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Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling

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ABSTRACT

Additive manufacturing (AM) technologies have been successfully applied in various applications. Fused deposition modeling (FDM), one of the most popular AM techniques, is the most widely used method for fabricating thermoplastic parts those are mainly used as rapid prototypes for functional testing with advantages of low cost, minimal wastage, and ease of material change. Due to the intrinsically limited mechanical properties of pure thermoplastic materials, there is a critical need to improve mechanical properties for FDM-fabricated pure thermoplastic parts. One of the possible methods is adding reinforced materials (such as carbon fibers) into plastic materials to form thermoplastic matrix carbon fiber reinforced plastic (CFRP) composites those could be directly used in the actual application areas, such as aerospace, automotive, and wind energy. This paper is going to present FDM of thermoplastic matrix CFRP composites and test if adding carbon fiber (different content and length) can improve the mechanical properties of FDM-fabricated parts. The CFRP feedstock filaments were fabricated from plastic pellets and carbon fiber powders for FDM process. After FDM fabrication, effects on the tensile properties (including tensile strength, Young's modulus, toughness, yield strength, and ductility) and flexural properties (including flexural stress, flexural modulus, flexural toughness, and flexural yield strength) of specimens were experimentally investigated. In order to explore the parts fracture reasons during tensile and flexural tests, fracture interface of CFRP composite specimens after tensile testing and flexural testing was observed and analyzed using SEM micrograph.

1. Introduction

1.1. Additive manufacturing

Additive manufacturing (AM) is defined as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [1]. AM technologies make it possible to build a large range of prototypes or functional components with complex geometries those are unable or at least difficult to be manufactured by conventional methods [2,3]. Compared with conventional methods, AM can shorten the design-manufacturing cycle and thus reduce the production cost and increase the competitiveness [4,5]. In addition, due to the improvements of processes and advancements of modeling and design [6], AM technologies have been involved in wider various applications in the past three decades. The largest three rapid-increasing applications of AM fall into the areas of aerospace, automotive, and medical [7,8]. Other applications include architecture [9], education [10], fashion [11], etc.

1.2. AM of plastics

The first developed AM techniques are typically applied to fabricate pure plastic parts those are mainly used as rapid prototypes for functional testing [12]. AM techniques include stereolithography apparatus (SLA) from photopolymer liquid [13], fused deposition modeling (FDM) from plastic filaments [14], laminated object manufacturing (LOM) from plastic laminations [15], and selective laser sintering (SLS) from plastic powders [16]. However, FDM is the most widely used method among all the AM techniques for fabricating pure plastic parts with low cost, minimal wastage, and ease of material change [17,18]. Before FDM-fabricating

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process, the STL file generated by the CAD software is sliced into horizontal layers and the thickness of each layer can be set depending on the demands of customers. As shown in Fig. 1, in FDM processes, the filament on the spool is fed into the liquefier head with the aid of feeding pressure generated from a driver gear and a grooved bearing. Plastic parts can be built layer by layer through depositing the filament material which is heated to glass transition state and extruded through the extrusion nozzle at a constant temperature. Liquefier head moves on the X–Y plane as the tool path generated by the software and deposits the first desired layer at a time onto the print bed to form a foundation for the part. When the layer is completed, the build platform moves downward for one layer thickness for following layer of filament material fabrication. Each single layer will be deposited repeatedly on the previous one in the same way until the part is completed. In the FDM machine with dual extrusion nozzles, build filament material with another color or support filament material can be simultaneously extruded through the second nozzle if necessary. After FDM fabrication, the support material can be easily removed either mechanically or chemically (e.g., using solvent) [19].

Currently, only thermoplastic filaments are used as feedstocks in FDM [20], including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactide (PLA), polyamide (PA), and the mixtures of any two types of thermoplastic materials [14,21]. FDM of plastics are usually used to make conceptual prototypes with mature development stages [12], since the pure thermoplastic parts built by FDM are lack of strength as the fully functional and load-bearing parts. Such drawback restricts the wide applications of FDM technology [22,23]. Therefore, there is a critical need to improve the strength of FDM-fabricated pure thermoplastic parts to overcome the limitations. One of the possible methods is adding reinforced materials (such as carbon fibers) into plastic materials to form thermoplastic matrix carbon fiber reinforced plastic (CFRP) composites [20,22,24]. In CFRP composites, the carbon fibers can be used to support the load. Meanwhile, the thermoplastic matrix can be used to bind and protect the fibers and transfer the load to the reinforcing fibers [25–28]. Currently, thermoplastic matrix CFRP composites are widely used in many applications, such as fuselage of Airbus A350 aircraft, components in automotive, blades of wind turbine, and endoscopic surgery [29,30].

