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Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites

Xiaoyong Tian *, Tengfei Liu, Chuncheng Yang, Qingrui Wang, Dichen Li

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, China

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ABSTRACT

A novel 3D printing based fabrication process of Continuous Fiber Reinforced Thermoplastic Composites (CFRTPCs) was proposed. Continuous carbon fiber and PLA filament were utilized as reinforcing phase and matrix, respectively, and simultaneously fed into the fused deposition modeling (FDM) 3D printing process realizing the integrated preparation and forming of CFRTPCs. Interfaces and performance of printed composites were systematically studied by analyzing the influencing of process parameters on the temperature and pressure in the process. Forming mechanism of multiple interfaces was proposed and utilized to explain the correlations between process and performance. Fiber content of the printed specimens can be easily controlled by changing the process parameters. When the fiber content reached 27%, flexural strength of 335 MPa and modulus of 30 GPa were obtained for the printed composite specimens. Composite components were fabricated to demonstrate the process feasibility. Potential applications could be found in the field of aviation and aerospace.

1. Introduction

Continuous Fiber Reinforced Thermoplastic Composites (CFRTPCs) are becoming alternative materials to replace the conventional thermal setting plastics and steel due to excellent mechanical performance, recycling, and potential light-weight structures [1,3,4]. Development of new fabrication process of CFRTPCs has been attracted many research activities for many years. Processes like vacuum forming, filament winding, pultrusion, bladder-assisted molding and compression process have been used in the fabrication of CFRTPCs. In all these conventional processes complicated moulds are required and the process is expensive and time-consuming. It is difficult and even impossible to fabricate complex composite components. Also, uncontrollable forming quality and low degree of automation are the limitations of the wide industrial applications of CFRTPCs. Innovation on the fabrication process is critical and urgent to the future development and application of CFRTPCs [2,3].

Fused deposition modeling (FDM) is one of the most commonly used 3D Printing (Additive Manufacturing) technologies. In a typical process, a filament of material is fed into a machine via a pinch roller mechanism. The feedstock is melted in a heated liquefier with the solid portion of the filament acting as a piston to push the melt through a print nozzle. A gantry moves the print nozzle in the horizontal x–y plane as the material is deposited on a build surface that can be moved in the vertical z direction. The extruded material rapidly solidifies and adheres with the surrounding material to accumulate the required complex plastic parts. The most common materials used in this type of process are amorphous thermoplastics, with acrylonitrile butadiene styrene (ABS), poly lactic acid (PLA) being the most common [5,6]. Recently, a few studies reported short or long fiber reinforced thermal plastics as the feedstock of FDM process. Tekinalp et al. [7], Zhong et al. [8], as well as Ning et al. [9] investigated short fiber reinforced acrylonitrile-butadiene-styrene (ABS) composites as a feedstock for 3D-printing in terms of their processibility, microstructure and mechanical performance. Gray IV et al. [10,11] developed polypropylene (PP) strands reinforced with thermotropic liquid crystalline polymer (TLCP) fibers for FDM process and investigated the effects of FDM processing conditions on short TLCP fiber reinforced parts. According to the mentioned research activities, a limited improvement of mechanical performance, for example up to 20% of tensile strength, has been achieved by adding short fiber into the plastic feedstock due to the limitations in the reinforcement of short fiber. So, using FDM to fabrication CFRTPCs components with much higher performance became a cutting-edge and interdisciplinary research topic in the last few years.

Researches related with FDM of CFRTPCs have been seldom found except some unconfirmed information from the websites.

* Corresponding author.
E-mail address: leoxyt@mail.xjtu.edu.cn (X. Tian).

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In 2014, Mark Forged Company developed a 3D printer for CFRTPCs process using pre-preg filament with continuous fiber and thermal plastic matrix [12]. The process capability would be limited by the type of pre-preg filament. The fiber content and interface performance could not be controlled. Meanwhile, Tian et al. [13] proposed a novel FDM process for CFRTPCs using fiber and plastic filament as the raw materials. Impregnation and extrusion happened simultaneously in the liquefier of printing head. Mechanism and performance have been studied by using carbon fiber as reinforcing phase and ABS as matrix. The flexural strength and modulus of printed composites samples was around 127 MPa and 7.72 GPa, which was almost six times higher than the conventional FDM ABS samples, and three times than the samples by injection molding. It is a very promising process for CFRTPCs. However, the interfaces of the printed composite specimens and the relationships with the process parameters have not been systematically studied yet. Moreover, ABS has a smaller melting flow index (0.6 g/10 min) in comparison with PLA (17.3 g/10 min) at 220 °C, which caused a worse impregnation of matrix into the fiber bundles and was detrimental to the performance of 3D printed composites.

In the present research, interface and performance of 3D printed continuous carbon fiber reinforced (CFR) PLA composites have been systematically investigated. Process parameters, such as temperature of liquefier, layer thickness, feed rate of filament, hatch spacing, transverse movement speed were studied and optimized according to their influence on the performance of the composites samples. Multiple interfaces between the fiber and matrix, deposited lines and layers were carefully observed. The correlations between process parameters, multiple interfaces, and final performance of printed specimens have been discussed. By using optimized process parameters, composite parts were fabricated to demonstrate the feasibility of the proposed 3D printing process for the fabrication of high performance composites.

2. Experimental procedures

2.1. Equipment and material

2.1.1. Experimental platform

As shown in Fig. 1a, the FDM-based equipment for CFRTPCs was independently developed and set up in the present research, which consists of extrusion head, control system, building platform, X-Y motion mechanism, etc. Fig. 1b shows the working process of the extrusion head, which receives thermoplastic polymer and continuous fiber to build a continuous fiber reinforced composites part.

