Composites Part B 80 (2015) 369–378

Contents lists available at ScienceDirect

Composites Part B

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

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

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ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form
1 June 2015
Accepted 11 June 2015
Available online 20 June 2015

Keywords:
A. Carbon fibre
A. Polymer-matrix composites (PMCs)
B. Mechanical properties
D. Mechanical testing
E. Extrusion

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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http://dx.doi.org/10.1016/j.compositesb.2015.06.013
1359-8368/

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].

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.

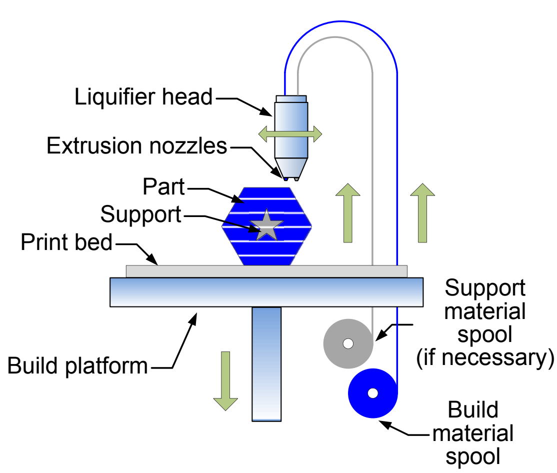


Fig. 1. Schematic of FDM process.

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

After the introduction, experimental set-up and measurement procedures will be illustrated in Section 2, then followed by the experimental results and discussions in Section 3. Finally, concluding remarks will be included in Section 4.

2. Experimental set-up and measurement procedures

2.1. Experimental set-up procedures

The entire fabricating process of thermoplastic matrix CFRP composites is shown in Fig. 2. The raw materials used in this paper were virgin ABS thermoplastic pellets and carbon fiber powders (Zoltek Companies Inc., St. Louis, MO, USA). The carbon fiber powders had two different average carbon fiber lengths, 150 μm (Panex 30) and 100 μm (Panex 35), with common fiber diameter of 7.2 μm. The pellets and carbon fiber powders were mixed in a blender with different carbon fiber contents (3 wt%, 5 wt%, 7.5 wt%, 10 wt%, and 15 wt%).

The plastic extruder (EB-1, ExtrusionBot Co. Chandler, AZ, USA) was used to fabricate the carbon fiber filled filaments. During the extrusion processes, extrusion temperature, filament yield speed, and nozzle diameter were set at 220 °C, 2 m/min, and 2.85 mm, respectively. The filaments could be cut into small pieces and refed in the extruder for the second extrusion to make them with high bulk density, which led to more consistent flow rates and fusion on each layer. During such process, filaments with more homogeneous distribution of carbon fibers could be obtained, thereby improving the FDM fabrication process and parts performance. The FDM 3D printer (Creatr, Leapfrog Co., Alphen aan den Rijn, Netherlands) was used to fabricate CFRP composite parts. The nozzle diameter of the FDM unit was 0.35 mm and nozzle temperature was set at 230 °C during FDM process. Printing velocity was set at 1.2 m/min for the

