An Overview of Research on FDM 3D Printing Process of Continuous Fiber Reinforced Composites

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Abstract. Continuous fiber reinforced composites have excellent mechanical properties, but traditional processes are costly, complex to form, have a long production cycle, and are only suitable for relatively simple structures, which limits the wider application of the material. Fuse Deposition Modeling (FDM) 3D printing has the advantages of simple process, fast molding, low cost, and the ability to manufacture high-complexity structures, which provides the possibility of low-cost and rapid prototyping of composite materials. In this paper, several FDM 3D printing processes for continuous fiber composites are reviewed, and the effects of some related process parameters on the properties of the composites are analyzed. Finally, the problems of FDM 3D printing continuous fiber reinforced composites are pointed out.

1. Introduction

At present, composite materials have been widely used in various fields, among which continuous fiber reinforced composites have the advantages of high specific strength, high specific stiffness, high designability, and multi-functional fusion (such as absorbing and heat insulation). Continuous fiber reinforced composites can be divided into metal-based, ceramic-based and resin-based materials. The resin-based composite materials have been intensively studied since the advent of the 1940s and are widely used in aerospace, automotive, marine, wind power generation\cite{1-2}, etc. In addition, continuous fiber reinforced composites are the most widely used in the aerospace industry. The use of continuous fiber reinforced composites has become one of the important signs of aircraft advancement\cite{3-4}. In the aerospace industry, high-silica glass fiber reinforced phenolic resin and carbon fiber fabric reinforced phenolic resin can be well applied to the ablation and heat-preventing materials of the rocket head\cite{5}.

The traditional manufacturing process of continuous fiber reinforced composites mainly comprises three steps. Firstly, prepreg is produced mainly by deposition and dipping. Then the composite parts with simple shape can be manufactured by spreading molding, pull-extrusion molding, winding molding and other processes. Finally, composite parts are prepared by machining, assembly, cementing, etc.\cite{6-7} The molding process of the traditional resin-based composite members is complicated in manufacturing process, requires secondary processing, and has a long production cycle. Most of the special molds require high cost and limited complexity of the parts. These shortcomings limit the application of the composite materials.

Compared with the traditional process, 3D printing technology has obvious advantages. It is characterized by the fact that no mold is required, and it can be quickly formed at one time without
secondary processing, and theoretically it is possible to manufacture a structure of any shape. At present, according to the different process flow, it can be mainly divided into Stereo Lithography Apparatus (SLA), Laminated Object Manufacturing (LOM), FDM and other technologies. Compared with other 3D printing technologies, FDM has become a hot research direction of composite 3D printing technology due to its advantages of high material utilization rate, clean and safe process, fast forming speed and low cost.

With the development of aerospace technology, the construction and operation of space exploration bases depend to a large extent on how to achieve efficient, reliable and low-cost "space manufacturing" to obtain the platform, tools and equipment needed for space exploration and overcome the limitations of the existing rocket delivery modes on space exploration activities in terms of load, volume and cost[12]. Especially for composite materials, which require complex processes and large equipment manufacturing, traditional processes cannot meet such requirements. However, FDM 3D printing technology can be quickly formed at one time, the equipment is small, and the production process is clean and safe. These features can well meet the needs of space manufacturing and have the potential to realize space manufacturing. At present, research on fiber-reinforced composite FDM 3D printing has achieved certain results, but in order to achieve space manufacturing in space, the process of FDM 3D printing faces many shortcomings and challenges.

2. Research overview

2.1. Research on FDM printing process of continuous fiber composites

In 2014, Mark Forged of the United States developed the first continuous carbon fiber reinforced thermoplastic resin composite 3D printer Mark One[13], which successfully realized the manufacture of continuous fiber reinforced nylon composites. The printer uses two independent nozzle designs. First, the nozzle A extrudes the thermoplastic resin to form the outer contour of the printing member; then the nozzle B conveys the continuous fiber prepreg tow, and the fiber tow is heated and melted near the nozzle opening, and is squeezed through the nozzle. The force is laid flat on the printing platform to form the internal structure of the print. Through the alternate operation of the nozzles A and B, the manufacture of the outer contour of the print and the inner filling structure is realized. Due to the better assurance of the outer contour of the resin, the internal fibers can better ensure the mechanical properties, so the printed parts have higher dimensional accuracy and better mechanical properties.

