Additive Manufacturing 16 (2017) 146–152

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing

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ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 19 May 2017
Accepted 14 June 2017

Keywords:
Carbon fibre
Glass fibre
Kevlar fibre
Additive manufacturing
Continuous fibres

ABSTRACT

This study evaluated the performance of continuous carbon, Kevlar and glass fibre reinforced composites manufactured using the fused deposition modelling (FDM) additive manufacturing technique. These nylon composites were fabricated using a Markforged Mark One 3D printing system. The mechanical performance of the composites was evaluated both in tension and flexure. The influence of fibre orientation, fibre type and volume fraction on mechanical properties were also investigated. The results were compared with that of both non-reinforced nylon control specimens, and known material property values from literature. It was demonstrated that of the fibres investigated, those fabricated using carbon fibre yielded the largest increase in mechanical strength. Its tensile strength values were up to 6.3 times that obtained with the non-reinforced nylon polymer. As the carbon and glass fibre volume fraction increased so too did the level of air inclusion in the composite matrix, which impacted on mechanical performance. As a result, a maximum efficiency in tensile strength was observed in glass specimen as fibre content approached 18%, with higher fibre contents (up to 33%), yielding only minor increases in strength.

1. Introduction

Additive Manufacturing (AM) is widely used for the fabrication of polymer components ranging from prototypes to 'final products' [1]. Various AM techniques for polymer manufacture have been developed, including; Stereolithography (SLA) applied using photopolymer liquids [2], Selective Laser Sintering (SLS) involves the use of polymer powders [4], while Fused Deposition Modelling (FDM) uses polymer filaments [3]. The latter is the most widely utilised system for polymer AM manufacture due to its relative low cost, low material wastage and ease of use [5]. The FDM process most often utilises a continuous polymer filament as a feedstock material. The polymer filament feeds into an extruder and is heated to a quasi-liquid state, enabling it to pass through a heated extruding orifice where it is fused in-place on a print surface. This extruding apparatus is typically mounted onto an X-Y CNC (Computer Numerical Control) gantry, allowing the printing of complex geometric patterns. Once a layer pattern is complete, the print platform drops down, or extruding orifice rises by the layer thickness to deposit a subsequent layer of material. Through the deposition of successive layers, 3D objects are fabricated [6]. At present thermoplastics are the most frequently utilised feedstock materials for FDM due to their low cost, and low melting temperatures [7]. These include Polycarbonate (PC), Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS) and Polyamide (PA or Nylon). The FDM technique can result in the formation of porous inner structures in the fabricated component which leads to poor mechanical strength, a further issue can be poor surface finishes due to the 'stair stepping' effect [8–10]. These limitations have hampered the wider adoption of 3D printed components for use as final products, leaving prototyping as the primary application.

Attempts have been made to overcome the poor mechanical performance of 3D printed parts with the addition of fibre or particle reinforcement. This has been utilised in the polymer industry to enhance structural strengths in traditional composites, forming what are known as fibre reinforced polymers (FRP) [11]. Zhong et al. for example incorporated chopped glass fibres into ABS polymers using an FDM printing process with the aim of increasing tensile strength [12]. This study demonstrated that interlayer bond strength was increased with increased fibre contents, due to 'bridging' of fibres across layers. A further study by Ning et al. also investigated ABS composites but this time with chopped carbon fibre materials demonstrating an increase in both tensile strength and stiffness [13]. Samples reinforced with 7.5 wt.% carbon fibre achieved a 27% increase in tensile strength over pure ABS specimen. Interestingly, it was also reported that fibre contents of 10 wt.% or

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http://dx.doi.org/10.1016/j.addma.2017.06.004
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higher resulted in a decrease in tensile strength. This was attributed to a reduction in fibre-matrix contact, as well as an increase in fibre-fibre contact, as the fibre content increased.

There have been a small number of reports on the fabrication of continuous fibre reinforced composites, one example being Namiki et al. [16], which utilised a unique dual extrusion method. This study, in which a print head was custom built, yielded continuous carbon fibre PLA composites with strengths of up to 190 MPa in tensile, and 133 MPa in flexure. Their values were 435% and 316% higher respectively, compared with the PLA only composites. A study by Van der Klift et al. [17] assessed carbon fibre reinforced specimen produced by the Markforged Mark One in order to obtain details relating to the mechanical performance of the proprietary fibre filament. Tensile specimens were produced and a 9-fold increase in strength was observed. A factor that may have affected the results in this study however is that the test specimens were cut post-printing in order to remove 'discontinuities' and excess matrix material which may influence the strength results. These authors observed large deviations between individual test results, with standard deviations in tensile strength as high as 22%, obtained from a 10-layer thick specimen containing 6 layers of CF reinforcement.

In this study, a more detailed evaluation of the performance of 3D printed composites with continuous carbon fibre (CF) reinforcement was carried out. This study also involved the fabrication of nylon composites with Kevlar® and glass fibres and the mechanical performance of all three composite types were compared. In addition, the influence of fibre volume fraction (VF), fibre placement and fibre orientation on the mechanical performance of the composite was evaluated.

