Shearing algorithm and device for the continuous carbon fiber 3D printing

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Abstract
The combination of the carbon fiber composite and 3D printing technology can be a powerful approach to produce the high-strength light-weight and complex construction mechanical parts. Compared with the short carbon fiber which has been widely used, application of continuous carbon fiber in 3D printing can undoubtedly better play its good mechanical properties. Usually, complex parts include multiple independent contours, which lead to discontinuous paths in the 3D printing process. For the continuity characters of the continuous carbon fiber composite, it needs to be sheared off due to the discontinuous molding printing path, so as to ensure the quality of the forming process. To solve this problem, a shearing method is put forward and the shearing device is realized. Based on the 3D printing planning path by the slicing process, the actual shearing position is calculated by shearing position recognition and distance compensation between the jump and the shearing point. On the basis of this method, the corresponding shearing device is designed to build a shearing system. The accuracy and feasibility of the continuous carbon fiber shearing system is verified by simulation analysis of path jump and single-layer and multi-layer model 3D printing experiment. The method provides basis for the realization of continuous carbon fiber composites 3D printing.

Keywords: Continuous carbon fiber composite, 3D Printing, Shearing system, Discontinuous path, Molding experiment

1. Introduction
Carbon fiber reinforced polymer (CFRP) is a lightweight and high-strength composite material which is made of carbon fiber as reinforcing material and thermoplastic resin as matrix material (Gao and Xu, 2010). It has good mechanical properties such as light weight, high strength and ability of anti-fatigue. The specific strength and stiffness of carbon fibers are much higher than other fiber composites and metallic materials. At present, carbon fiber composites are widely used in aerospace, automobile manufacturing, petrochemical industry and so on (Sun, 2016). However, due to the high strength, poor thermal conductivity and thermostability of carbon fiber materials, the forming process of the carbon fiber is complicated and the high accuracy mold is required. So, it is difficult to form a complex model. 3D printing, as a kind of material addition manufacturing technology, which can avoid the mould demand of traditional manufacturing, and simplify the process flow and production cycle greatly (Song et al., 2016). Thus, the continuous carbon fiber 3D printing technology can combine the performance advantages of carbon fiber material and the molding advantage of integrally formed (Tian et al., 2016).

For the research of carbon fiber composites 3D printing, the short fiber composite and thermoplastic materials is applied. The method of short carbon fiber reinforced ABS resin was proposed by Tekinalp and Fuda Ning. They printed the mechanical parts made of this composite material and tested their mechanical properties. The results showed that short fibers had a certain degree of enhancement to ABS materials, but the effect was not very good (Tekinalp et al., 2014, Ning et al., 2015). Later, continuous carbon fiber 3D printing was also proposed, and gradually developed into a new manufacturing method (Ryosuke et al., 2016). The curve parts with composite material made of continuous carbon fiber and PLA are printed. The tensile strength and flexural strength of the composite parts increased by 225% and 194%.
respectively compared to the same one made of PLA (Li et al., 2016). A test sample with sandwich structure made of composite material are printed. Carbon fibers are embedded by being sandwiched between 3D-printed ABS layers without fibers (Nakagawa et al., 2017).

At present, the development of 3D printing for continuous carbon fiber is still in the initial stage. Based on the optimization of the continuity path, the jump point is unavoidable in the process of complex model forming, including the jump between different outlines and different layers. So, the shearing system should be used to realize the complex model 3D printing. In this process, the cutting position and forming accuracy should be ensured. The 3D printer produced by the Mark Forged in the United States has a front-end shearing device, which can shear off the carbon fiber in real time before the material is fed into the nozzle (Today M., 2015). The front-end device can shear off the continuous carbon fiber without affecting the formed model, compared to the back-end shearing device (carbon fiber was cut off after extruded from the nozzle). Also, the molding process can’t be affected by the shearing device. However, the shearing position of the Mark Forged 3D printer is far away from the nozzle in the front-end shearing mode, which leads to long shearing interval. The device can not shear off CFRP accurately when the length of a continuous path is less than the shearing interval, which may reduce the forming dimensional accuracy of the model. Therefore, in order to solve the above problem, it is necessary to propose a appropriate shearing method and device to realize the complicated structure continuous carbon fiber 3D printing. To achieve this goal, when the discontinuous path occurs, the continuous fiber should be sheared off in real time and the nozzle can jump to next starting point.

