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Exploiting cyclic softening in continuous lattice fabrication for the additive manufacturing of high performance fibre-reinforced thermoplastic composite materials

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ABSTRACT

Continuous lattice fabrication (CLF) was recently introduced as a new additive manufacturing (AM) technology capable of printing continuous fibre-reinforced thermoplastic composites along desired trajectories in three-dimensional space. In a systematic attempt to maximize the mechanical properties of the printed extrudate by minimizing the residual void content, this study investigates the thermal deconsolidation behaviour observed in pultruded unidirectional fibre-reinforced thermoplastic composite material when it is reheated above its melting point and exposed to ambient pressure. Fibre decompaction, generally accepted to be the primary cause for deconsolidation in fibre-reinforced thermoplastics, was investigated to assess the influence of cyclic softening of the fibrous media on the residual void content of the extruded material. The magnitude and rate of fibre decompaction were observed to decrease with the number of consolidation-deconsolidation cycles to which the material was subjected. A model was developed to predict the degree of deconsolidation in the CLF process as a function of temperature, processing speed, and processing history. Based on the deconsolidation behaviour observed, a multi-stage pultrusion module was designed that exploits cyclic softening and was demonstrated to reduce the residual void content of the printed extrudate by over 80%.

1. Introduction

Additive manufacturing (AM) technologies have the advantages, in comparison to casting and subtractive manufacturing processes, of eliminating some of the costs associated with complex geometries and individually tailored designs, while also reducing waste [1]. The emergence of AM as a viable approach for the production of end-use components remains the target for many low-volume applications [2]. The AM of high performance fibre-reinforced polymer composites (FRPC) is particularly attractive for enabling a new design space for ultra-lightweight structures in aerospace, medical engineering and robotics amongst others. Although efforts to apply layer-by-layer AM strategies to anisotropic FRPC materials have met with moderate success [3–10], in order to fully harness the potential of FRPC materials in engineering structures, alternatives to the planar layer-by-layer approach must be developed which allow for the orientation of anisotropic materials along all relevant vectors, including those positioned out-of-plane.

Recently, we introduced continuous lattice fabrication (CLF) as an AM-based solution for freely depositing continuous fibre-reinforced thermoplastic composites in three-dimensional space [11]. CLF is capable of depositing free-standing self-supporting filaments by spatial extrusion without the use of supporting sacrificial structures (see Fig. 1A), as well as laying consecutive layers directly onto a substrate (see Fig. 1B). Examples of applications in which these manufacturing capabilities are practical are in the production of lattice cores for ultra-lightweight sandwich panels (see Fig. 1C) and for locally-reinforcing structures with stiffening elements (see Fig. 1D).

CLF functions by means of a serial pultrusion-extrusion system (see Fig. 2A) that enables the *in situ* consolidation of cost-effective unconsolidated feedstock materials, e.g. commingled yarns. A feeder system pulls the incoming bundle of commingled yarns through a temperature-controlled tapered pultrusion module where the thermoplastic composite intermediate material is melted, consolidated, and cooled. The upper two optical microscopy images in Fig. 2B show cross-sectional images of the material before and after being processed in the pultrusion module. These images indicate that an excellent degree of consolidation and very low void content in the pultruded material is

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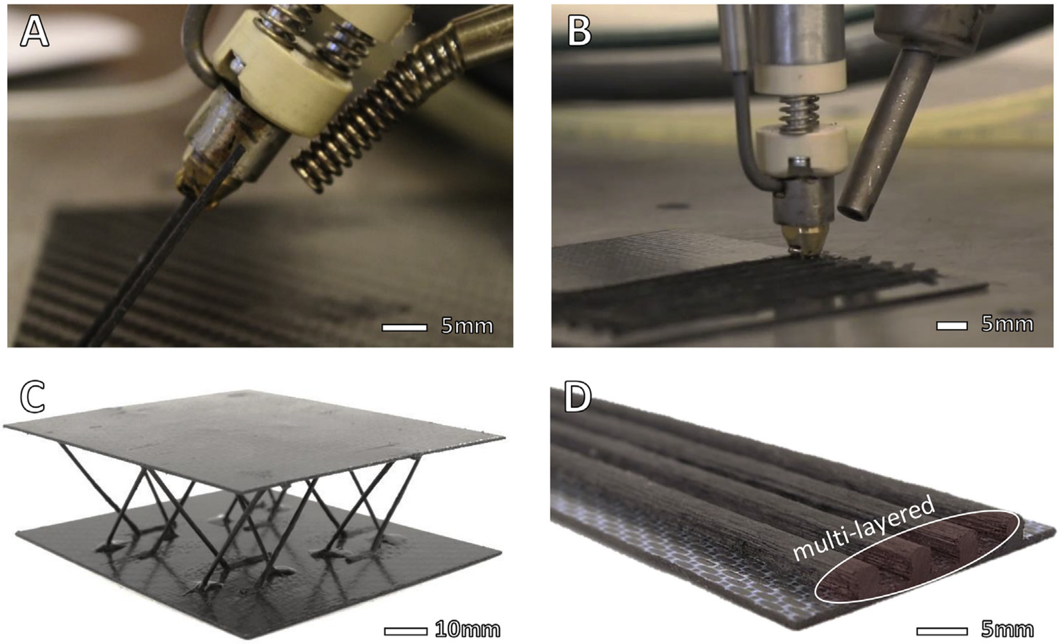

