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Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics

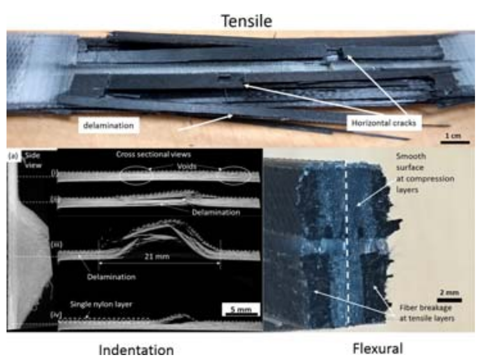
G.D. Goh [a], V. Dikshit [b], A.P. Nagalingam [b], G.L. Goh [a], S. Agarwala [a], S.L. Sing [a,b], J. Wei [c], W.Y. Yeong [a,b,*]

[a] Singapore Centre for 3D Printing, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[c] Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, 638075, Singapore

HIGHLIGHTS

- A comparison of fracture behaviors between 3D-printed carbon and glass fiber reinforced composites is performed.
- Difference in fracture behavior between glass and carbon fibers reinforced composites is observed in flexural test.
- Similar fracture behavior is observed for tensile and quasi-static indentation tests.

GRAPHICAL ABSTRACT



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ABSTRACT

Continuous fiber-reinforced polymer (FRP) composites have been used for many applications to create strong yet lightweight products due to their high strength-to-weight and stiffness-to-weight ratios. Aerospace [1], automotive [2], and sport [3]industries are three of the few industries that have been using FRP composites. The increasing need for prototyping and customization of fiber reinforced polymer composite parts is prompting innovations in new manufacturing processes to realize short manufacturing cycle time and low production cost, which is challenging to accomplish using conventional molding process. Fused filament fabrication (FFF) - a material extrusion additive manufacturing (AM) technique trademarked as fused deposition modelling (FDM) by Stratasys- holds promise to achieve low-cost production on continuous fiber-reinforced thermoplastic (FRTP) composites. In this paper, the FFF technique is employed to fabricate continuous carbon and glass FRTP composites and its microstructural characteristics and the resulting tensile, flexural, and quasi-static indentation characteristics of the printed composites are examined. Additionally, the fracture behavior of each test sample is evaluated and discussed in detail.

1. Introduction

Additive manufacturing (AM) is a layer-by-layer manufacturing process in which parts are robotically manufactured from digital geometries [4]. It is a disruptive technology because it dramatically shortens

* Corresponding author at: School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore.
E-mail address: WYYeong@ntu.edu.sg (W.Y. Yeong).

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the timeline for parts being designed and fabricated according to end user requirements. Parts with intricate internal geometries such as honeycomb structure can be fabricated using AM which would otherwise be challenging or impossible using conventional techniques [5–7]. In polymer printing, many materials have been developed which are specific to the AM techniques employed [8]. For instance, thermoplastic polymer are developed for fused filament fabrication [9], powder materials for selective laser sintering [10] and liquid photopolymers for polyjet and stereolithography [11,12]. However, the low mechanical properties that pure polymers typically exhibit are not suitable for high performance engineering applications. Recent trend shows the development of composite materials specifically for AM with enhanced mechanical properties over existing polymeric materials [13].

A composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material that offers superior overall performance compared to the individual components [14]. Research on development of composite materials for AM processes has been ongoing for more than a decade [15]. Most studies were focused on the development of materials with short fiber reinforcements [16–27] with only a few on continuous fiber reinforcements [28–38]. Although short fiber reinforced composites offer better mechanical performance compared to their unreinforced counterparts, there is still a substantial gap between the mechanical properties of additively manufactured composites and conventionally manufactured fiber reinforced polymer (FRP) composites, which mainly use continuous fiber reinforcement, in terms of mechanical properties. For instance, the tensile strengths of additively manufactured short fiber composites are in the range of 70 MPa [16,17,39] which are inferior to the strengths of conventionally manufactured FRP's (200–1500 MPa) [40].

Although AM of composite material have been ongoing for the past decade, AM of continuous fiber reinforced thermoplastics (FRTP) composites are still in its infancy. To date, only stereolithography [28–30] and fused filament fabrication (FFF) [31–37] have been used to fabricate continuous fiber reinforced composites. FFF -a material extrusion AM technique- is seen to be the more promising technique compared to stereolithography to realize the fabrication of FRTP due to several reasons. Firstly, it is technologically less demanding and can be achieved with a slight modification on the extrusion print head. Secondly, the FFF feedstock materials have much longer shelf life as they are less susceptible to degradation.