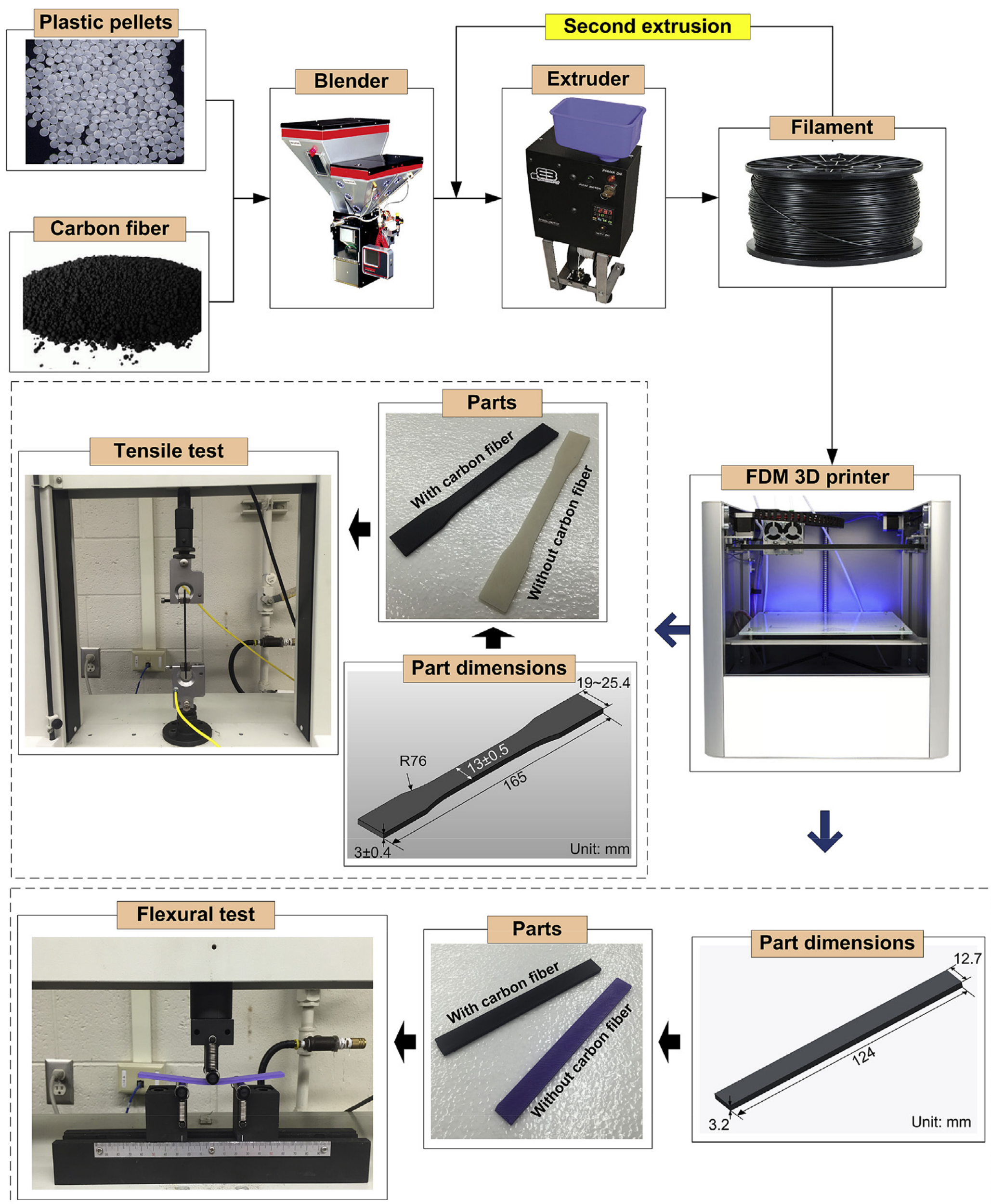


Fig. 2. Fabrication and testing processes.

first layer and maintained at 1.5 m/min for the rest layers. 14 layers were printed with each layer thickness of 0.2 mm. The infill pattern deposition directions for different layers were 45° and 135°, alternately. The infill density was set at 100%.

2.2. Measurement procedures

ASTM D638-10 standard [33] and ASTM D790-10 standard [34] were followed for tensile test and flexural test, respectively. Five thermoplastic matrix CFRP composite specimens of each sample were prepared by FDM for both tests. Type-I specimen dimensions in ASTM D638-10 standard were used for tensile testing of FDM-fabricated parts. Proper dimensions of specimen were also selected for flexural test according to ASTM D790-10 standard. The detailed dimensions of specimen and set-up for both tests are also illustrated in Fig. 2. The mass values of the specimens were measured by a precision balance (PN-6100 A, American Weigh Scales INC., Norcross, GA, USA). Tensile test and flexural test were conducted in a test machine (AGS-J, Shimadzu Co., Kyoto, Japan) with a 10 kN force transducer capacity. Tensile test employed two grips (one fixed grip and one movable grip) to hold the specimens, and a three-point bending set-up (including one midway loading nose and the two supports) was utilized in flexural test. The relationships between force (N) and displacement (mm) were collected by computer with help of a data acquisition software (Trapezium, Shimadzu Co., Kyoto). The specific testing parameters for the tensile test and flexural test were listed in Table 2. The mechanical properties of CFRP composite parts were obtained five times by testing five specimens at each carbon fiber content. Fracture interface of the specimens was observed using a SEM (S4300, Hitachi Co., Tokyo, Japan) with different magnifications.

3. Experimental results and discussions

3.1. Effects of carbon fiber content on tensile properties

Typical tensile strain–stress curves of all the specimens with different carbon fiber contents are illustrated in Fig. 3. For the testing specimens with carbon fiber content of 5 wt% and average length of 150 μm, for example, the curve was selected from the results of five specimens, depending on the maximum number of values those were the most closed to the mean value of each tensile properties.

Effects of carbon fiber content on tensile properties (including tensile strength, Young's modulus, toughness, yield strength, and ductility) of CFRP composite specimens are shown in Fig. 5. Boxplots were used to express the distributions of data at each carbon fiber content. The box range covered from 25% to 75% percentile of confidence interval. Mean value in the middle of the box was used to express the trends on effects of carbon fiber content on tensile properties. In the following Sections, the strain–stress curves were selected in the same methodology and boxplots were defined in the same way.

Table 2
Testing parameters.

Categories	Tensile test	Flexural test
Testing speed	5 mm/min	1.4 mm/min
Sampling frequency	20 Hz	20 Hz
Distance between two grips	115 mm	/
Distance between two supports	/	51.2 mm

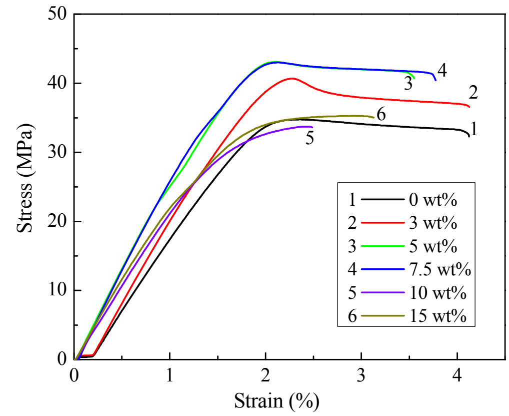


Fig. 3. Typical tensile strain–stress curves for specimens with different carbon fiber contents (Carbon fiber length is 150 μm).