Fig. 1. The CLF process is applied to shape in situ consolidated continuously reinforced thermoplastic filaments. The CLF print path trajectory is determined by the relative movement between the CLF processing head and the substrate in all directions, including the out-of-plane direction. CLF is capable of (**A**) printing suspended free-form structures as well as (**B**) directly depositing fibre strands onto a base substrate. Structures made by CLF include amongst others, (**C**) ultra-lightweight sandwich cores composed of structures with slender lattice networks and (**D**) multi-layered stiffening elements onto a FRPC plate.

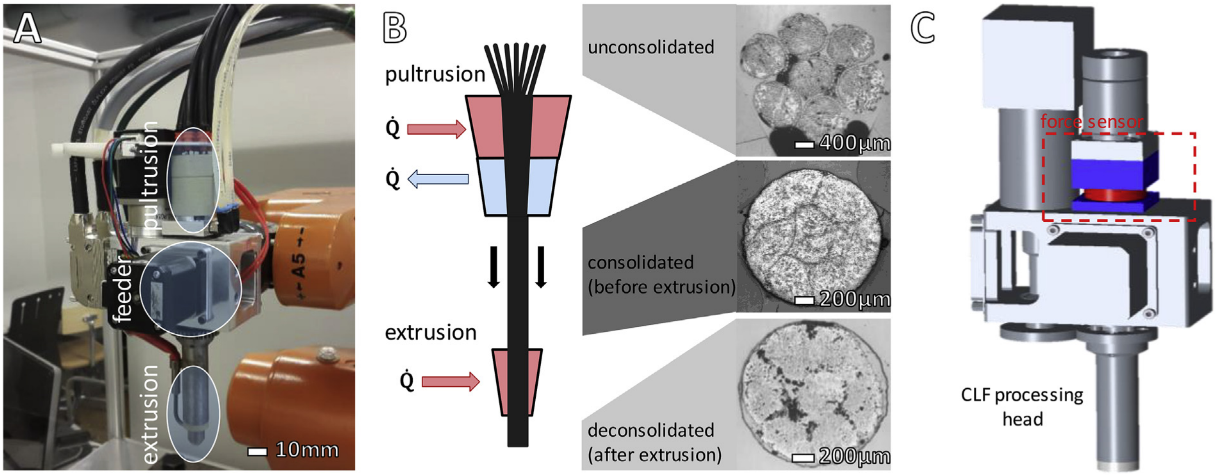

Fig. 2. The CLF head is comprised of a two-stage pultrusion-extrusion system. (**A**) Photograph of CLF head. (**B**) Schematic of the CLF process, illustrating the active thermal management of the heated and cooled pultrusion module as well as the heated extrusion stage. Heat flow into and out of the composite material is represented by $\dot{Q}$. Optical microscopy images show the unconsolidated feedstock material prior to being pultruded, the consolidated semi-finished prepreg material before extrusion and the final extruded material indicating some level of deconsolidation. (**C**) Schematic of CLF head with integrated pulling force sensor.

achieved. The fully consolidated material is then fed into a temperature-controlled extrusion module similar to those used in fused filament fabrication [12], where it is reheated and discharged from the extrusion nozzle at a temperature above the melting point of the polymer so that it can be formed into the desired shape. However, upon reheating, significant deterioration in material quality is observed as shown by the increase in void content found in the optical microscopy image provided in the lower micrograph of Fig. 2B. This formation of voids is attributed to the deconsolidation of the FRPC material which occurs when residual stresses are released as the temperature of the thermoplastic matrix rises above its melt/glass transition temperature. The deconsolidation of fibre-reinforced thermoplastic composite materials upon reheating has been studied in literature. Three mechanisms have been identified as being responsible for providing the driving force for the deconsolidation of fibre-reinforced thermoplastic composites: (i) the expansion of trapped gases, (ii) bubble coarsening and coalescence, and (iii) the decompaction of the fibrous media [13–15]. Of these mechanisms, the decompaction of the fibrous media has been reported to dominate the deconsolidation behaviour [16].

When fibre-reinforced thermoplastic composites are processed under heat and applied pressures, the fibrous media experiences elastic and inelastic deformations [17–19]. These deformations and the associated stresses are frozen into the consolidated material upon cooling and solidification of the thermoplastic matrix. When the thermoplastic matrix is re-melted, the stored elastic energy may be released, resulting in the expansion of the material and the formation of voids. The degree to which the fibre network decompresses is dependent on the fibre properties, the fibre network configuration, the fibre volume content,