In general, two methods have been developed for the FFF technique to realize the fabrication of FRTP composites, they are (1) *in-situ* fusion [31–36] and (2) extrusion of pre-impregnated fiber [41–44]. In *in-situ* fusion method, dry carbon fibers are fused with melted thermoplastics resins such as ABS and PLA in the FFF print head extruder. This method has the potential to create functionally graded composite parts by varying the amount of thermoplastic being extruded which in turn changes the fiber volume fraction. However, poor bonding at the fiber matrix interface resulting from the in-situ fusion remains one of the key challenges to be addressed [45]. On the other hand, although extrusion of pre-impregnated fiber (Fig. 1) does not give the flexibility to change the fiber volume fraction, it eliminates the problem of poor fiber matrix interface. This is because good impregnation can be performed with proper monitoring and quality control during the fabrication of pre-impregnated fibers. The fabrication of continuous fiber reinforced composites directly from pre-impregnated fiber has been attempted.

The MarkOne composite printer that uses extrusion technique to print continuous glass and carbon fibers has also been made available commercially giving product designers an alternative to realize their product design [46]. A detailed evaluation of mechanical properties of additively manufactured carbon fiber and glass fiber reinforced are very limited to the authors' knowledge. Potentially, there is a need to characterize the mechanical properties and fracture behaviors of the additively manufactured continuous FRP composites to give product designers a detailed understanding on the characteristics of the additively manufactured continuous FRP composites.

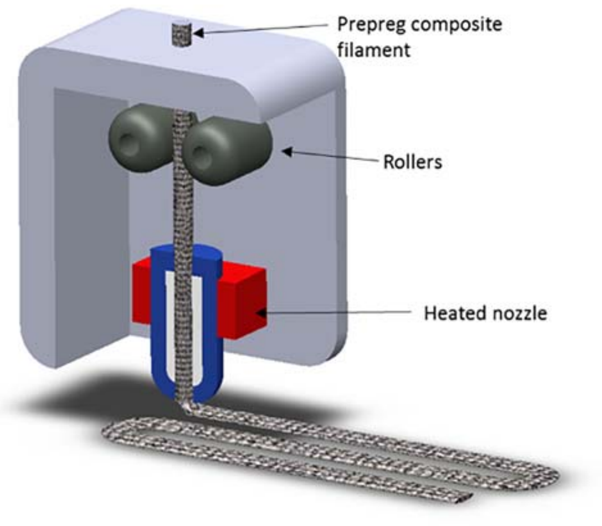

Fig. 1. Extrusion of pre-impregnated continuous fiber composite filament in FFF.

In this paper, the two types of commonly used fibers (carbon and glass fibers) are chosen to be evaluated due to their distinctly different raw material cost. Carbon fibers are known for their high stiffness-to-weight ratio but are expensive (\$150 per 50 cm^3) and hence are only used in industries that are very particular about weight such as aerospace industry. On the other hand, glass fibers are relatively inexpensive (\$75 per 50 cm^3) and exhibit fairly good mechanical properties and are suitable for parts that are less stringent on weight and strength (especially for sports industry) so that parts can be fabricated at lower cost. Various mechanical properties that are relevant to sports, automotive, and aerospace industries, such as tensile, flexural, and indentation resistance of additively manufactured continuous carbon and glass FRTP are evaluated by conducting mechanical testing. In addition to that, scanning electron microscopy (SEM) and micro-computerized tomography (μCT) - scan were also used to observed the microstructures and fracture mechanism of the composites.

2. Material and test methods

2.1. Manufacturing process

The carbon and glass fibers are provided by Markforged, United States. The materials are composed of multiple strands of carbon or glass fibers coated with nylon matrix and come in spools [47]. The diameter and density of the carbon fiber composite filament were measured to be 370 μm and 1.30 g/cm^3. Similarly, the diameter and density of the glass fiber composite filament were measured to be 290 μm and 1.45 g/cm^3. The extruder temperature was set to 260 °C. The parts were fabricated with unidirectional pattern (0°) as shown in Fig. 2. Layer height was set as 0.1 mm. Air gap was kept zero to ensure the specimens were solid. Table 1 illustrates the parameters selected for part fabrication.

2.2. Experimental methods

2.2.1. Microstructure analysis

After the tests, μCT-scan (Skyscan 1173, Bruker Co., United States) images of the fractured specimen were taken to observe the fracture mode and determine the porosity. The μCT-scan machine has a CCD sensor with 2240 × 2240 pixels, each with the pixel size of 50 μm. 1 × 1 camera binning mode was used and the resulting image pixel size was 16.404 μm when the object was placed 119.318 mm from the source.