3.1.1. Effects on tensile strength

Fig. 4 (a) shows that with the increase of carbon fiber content from 0 wt% to 5 wt%, tensile strength firstly increased, and then it decreased with the levels of carbon fiber content increasing from 5 wt% to 10 wt% (especially when the carbon fiber content increased from 7.5 wt% to 10 wt%, a sharp reduction of tensile strength occurred). Tensile strength increased again from 10 wt% to 15 wt% of carbon fiber content. The largest mean value (42 MPa) could be found at 5 wt% carbon fiber content, while the smallest mean value was about 34 MPa when carbon fiber content was 10 wt % (almost the same with that of pure ABS plastics).

3.1.2. Effects on Young's modulus

Effects of carbon fiber content on Young's modulus is shown in Fig. 4 (b). After an increase of Young's modulus with increasing of carbon fiber content from 0 wt% to 7.5 wt%, there was a sudden decrease in Young's modulus when the carbon fiber content increased from 7.5 wt% to 10 wt%. Continuing increasing carbon fiber content to 15 wt% resulted in Young's modulus increasing again. Young' modulus was the largest (2.5 GPa) at 7.5 wt% carbon fiber content, while the smallest mean value (1.9 GPa) was found in pure plastic specimen.

3.1.3. Effects on toughness and yield strength

There were similar relationships between carbon fiber content versus toughness and carbon fiber content versus yield strength, as illustrated in Fig. 4 (c) and 4 (d). It can be observed that both mean values of toughness and yield strength had an overall decreasing tendency when carbon fiber content increased from 0 wt% to 10 wt % (except for a gentle rise at 5 wt% carbon fiber content). Toughness and yield strength of the parts with carbon fiber content lower than 10 wt% were larger than those of the parts with carbon fiber content higher than 10 wt%. When carbon fiber content exceeded 10 wt %, these two mechanical properties increased again. The largest mean values for both toughness and yield strength could be found in pure plastic specimen. CFRP specimen with 10 wt% carbon fiber content generated the smallest mean values of toughness and yield strength (6.3 $J^*m^{-3}*10^3$ and 18.75 MPa, respectively).

3.1.4. Effects on ductility

Effects of carbon fiber content on ductility is shown in Fig. 4 (e). It can be observed that the ductility decreased with increasing of carbon fiber content from 0 wt% to 10 wt%. Then, the ductility increased when carbon fiber content exceeded 10 wt%. The pure plastic specimen had the largest mean ductility of 4.14%. The CFRP

