3D Printing Method of Spatial Curved Surface by Continuous Natural Fiber Reinforced Composite

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Abstract. A method for printing continuous flax fiber-reinforced plastic (CFFRP) composites parts by five-axis three-dimensional (3D) printer based on fused deposition modelling (FDM) technology has been developed. FDM printed parts usually need supporting structures, have stair step effect, and unfavorable mechanical properties. In order to address these deficiencies, continuous natural fiber prepreg filaments were first manufactured, followed by curved path planning for the model for generating the G-code, and finally printed by five-axis 3D printer. The surface quality of printed parts had been greatly improved. The compressive strength and modulus of the 3D-printed CFFRP specimens increased by 29% and 522% respectively, compared with planar slicing method.

1. Introduction

Three-dimensional (3D) printing technology, also called rapid prototyping or additive manufacturing, has been rapidly developed and widely used in various field [1]. Fused deposition modelling (FDM) is one of most widely used 3D printing technologies due to inexpensive equipment and materials, and easy to operate [2]. FDM forms a 3D geometry by slicing a model along the XY-plane and assembling the resulting individual layers along the Z-axis, with extruded thermoplastic filaments, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), or polyethylene (PE) [3]. Much research has focused on the limitations of the FDM process, such as the stair step effect and inadequate mechanical strength, and put forward corresponding solutions.

Regarding path planning and printer machine, Huang et al. [4], Jin et al. [5], Zhang et al. [6], and Allen et al. [7] proposed a curved layer slicing method in contrast with the flat layer slicing. In order to print the path by curved layer slicing, it should be combined with a multi-axis printer. Enferadi et al. [8] added two degrees of freedom to the platform on the Delta printer model. Grutle [9] added the A and C axes to the platform on the Cartesian printer model, and Asif et al. [10] added the A and B axes to the extruder. The main limitation of FDM is its inferiority in-terms of the mechanical properties of the resulting prototypes. This led to the development of various types of alternative materials in order to improve the application domain of this technology [11]. In experiments with continuous fiber-
reinforced composites, Tian et al. [12-14], Yao et al. [15], Zhang et al. [16], and Hao et al. [17] studied composite behavior and printing using continuous carbon fiber-reinforced plastic (CCFRP). On this basis, Hu et al. [18] manufactured continuous carbon fiber prepreg filaments, in which the flexural strength of the final printed parts can reach as much as 610.092 MPa.

However, many limitations persisted in the CCFRP printing process due to the stiffness of carbon fiber, most machines adopt the solution of double nozzles (e.g., Markforged, Anisoprint). And carbon fiber manufacturing process is complex, high cost, high energy consumption and low output. On the contrary, natural fibers have not only high strength and modulus, but also light density, low price and abundant sources. If natural fibers can be used instead of carbon fibers in the field of lightweight, it will be very meaningful, resulting in the eventual choice of continuous flax fiber. At the same time, in order to improve the printing quality and mechanical strength, two degrees of freedom were added to the printer. Taking the factors discussed above into consideration, this paper presents a novel method to print Continuous Flax Fiber Reinforced Plastic (CFFRP).

2. Materials and Methods

2.1. CFFRP filament manufacturing

As shown in Fig.1, a single screw extruder and composite extrusion mold were employed for the manufacturing process. The diameter of PLA pellets was 0.5mm, added through the barrel. The single screw extruder squeeze the molten PLA resin into the composite extrusion die. The die had a vertical opening where a 3D printer nozzle was attached and a flax fiber was introduced and coated by the molten PLA resin. The diameter of the CFFRP prepreg filaments could be changed by varying the 3D printer nozzle. The melt extrusion temperature of PLA was set at 190°C. The extrusion speed of the screw was from 200 mm/min to 600 mm/min. The flax was a two-ply yarn of 68 Tex. The diameter of CFFRP prepreg filaments was set to 1.0 mm by the 3D printer nozzle.