2.1.2. Raw materials for 3D printing

In the present research, polylactide (PLA/1.75 mm) from FLASHFORGE Corp. in China has been used as the thermoplastic material, and carbon fiber (1000 fibers in a bundle) from TENAX-J Corp. in China has been used as the reinforcement. The CFRTPCs specimens were all prepared by the aforementioned equipment for the measurement of mechanical properties. The main printing process parameters in FDM for CFRTPCs are listed in Table 1.

2.2. Experimental plan

2.2.1. Parameter matrix of the process

In the 3D printing process of continuous fiber reinforced PLA composites, there are many process factors which may have influence on the produced PLA composites. In the present research, five of them were chosen according to their effects on the pressure and temperature in the process, which have significant influence on the performance of composites. Five selected parameters are shown in Table 1. Temperature of liquefier is critical to the melting flow capability of the plastic, as shown in Fig. 2. Layer thickness, feed rate of the filament, hatch spacing, transverse movement speed will change the contact pressure between the nozzle and deposited layer, also the fiber content of the printed composite. Furthermore, all the parameters will cause different mechanical performance of the printed parts. In order to optimize the process parameter and obtain optimal performance, each parameter has been investigated in a very wide range according to certain experimental conditions, as shown in Table 1. The nozzle used in the printing head had a tip diameter of 2 mm, and worked in an ambient temperature. The tool path of the printing head was chosen along the direction in the length of fabricated specimens.

2.2.2. Experimental procedure

Melting flow index was measured by using MFR (melt mass flow rate XNR-400B, JINHE Corp., China) to study the influence of temperature on the melting viscosity of PLA, which is critical to the interfacial impregnation between fiber and PLA matrix. After the melting flow properties of PLA was checked, the temperature range suitable for 3D printing was fixed for the following experiments. Temperature in the printing head was first studied as a target parameter in the range of 180–240 °C with other constant process parameters as shown in Table 1. Layer thickness (L) is the height of one single layer which were chosen from 0.3 mm to 0.8 mm according the previous experiments from 0.3 to 0.8 mm. Feed rate of filament (E) is selected from 60 to 160 mm/min to control the unit volume fed into the printing head. Hatch spacing (H) is the central distance between two adjacent deposited lines changing from 0.4 to 1.8 mm. Transverse movement speed (V) is the moving speed of the printing head in the range of 100–600 mm/min which is directly linked to the fabrication efficiency. All the process parameters was illustrated in Fig. 2 and has been carefully investigated according to all-parameter experimental design as shown in Table 1.

2.3. Mechanical and physical properties

To evaluate the performance of 3D printed CFR PLA composites, several measurement were conducted. Flexural strength was measured using universal testing machine (PLD-5kN, LETRY Corp., China) according to the standard of ISO 14125:1998 on 3D printed composite specimens with a size of $100 \times 15 \times 2$ mm. Density of printed composite specimens was measured using Archimedes principle on the testing device (DX-300, QUNLONG Corp., China). Fracture surfaces of the tested specimens were observed with a Hitachi S-3000N SEM to evaluate the interfaces between deposited lines as well as fibers in matrix. For each experimental group, five specimens were prepared to obtain an average value of the targeted properties.

3. Experimental results and discussion

3.1. Experimental results

3.1.1. Temperature of liquefier

Temperature is one of the critical condition for the fabrication of composites, which has significant influence on the impregnation of fiber and matrix. In 3D printing process, temperature of liquefier in the printing head was also important to the bonding strength between deposited lines and layers. To investigate the influence of temperature on the 3D printing process and the performance of printed parts, specimens with different printing temperature from 180 to 240 °C were prepared under certain experimental

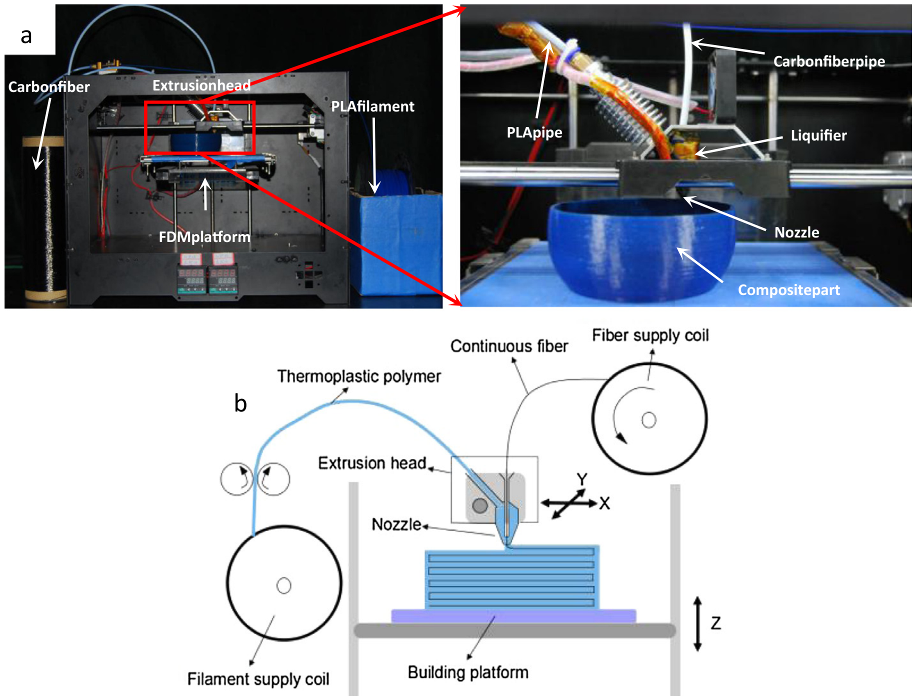

Fig. 1. Equipment and scheme of 3D printing for CFR PLA composites, (a) the setup for the 3D printing of CFRTPCs, (b) scheme of the printing process [13]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Parameter matrix of CFR PLA 3D printing process.