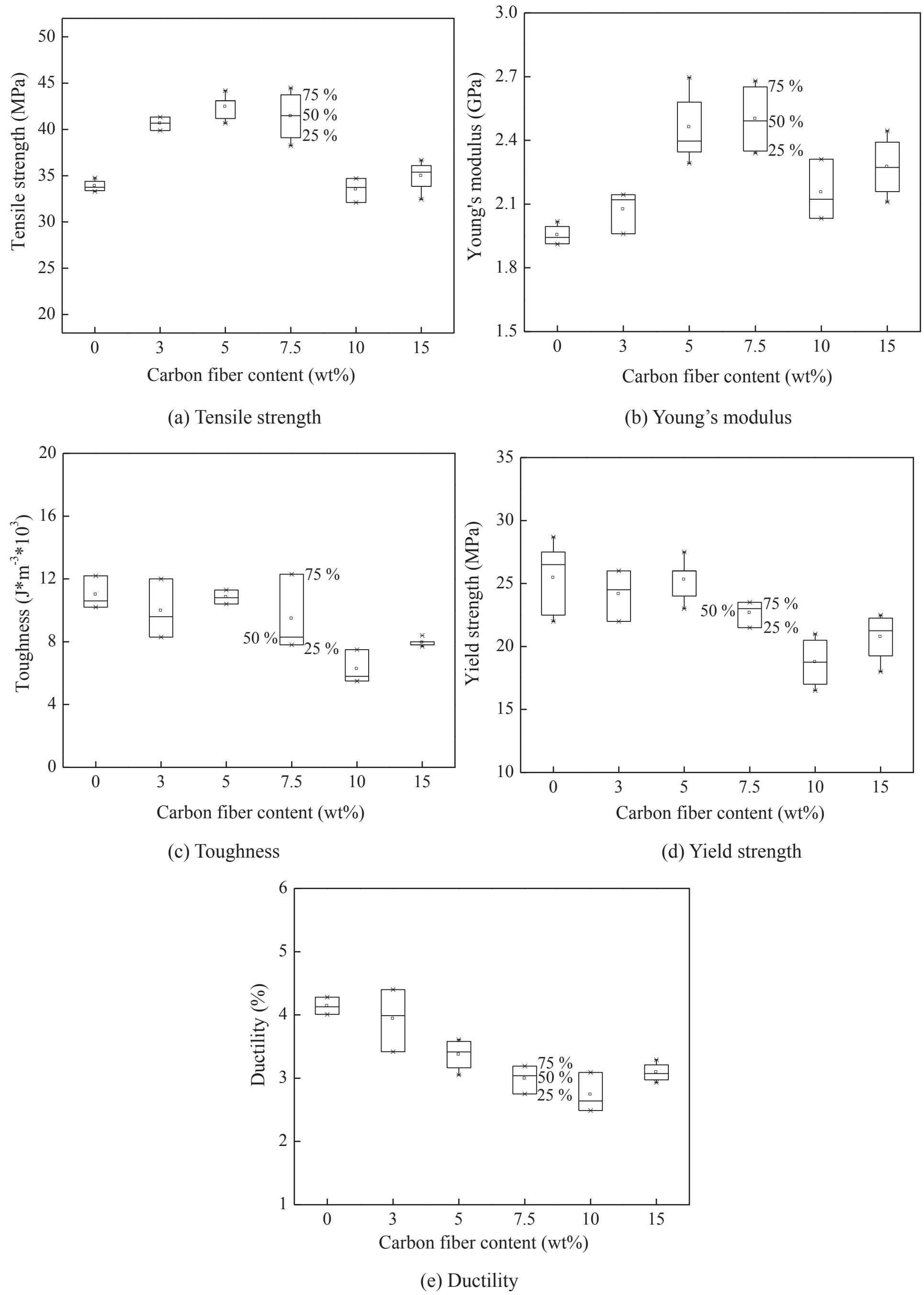


Fig. 4. The effects of carbon fiber content on tensile properties (Carbon fiber length is 150 μm).

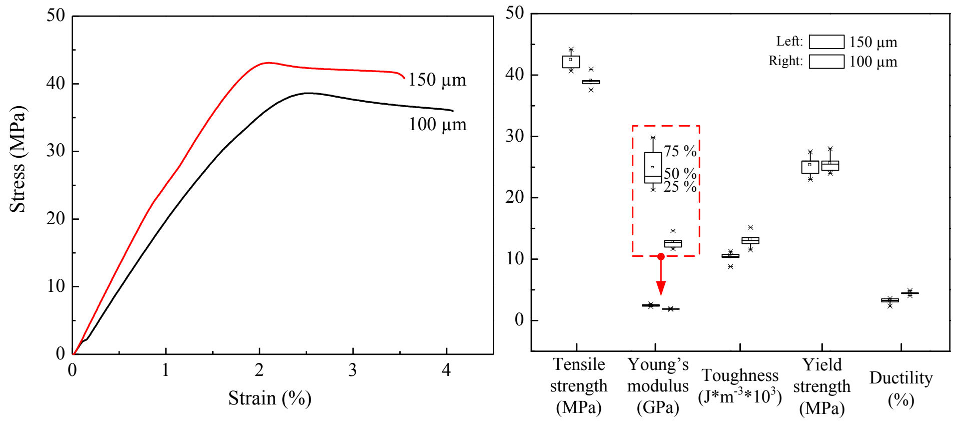
composite specimen with 10 wt% carbon fiber led to the smallest mean ductility of 2.74%.

3.2. *Effects of carbon fiber length on tensile properties*

A comparison of the typical tensile strain–stress curves of CFRP composite parts between two carbon fiber lengths (100 μm and 150 μm) at 5 wt% carbon fiber content is shown in Fig. 5 (a). It can be seen that as strain increased, the specimen with carbon fiber length of 150 μm first reached the maximum tensile stress.

Fig. 5 (b) illustrates comparisons of each tensile property between the two types of specimens. It can be seen that CFRP composite specimen with 150 μm carbon fiber had larger tensile strength and Young's modulus than that with 100 μm carbon fiber. Compared with CFRP composite specimen with 100 μm carbon fiber, specimen with 150 μm carbon fiber had smaller toughness and ductility, respectively.

A paired sample t-test has been conducted to compare the yield strength between these two kinds of specimens. Null hypothesis is that there is no significant difference in yield strength between specimens with carbon fiber length of 100 μm and that of 150 μm. The associated P-value (0.891) in the t-test indicates that the null hypothesis cannot be rejected at the common statistical level of 0.05. That means the difference of yield strength value between the two kinds of specimens is not statistically significant.



(a) Tensile strain-stress curves (b) Tensile properties

Fig. 5. Effects of carbon fiber length (Carbon fiber content is 5 wt%).

3.3. *Effects of carbon fiber content on flexural properties*

Flexural tests were conducted to compare flexural properties of the specimens with and without carbon fibers. According to the ASTM D790-10 standard [34], flexural test would be terminated when the maximum strain in the outer surface of the specimen reached 5% or when break occurred prior to reaching the maximum strain. In this investigation, specimens did not break within the 5% strain limit in the flexural test. Typical flexural strain–stress curves of specimens with and without carbon fibers (150 μm) are illustrated in Fig. 6. It can be seen that flexural stress at almost every given strain of the specimen with carbon fiber was larger than that of the specimen without carbon fiber.

Comparisons of flexural properties (including flexural stress, flexural modulus, flexural toughness, and flexural yield strength) between the pure plastic specimen and CFRP composite specimen with 5 wt% carbon fiber content are shown in Fig. 7. The differences of flexural properties between two types of specimens are significant. It can be seen that adding 5 wt% carbon fiber could improve almost all the flexural properties except for flexural yield strength. Based on the mean values of each flexural property, the flexural stress, flexural modulus, and flexural toughness of CFRP composite specimen with 5 wt% carbon fiber content were increased by 11.82%, 16.82%, and 21.86%, respectively, as compared with the pure plastic specimen.