Hu, et al.[14] used the self-made carbon fiber prepreg in the print head to be melted and heated, and then directly laid on the printing table to form a printed piece layer by layer. The single-screw extruder and the coaxial extrusion die are used to extrude the pre-impregnated filaments, and then, after being pulled by the tractor, dried by water cooling and a blower at a constant speed, continuous carbon fiber prepreg filaments are produced for printing. The prepreg passes through a PTFE conduit that passes straight to the end of the nozzle as shown in figure 1. The unprinted prepreg in this process can be pulled out of the nozzle by the continuous fiber prepreg which has been bonded to the substrate, so that no motor supply wire is required in the process, which makes the structure of the print head simpler. The PTFE conduit during this process ensures uniform heating of the prepreg and reduces friction with the metal conduit and nozzle. In addition, the nozzle uses a nozzle having a larger diameter than the wire to prevent clogging of the nozzle or breakage of the wire during printing. The carbon fiber reinforced PLA composite parts manufactured by the device have a flexural strength of 610.092 MPa and a flexural modulus of 40.13 GPa.
Tian, et al.[15] used a combined print head, the principle is shown in figure 2(a), the continuous carbon fiber dry wire and ABS are heated and mixed in the print head and then extruded from the print head to form a mixed melting of ABS and carbon fiber. The ribbon is finally laid on the printing platform layer by layer until a complete component is formed. The printing equipment and printing process are shown in figure 2(b). The composite material with 10% carbon fiber content can achieve a maximum flexural strength of 127 MPa and an average tensile strength of 147 MPa, which is much higher than the traditional ABS parts of 3D printing. And close to the injection molded carbon fiber reinforced ABS composite samples with the same fiber content (the bending strength is about 140MPa, the tensile strength is about 197MPa), in addition, these test results reveal the interlaminar shear strength (only 2.81MPa, the interlaminar shear strength of ABS injection molded parts is 24MPa) and poor interface properties. The thin-walled rotating body structure printed by this process is shown in figure 2(c), which shows that the 3D printing process of the continuous fiber-reinforced composite material has a good forming effect on the thin-walled rotating body.

Hou, et al.[16] used continuous carbon fiber dry wire and PLA to heat and mix in the print head and then extrude from the print head to form a mixed molten ribbon of PLA and carbon fiber. The mechanical arm is used as a printing platform, and the device is shown in figure 3(a). The device is designed to print lightweight structures of continuous carbon fiber reinforced composites for large print sizes. In this process, a method of fabricating a cross-lap and core lap design of a printing path to produce a continuous carbon fiber reinforced composite material having a complicated shape is proposed, as shown in figure 3(b). During the experiment, with the increase of the printing layer thickness, the mechanical properties of the printed article decreased. After optimizing the printing parameters, the maximum compressive strength of the lightweight structure of the 3D printed continuous carbon fiber reinforced composite material with the fiber volume content of 11.5% reached
17.17 MPa. This process has great potential for manufacturing lightweight carbon fiber reinforced composite lightweight structures with high complexity shapes and high mechanical properties.

Liu, et al.[17] proposed a novel free-hanging 3D printing method for the first time to fabricate the core structure of a continuous carbon fiber reinforced composite sandwich structure. It uses continuous carbon fiber and PLA to print in the print head. The mixed ribbon is cooled and solidified after extrusion of the print head, and the angle of the print head speed is adjusted. Finally, a hanging print strip is formed. The printing process is shown in figure 4(a). This method breaks through the printing method of Z-axis growth of XY plane fiber, and can realize cell structure of different topologies, such as tetrahedron, pyramid, kagome, octagonal truss, circular grid, and even more complicated structure. For example, the manufacture of a variable thickness monolithic wing structure is shown in figure 4(b). However, the printing device can only print a single print strip, and the print strips cannot be fused, so that the print layer cannot be formed, and at the same time, due to the low printing pressure, the presence of voids can be observed in the cross-sectional micrograph of the fiber intersection apex in the sandwich cell. Although this method is flawed, it has lower cost and difficulty, and can manufacture functional structures that are currently temporarily impossible to manufacture, and can provide reference for more flexible structural design in the future.