Target parameter	Range	Other process parameters
Temperature of liquifier (T/°C)	180, 190, 200, 210, 220, 230, 240	L 0.65 mm, V 100 mm min^{-1}, E 150 mm/min, H 1.2 mm
Layer thickness (L/mm)	0.3, 0.4, 0.5, 0.6, 0.7, 0.8	T 210 °C, V 100 mm min^{-1}, E 100 mm/min, H 1.2 mm
Feed rate of filament (E/mm min^{-1})	60, 80, 100, 120, 140, 160	T 210 °C, L 0.5 mm, V 100 mm min^{-1}, H 1.2 mm
Hatch spacing (H/mm)	0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8	T 210 °C, L 0.5 mm, V 100 mm min^{-1}, E 100 mm/min
Transverse movement (printing) speed (V/mm min^{-1})	100, 200, 300, 400, 500, 600	T 230 °C, L 0.65 mm, E 150 mm/min, H 1.2 mm

condition as shown in Table 1. When the temperature is lower than 180 °C, it was very difficult to extrude the melt plastic with the fiber due to the poor flowability and even harder to fabricate composite parts. When the temperature is higher than 240 °C, the PLA filament was melt almost into liquid and could flow naturally from the printing nozzle with the action of the gravity, which is not suitable for the 3D printing process. The MFR measurement for PLA was conducted to verify the experimental phenomenon. As shown in Fig. 3, the melting flow index of PLA at the temperature of 180 °C is around 2 g/10 min which is much lower than the value of 36 g/10 min at the temperature of 240 °C. Increasing melting flow capability of PLA would improve the impregnation of PLA into the carbon fiber bundle, and then drastically enhance the mechanical properties of the 3D printed PLA/C composite specimens.

Flexural strength and modulus were measured for the specimens prepared with different temperature in liquefier of the printing head. The results are shown in Fig. 4. It's obvious that the flexural strength and modulus are positively related to the temperature until 240 °C up to 155 MPa and 8.6 GPa, respectively. However, the specimen prepared at the temperature of 240 °C lost surface accuracy due to the overflow of melt PLA. So, the recommended maximum temperature in the printing head is 230 °C, at which the flexural strength and modulus of composite specimens prepared under the specified are 145 MPa and 8.6 GPa, respectively. The suitable process temperature was in the range of 200–230 °C.

3.1.2. Layer thickness

Layer thickness is a featured parameter for 3D printing process, which is important to the fabrication accuracy, efficiency, and mechanical properties of normal FDM components. It is even more significant to CFR PLA composite due to the possibility to changing the carbon fiber content of the fabricated specimen. More layers will integrate more carbon fibers in the printed specimen. Several values for layer thickness were chosen from 0.3 to 0.8 mm to investigate its influence on the flexural strength with temperature in the printing head of 210 °C, feed rate of 100 mm/min, printing speed of 100 mm/min, hatch spacing of 1.2 mm. The flexural strength was dramatically decreased with a enlarged value of thickness. With the layer thickness of 0.3 mm, maximum flexural strength was obtain up to 240 MPa. When the layer thickness was changing from 0.4 to 0.6 mm, the flexural strength of composites specimens decreased slightly, and then heavily declined with layer thickness of 0.7 and 0.8 mm, as shown in Fig. 5. Considering both flexural strength and fabrication efficiency, the recommended value of layer thickness is ranging from 0.4 to 0.6 mm.

3.1.3. Hatch spacing

As shown in Fig. 2, hatch spacing is the central distance between two adjacent lines. To keep contact between adjacent lines, there must be overlaps between them. Considering the nozzle tip diameter used in the present research is 2 mm, the maximum value for hatch spacing is fixed 1.8 mm. The extremely

