3D printing of continuous fiber reinforced composites with a robotic system for potential space applications

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1. Introduction

Space exploration relays on the space manufacturing with high efficiency and reliability as well as low cost, thus can overcome the limitations on the payload, volume and expense with the current launch vehicles [1]. The key point of the space manufacturing is to solve the rigorous requirements for the processes and equipment from the outer space environment in the aspects of extreme temperature, energy consumption, and material performance. So, innovation on the fabrication process and material is urgent for the realization of space manufacturing. Additive manufacturing or 3D printing technology has a potential advantage for the applications in space due to the flexibility in the fabrication of complex structure and integration of material preparation and forming [2]. Among all the materials and processes utilized in 3D printing process, continuous fiber-reinforced thermal plastic composites (CFRTPCs) are the most promising candidate in the space application as the light weight and high performance structure [2].

In 2014, Mark Forged Company developed a 3D printer for CFRTPCs process using pre-preg filament with continuous fiber and thermal plastic matrix. The process capability would be limited by the type of pre-preg filament. The fiber content and interface performance could not be controlled. Meanwhile, X. Tian et al [3] 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, by which the flexual strength of composites samples was 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.

In the present paper, the mechanism for FDM of CFRTPCs will be introduced by analyzing the influence of process parameters on the mechanical properties of CFRTPCs specimens. The micro structure has been analyzed to verify the possibility to control the carbon fiber content and orientation. To realize the controllable performance and fit the application environment in space, a multi degree of freedom (MDOF) 3D printing system has been established. MDOF 3D printing has been achieved by the planning the printing path on a curved surface.

2. Experimental procedure

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.

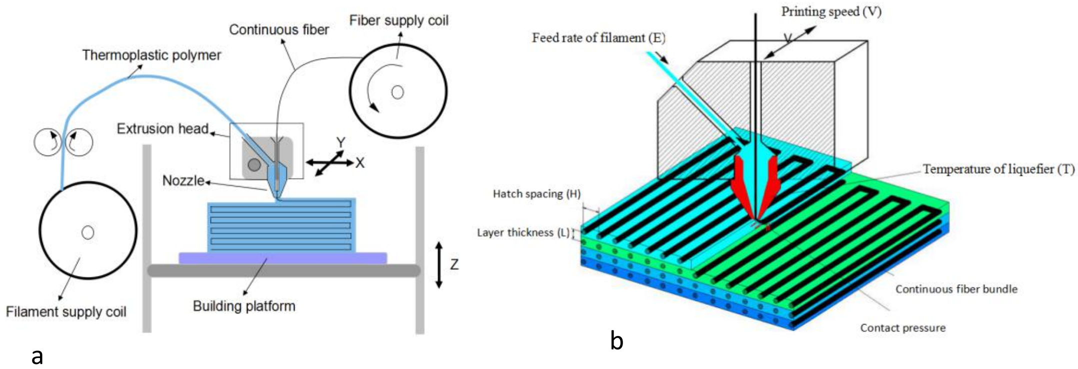

Fig. 1 Schematic of 3D printing equipment for CFRRPCs composites a), and scheme of the printing process b)

In this paper, acrylonitrile-butadiene-styrene (ABS/1.75 mm) from FLASHFORGE Corp. in China has been used as the thermoplastic material, and carbon fiber (1000 fibers in a bundle) from ANJIE Corp. in China has been used as the reinforcement. The continuous carbon fiber reinforced ABS (CCF/ABS) specimens were all prepared by the aforementioned equipment for the measurement of mechanical properties. The main printing process parameters in FDM for CCF/ABS specimens are listed in Table I, in which case the carbon fiber content in these specimens could approximately equal 10 wt%.

Table I 3D printing process parameters for CCF/ABS specimens

Description	Value
Nozzle diameter	0.8 mm
Bead width	0.8 mm
Layer thickness	0.5 mm
Extrusion temperature	230 ℃
Envelope temperature	90 ℃
Feeding speed	5 mm/s
Printing speed	10 mm/s

3. Experimental results and discussion

3.1. Experimental results

3.1.1. Mechanical properties of CFRTPS prepared by FDM

The proposed 3D printing process for CFRTPs was used to integrate the composite material preparation and in-situ forming for the complex structures. As shown in Fig.2, the flexural strength of the printed parts can reach 127 MPa, far greater than the flexural strength of ABS parts (80 MPa) and close to the one of CCF/ABS (140 MPa fabricated by the traditional injection molding method. The flexural modulus of these CCF/ABS specimens is 7.72 GPa, more than three times the flexural modulus of ABS (2 GPa)[3].

