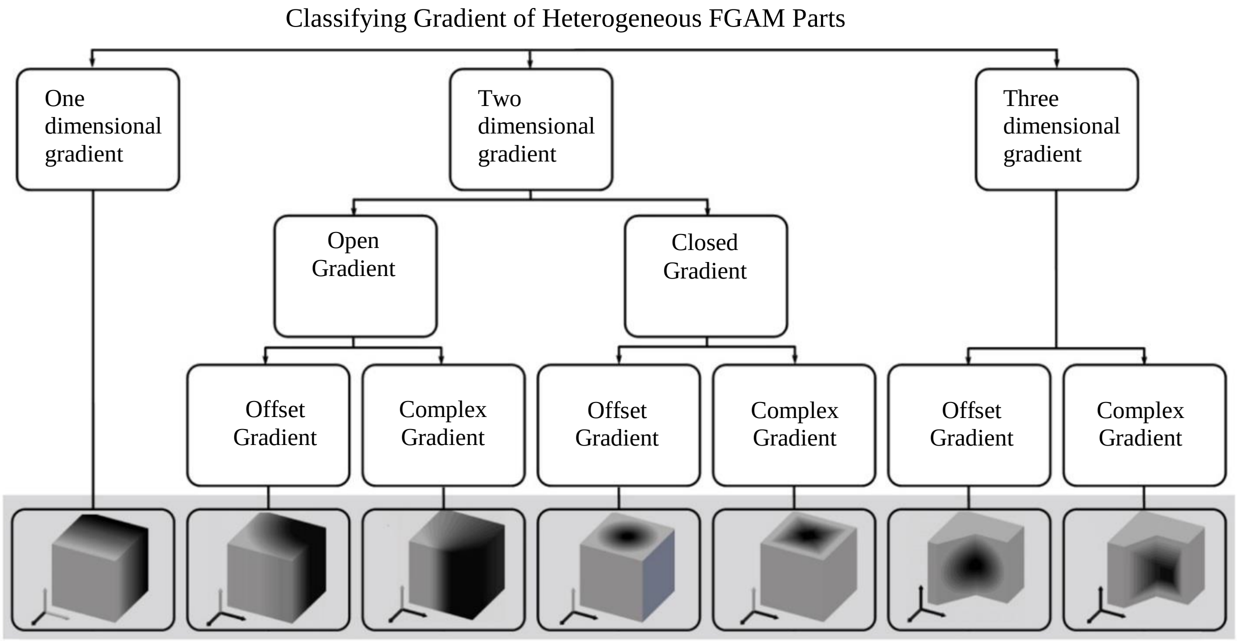


Figure 7: Representation of classifying FGAM Gradients (Muller, 2011)

3 Existing Technological Limitations and Conclusion

General AM has provided benefits including design freedom, reduced time to market in product development, service and increased R&D efficiency (AM Platform, 2014). FGAM expands the potential of prototyping to the production of highly customizable internal features with integrated functionalities that would be impossible to produce using conventional manufacturing techniques and consolidate several machining steps into one without additional tooling cost (AM Platform, 2014). FGAM advances material-processability and contribute to efficient conservation of material usage (Oxman, 2011b).

As the field of FGAM is still developing, existing knowledge about the composition of the material, fabrication process, and simulation in a CAD software are lacking (Pei et al., 2017; Sheng, 2003). First, material processability is fundamental to the performance of printed part (AM Platform, 2014). Knowledge on the characterisation of FGAM materials and their processing parameters is complex. It is a technical challenge to determine the overall component geometry and to regulate the optimal spatial distribution and the transition between the heterogeneous materials. Shared databases of material characteristics should be established, as well as to develop a predictive model for proper process control (Mahamood, 2012). Next, the approach of a current AM method is to assign the material to the CAD component, focusing around the geometrical description of form as a property-less feature. Therefore, the present delivery mechanism is still limited in capacity and scale, and not successfully set up to take graded properties within a printed solid into account. Lastly, for FGAM to take off, it requires a new approach of computer-aided engineering (CAE) analysis that can specify, model and manage material information for local composition control (LCC) (Chiu, 2008). The LCC data can be sent to the machine in a layer-by-layer pixel sheet so that when they are stacked, they are expressed as 3D data voxel cloud. Advanced data driven AM fabrication technologies should permit the ability to strategically control the density and directionality of material substance in the generation of form. The software should enable the management of layering or compounding dissimilar materials, controlling the variation of stiffness variation using a pre-determined distribution of hard and soft materials throughout the geometry. Lastly, CAD limitations arise from inadequate file formats in employing digital entities capable of describing the micro-scale physical properties of materials. Although some approaches such as voxels (voxel-based graphics methodologies), finite-element analysis (FEA), particle system elements and vague discrete modelling elements (VDM) exist to generate lattices for material based model (Aremu, 2016). However, editing the data is difficult due to the lack of robust methods to handle the modelling and analysis. The major drawbacks include the huge computational power in calculations that can result in a long processing time to generating individual voxels and sheets of pixels for each layer. There are several data exchange formats including AMF (Additive Manufacturing Format), FAV (Fabricatable Voxel) and 3MF (3D Manufacturing Format) which shows promise for FGAM adoption to support better modelling and to control complicated internal structures and the material attributes. Fujii (2017) described that these data exchange formats can eliminate data conversion processes during the CAD workflow. However, little work has been done to investigate the advantages and limitations of these data exchange formats for FGAM.

FGAM sets a whole new paradigm in the world of digital fabrication and a range of opportunities for design with increased functionality, performance, cost effective and improved lifespan. There are two distinct markets for FGAM applications– industrial/ production market and consumer market where the performance of material can be used to compose the product functionality (Knoppers, 2004). (AM platform, 2014). The industrial/ production market includes medical, dental, aerospace, automotive, defence and power generation whereas the consumer markets includes home accessories, fashion and entertainment. The key sectors identified for FGAM adoption in present stages are medical devices, scaffolds and implants, aerospace for light-weighting or topology optimisation and the creative industries (Materials KTN, 2012).

In this paper, the concept and approach of FGAM is clarified whereby this process optimises the exploitation of materials in the manufacturing stage with excellent freedom of geometry. Suitable methodologies are yet to be established to fully enable and exploit the true potential of FGAM on an economic scale. However, as a first step in this new horizon of advanced

Additive Manufacturing, we have presented a clear conceptual understanding of FGAM and its limitations, much uncertainty still exists between the knowledge of materials, the availability of computational tools and the delivery mechanism. Criteria must be established to choose the best strategies in material characterization, defining the optimum material distribution and exploration on the methodology to measure the material properties of manufactured components (T-Williams, 2016). In parallel, future work needs to emphasis on software engineering of 3-D forms incorporating material properties and behaviour with potentially real-time fabrication feedback. The range of expression and applications will simultaneously increase as the processing technology, cost of production and properties of FGM improve.

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