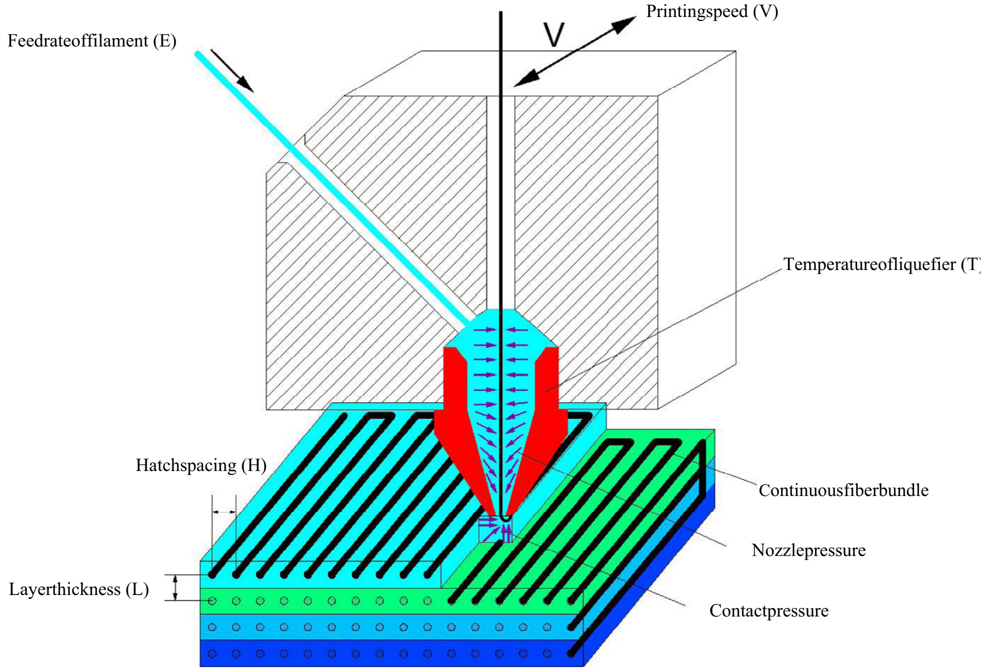

Fig. 2. Schematic of process parameters for 3D printing of CFR PLA composites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

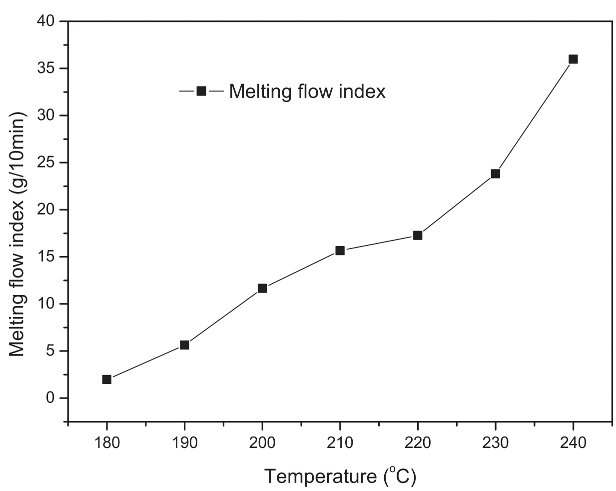

Fig. 3. Melting flow index of PLA with temperature from 180 °C to 240 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

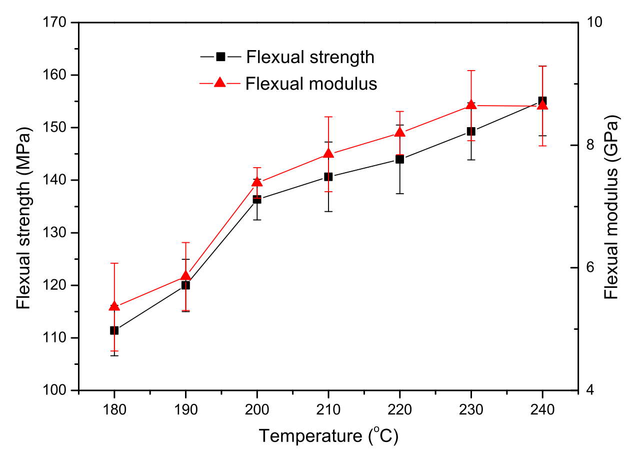

Fig. 4. Influence of temperature in liquefier on the flexural strength and modulus of the 3D printed CFR PLA composites under experimental condition of L 0.65 mm, V 100 mm/min, E 150 mm/min, H 1.2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lower limitation for the hatch spacing is chosen as 0.4 mm according to the trial experiments. Hatch spacing lower than 0.4 mm will cause excessive overlaps and disrupt the printing process. When decreasing the hatch spacing from 1.8 to 0.4 mm under the experimental conditions shown in Table 1, the average flexural strength of 3D printed composites specimens increased from 130 MPa to 335 MPa, and simultaneously flexural modulus was improved from 6.26 GPa to 30 GPa, as shown in Fig. 6.

3.1.4. Feed rate of the filament and printing speed

Feed rate of the filament (E) is related to the unit volume of material fed into the printing head. With the same tip diameter of extrusion nozzle, the parameter E determined inner pressure and extrusion speed of melt material in the printing head. As shown in Fig. 7, the flexural strength of PLA composites increased dramatically with an improved feed rate from 60 mm/min to 80 mm/min. This might be caused by the increase of inner pressure in liquefier and overlapping contact pressure between adjacent deposited lines due to large unit volume of extruded materials, which formed the dual interfaces between fiber and matrix, as well as deposited lines in the 3D printed CFR composites. However, with further increase of feed rate, the flexural strength did not make a further improvement probably due to short impregnation period for fiber with matrix. Meanwhile, high printing speed would also decrease impregnation period and pressure but increase the overall fiber content of the composites specimens. These are two contradictory factors, which caused printing speed as an insignificant influence on the flexural strength, as shown in Fig. 7.

