

Special Section on Functionally Graded Rapid Prototyping, 4D Printing & Self-Assemblies guest edited by Eujin Pei

Through advancements in material science and technology, four-dimensional (4D) printing (4DP) has seen rapid growth in terms of research and development. It is an approach for designing and fabricating self-evolving structures that can react to the environment or applied external stimuli and whose parts can transform into predetermined shapes or its physical properties over time after fabrication. The fourth dimension in 4DP is described as transformation over time, underlining that three-dimensional (3D)-printed structures are no longer static but are programmable, active and can continue to evolve after being built. Specific materials are chosen to harness the unique properties that activate the process. For example, the expansion of water-absorbing material provides the energy to trigger a bending or twisting action to close a cover. 4D-printed parts can be fabricated using a single material, as two or more separately printed components that are conjoined, or by using functionally graded materials (FGMs). The use of smart materials for 4DP include shape memory polymers that can self-sense, self-actuate and shape-change when an external stimulus is applied. (Bogue, 2013; Pei, 2014). This “smart” behaviour is known as the shape memory effect. The source of external stimuli can be categorized into physical or chemical parameters (i.e. temperature, humidity, light, magnetic sources or contact with specific chemicals). The design and constraints of the geometric programme embeds the capacity for a state which induces geometric folding, curling, expansion and various other changes. Specifically, we define 4DP as a layer-by-layer process of creating a physical object using either a single stimulus-responsive composite, multi-materials with varying properties or through FGMs. After being built, the object reacts to stimuli from the natural environment or to human intervention, resulting in a physical or chemical change of state over time that can provide a secondary function (Pei, 2014).

In contrast to conventional additive manufacturing (AM), which focuses on shape-centric prototyping, functionally graded additive manufacturing (FGAM) focuses on material-centric production by highlighting the structure–property relationship. The process is characterized by simultaneous synthesis and densification of 3D objects that are driven by its material organizations of varied properties. FGAM focuses on material behaviours as opposed to only its geometry. FGMs belong to a class of advanced substances characterized by the variation in their composition and structure gradually over volume, resulting in corresponding changes in the material properties. Within FGMs, different micro-structural phases have different functions. FGMs derive their multifunctional characteristic from the smooth transitions of constituent phases, and they can be designed and engineered for a specific set of functions and application,

such as mechanical shock resistance, thermal insulations, catalytic efficiency and relaxation of thermal stresses (Oxman, 2011). We define FGAM as an *in-situ*, layer-by-layer fabrication process that involves gradational mixing of materials to create freeform geometries with variable properties within a single component.

For this special issue, we have selected papers that cover applications in 4DP, exploring new material properties in terms of the friction coefficient (μ), as well as characterization and enhancement of colour binder jetting. The papers in this special issue are “Intelligent materials: a review of applications in 4D printing” by Xin Li and Zhuo Wang; “Investigating the friction coefficient in functionally graded rapid prototyping of Al-Al₂O₃ composite prepared by fused deposition modelling” by Rupinder Singh and Sunpreet Singh; “A method for characterization and enhancement of 3D printing by binder jetting applied to the textures quality” by Gardan Julien and “Exploring the concept of functionally graded additive manufacturing” by Eujin Pei, Giselle Hsiang Loh, David Harrison, Henrique Amorim Almeida, Mario Monzón and Rubén Paz.

In the first paper, “Intelligent materials: a review of applications”, the authors describe the development of intelligent materials and the emerging 4DP technology by introducing recent advances and applications of intelligent materials being adapted for AM. The paper begins with an overview of the development of intelligent materials around the world as well as 4DP processes. The authors cite that the additional dimension in 4DP refers to the ability of a 3D-printed item to switch its geometric configuration in a fully controllable manner. A particular stimulus, such as heat (thermo-responsive), solvent (chemo-responsive) and light (photo-responsive), may be applied to activate the switching process in either a reversible or non-reversible fashion. The paper also provides an overview of the fabrication methods and applications of intelligent materials as well as the capabilities of intelligent materials, such as shape-memory, self-assembly, self-actuating and self-sensing, before suggesting novel applications such as self-deployable systems and foldable robot components. Finally, the authors provide a brief outline of their ongoing research on the use of a thermosetting polyurethane that shows promise as a potential shape memory material.