3.4. *Fracture interface observations after tensile testing and flexural testing*

Based on experimental results in the Section 3.1, it could be concluded that, most of tensile properties of specimen with 10 wt% carbon fiber content had the worst mean values. To investigate the reasons of such phenomenon, the fracture interface of CFRP composite specimens with different carbon fiber contents after tensile testing was observed by a SEM to explore the specimen porosity as well as interfacial adhesion between carbon fibers and thermoplastic matrix, as shown in Fig. 8. It can be seen from the SEM micrographs that with the increase of carbon fiber content, porosity got increasingly larger and became the largest at 10 wt% carbon fiber content, resulting in the weakest specimen with such carbon fiber content. The second largest porosity was observed at fracture interface of specimen with 15 wt% carbon fiber content after tensile testing. The largest porosity was one of the possible reasons that the specimen with 10 wt% carbon fiber content had the smallest tensile properties (such as tensile strength, toughness, ductility, and yield strength). Specimens with 15 wt% carbon fiber content also had relative smaller tensile strength, toughness, ductility, and yield strength. In addition, the SEM micrographs also showed that many carbon fibers had been pulled out of the matrix especially at 10 wt% carbon fiber content, indicating that the interfacial bonding

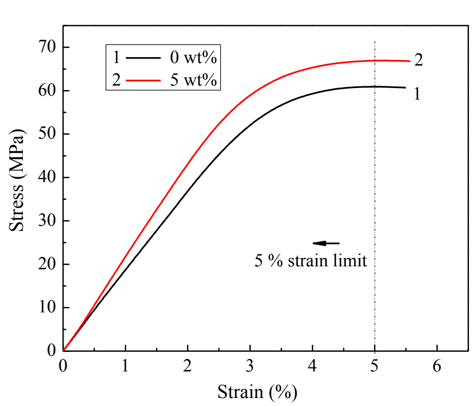


Fig. 6. Typical flexural strain–stress curves for specimens with and without carbon fibers (Carbon fiber length is 150 μm).

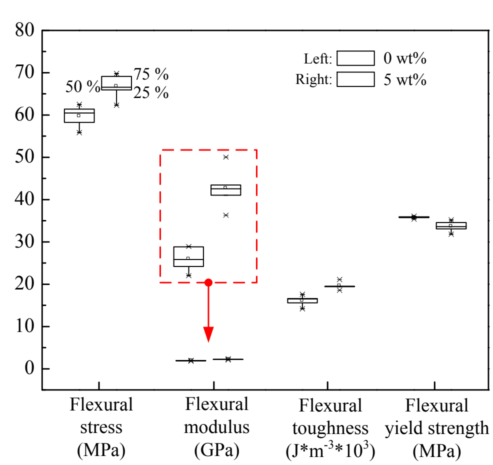


Fig. 7. Comparisons of flexural properties for specimens between with and without carbon fibers (Carbon fiber length is 150 μm).

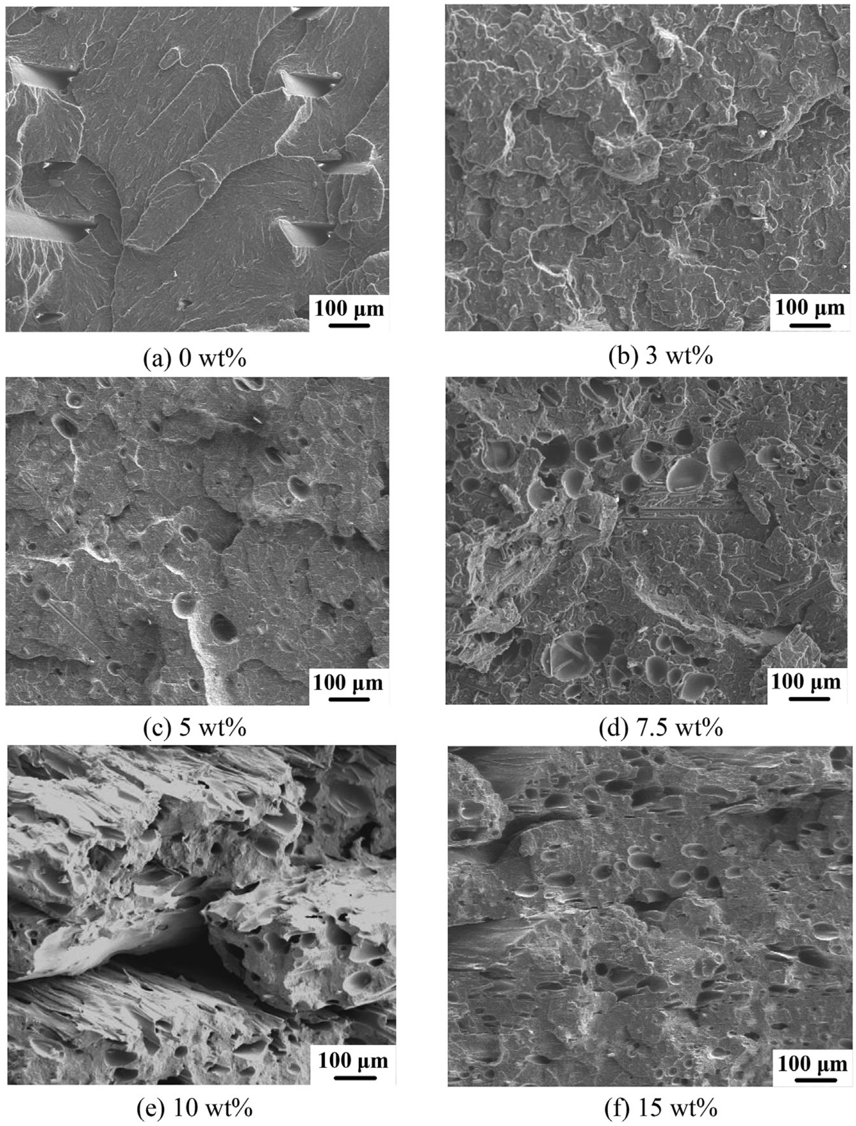


Fig. 8. The SEM fracture interface of specimens with different carbon fiber contents after tensile testing (Carbon fiber length is 150 μm).

between thermoplastic matrix and carbon fibers was insufficient to provide satisfactory reinforcement in the composites, as shown in Fig. 9.