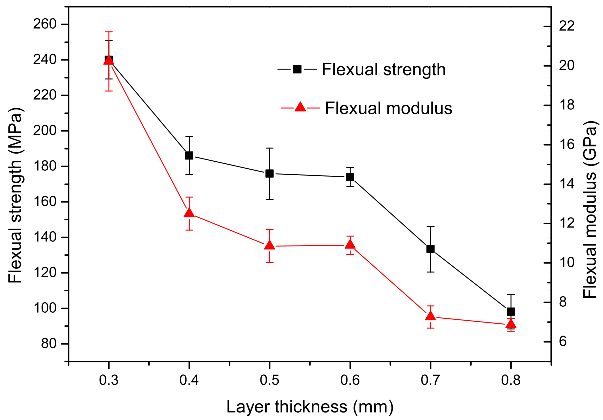

Fig. 5. Influence of layer thickness on the flexural strength the 3D printed CFR PLA composites under the experimental condition of T 210 °C, V 100 mm/min, E 100 mm/min, H 1.2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

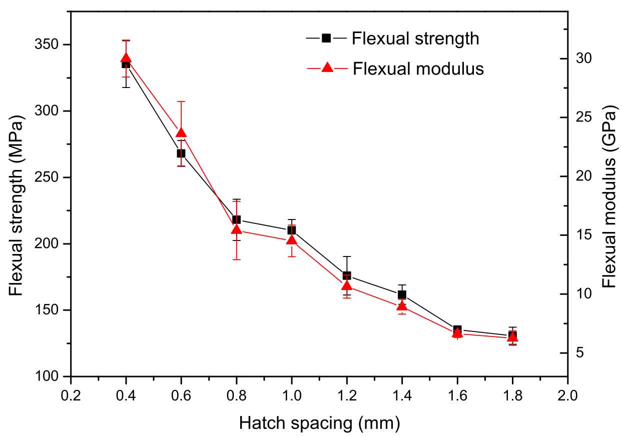

Fig. 6. Influence of hatch spacing on the flexural strength and modulus of the 3D printed CFR PLA composites under the experimental condition: T 210 °C, L 0.5 mm, V 100 mm min^{-1}, E 100 mm/min. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

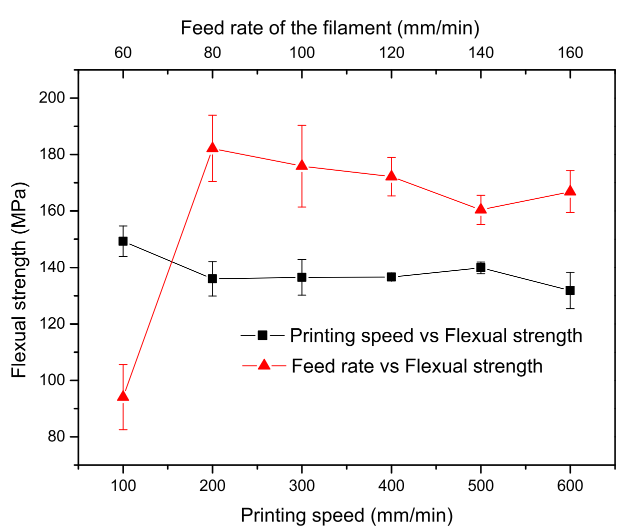

Fig. 7. Influence of feed rate of the filament and printing speed on the flexural strength under the experimental condition: Feed rate - T 210 °C, L 0.5 mm, V 100 mm/min, H 1.2 mm; Printing speed - T 230 °C, L 0.65 mm, E 150 mm/min, H 1.2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Discussion

It is well known that performance of composites is determined by the interfaces in the microstructures and the overall carbon fiber content. For 3D printed CFR PLA composites, interfaces became complicated due to the appearance of multiple interfaces and variable forming mechanism. Interfaces appeared between fiber and matrix, deposited adjacent lines, and layers. In order to control and improve the quality of interfaces, the forming mechanism and influencing factors should be investigated. Furthermore, carbon fiber content is another significant factor to the mechanical properties of 3D printed CFR PLA composites. The influence of process parameters on the carbon fiber content will also discussed in this section.

3.2.1. Multiple interfaces in the 3D printed composites

In the conventional forming process of composites, temperature and pressure are two important parameters to the performance of produced composites. It is same for the 3D printed CFR PLA composites except that heating happened in the printing head and pressure took place in the liquefier and between platform or deposited layer and printing nozzle, from which the melt plastics came out from the printing head. Temperature of liquefier in the printing head could be simply set as an equipment parameter. However, controlling pressure is complicated and influenced by at least two parameters, layer thickness and hatch spacing. All these parameters will be discussed in this section.

3.2.1.1. Temperature of liquefier T (°C) and interfaces. The flowability and viscosity of melt thermal plastics had an essential influence on the impregnation process of melt plastics into the fiber bundle. Also, after the melt plastics were extruded out from the nozzle of the printing head, it will be solidified quickly and simultaneously bonded to the previously deposited materials in the present and lower layer, as shown in Fig. 2. Higher temperature in the liquefier could also enhance the bonding between adjacent lines. Higher temperature had prompted the mechanical properties of the composite samples, as shown in Fig. 4. Microstructures and fracture patterns in the broken cross sections were also observed, as shown in Fig. 8. Delamination was observed between two layers due to insufficient bonding between layers with a lower temperature in liquefier of 180 °C, as shown in Fig. 8a. On the contrary, when the temperature was increased to 240 °C, flowability of melt plastics were improved dramatically and no interfaces between layers could be recognized, as shown in Fig. 8d. Closer observation was taken into the impregnation between fiber bundle and the matrix, as shown in Fig. 8b and f. There was no impregnation of matrix into the fiber bundle taken place when the temperature is 180 °C due to the low flowability with a melt flow index of 1.98 g/10 min (shown in Fig. 2). Melt flow index of matrix increased from 1.98 to 35.59 g/10 min when the temperature improved to 240 °C. Meanwhile, the carbon fiber bundle was impregnated with matrix, and well bonding between single carbon fiber and matrix were achieved, as shown in Fig. 8e. Mechanical properties and fracture patterns are the outward manifestation of the interfacial microstructure. During the fracture strength measurements, fibers were pull out and stripped from the matrix. Thus, the matrix materials would broken first and the load could not transfer to the fiber bundle (Fig. 8c), which caused a low flexural strength of 110 MPa, as shown in Fig. 4. However, with a temperature of 240 °C, the fracture pattern was totally different from the previous one with a fiber bundle breakage (Fig. 8f), thus the average flexural strength reached 155 MPa, as shown in Fig. 4.