Hao, et al.[18] printed by an improved 3D printer consisting of a printhead, fiber bundle tube, epoxy pool, control system, building platform, X-Y motion mechanism and other related components. The structure is shown in figure 5. The printing process is that the fiber bundle passes through the epoxy resin pool and enters the printing head. Under the control of the printing software, the fiber bundle is printed on the building platform and then moved to a high greenhouse for heating and curing. The tensile strength and elastic modulus of the resulting reinforced thermosetting composite were 792.8 MPa and 161.4 GPa. In addition, the flexural strength and the elastic modulus were 202.0 MPa and 143.9 GPa, respectively. There is little research on printing processes and equipment for thermostet materials in the literature on printing continuous fiber reinforced composites. Hao’s improved printers expand the range of applications for continuous fiber composite 3D printing.

Mori, et al.[19] conducted in-depth research on the continuous carbon fiber reinforced FDM 3D printing process. First, a layer of the bottom of the part was printed with a resin material, and then the carbon fiber was embedded in the resin which had been solidified, and the resin printing was
continued. The final part is finished and finally placed in a heating box to heat the carbon fiber into the matrix. The printing process is shown in figure 6. In this paper, the mechanical experiments of unheated composites and heated composites are compared, in which the mechanical properties of the heated composites are better than those of the unheated composites. It can be seen from the experimental results that the impregnation effect of the fiber and the resin is improved after heating by the heating box.

Figure 5. Thermosetting composite FDM 3D printer[18].

Figure 6. Printing process[19].

Saari, et al.[28] developed a new 3D printing technology that aims to expand the FDM 3D printing process to enable 3D printing of a variety of materials, combining metal wires or other fibers with polymers such as resins. The device is a traditional FDM 3D printer with a shaft to connect a guide tube for conveying fibers to ensure that the fiber supply speed is coordinated with the extrusion nozzle speed. The process is shown in figure 7. The fibers are laid while the nozzle is extruded from the molten matrix material such that the fibers are immediately coated with the matrix material to form a composite print ribbon. The process of this method is simple and does not require prepreg, but it still needs to be further improved in printing complex curve paths and fiber automatic feeding and stopping.

Figure 7. Nested print schematic[28].

2.2 Study on properties of continuous fiber composite FDM printing members
The current research on the characteristics of continuous fiber composite FDM 3D prints is mainly aimed at the study of the mechanical properties of printed parts of composite materials. By studying the factors affecting the performance of the print by changing the printing parameters, the fundamental factors determining the characteristics of the print are derived, and finally the printing process method and equipment are improved.

Tian, et al.[20] used the equipment as shown in figure 8 to realize 3D printing of continuous carbon fiber and PLA composites. By changing printing parameters such as printing temperature, speed, layer height and filling rate, they studied the influence of printing parameters on mechanical properties of continuous fiber composites. As the printing temperature and the filling rate are increased, the printing speed and the layer height are lowered, and the mechanical properties of the printing sheet are gradually improved. The higher the filling rate, the lower the printing speed and the height of the layer. The pressure on the bottom plate of the printing strip is greater. Combined with the experimental results, the temperature and pressure can be analyzed as the key factors in the formation process, which determines the interface and mechanical properties of the composite. Experiments have shown
that when the layer thickness is 0.4 mm to 0.6 mm and the filling pitch is about 0.6 mm, the bonding strength between the printing strip and the printing layer, the printing strip and the printing layer can be optimal. When the fiber content reaches 27%, and the process parameters are optimized, the maximum flexural strength of the 3D printed continuous carbon fiber PLA composite can reach 335 MPa and the maximum flexural modulus can reach 30 GPa.