Fracture interface of the specimens after flexural testing was also observed by SEM, as shown in Fig. 10. Compared with the pure plastic parts, the carbon fibers in the CFRP composite parts can be used to support the load during the bending process of part. The ruptured fibers in the fracture interface indicated that load was effectively transferred from the thermoplastic matrix to the carbon fibers to achieve good properties.

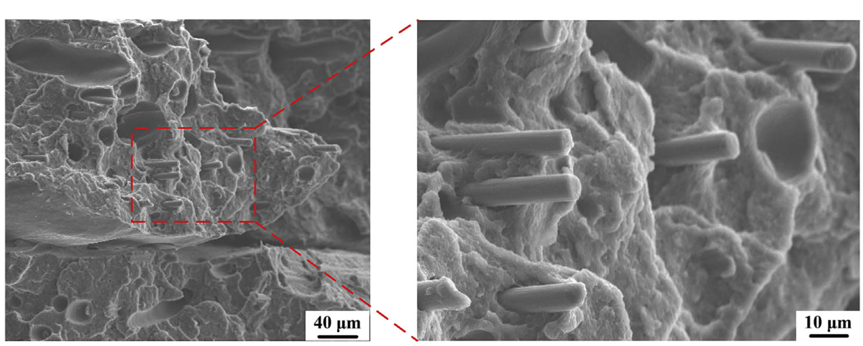


Fig. 9. The pulled-out carbon fibers in the fracture interface of CFRP composites (Carbon fiber content is 10 wt%; Carbon fiber length is 150 μm).

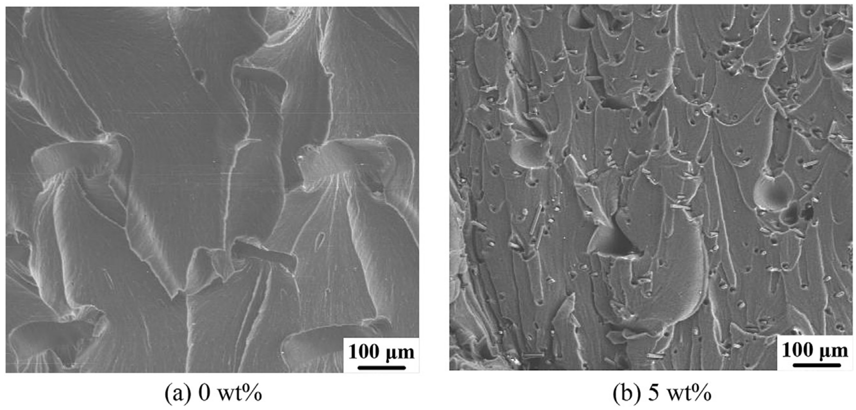


Fig. 10. The SEM fracture interface of the specimens with and without carbon fibers after flexural testing (Carbon fiber length is 150 μm).

3.5. Effects of carbon fiber content on porosity

Different categories of the specimen porosity are illustrated in Fig. 11. Pore type 1, gas evoluted pore, was mainly generated during the fabrication of feedstock filament by extrusion. When depositing the materials using FDM, various carbon fiber distributions in the filament resulted in inconsistent fusion of the layers. Pore type 2, physical gap at layer/layer interfaces, was also generated by the voids between different individual layers. In addition, holes (No. 3 in Fig. 11) generated by the pulled-out carbon fibers existed on the fracture interface of the specimen, but these holes should not be considered as the intrinsic porosity of the specimen. Therefore, the porosities in first two conditions should be taken into consideration and the overall porosity P could be expressed by the equation below:

$$P = \frac{V_t - V_a}{V_t} \quad (1)$$

where V_t is theoretical volume of the specimen after the FDM fabrication and V_a is actual volume of the specimen. The volume of designed solid object in CAD software was 8.45 cm^3. However, such value could not be directly applied into V_t due to the shrinkage of the fabricated parts and printing accuracy error of the FDM machine. To calculate V_t, the specimen was cut into a regular morphological volume which would be weighed for calculating the average specimen density ρ. Such measurement was repeated five times by calculating the five specimens at each carbon fiber content. Based on the actual measured mass of the specimen M and the calculated specimen density ρ, the theoretical volume of the specimen V_t could be obtained for each specimen.

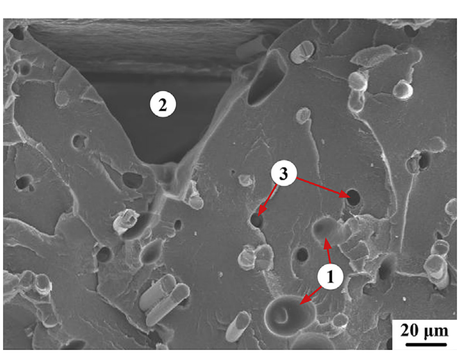


Fig. 11. Illustration of different categories of the specimen porosity (Carbon fiber content is 10 wt%; Carbon fiber length is 150 μm).