In this paper, based on the FDM principle of carbon fiber 3D printing process, the front-end shearing mode is adopted. Firstly, the shearing algorithm and the control instruction are proposed. Secondly, a shearing device is designed. The shearing interval is minimized when the shearing demand is met. Finally, the feasibility of the shearing algorithm and the accuracy and stability of the shearing system are verified by theoretical simulation analysis and printing experiments.

2. 3D printing forming process of continuous carbon fiber composite

Due to the high temperature resistance of carbon fibers, the traditional FDM principle can not be applied to 3D printing of carbon fibers. Carbon fibers (CF) must be pretreated with thermoplastic resin to prepare carbon fiber composites. In the process of forming, the composite material is fed to the high temperature nozzle by the feeding device, and the resin on the surface of the carbon fiber is heated to molten state. After preprocessing the 3D model by the slice system, path optimization, jump processing and parameter matching are used to get the path code suitable for continuous carbon fiber molding. The control system recognizes the path code and drives the printer to move according to the specified path. When the nozzle contacts the worktable, the fused carbon fiber composite is adhered to the worktable. With the movement of the nozzle, the composite material is selectively coated on the surface of the worktable and solidified rapidly, forming by layer, and finally stacked into a three-dimensional model. Figure 1 shows the process of continuous carbon fiber 3D printing. In the forming process of complex models, the path produced by the slicing system is necessarily discontinuous, and the nozzle will jump from one point to another during continuous motion. In order to ensure the forming precision of the model, there is no carbon fiber composite attached to the worktable along the path of the jump, so it is necessary to shear off the carbon fiber composite in real time.

Due to the continuity characteristics of carbon fiber composite wire, no continuous feeding is needed in the printing process. The composite wire will continue to pull out with the movement of the nozzle, and be pressed by the pressure between the nozzle and the working table and the pressure between the nozzle and the solidified model when heated to melting, so that it is formed by adhesion. When slicing produces discontinuous paths, it is necessary to identify jump position accurately and shear off composite wires in real time, so as to realize the formation of discontinuous paths.
Based on the above forming process, we need to complete the following tasks in order to achieve shearing of continuous fibers to improve printing quality: (1) Shearing Position Recognition: because of the application of front-end shearing mode, the jump position does not coincide with the shearing position, and the shearing position needs to be identified accurately. (2) Control Instruction Design: based on the path code, the appropriate shearing instruction and feeding instruction are matched at the right position to ensure the continuous and accurate forming process. (3) Building a Front-end Shearing Device: analyzing the mechanical properties of the composite material and designing a reasonable cutting device. Minimizing the shearing interval when ensuring fast and accurate shearing. (4) Verification Experiment: simulation analysis and printing experiments of the proposed shearing algorithm and shearing device are carried out to ensure its feasibility and stability.

3. Shearing algorithm

This paper is based on the front-end shearing mode. The carbon fiber composite is sheared off before it is fed into the nozzle and melts, which avoids the motion interference between the device and the solidified model and ensures the quality of the forming. Because of the continuity of carbon fiber, the discontinuous feeding device will feed the material to the nozzle after the composite was sheared off and no longer work until next shearing. The composite will be pulled out continuously during the forming process and solidify with the movement of the nozzle. When the jump occurs, the composite material is cut off in real time at the recognized shearing position, and is fed again to ensure the accurate and continuous forming of the model.
3.1 Analysis of 3D printing drive file for continuous carbon fiber