3.2.1.2. Layer thickness and interfaces. 3D printed PLA composites was prepared by impregnating of fiber and matrix, depositing onto previous layer, and bonding to adjacent lines. The preset value of

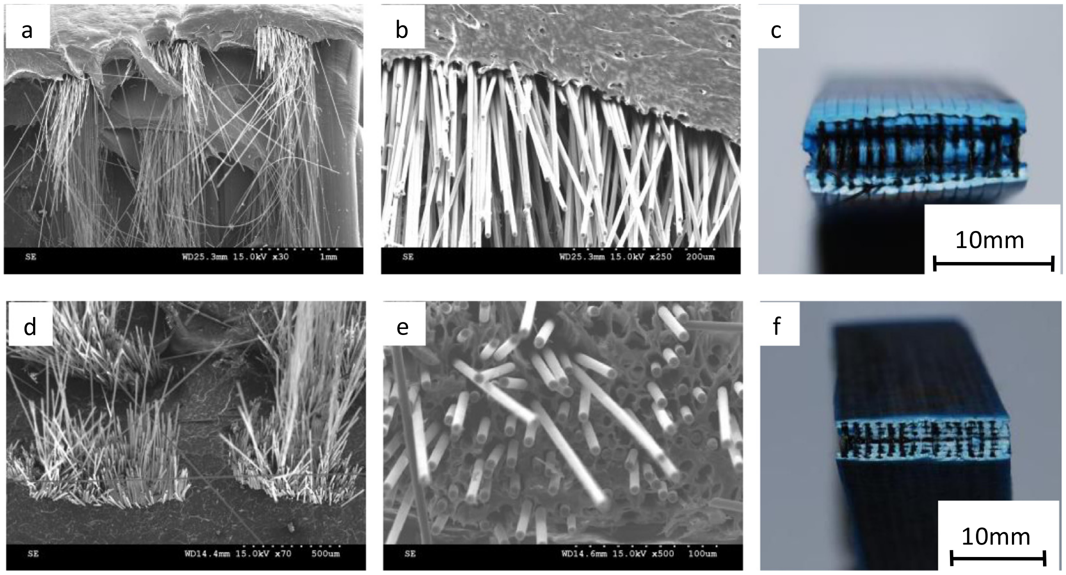

Fig. 8. Microstructures of fractured cross section of CFR PLA composites with temperature in the printing head of 180 °C (a, b, c) and 240 °C (d, e, f), respectively: (a) and (d) overall cross section, (b) and (e) interface, (c) and (f) fracture pattern, under experimental condition of L 0.65 mm, V 100 mm/min, E 150 mm/min, H 1.2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

layer thickness determined the distance between nozzle and previous layer, as shown in Fig. 2. When all the other process parameters were exactly same, small layer thickness caused a tight space for the just deposited melt materials and increased the contact pressure between nozzle and surrounding deposited lines. It was expected that the increased pressure would improve the bonding of deposited lines and further promote the mechanical performance. This hypothesis was verified by observing the microstructure as shown in Fig. 9. With a layer thickness of 0.5 mm, the bonding between layers are homogeneous and no obvious delamination in the interfaces (Fig. 9a). Meanwhile, melt PLA matrix impregnated into the fiber bundles (Fig. 9b) and the load could be transferred from the matrix to the fiber when fracture happened. Significant reinforcement was achieved with a average flexural strength of 176 MPa, as shown in Fig. 5. On the contrary, when a larger layer thickness of 0.7 mm was chosen, loose bonding (Fig. 9d), insufficient impregnation (Fig. 9e), and shear delamination as well as fiber pull-out (Fig. 9f) were found in the broken composite specimens, which finally caused a relatively lower average flexural strength of 132 MPa (also in Fig. 5).

3.2.1.3. Hatch spacing and interfaces. Hatch spacing is a parameter related to the extent of overlapping with the already deposited lines, as shown in Fig. 2. The influence of hatch spacing on contact pressure was similar with that of layer thickness. Small hatch spacing improved the overlapping extent and achieved large contact pressure. Considering that nozzle used in the present research had a diameter of 2 mm, overlapping of 70% and 20% have