Since there is no interfacial reaction between ABS and carbon fiber, V_a could be calculated as follows:

$$V_a = \frac{M \times ABSwt\%}{\rho_{ABS}} + \frac{M \times CFwt\%}{\rho_{CF}} \quad (2)$$

where,

M is the actual mass of the specimen;
ρ_{ABS} is the density of ABS plastic (1.05 g/cm^3);
ρ_{CF} is the density of carbon fiber (1.55 g/cm^3).

The effects of carbon fiber content in CFRP composites on mass and porosity are shown in Fig. 12 (a) and 12 (b), respectively. It can be seen that with the increase of carbon fiber content, mass increased firstly and began to decrease at 7.5 wt% carbon fiber content, leading to the lowest mass when the carbon fiber contents were 10 wt% and 15 wt%, where the masses were nearly the same. The porosity decreased when carbon fiber content increased from 0 wt% to 3 wt% and then increased to the largest mean value (9.04%) at 10 wt% carbon fiber content, with the second largest mean value (3.27%) when carbon fiber content increased to 15 wt%. CFRP composite specimens with 10 wt% carbon fiber had significantly high porosity. Such porosity trend was consistent with the fracture interface observations results in Section 3.4.

4. Conclusions

In this study, CFRP composite filaments were firstly prepared from carbon fiber and ABS by extrusion processes. Experimental investigations on if adding carbon fiber (different content and length) into ABS plastic can improve the mechanical properties of FDM-fabricated parts have been conducted. Effects on 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 investigated. Fracture interface of CFRP composite specimens after tensile testing and flexural testing was observed and analyzed using SEM micrograph. The following conclusions were drawn from this study.

1) Compared with pure plastic specimen, adding carbon fiber into plastic materials could increase tensile strength and Young's modulus, but may decrease toughness, yield strength, and ductility.

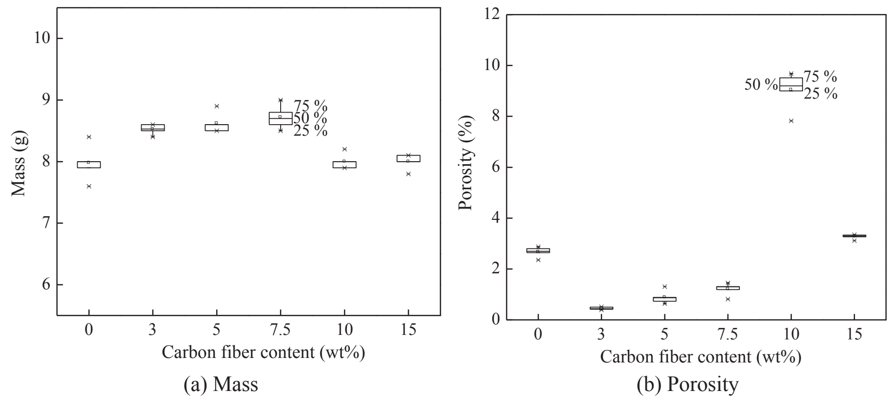


Fig. 12. The effects of carbon fiber content in CFRP composites on mass and porosity (Carbon fiber length is 150 μm).

2) Specimen with 5 wt% carbon fiber content had the largest mean value of tensile strength and specimen with 7.5 wt% carbon fiber content had the largest mean value of Young' modulus. The tensile strength and Young's modulus of fabricated specimen with 5 wt% or 7.5 wt% carbon fiber content could increase 22.5% and 30.5%, respectively.
3) CFRP composite specimen with 150 μm carbon fiber had larger tensile strength and Young's modulus than that with 100 μm carbon fiber. Compared with CFRP composite specimen with 100 μm carbon fiber, specimen with 150 μm carbon fiber had smaller toughness and ductility. There were no significant difference in yield strength value between these two kinds of specimens.
4) Compared with the pure plastic specimen, CFRP composite specimen with 5 wt% carbon fiber content had larger flexural stress, flexural modulus, and flexural toughness with an increase of 11.82%, 16.82%, and 21.86%, respectively.
5) Porosity became the severest in the specimens with 10 wt% carbon fiber content. The porosity trend was consistent with the fracture interface observations results. This phenomenon could be the reason for that adding carbon fiber content to 10 wt% resulted in all the smallest mean values of tensile strength, toughness, yield strength, and ductility.

Acknowledgment

This paper is supported by the Foundation of the Whitacre College of Engineering and the Office of Vice President for Research at Texas Tech University. The authors also would like to extend the acknowledgements to Zoltek Companies Inc. for providing carbon fiber powders for this work.