The driving file of carbon fiber 3D printing is based on G-code and combined with M-code for auxiliary control. G-code is a common NC instruction, which can realize various functions such as quick positioning, linear interpolation, circular interpolation, etc. Based on the principle of FDM 3D printing, the 3D model is processed by the slicing system, and the G-code instructions for controlling the movement path of the nozzle are generated. This control instruction has the following characteristics: (1) Interpolation fitting: there is no circular interpolation in the G-code for 3D printing. The track of any line segment is fitted by the linear interpolation instruction G1. When the G1 instruction is executed, the carbon fiber composite material is extruded and formed according to the instruction information; (2) Quick positioning: the G0 instruction is a quick positioning instruction. After each continuous interpolation, it will move to the next interpolation starting position through quick positioning instructions. That means the G0 instruction is the jump marking instruction for the nozzle; (3) The length of the path is in accordance with the feed length of the composite: because of the continuity of carbon fiber, the composite continues to be pulled out as the nozzle moves, and the length of the moving path of the nozzle is consistent with the length of the carbon fiber all along.

Using the front-end shearing mode, the shearing position must have an advance quantity relative to the actual jump position, which is a straight distance from the shearing device to the nozzle and set to \( l \). To achieve accurate shearing, according to the characteristics of the G-code, it is necessary to make the sum of the linear distances of each point between G1 instruction line containing the shearing position information and the G0 instruction line that contains the jump position information is \( l \). Figure 2 shows the G code instruction that contains the jump information. We need to locate the appropriate shearing position and insert the shearing instruction according to the jump position information.

![G-code](image)

3.2 Shearing position recognition

In G-code instructions, X and Y represent the transverse and vertical coordinates of the Descartes coordinate system established on the workbench, indicating any point on the plane. Two lines of adjacent G1 code represent a straight line path. Therefore, there are two cases of shearing position:

1) The shearing position is between the two G-code lines;
2) The shearing position coincides with the coordinate position contained in a G-code line.

To find suitable shearing position for the above two situations, define the following parameters:

(1) \( X_{n+1}, Y_{n+1} \) and \( X_n, Y_n \) are the coordinates of two adjacent points;
(2) \( \Delta_n \) represents the linear distance between \( X_{n+1}, Y_{n+1} \) and \( X_n, Y_n \):

\[
\Delta_n = \sqrt{(X_{n+1} - X_n)^2 + (Y_{n+1} - Y_n)^2}
\]  

(1)

(3) \( l \) is the straight distance from the shearing position to the nozzle.
For the first case, take the coordinate point in Fig. 3 as an example. If \( X_n, Y_n \) is a jump position coordinate, the shearing position coordinates are located between \( X_{n-m}, Y_{n-m} \) and \( X_{n-m+1}, Y_{n-m+1} \). It is bound to satisfy the following expressions:

\[
\Delta_{n-2} + \Delta_{n-3} + \cdots + \Delta_{n-m+1} < l < \Delta_{n-2} + \Delta_{n-3} + \cdots + \Delta_{n-m+1} + \Delta_{n-m}
\]

(2)

The line between point ‘\( X_{n-m}, Y_{n-m} \)’ to point ‘\( X_{n-m+1}, Y_{n-m+1} \)’ needs to be split to obtain the accurate shearing position coordinates. Its form is shown as shown in Fig. 4.

For the second case, the coordinate of the shearing positions is \( X_{n-m}, Y_{n-m} \), conforms to \( \sum_{i=n-2}^{n-m} \Delta_i = l \). So it can be also expressed as Eq. (3) and Eq. (4).

3.3 Action instruction matching

Based on the traditional 3D slicing system and shearing position recognition, it is necessary to add functions and match instructions according to printing requirements. The functional system model is built to realize the coordination work between shearing and feeding, so as to improve the molding quality and efficiency of continuous carbon fiber 3D printing.

For this algorithm, the following instruction forms that meet the control requirements of device are presented. Based on the algorithm for shearing position recognition, \( X_{\text{cut}}, Y_{\text{cut}} \) is the shearing position coordinate found by the algorithm as is shown in Fig. 5. Then the shearing point coordinate, the shearing instructions and the feed instructions are inserted after calculating the exact shearing position.
When the nozzle moves to the shearing position, the shearing instructions drive control system to complete shearing and moves to the jump position. Then the feeding device begins to work, the material is extruded forward to the length $l$, that is the distance from the shearing position to the nozzle. The nozzle begins to print the next continuous path after the feed is finished. Figure 6 shows the printing process. Shearing algorithm identifies the shearing position and matches the instructions during the slicing process. In the printing process, the shearing mode and the feeding mode will alternate to ensure that the printing can be fast and continuous.

