TECHNICAL REPORT

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Additive manufacturing — Design — Functionally graded additive manufacturing

Fabrication additive — Conception — Fabrication additive à gradient fonctionnel

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Foreword

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This document was prepared by ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM F 42, *Additive manufacturing technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing*, in accordance with the agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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Introduction

Functionally Graded Materials (FGMs) were developed in 1984 for a space plane project to sustain high thermal barriers to overcome the shortcomings of traditional composite materials (AZO Materials, 2002). Traditional composites [Figure 1 a)] are homogeneous mixtures, therefore involving a compromise between the desirable properties of the component materials. Functionally Graded Materials (FGMs) are a class of advanced materials with spatially varying composition over a changing dimension, with corresponding changes in material properties built-in[56]. FGMs attain their multifunctional status by mapping performance requirements to strategies of material structuring and allocation [Figure 1 b)].

The manufacturing processes of conventional FGMs include shot peening, ion implantation, thermal spraying, electrophoretic deposition and chemical vapour deposition. Since additive manufacturing processes builds parts by successive addition of material, they provide the possibility to produce products with Functionally Graded properties, thereby introducing the concept often known as Functionally Graded Additive Manufacturing (FGAM). As this area of work is new, driven by academic research, and lacks available standardisation, there have been multiple different names proposed by different researchers in different publications as terms for this area, for example, functionally graded rapid prototyping (FGRP)[56], varied property rapid prototyping (VPRP)[57] and site-specific properties additive manufacturing[72]. However, even if there clearly is a great need for clarification of key terms associated with FGAM, this document does not include any attempts of alignment in terminology. This document is an overview of state of the art and the possibilities for FGAM enabled by present AM process technology and thus a purely informative document. Since this overview is based on available publications, and in order to facilitate cross referencing from these publications, this document has used the terms concerning FGAM as they are used in the original publications.

a) Traditional composite

b) FGM composite

Figure 1 — Allocation of materials in a traditional composite and an FGM composite

Additive manufacturing — Design — Functionally graded additive manufacturing

1 Scope

The use of Additive Manufacturing (AM) enables the fabrication of geometrically complex components by accurately depositing materials in a controlled way. Technological progress in AM hardware, software, as well as the opening of new markets demand for higher flexibility and greater efficiency in today's products, encouraging research into novel materials with functionally graded and high-performance capabilities. This has been termed as Functionally Graded Additive Manufacturing (FGAM), a layer-by-layer fabrication technique that involves gradationally varying the ratio of the material organization within a component to meet 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 document is to present a conceptual understanding of FGAM. The current-state of art and capabilities of FGAM technology will be reviewed alongside with its challenging technological obstacles and limitations. Here, data exchange formats and some of the recent application is evaluated, followed with recommendations on possible strategies in overcoming barriers and future directions for FGAM to take off.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Abreviations

AM	Additive Manufacturing (see ISO/ASTM 52900)
AMF	Additive Manufacturing Format, see 8.4.2.1 (see ISO/ASTM 52900)
CAD	Computer Aided Design[48]
CAE	Computer Aided Engineering[14]
DED	Directed Energy Deposition, see Clause 6 (see ISO/ASTM 52900)
DMLS	Direct Metal Laser Sintering, the name for laser-based metal powder bed fusion process by EOS Gmbh[40]
EBM	Electron Beam Melting, the name for electron beam based metal powder bed fusion process by Arcam AB[40]
FAV	Fabricatable Voxel, see 8.4.2.2[19]