Caminero et al.[21] printed three samples in a test using a modified MARK TWO printer: a pure nylon sample, a reinforced layer and a nylon layer alternately printed (sample A) and a pure fiber reinforced layer printed sample (sample B) to test the inter-bonding strength of the printed sample layer. In addition, reinforcing fibers can be classified into glass fiber, carbon fiber and Kevlar® reinforcement. By comparing the bonding strength of the pure nylon sample test pieces with different printing thicknesses, the smaller the printing layer thickness is, the stronger the bonding strength between the layers is. At the same time, combined with the microscopy experiment, it can be seen that the thicker the printing layer is, the lower the pressure will be in the process of printing, which will increase the porosity of the printed part and eventually lead to the decrease of adhesive strength. By comparing Sample A and Sample B of the same reinforcing fiber, it can be analyzed that the reinforcing fiber content promotes the interlayer bonding strength to some extent. The final comparison of Sample A of the reinforcing fibers showed that the carbon fiber with the best impregnation exhibited the strongest bonding performance, while the Kevlar® with the worst impregnation exhibited the worst adhesion, indicating the impregnation of the fiber and nylon matrix. It also affects the adhesion of the printed layer. It can be seen from the experimental results that the factors affecting the adhesion between the layers are: printing pressure, reinforcing fiber content and interface effect between the fibrous substrates.

Caminero et al.[22] used FDM to manufacture continuous glass fiber, carbon fiber and Kevlar® fiber reinforced nylon composites to study the impact damage properties of 3D printed continuous fiber reinforced thermoplastic composites. During this process, the three printing parameters of the reinforced sample, namely layer thickness, construction orientation and fiber volume content, were changed. And the Flat sample (notched sample perpendicular to the printed layer, as shown in figure 9(a) and One-edge sample (with print) were performed according to ASTM standards. A layer of parallel notched samples, as shown in figure 9(b). The experimental results show that when the reinforcing fiber is not included, the thickness of the Flat sample increases with the thickness of the layer, and the impact strength increases. The sample exhibits a more ductile fracture characteristic. The One-edge sample decreases with the thickness of the layer, and the impact strength decreases. A higher breaking strength than the One-edge edge sample. When the reinforcing fiber is used, the impact resistance of the Flat sample increases with the increase of the fiber volume content. The One-edge sample has higher breaking strength than the Flat sample, and the glass fiber reinforced composite exhibits the best impact resistance, while the carbon fiber lowest. From the experimental results, it can be analyzed that the fiber content has a significant effect on the impact resistance, and the difference in the printing path also leads to the difference in impact resistance.
3. Problems and solutions in current research

3.1. Printing material
The commonly used composite FDM 3D printing substrates are ABS, ASA, PC, PLA, Nylon, ULTEM. Except ULTEM, the performance of these materials does not fully meet the aerospace material performance requirements. But FDM 3D printing studies of other resin-based composite materials such as epoxide resin, BMI and phenol-ether resin, which are commonly used in the aerospace industry, are almost blank. Therefore, on the one hand, research on FDM 3D printing process for high performance resin which is widely used nowadays, on the other hand, FDM 3D printing material with performance close to or beyond these materials is developed, which is to realize continuous fiber reinforced composite FDM 3D printing in aerospace The basis for widespread use in the field.

3.2. Molding process
At present, the main research is to study the influence of environmental temperature, printing thickness, speed, filling rate and other factors on the mechanical properties of printed parts. However, from the current research results, the improvement of the mechanical properties of the printed matter by changing these factors is limited, especially the interlaminar shear strength of the printed article is much lower than that of the composite member manufactured by the traditional process. The shear strength between the layers has a direct effect on the flexural strength of the material. Because it is different from isotropic materials, when the anisotropic material undergoes deformation under the bending moment, the strain between the different layers is different, resulting in shear stress between the layers, which leads to interlayer separation of the material and causes the material to fail. Thus the interlaminar shear strength of the composite material plays a key role in the mechanical properties of the composite component. How to solve the problem of insufficient interlaminar shear strength of printed parts is the focus of future research on FDM 3D printing process.