2.2. Five-axis 3D printer

3D printed CFFRP specimens were manufactured using five-axis 3D printer which had an added B-axis with extruder that rotated around the Y-axis and C-axis with platform that rotated around the Z-axis, in addition to the three ordinary axes of the Cartesian printer model. As shown in Fig.2, when the B-axis points to the negative direction of the X-axis, it was 0°. However, it could be rotated from -90° to 90°, while the C-axis could be rotated freely (360°). The minimum angle of rotation for each of the two revolving axes was 0.16875°. The printer adopted ATmega2560 which used the same CPU as Arduino MEGA as the master control chip of the slave computer, called RUMBA (RepRap Universal Mega Board with Allegro driver).
2.3. Parameters of specimen

The geometry of the specimen was designed using software exported as an STL file. The main dimensions of the specimen were shown in Fig. 3. The specimens were 80 mm in length, 10 mm in width, 3 mm in thickness, and the radius of the curved was 60 mm. In this experiment, all parameters of printing except the build orientation were constant. The build orientation was divided into three types: upright, flat and curved. For PLA printed, the temperature of nozzle was 190°C, layer thickness was the height of a single layer, chosen as 0.35 mm, both the number of contours and number of roof and floor layers were 1, and the fill density of specimens was 100%. For upright and flat build orientation, the model was imported into the Repetier-Host software using the conventional 3D print Cura slicing engine for slicing, and the raster angle was 45°. Compressive tests were conducted using the microcomputer controlled electronic testing machine (WDW-1, SONGDUN Corp., China). Surfaces of the filaments and fracture surfaces of the tested specimens were observed with a HITACHI SU-1510 scanning electron microscope (SEM).

3. Results and discussion

Fig. 4 depict the compressive strength and modulus tests of specimens. As shown in Fig. 3a, when the build orientation was upright, the stair step effect was obvious. The compressive strength was 2.413 MPa and the compressive modulus was 8.761 MPa. A serious problem was that during the process of support stripping, the surface of the model would be damaged, and the roughness would be greatly increased. Compared with Fig. 3b, when the build orientation was flat, it needed no support. However, it was not applicable to all curved surface models. Most models still needed to be supported when they were printed in the flat direction, and the surface roughness was similar to that obtained when the direction was upright. The maximum compressive strength was shown in the samples printed in PLA (non-reinforced), the value was 5.113 MPa because the 45° intersection filling path provided a good
load bearing capacity on the stress surface in the compressive test. Fig.3c displays the specimens of the curved build orientation by the five-axis machine. Although the specimen still needed support, the support did not need to be peeled off so that they were destroyed, and could be reused with the help of masking tape. The curved path eliminated the stair step effect and improved the surface quality. In the compressive test, the compressive strength was 4.488 MPa, slightly lower than that in flat printing, which was due to the compactness of filling, that is, the void formation inside the model. Moreover, the compressive modulus was the highest in PLA specimens, and the value was 18.139 MPa. Because the curved path ensured the continuity of the filling of the filaments, the deformation of the continuous filaments required greater force. Compressive strength and modulus of CFFRP composite materials are 139% and 1187% higher than those of upright build orientation, and 29% and 522% higher than those of the same curved path printing of PLA filaments.

Figure 4. Compressive strength and modulus tests results for composite panels.

4. Conclusion
In order to improve the FDM process, the prepreg filaments were manufactured at first. Subsequently, the angle of the extruder according to the path of the curved layer is calculated. At last, the specimens are printed by five-axis 3D printer which is added B-axis to the extruder and C-axis to the platform on the Cartesian printer model. Since the filaments are of non-standard diameters (1.75 mm or 3 mm), the extruder is simply modified. We have studied the compressive test of printed specimens, which achieved considerable improvement compared to parts printed with pure PLA. CFFRP filaments and curved path printing make up for the shortage of FDM process. If natural fibers such as flax can be used in FDM printing of functional parts, it will have far-reaching significance in the field of composite fabrication where the most demand is for low-weight and high-performance parts.

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