4D Additive Manufacturing of Structural Composites with Programmed Stimuli-Response

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In biologically engineered architectures, ‘morphogenesis’, a dual strategy for growth and form, exists where the mechanics of design evolves, as an adaptive organism, through the dynamic and continuous ‘negotiation’ between design intent and material emergence. Clearly the ability to replicate a similar strategy in engineering, where structural reinforcement adapts and remodels depending upon the local manufacturing requirements or loading environment, is a very desirable outcome.

To achieve synthetic ‘morphogenesis’ materials, active material constructs and new manufacturing techniques, exhibiting programmed intelligence in complex 3D architectures, will have to be developed. One possible approach is 4D Additive Manufacturing (AM) [1]. 4D AM is the 3D printing of an active part that is able to move and change-shape on demand in response to an external stimulus. In this study, we actively align discontinuous reinforcement utilizing an ultrasonic field with a hydrophilic polymer network which is able to undergo large volume changes through stimuli-triggered absorbance and release of water. This methodology is outlined in Figure 1 and consolidates our previous acoustophoresis work [2-3] with our ongoing research in 4D morphing hydrogels [4].

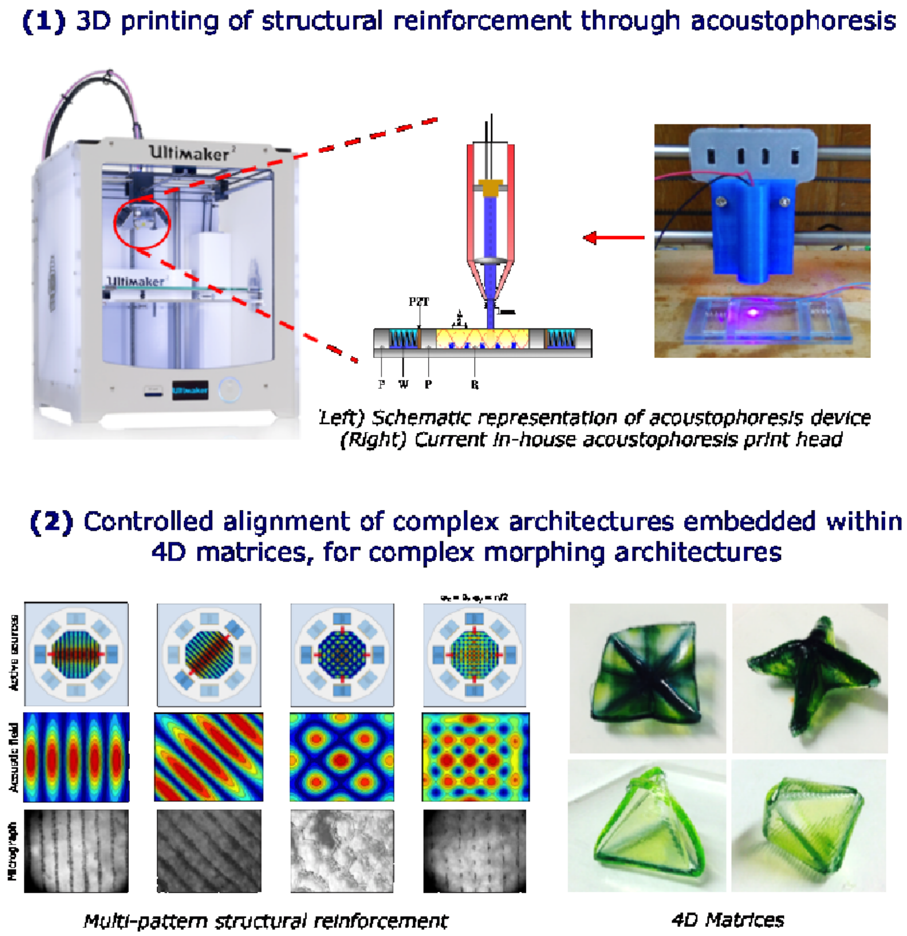

Figure 1: 4D programmed stimuli-responsive structural reinforcement. (1) Alignment of structural reinforcement through acoustophoresis within ALM [3]. (2) Reinforcement configurations as a function of ultrasonic triggered pattern, and 4D shape changing materials [4].

Aligned short fibres are found in the self-shaping mechanisms of many natural systems, utilising specific orientations to generate bending, twisting and multi-motion movements. Inspired by these systems, our paper will show the ability to grow new geometrical architectures by controlling the continuous 'negotiation' between design intent and material emergence locally at the ALM print-head (see Figure 2), and then globally through stimuli triggered movement of the matrix material (see Figure 3).