FEA	Finite Element Analysis[48]
FEF	Freeze-form Extrusion Fabrication, a material extrusion process based on the extrusion of feedstock in the form of pastes and application of freeze drying to form a green body which can be consolidated to the desired material properties by sintering. Presently only used for research and development projects.[34]
FEM	Finite Element Method[18]
FDM	Fused Deposition Modelling, name for material extrusion processes by Stratasys Ltd.[39]
FGAM	Functionally Graded Additive Manufacturing[61]
FGMs	Functionally Graded Materials[61]
FGRP	Functionally Graded Rapid Prototyping, name for FGAM used by Neri Oxman in some publications.[56]
LMD	Laser Metal Deposition, a common name for directed energy deposition processes that uses laser as the source of energy to melt and fuse metallic materials as they are being deposited, see Clause 6.[21]
LOM	Laminated Object Manufacturing, name of sheet lamination processes originally developed by Helisys Inc.[42]
MMAM	Multi-Material Additive Manufacturing, name used for AM when using more than one material in the same process.[61]
MM FGAM	Multi-Material Functionally Graded Additive Manufacturing, name for FGAM when the functional grading is based on building parts using more than one material in the same process, and the composition of the different material components is controlled by the computer program.[43]
PBF	Powder Bed Fusion (ISO/ASTM 52900)
SHS	Selective Heat Sintering, name of a powder bed fusion process that fuse polymer powder by means of a thermal printhead instead of the more common laser. The process was originally developed by Blueprinter but has been withdrawn from the market following the bankruptcy of this company.[40]
SLM	Selective Laser Melting, name for laser-based metal powder bed fusion process originally developed in collaboration between F&S Stereolithographietechnik GmbH (Fockele & Schwarze) and Fraunhofer Institute for Laser Technology. This name is a registered trademark of SLM Solutions Group AG and Realizer GmbH.[40]
SLS	Selective Laser Sintering, name for powder bed fusion process originally developed by DTM Corp, but which has been assumed by 3D Systems by the acquisition of this company. Since this was the first powder bed fusion process to be commercialized, it has sometimes been used synonymously for all powder bed fusion processes.[40]
STL	Stereolithography, name for a digital file format for three dimensional solid models originally developed for the Stereolithography process by 3D Systems, hence the name. Since this conversion to this format has been commonly available in several CAD programs this file format has until present times effectively been functioning as a de-facto standard for AM processes. (see ISO/ASTM 52900)
UAM	Ultrasonic Additive Manufacturing, name for a metal sheet lamination process by Fabrisonic LLC. The process fuses thin sheets (or ribbons) of metal by ultrasonic vibrations.[43]

VDM Vague Discrete Modelling[8]

VPRP Variable Property Rapid Prototyping, name for FGAM used by Neri Oxman in some publications.[57]

3MF 3D Manufacturing Format, a digital file format for three dimensional solid models in additive manufacturing, developed by the 3MF consortium, see 8.4.2.3.[3]

5 Concept of Functionally Graded Additive Manufacturing (FGAM)

5.1 General

Additive Manufacturing (AM) is the process of joining materials to make *parts* from 3D model data, usually *layer* upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies (ISO/ASTM 52900). AM enables the direct fabrication of fine detailed bespoke components by accurately placing material(s) at set positions within a design domain as a single unit[76]. The use of AM has given opportunity to produce parts using FGM, through a process known as Functionally Graded Additive Manufacturing (FGAM). AM technologies suitable for the fabrication of FGMs include Material Extrusion, Direct-Energy Deposition, Powder Bed Fusion, Sheet Lamination[43] and PolyJet technology.

Functionally Graded Additive Manufacturing (FGAM) is a layer-by-layer fabrication technique that intentionally modify process parameters and gradationally varies the spatial of material(s) organization within one component to meet intended function.

FGAM offers a streamlined path from idea to reality. The emergence of FGAM has the potential to achieve more efficiently engineered structures. 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 signifies a shift from contour modelling to performance modelling. Having the performance-driven functionality built-in directly into the material is a fundamental advantage and a significant improvement to AM technologies. An example includes highly customizable internal features with integrated functionalities that would be impossible to produce using conventional manufacturing[5]. 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[18].

Reference [57] 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, phase or microstructure with a 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;

c) using a combination of variable densification within a heterogeneous composition.

These three types of characteristics are described in 5.2 and 5.3.