The weak link of the fiber-reinforced composite material produced by the traditional process is also in the shear strength between the layers, and the factors affecting it mainly have three aspects. Firstly, it is related to the interface effect of the two-phase material. The better the interface effect, the stronger the inter-layer shear strength[23-24]. At the same time, it is also related to the porosity of the material[25]. Practice has shown that when the void ratio of the composite article is less than 4%, the interlaminar shear strength is reduced by about 7% for every 1% increase in void ratio[26]. Finally, compared to the conventional process, the strength of the connection bond between the layers of the continuous fiber composite FDM 3D printing is weak. For example, the autoclave forming process currently used in the aerospace industry is to form a stable chemical bond between the prepreg layers by stable humidity, temperature and pressure. In the current FDM 3D printing composite process, the
The former layer has been cured before bonding with the new layer, and it is difficult to form a stable chemical bond between the two layers. This is the reason why the bonding strength between the layers of the printing material is seriously degraded compared with the conventional process. These three factors are the key factors affecting the interlaminar shear strength, and pressure and temperature are the process parameters that play a decisive role in these three factors. Therefore, from the aspects of printing pressure and temperature, the problem of insufficient interlaminar shear strength of FDM 3D printed parts can be solved. At the same time, the temperature of the underlying layer does not reach the melting temperature of the substrate when the layers are combined, resulting in the inability to form stable chemical bonds between the layers. Ultimately, the interlaminar shear strength of the print is much lower than that of the conventional process.

Compared to traditional processes, there is currently no research on the physical model of the formation process of FDM 3D printed composites. Although the current printing process is mostly experimental, the performance is lacking, and the performance of the printed product does not reach the application standard of the composite material. However, the research on the physical model in the printing process has profound significance for the in-depth study of the forming mechanism of FDM 3D printing. Further research will play a guiding role in the research of process methods and process equipment.

3.3. Printing equipment
Due to the imperfect FDM 3D printing process, the performance of the printing device is incomplete and unstable. The mechanical properties of the print are significantly weaker than conventional process parts, especially interlaminar shear strength. In the existing research, we already know that the temperature of the bottom layer and the pressure of the printing layer play a key role in the mechanical properties of the printed matter, especially the interlaminar shear strength, but the existing equipment lacks the design of these two factors. Drawing on the forming conditions and process parameters of the traditional process, the existing printing equipment can be changed to meet the conditions and parameters of these aspects, which is of guiding significance for the research and design of the printing equipment. However, the temperature and pressure of the FDM 3D printing process are difficult to meet the standards of traditional processes. We need to consider the special process to make the humidity, temperature and pressure in the printing process reach or close to the standard of traditional technology, so that the printed parts may be close. For example, Parandoush[27] used the equipment shown in figure 10, with the aid of laser and rolling, the interlayer adhesion of the material is even better than that of the compression molding process, mainly in the lower porosity and higher peeling power of the printed part. In addition, the continuous fiber composite FDM 3D printing and the ordinary FDM 3D printing have similarities in the interlayer bonding mode, and the bonding between the layers mainly depends on the matrix connection between the layers. Ordinary FDM 3D printing research is relatively early, and the research results can be used to find a solution to the problem of composite FDM 3D printing.

![Figure 10. Schematic of laser assisted 3D printer][27]

4. Conclusion
At present, research on continuous fiber reinforced composite FDM 3D printing has achieved a lot of
results, and has achieved printing of multiple materials and multiple processes. The mechanical properties of prints of some materials are close to the injection molding process. However, there is a lack of research on 3D printing of high performance resin composite materials suitable for the aerospace industry.

The existing FDM 3D printing research mainly studies the effects of ambient temperature, printing temperature, thickness, speed, filling rate and other factors on the mechanical properties of printed parts. However, by improving these factors, the improvement of the mechanical properties of the printed materials is limited, and there is still a gap between the traditional processes and the conventional processes, especially the interlaminar shear strength which is much lower than that of the composite materials produced by the conventional process. At the same time, there is a lack of key factors for the formation of composite materials: the study of pressure and interlayer bonding. Furthermore, there is insufficient research on the physical model of FDM 3D printing composite material formation process, which is not conducive to the in-depth study of FDM 3D printing mechanism.

Finally, there are a variety of FDM 3D printing devices for different printing processes, with 3D printing manufacturing capabilities of fiber reinforced composite materials, and good printing results. However, the current printing equipment lacks a design for composite molding pressure and interlayer fusion, so that the mechanical properties of the print have a certain gap compared with the conventional process. The molding conditions of current FDM 3D printing cannot meet the standard molding conditions in the traditional process. The future research needs to improve the equipment or break through the traditional process to make the molding conditions of 3D printing reach the standard molding conditions of composite materials, and finally realize the standardization of 3D printing.

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