References

[1] ASTM F2792–12a. Standard terminology for additive manufacturing technologies. West Conshohocken: ASTM International; 2012.
[2] Alimardani M, Toyserkani E, Huissoon JP. Three-dimensional numerical approach for geometrical prediction of multilayer laser solid freeform fabrication process. J Laser Appl 2007;19(1):14–25.
[3] Yakovlev A, Trunova E, Grevey D, Pilloz M, Smurov I. Laser-assisted direct manufacturing of functionally graded 3D objects. Surf Coatings Technol 2005;190(1):15–24.
[4] Hague R, Campbell I, Dickens P. Implications on design of rapid manufacturing. Proc I Mech Eng C-J MEC 2003;217(1):25–30.
[5] Hague R, Mansour S, Saleh N. Design opportunities with rapid manufacturing. Assem Autom 2003;23(4):346–56.
[6] Sugavaneswaran M, Arumaikkannu G. Modelling for randomly oriented multi-material additive manufacturing component and its fabrication. Mater Des 2014;54:779–85.
[7] Royal Academy of Engineering. Additive manufacturing: opportunities and constraints. 2013. Available from: http://www.research.lancs.ac.uk/portal/files/43819245/RAEng_Roundtable_Document.pdf.
[8] Zeng WL, Guo YL, Jiang KY, Yu ZX, Liu Y, Shen YD, et al. Laser intensity effect on mechanical properties of Wood-Plastic composite parts fabricated by selective laser sintering. J Thermoplast Compos 2012;26(1):125–36.
[9] Kolarevic B. Digital fabrication: manufacturing architecture in the information age. New York. In: Proceedings of association for computer aided design in architecture; 2001. p. 268–77.
[10] Flowers J. 3D laser scanning in technology education. Technol Teach 2000;60(3):27–30.
[11] Choi SH, Cheung HH. A multi-material Virtual prototyping system. Comput Aided Des 2005;37(1):123–36.
[12] Gu DD, Meiners W, Wissenbach K, Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. Int Mater Rev 2012;57(3):133–64.
[13] West AP, Sambu SP, Rosen DW. A process planning method for improving build performance in stereolithography. Comput Aided Des 2001;33(1):65–79.
[14] Dudek P. FDM 3D printing technology in manufacturing composite elements. Arch Metall Mater 2013;58(4):1415–8.
[15] Park J, Tari MJ, Hahn HT. Characterization of the laminated object manufacturing (LOM) process. Rapid Prototyp J 2000;6(1):36–50.
[16] Kruth JP, Wang X, Laoui T, Froyen L. Lasers and materials in selective laser sintering. Assem Autom 2003;23(4):357–71.
[17] Stratasys Inc. Technical application guide: FDM for Jigs and Fixtures. 2013. Available from: http://www.stratasys.com/~/media/Main/Secure/Technical_Application_Guides-TAG/SSYS-TAG-JigsFixtures-11-13.pdf.
[18] Kai CC, Fai LK, Chu-Sing L. Rapid prototyping: principles and applications in manufacturing. 2nd ed. Singapore: World Scientific Publishing; 2003.
[19] Gibson I, Rosen DW, Stucker B. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. 2nd ed. New York: Springer; 2010.
[20] Tekinalp HL, Kunc V, Velez-Garcia GM, Duty CE, Love LJ, Naskar AK, et al. Highly oriented carbon fiber-polymer composites via additive manufacturing. Compos Sci Technol 2014;105(10):144–50.
[21] Marcincinova LN, Marcincin JN, Barna J, Torok J. Special materials used in FDM rapid prototyping technology application. In: Proceedings of IEEE 16th International Conference on Intelligent Engineering Systems (INES), Lisbon; 2012. p. 73–6.
[22] Shofner ML, Lozano K, Rodríguez-Macías FJ, Barrera EV. Nanofiber-reinforced polymers prepared by fused deposition modeling. J Appl Polym Sci 2003;89(11):3081–90.
[23] Zhong W, Li F, Zhang Z, Song L, Li Z. Short fiber reinforced composites for fused deposition modeling. Mat Sci Eng A Struct 2001;301(2):125–30.
[24] Karsli NG, Aytac A. Tensile and thermomechanical properties of short carbon fiber reinforced polyamide 6 composites. Compos Part B Eng 2013;51:270–5.
[25] Chung DDL. Composite materials science and applications. 2nd ed. UK: Springer; 2010.
[26] Gay D, Hoa SV, Tsai SW. Composite materials design and applications. 4th ed. Boca Raton: CRC Press; 2003.
[27] Kinet D, Mégret P, Goossen KW. Fiber Bragg grating sensors toward structural health monitoring in composite materials: challenges and solutions. Sensors 2014;14(4):7394–419.
[28] Shubhra QTH, Alam AKMM, Quaiyyum MA. Mechanical properties of polypropylene composites: a review. J Thermoplast Compos 2011;26(3):362–91.
[29] TenCate supplies thermoplastic composites to airbus A350 XWB. 2014. Available from: http://www.innovationintextiles.com/tencate-supplies-thermoplastic-composites-to-airbus-a350-xwb.
[30] Biron M. Thermoplastics and thermoplastic composites. 2nd ed. London: Elsevier; 2013.

[31] Gray RW, Baird DG, Bohn JH. Effects of processing conditions on short TLCP fiber reinforced FDM parts. Rapid Prototyp J 1998;4(1):14–25.
[32] Gray RW, Baird DG, Bohn JH. Thermoplastic composites reinforced with long fiber thermotropic liquid crystalline polymers for fused deposition modeling. Polym Compos 1998;19(4):383–94.
[33] ASTM D638-10. Standard test method for tensile properties of plastics. West Conshohocken: ASTM International; 2010.
[34] ASTM D790-10. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. West Conshohocken: ASTM International; 2010.