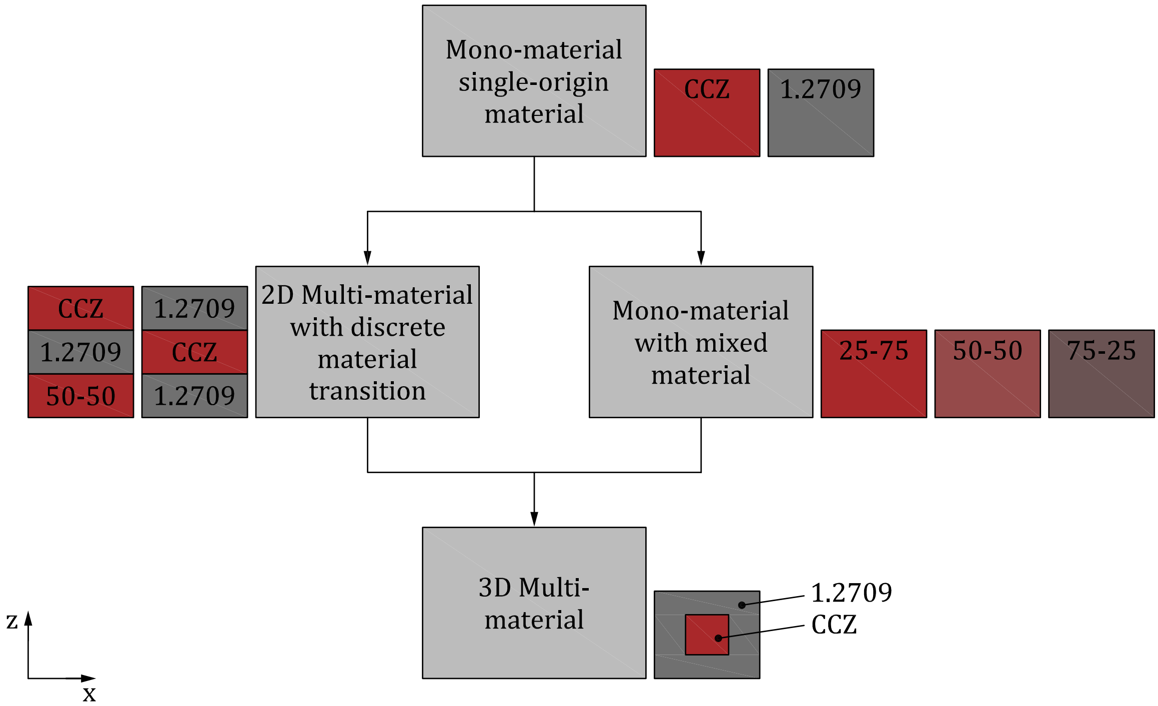
5.2 Homogeneous compositions — Single Material FGAM

FGAM can produce efficiently engineered structures by strategically modulating the spatial position (e.g. density and porosity) and morphology of lattice structures across the volume of the bulk material[43]. We term this as varied densification FGAM (also known as porosity-graded FGAM). Reference [56] proposed this as a biological-inspired rapid fabrication that occurs in nature such as the radial density gradients in palm trees, spongy trabecular structure of bone and tissue variation in muscle which is heterogeneous in elasticity and stiffness. The directionality, magnitude and density concentration of material substance in a monolithic anisotropic composite structure contribute to functional deviations to modulate the physical properties, and to create functional shapes through structural hierarchy[54].