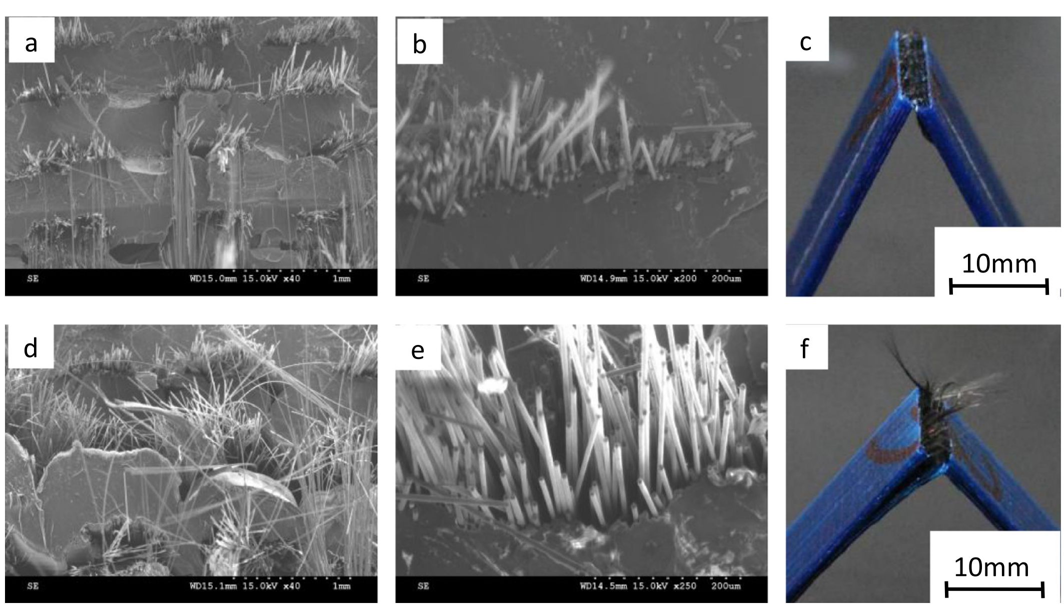

Fig. 9. Microstructures of fractured cross section of CFR PLA composites with layer thickness of 0.5 mm (a, b, c) and 0.7 mm (d, e, f), respectively: (a) and (d) overall cross section, (b) and (e) interface, (c) and (f) fracture pattern, under the experimental condition of T 210 °C, V 100 mm/min, E 100 mm/min, H 1.2 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

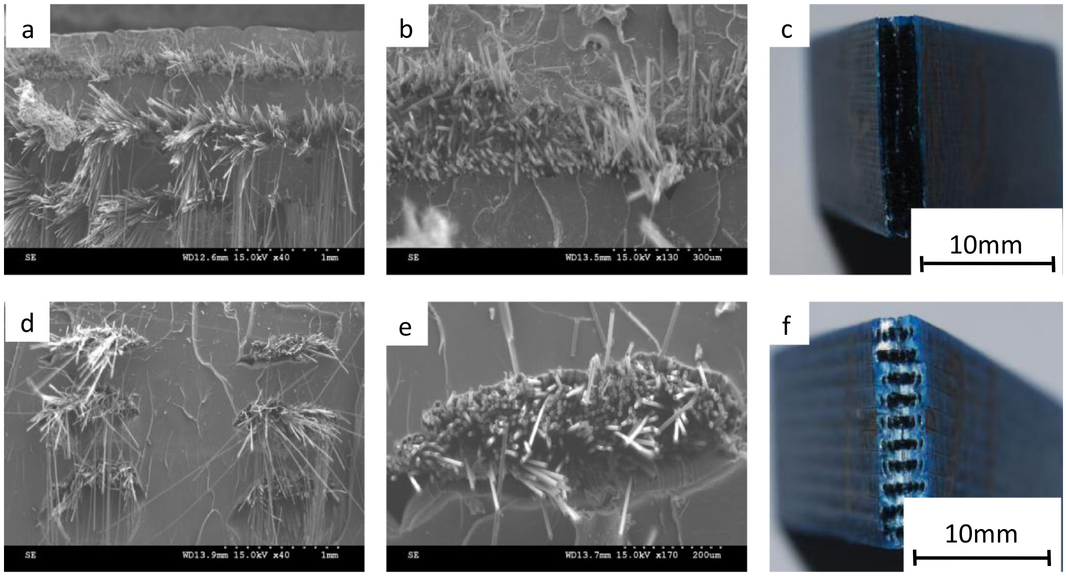

Fig. 10. Microstructures of fractured cross section of carbon fiber reinforced PLA composites with hatch spacing of 0.6 mm (a, b, c) and 1.6 mm (d, e, f), respectively: (a) and (d) overall cross section, (b) and (e) interface, (c) and (f) fracture pattern, under the experimental condition: T 210 °C, L 0.5 mm, V 100 mm/min, E 100 mm/min. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

been achieved when the hatch spacing was 0.6 mm and 1.6 mm, respectively, as shown in Fig. 10. Impregnation of melt PLA matrix into the carbon fiber bundle could be prompted when decreasing the hatch spacing from 1.6 mm to 0.6 mm, as shown in Fig. 10e and b, respectively. The maximum average flexural strength of 335 MPa and flexural modulus of 30 GPa have been obtained for the 3D printed composite specimens.

Certainly, the increasing contact pressure due to reduced layer thickness and hatch spacing contributed partially to the improvement of multiple interfaces and thus prompted the mechanical performance of the 3D printed composites. But above this, all these process parameters dramatically changed the carbon fiber content of the composite specimens, which was even more critical to properties of composites.

3.2.2. Carbon fiber content

In 3D printing process of PLA composites, carbon fiber was extruded together with melt plastics and continuously distributed along the tool path of printing head. The carbon fiber length could be automatically calculated by the length of tool path and the weight of carbon fiber in the specimen could be calculated by multiplying the weight per unit length. Thus carbon fiber content can be considered as the weight ratio of carbon fiber to composite specimen. The carbon fiber content in the printed composites specimens was directly determined by the tool path and unit volume of extruded plastic matrix, which were reflected by layer thickness, hatch spacing, and feed rate of filament, respectively. The relationships between process parameters and carbon fiber content are shown in Fig. 11. With increasing layer thickness and hatch spacing, carbon fiber content decreased with certain geometric principles and further reduced the flexural strength of the composites specimens, as shown in Figs. 5 and 6. Maximum carbon fiber content of 27% was achieved with hatch spacing of 0.4 mm, meanwhile the average flexural strength reached to 335 MPa. It is obviously that the flexural strength and modulus could be controlled by adjusting the hatch spacing and layer thickness, which are negatively correlated with both the fiber content and the contact pressure between nozzle and deposited lines. For feed rate of the filament, high feed rate will significantly decrease the fiber content as shown the inset figure in Fig. 11. However, in the previous mechanical measurement as shown in Fig. 7, feed rate promoted the flexural strength to a certain extent and kept unclear correlation. It might because high feed rate will increase the inner pressure in the liquefier and the contact pressure mentioned before. High pressure and low fiber content caused a unpredictable relationship between feed rate of filament and mechanical properties. To balance these contradictory effects, a suitable feed rate of 80–100 mm/min could be recommended for the further experiments.