2. Experimental

2.1. Materials

Nylon filament was supplied by Markforged [14], it is their proprietary blend, and has a diameter of 1.75 mm. Prior to use, this polymer was stored in a moisture-sealed Pelican 1430 modified dry box to prevent deterioration of the filament due to moisture absorption during storage [15]. The reinforcing glass fibre (GF), carbon fibre (CF) and Kevlar® fibre (KF) were also supplied by Markforged. While these are referred to as 'fibres', these are composed of fibre bundles infused with a sizing agent. Fibre Bundles of Kevlar and Glass were 0.3 mm in diameter and carbon fibre bundles 0.35 mm. The individual fibre diameters within these bundles were 10 ±2um (as observed under Scanning electron microscopy, SEM) in all cases, with bundles containing ~1000 fibres. Carbon fibre bundles were observed to contain a higher amount of sizing agent, giving these bundles their larger diameter. All information regarding the fibres mechanical properties or chemical composition were withheld by the supplier.

2.2. The Mark One Composite 3D printer

Fig. 1 shows a photograph of the Markforged Mark One 3D printing equipment from which test specimens were fabricated. The printing process consists of two stages, each of which is performed by a separate print head. These stages are firstly nylon (matrix) printing and secondly fibre reinforcement printing. The nylon and fibre layers are printed with a hot end temperature of 263 °C onto a non-heated print bed (A typical deposition time for a 1 × 1 cm sample with a single layer thickness of 0.1 mm is 15 s). The design of the 3D printer allows continuous fibre reinforcement to be positioned as required.

The focus of this study was to print test specimens for both tensile and flexural examination. Kevlar and glass printed test pieces comprised of 32 layers (3.2 mm total thickness) of material, each with a thickness of 0.100. The carbon fibre however had a higher filament thickness (0.35 mm) and is printed in layers of 0.125 mm, therefore only 26 layers were used to fabricate this composite. In order to facilitate a direct comparison between fibre types, only 8 layers of the test coupons were fibre reinforced. To produce 3D printed samples comparable to moulded composites, these fibre layers were distributed evenly through the sample thickness, the stacking sequence used is demonstrated in Fig. 2c.

To study the effect of fibre volume fraction on mechanical performance, a number of additional specimens were produced with 4, 12 and 16 reinforced layers. Control test pieces consisted of a solid nylon print (also 32 layers), which contained no fibre. Typical fabrication times of between 90 and 120 min (depending on fibre used) were required for a single test specimen, after which the dimensions were verified using a Vernier callipers. Tensile specimen were 183 × 23 × 3.2 mm in size, in accordance with standard ASTM D638 and flexural specimen 123 × 12.7 × 3.2 mm in accordance with ASTM D7079-10.

2.2.1. Fibre pattern

The effect of fibre-laydown pattern on part mechanical performance was examined; the fibre patterns investigated were 'Concentric' and 'Isotropic' as shown schematically in Fig. 2a and b. The 'Concentric' fibre pattern consists of a spiral shaped laydown, fibre strands begin at the outer edge of the part and wrap inwards toward the parts centre, forming annular rings. The user can define the number of these rings, with 5 rings chosen for test specimen fabrication in this study. The Isotropic fibre pattern consists of parallel lines, with areas void of fibre being filled by nylon before the subsequent layer is printed.

The terms 'Concentric' and 'Isotropic' are labels given to these fibre patterns by Markforged, they do not define the mechanical properties of the final test piece. Isotropic fill in this case resulted in a unidirectional anisotropic test piece. For ease of reference purposes 'Concentric' and 'Isotropic' patterns are labelled as 'A' and 'B' respectively in this study. The Mark One equipment does not have the capability of laying down carbon fibre in pattern 'B' (possibly due to the stiffness of the material), therefore specimens with carbon fibre were examined using pattern 'A' only.

2.3. Characterisation equipment

Tensile tests were performed utilising a Hounsfield H50KS screw-drive materials testing machine. The specimens were held in place using wedge clamps, under a preload of 3 N, and tested at a crosshead speed of 5 mm/minute as per ASTM D638 standard.

Flexural tests were performed on an Instron 100KN 8501 hydraulic tester. With a preload of 2 N and a crosshead speed of 2.2 mm/min, as per ASTM 790 standard, and specimens were tested to failure. Subsequent to tensile and flexural testing, the fractured specimens were examined using SEM (TM-1000 Hitachi).

2.4. Results & discussion

The Markforged equipment was used to fabricate nylon only, carbon, Kevlar and glass fibre samples for tensile and flexural testing. The performance of these test samples are discussed in this section.

Tensile Testing – As detailed in the introduction, Van der Klift et al. reported problems with 'discontinuities' (The start and end points of the fibre reinforcement) causing premature failure, and resorted to cutting the specimens preferentially around these anomalies to avoid this effect [17]. In order to overcome this 'dis-