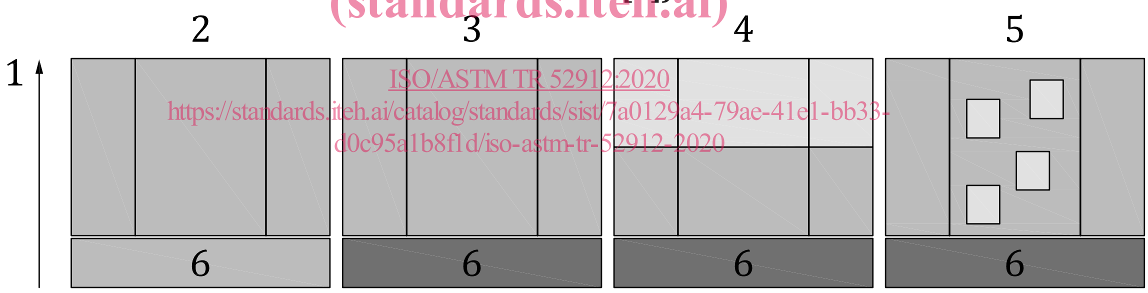
Man-made structures such as concrete pillars are typically volumetrically homogeneous[27]. Varied densification single-material FGAM was demonstrated through Steven Keating's work on functionally graded concrete being fabricated by a MakerBot machine with a modified material extruder. The concrete piece showed a functional gradient of density to mimic the cellular structures of a palm tree, from a solid exterior to a porous core. The porosity gradient was achieved by varying the powder particle sizes that were assigned in different locations during the gradation process or by varying the production process parameters[43]. For Reference [27], the density was controlled by aggregating the water ratio of the concrete at a given position, which led to excellent strength-to-weight ratio, making it lighter and yet more efficient and stronger than a solid piece of concrete.

5.3 Heterogeneous compositions — Multi-material FGAM

Multiple-material Additive Manufacturing (MMAM) is achievable using conventional 3D printers with multiple nozzles to deliver different materials to the platform[77]. In powder bed fusion, MMAM can be realized by utilizing a conventional delivery device in combination with a suction module to remove powder after the solidifying process-step[7]. As sharp interfaces exist in most conventional MMAM composites where two materials meet and interact, this creates a brittle phase[72]. Failure is commonly initiated between discrete change of materials properties, such as delamination or cracks caused by the surface tension between two materials[17]. Multi-material (MM) FGAM seeks to improve the interfacial bond by removing the distinct boundaries between dissimilar or incompatible materials. The mechanical stress concentrations and thermal stress caused by different expansion coefficients will be largely reduced[72]. Figures 2, a) and b) explain the approach of voxellization of Multi-material Additive Manufacturing according to Reference [7].



a) Conceptual diagram showing voxels arranged in 3D form (Fraunhofer IGCV and Reference [7])



b) Illustration of MMAM (Fraunhofer IGCV and Reference [7])

Key

1 building direction
2 mono-material
3 2D hybrid
4 2D multi-material
5 3D multi-material
6 substrate

Figure 2 — Voxellization of multi-material additive manufacturing

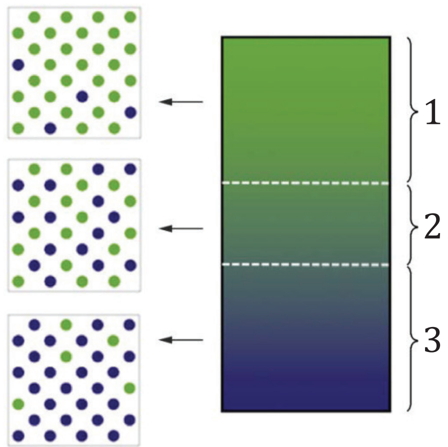
a) Multi-material AM **b) Functionally graded AM**

Key

1 discrete change of material properties
2 hard material for reinforcement
3 pillar to reinforce shape
4 smooth variation in material change

Figure 3 — Example of a part with multi-materials[73]

Reference [10] 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[22][28]. As the geometric arrangement of the two phases influences the overall material properties, the accuracy of the AM process is properly managed to ensure that the final component fulfils the expected functional requirements[72]. The difference between a Multi-material AM and a Functionally Graded AM part is illustrated in Figure 3 by Reference [73]. Figure 4 further describes the continuous graded microstructure of FGAM using 2 materials.



Key

1 phase 1 (particles with phase 2 as matrix)
2 transition phase
3 phase 2 (particles with phase 1 as matrix)

Figure 4 — Continuous graded microstructure of FGAM — 2 materials

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[43]. According to