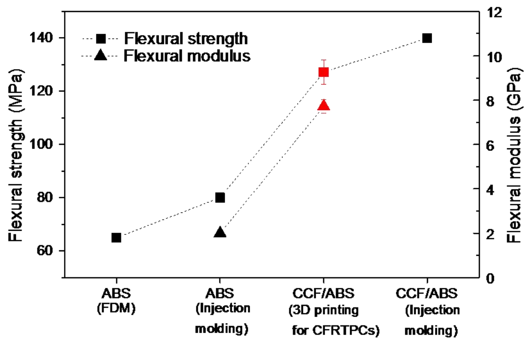

Fig.2 comparison of flexural strengths and modulus of ABS (FDM), ABS (injection molding), 10 wt% CCF/ABS (3D printing for CFRTPCs) and 10 wt% CCF/ABS (injection molding) **(b)**

3.1.2. FDM system for CFRTPS with MDOF

Due to the advanced performance of CFRTPCs, the proposed 3D printing process has the potential to be used in space for the in-situ space fabrication. In order to explore the potential application in space, a robotic system with multiple degree of freedom is utilized for the 3D printing process to fit in the real situation outside the space station, where a robotic arm is normally used to achieve the outboard maintenance.The 3D printing process on a robotic system is demonstrated in the laboratory, as shown in Fig.3. Samples has been fabricated by this robotic 3D printing system. However, the robotic system out of the space station normally has a low kinematic accuracy, which is not sufficient for 3D printing. In order to solve this limitation, an end effector for 3D printing and a visual identification system were utilized to demonstrate the application environment, as shown in Fig.4. Related research work is still ongoing.

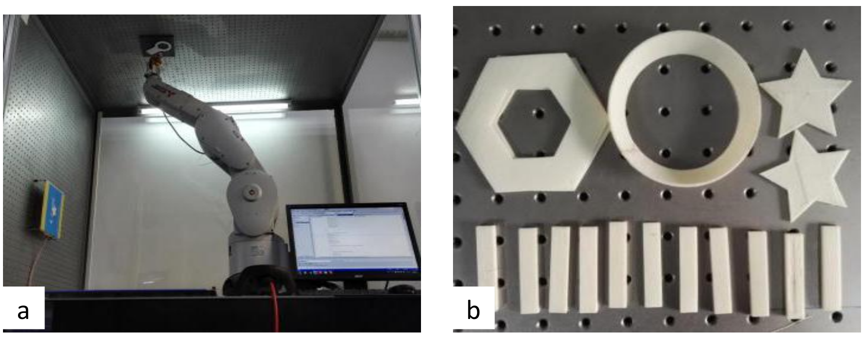

Fig.3 Robotic system for the 3D printing **(a)**, and some samples fabricated by the robotic system **(b)**

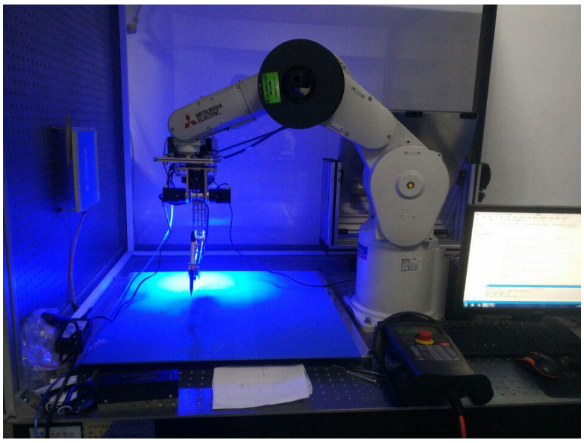

Fig.4 A robotic system with an end effector for 3D printing and a visual identification system

3.2. Discussions

3.2.1. Controllable fiber orientation and content

The 3D printing technology for CFRTPCs, which is a integrated transient process consisting of the thermoplastic polymer melting, the continuous fiber hot-dipping and the composite materials mixed extruding, manufactures composite parts line by line and layer by layer. This technology can realize the preparation of CFRTPCs material and the integrated manufacturing of the parts with complex structure. Hence, it is advantageous to design, arrange and realize the orientation and distribution of the fibers inside the thermoplastic matrix by designing the printing strategy and optimizing the printing process parameters. As shown in Figure 5, a reasonable printing path in 3D printing can arrange fibers to obtain a consistent direction and an uniform distribution in composite parts. Moreover, to adjust some process parameters in 3D printing technology, such as feeding speed of material, traveling speed, the diameter of polymer filament, etc., can change the fiber content readily (Figure 6). Obviously, different fiber orientation, distribution and content have a significant impact on the mechanical properties of CFRTPCs.