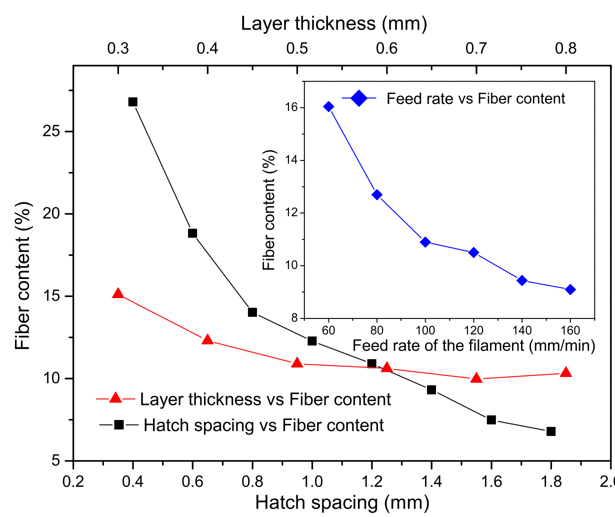

Fig. 11. Influence of process parameters on the fiber content in the 3D printed composites specimens under each experimental condition shown in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.3. Demonstration of 3D printed PLA composite parts

3D printed CFR PLA single-wall parts were fabricated by using the following process parameters: T of 220 °C, L of 0.5 mm, V of 100 mm/min, E of 100 mm/min. As shown in Fig. 12, each part was fabricated in one process cycle with a continuous fiber bundle inside the body (black area in the single wall). Carbon fiber bundle

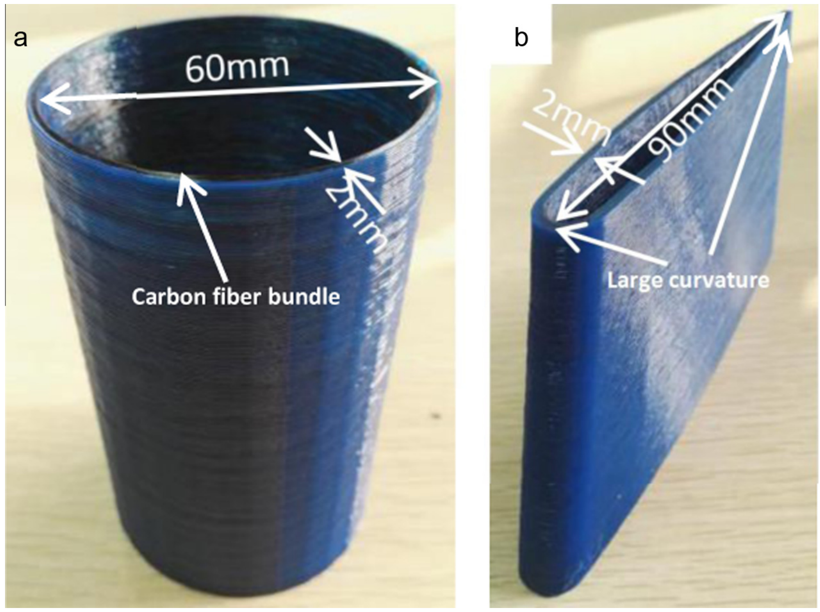

Fig. 12. CFRTPCs components fabricated by 3D printing process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shifted from the right center of the single wall due to the drawing force in the extrusion process, which was more obvious at the tool path with a large curvature, such as both edges shown in Fig. 12b. The influence of fiber shifting on the performance of composites would be further investigated and overcame in the future research. The average density of 3D printed CFR PLA composites was around 1.2 g/cm^3. With the good performance of the fabricated composites, advanced light structures could be designed and fabricated for the potential applications in aviation and aerospace.

4. Conclusions

3D printing of CFR PLA composites was proposed and studied in the present research. Rapid fabrication of composite components has been realized by using continuous carbon fiber as reinforcement phase and plastics as matrix. Temperature and pressure are critical parameters to the forming process, which determine the mechanical properties of composites. Interface and carbon fiber content are key technical specifications for the composites. Based on these fundamental theories, the influence of process parameters in 3D printing process on the interfaces and performance of printed composites have been systematically investigated. Impregnation of plastics into the fiber bundle could be achieved when the temperature of liquefier was in the range of 200–230 °C. Bonding strength between lines and layers could be guaranteed with the layer thickness from 0.4 mm to 0.6 mm and hatch spacing of around 0.6 mm. With the optimized process parameters, 3D printed CFR PLA composites with a fiber content of 27% can achieve the maximum flexural strength of 335 MPa and flexural modulus of 30GPa. Advanced mechanical performance of the printed CFR PLA composites ensured the future potential applications for the light structures in the field of aviation and aerospace.

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