1.3. Present state of knowledge in FDM of composites

Among reported literatures, there are limited numbers of studies on developing new materials especially the fiber reinforced thermoplastic composites using FDM process. Zhong et al. [23] conducted experiments to investigate the processability of glass fibers reinforced ABS matrix composites with three different glass fiber contents used as feedstock filaments in FDM. The results showed that glass fibers could significantly improve the tensile strength and surface rigidity of the ABS filament. Gray et al. [31,32] presented thermotropic liquid crystalline polymer (TLCP) fiber reinforced polypropylene (pp) composites filament for FDM. Compared with chopped fiber, using longer TLCP fibers (length/diameter ratio > 100) in the composites led to larger tensile strength and better functionality of the fabricated prototypes. The tensile strength of TLCP fiber reinforced pp composites was much larger than that of most of other FDM fabricated materials. Shofner et al. [22] developed nano-fiber reinforced ABS matrix composites using FDM. Feedstock filaments consisted of single-walled carbon nanotubes and ABS plastics. Compared with unfilled ABS specimens, nearly 40% and 60% increase in tensile strength and tensile modulus were obtained at nanofiber loading of 10 wt%, respectively. Tekinalp et al. [20] compared carbon fiber reinforced ABS composites fabricated by both compress molding and FDM. Tensile testing was conducted in this work and tensile strength and Young's modulus were measured for the comparisons, but no other tensile properties were investigated for details. The results showed that the FDM-fabricated parts had lower tensile strength than those made by compress molding at almost all the fiber contents, and parts made by both FDM and compress molding methods show significant increases in both tensile strength and Young's modulus with the increase of carbon fiber content.

Although some attempts have been made to develop different reinforcement plastic matrix composites to improve the properties of the existing thermoplastics for the FDM process, there are no reported comprehensive experimental investigations on many different aspects of mechanical properties (including tensile properties and flexural properties) in FDM of CFRP composite parts through American Society for Testing and Materials (ASTM) standardized methods [33,34].

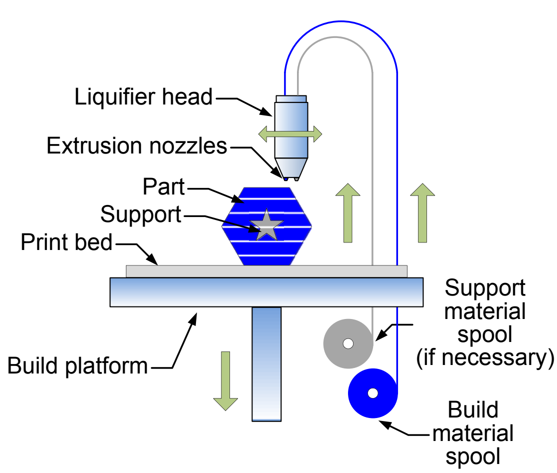

Fig. 1. Schematic of FDM process.

1.4. Outline of the paper

In this paper, the authors are going to experimentally investigate if adding carbon fiber into ABS plastic can improve the mechanical properties of FDM-fabricated parts. Tensile test and flexural test were conducted according to ASTM standards [33,34] for CFRP composite parts to obtain the mechanical properties, as listed in Table 1. Effects of carbon fiber content and length on the mechanical properties and porosity of fabricated parts were investigated. Fracture interface of CFRP composite parts at each carbon fiber content was observed using SEM micrograph to analyze the parts fracture reasons. Successfully accomplishing such investigation will provide knowledge on the improvement of FDM-fabricated parts. There are 3 sections in the remainder of this paper.

Table 1
Mechanical properties measured in this paper.

Categories	Properties	Unit
Tensile test	Tensile strength	MPa
	Young's modulus	GPa
	Toughness	J*m^{-3}*10^{3}
	Yield strength	MPa
	Ductility	%
Flexural test (within 5% strain limit)	Flexural stress	MPa
	Flexural modulus	GPa
	Flexural toughness	J*m^{-3}*10^{3}
	Flexural yield strength	MPa