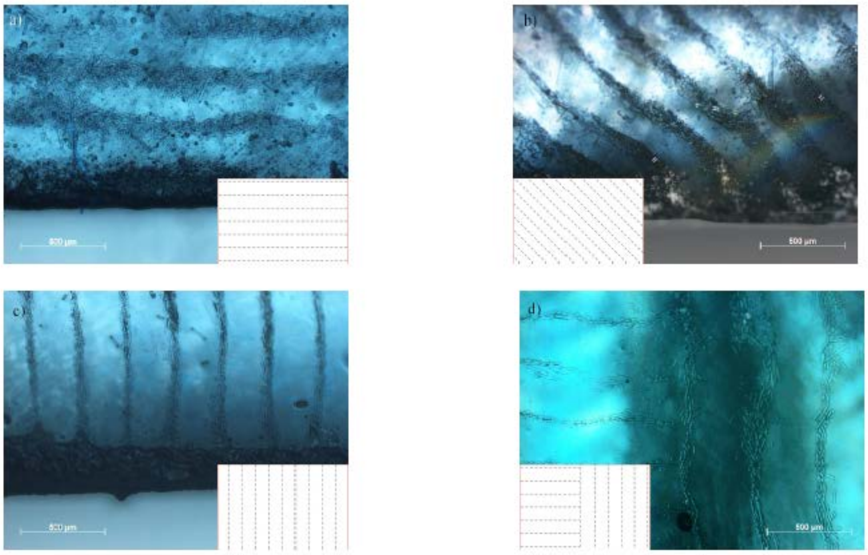

Figure 2: Demonstration of varying fibre angle within a printed component, with desired microstructure shown in inset. All parts had dimensions 20mm (l) x 2mm (w) x 1mm (t). a) Fibres aligned along part axis. b) Fibres aligned at 45 $^{\circ}$ to part axis. c) Fibres aligned at 90 $^{\circ}$ to part axis. d) Demonstration of orthogonally aligned reinforcement within the same printed layer.

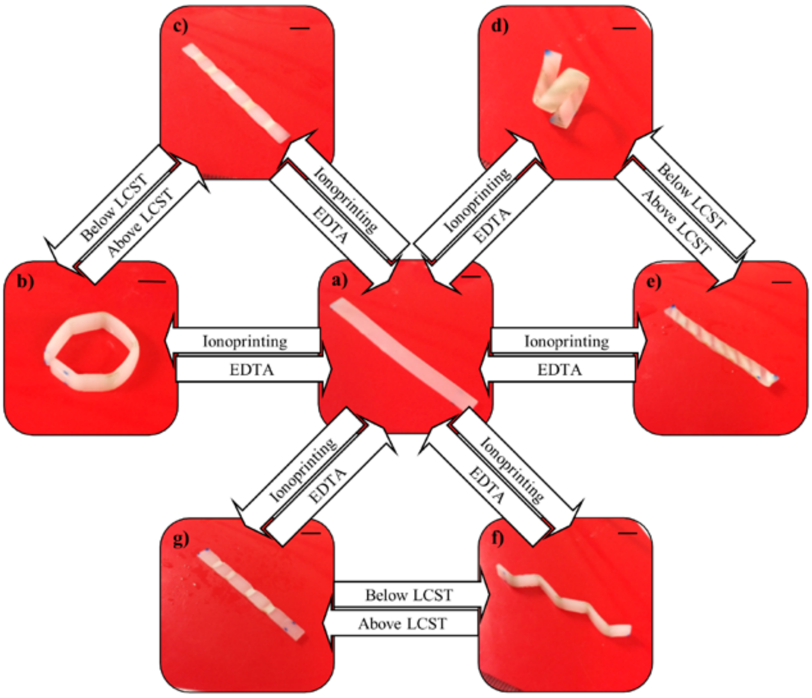

***Figure 3:** Multi-shape reversible actuation through chemical ionoprinting patterns formed: (a) flat hydrogel bar ionprinted into (b) a hexagon, (d) a coil, (f) a zig-zag, capable of unfolding to a flat configuration (c), (e) and (g), and refolding to reform their hexagon (b), coil (d) and zig-zag (f) shapes, by transitioning through a lower critical solution temperature. Scale bar = 5 mm [4]*

A key feature of this concept is the controlled 3D placement of micro- or nano-length reinforcement which can promote or arrest the movement of the 4D matrix; offering a unique programmed approach in the construction of fibre reinforced composites for complex 3D architectures. This study will specifically examine the role of optimisation of the fibres, resin and resultant composite to create programmable, predictable and repeatable self-shaping components.

Acknowledgements

This work is supported by US Airforce EOARD funding (Grant number FA9550-16-1-0307) and the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Advanced Composites for Innovation and Science (grant number EP/G036772/1). The authors gratefully acknowledge the support of the UK Engineering Physical Sciences Research Council (EPSRC) for funding Dr Richard S Trask's fellowship and research under EPSRC 'Engineering Fellowships for Growth', (grant number EP/M002489/1).

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