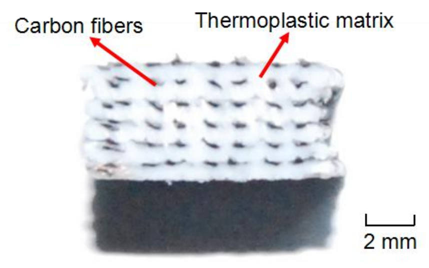

Figure 5 A consistent direction and an uniform distribution in composite parts [3]

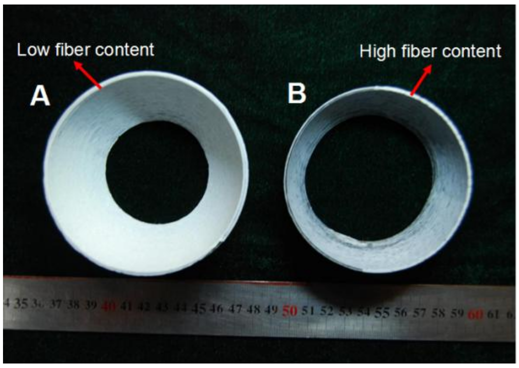

Figure 6 Parts with different fiber contents: in the printing process, the feeding speed of thermoplastic material for part (A) is 1. 5 times than the one of part (B), leading to the lower fiber content [3]

3.2.2. Path planing on curved surface for 3D printing

Path planning algorithm for curved surface has been developed to overcome the conventional X-Y slicing methods, especially for shell structures, as shown in Fig.7a. Depositing on a curved surface has overcome the bonding strength between layers. The overall strength and stiffness of the structure were improved and more fiber orientations are possible to be controlled for a higher overall performance for printed CFRTPCs, as shown in Fig.7b. The influence of curved path on the mechanical performance of the fabricated parts is still under investigation.

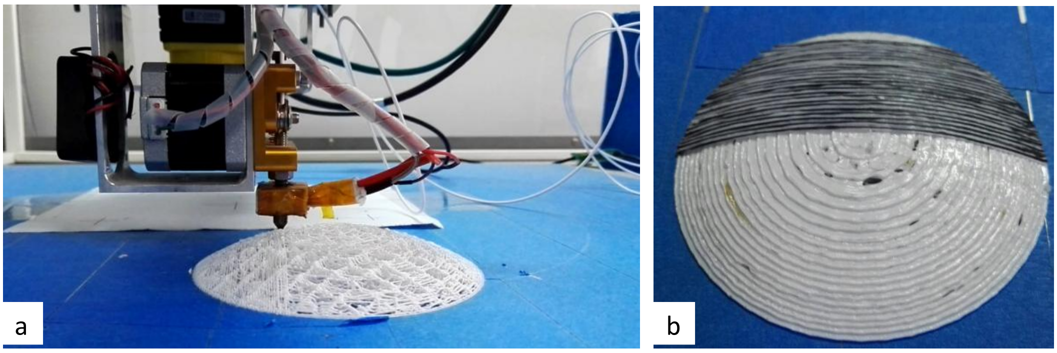

Fig. 7 3D printing process on a curved surface a) and deposited CFRTPCs on the curved surface b)

4. Conclusion

Spacial surface identification and self-adapting multidimensional path generating algorithm has been developed to meet the requirements for the space manufacturing and in-situ repairing. However, for the in-situ space manufacturing, thermal environment must be controlled for the 3D printing process. The thermal control system for the 3D printing nozzle and related micro-environment has to be established by exploring the new utilizing method of space energy in order to achieve the low electricity consumption. The validation platforms for the multidimensional 3D printing and vacuum / thermal radiation 3D printing will been built up to optimize the proposed 3D printing process and provide technical support for the future space manufacturing.

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Robotics and Systems - HIT, and the Research Funds from School of Mechanical Engineering, XJTU.

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