“Investigating the friction coefficient in functionally graded rapid prototyping of Al-Al₂O₃ composite prepared by fused deposition modelling” studies the friction coefficient in the functionally graded rapid prototyping of Nylon6-Al-Al₂O₃ composites being prepared using fused deposition modelling (FDM), assisted by an investment casting (IC) process. The optimized settings of the process parameters, such as filament proportion, volume of FDM pattern, density of FDM pattern, barrel-finishing time, barrel-finishing media, weight and number of IC slurry layers, suggested that the research work will help fabricate parts with a potentially higher frictional coefficient. Initially, the melt flow index (MFI) of two different proportions of Nylon6-Al-Al₂O₃ (as an alternative FDM filament material) were tested on a melt flow indexer and matched with the MFI of a commercially used acrylonitrile-butadiene-styrene filament. The selected proportions of Nylon6-Al-Al₂O₃ were prepared in the form of FDM filaments by using a single screw extruder. Castings developed were tested for their wear resistance properties on a

pin-on-disc type tribo-tester under dry sliding conditions to check their suitability as frictional devices for industrial applications. For the methodology, Taguchi orthogonal array was used to study the effect of selected process variables on the coefficient of friction (μ). It was found that filament proportion, volume of FDM pattern and density of FDM pattern significantly affected the μ values. Further, density of FDM patterns was found to have 91.62 per cent contribution in obtaining μ values. The scanning electron micrographs highlighted uniform distribution of Nylon6-Al-Al₂O₃ particles in the Al-matrix at the suggested optimized settings. This paper describes the effect of process parameters on wear properties of a Nylon6-Al-Al₂O₃ composite developed as an FGM by the FDM-based pattern in the IC process. In conclusion, this work illustrates the development of an FGM that is surface reinforced by Nylon6-Al-Al₂O₃ particles, which could have industrial applications for manufacturing friction surfaces when producing clutch plates and brake drums.

“A method for characterization and enhancement of 3D printing by binder jetting applied to the textures quality” presents a technical approach to evaluate the quality of textures of inkjet printing, specifically for binder-jetting processes, on the powder bed. The author suggests using contour detection so as to improve the quality of the surface printed. Inkjet problems from 3D printing can be observed depending on product orientation in manufacturing, and in practice, colour 3D printing produces a visual difference in product surfaces. This difference is because of the grains of powder on the surface, as well as the projection of the micro-ink droplets on the surfaces of the part. Other studies show that the selection of a proper binder is essential in manufacturing to achieve good surface finish, dimensional accuracy and high resolution. In this work, image processing is used to measure the edge deviation of the texture on the granular surface with the aim of implementing a correction feature during the printing process using a design for manufacturing approach. The tests reveal shape alteration in the printed image using the product, and image processing is used to improve the quality of the output, thereby reducing and compensating for print errors that occur.

Lastly, the paper “exploring the concept of functionally graded additive manufacturing” clarifies the concept of FGAM and 4DP. The authors define that FGAM is a single AM process that includes gradational mixing of materials to fabricate freeform geometries with variable properties within

one component and is not to be confused with 4DP wherein smart materials are used in AM to produce parts that have the ability to change when exposed to an environmental stimulus. The authors highlighted that FGAM requires better computational tools for modelling, simulation and fabrication because current computer-aided design systems are incapable of supporting the complex workflow, suggesting that future work should focus on aspects of material characterization and better control processes.

References

- Bogue, R. (2013), “3D Printing: the dawn of a new era in manufacturing”, *Assembly Automation*, Vol. 33, pp. 307-311.
- Oxman, N. (2011), “Variable property rapid prototyping”, *Virtual and Physical Prototyping*, Vol. 6 No. 1, pp. 3-31.
- Pei, E. (2014), “4D Printing: dawn of an emerging technology cycle”, *Assembly Automation*, Vol. 34, pp. 310-314.

Further reading

- Oxman, N., Keating, S. and Tsai, E. (2011), *Functionally Graded Rapid Prototyping*, Mediated Matter Group, MIT Media Lab.

About the author

Dr Eujin Pei's research interests centre on additive manufacture and functionally graded rapid prototyping. He is a senior lecturer at the Department of Design and the Programme Director for the BSc Product Design and BSc Product Design Engineering courses at Brunel University London in the United Kingdom. He is the Convenor of the International Standards Organisation (ISO) Technical Committee (ISO TC261/WG4) for Data and Design Guidelines for Additive Manufacture and a committee member of the British Standards Institution (BSI) AMT/8 Group for Additive Manufacture. Eujin is also a Chartered Technological Product Designer and a Member of the Institution of Engineering Designers. He serves as an Associate Editor for the *Assembly Automation Journal* with a track record of generating new knowledge and finding solutions with a significant impact on industry. He welcomes opportunities for joint PhD supervision, industry projects and multidisciplinary partnerships.