4. Functional design of shearing system

4.1 Analysis of shearing system

In order to make the shearing device cut off the composite quickly and accurately, it not only needs to match the appropriate shearing position, but also needs the device to respond in real time, execute the shearing instruction quickly and realize the free jump. So the model can be accurately formed.
In the structure of the shearing device, the Synchronous Belt Drive is used as the driving forms between the stepper motor providing driving force and the shearing tool. This enables synchronous work of command sending, motor driving and tool rotation to ensure the real-time performance of the device.

In order to ensure stable operation of the shearing device, sufficient torque provided by stepper motor is required to drive the shearing tool so that the composite can be cut off in real time. The torque of stepper motor is proportional to its volume. The large size of the motor will inevitably increase the volume and weight of the shearing device, occupy the printing space, increase the stress and deformation of the movement structure, and affect the molding quality. Therefore, under the premise of meeting the conditions of cut-off torque, the motor should be reasonably selected to make the shearing device simple, compact and light in weight. The composite materials used in the experiment are made of nylon (PA6) and PLA (polylactic acid) as matrix materials and carbon fiber as reinforcing materials as is shown in Fig. 7. According to different printing requirements, composite wire diameter has different specifications from 0.4mm to 1.0mm. Therefore, the shearing device is universally applicable and can cut off different kinds composite materials with different specifications quickly and accurately.

In the prepared composites, the carbon fiber content is low and its shear strength and the bending strength are very poor. Therefore, carbon fiber can be ignored when calculating the shear force of the composite wire, and only the matrix material is analyzed.

The mechanical properties of PA6 and PLA materials used in the experiment are shown in the table 1 (Quan et al., 2017, Torres et al., 2016, Meng, 2013, Tanaka et al., 2009, Miao et al., 2018).

| Mechanical Property          | PA6   | PLA   | CF   |
|------------------------------|-------|-------|------|
| Density/(g/cm³)              | 1.14  | 1.24  | 1.8  |
| Melting Point/(°C)           | 215~225 | 130~230 |      |
| Fracture Elongation /(%)     | 200   | 7.0   | 2.1  |
| Bending Strength /(Mpa)      | 120   | 62    |      |
| Tensile Strength /(Mpa)      | 74    | 55.6  | 4900 |
| Shear Strength /(Mpa)        | 38.3  | 53    |      |
| Notch Impact Strength /(J/m) | 56    | 195   |      |
| Rockwell Hardness            | 114   | 88    |      |

According to the mechanical properties of materials, it can be concluded that shear failure is the main form of damage. Therefore, shear strength of material is used to check the shear force of the device.

The shear strength of the checking material has the following formula:
\[ \tau = \frac{F_s}{A} > [\tau] \]  

(5)

\( \tau \) — Actual shear stress of material  
\( F_s \) — Shear force  
\( A \) — Sectional area of material  
\([\tau]\) — Permissible shear stress

There is the following relationship between the torque supplied by the motor and the shear force \( F_s \):

\[ M = F_s \cdot d \]  

(6)

d indicates the distance between the breakpoint of the material and the center of the tool rotation. To ensure that the shearing tool can cut off different specifications of different materials, the maximum shear strength and the maximum diameter of the composite should be checked. That is, \([\tau] = 53 \text{MPa} \), \( A = \pi r^2 = 7.85 \times 10^{-7} \text{m}^2 \). The calculation of the required shear force is \( F_s = 41.6 \text{N} \). In the case of the appropriate cutting torque \( d \), small stepper motor can be selected to reduce the volume and weight of the device.

4.2 Structure design of shearing device

Whether the structure of the shearing device is reasonable or not directly affects the cutting effect and the stability of the system. Therefore, the design of a stable and effective shearing device provides a working carrier for the printing system, and is the foundation for continuous and accurate 3D forming of carbon fiber composite. Based on the shearing system analysis and the front-end shearing mode, the structure design of the device is carried out. In this design, the output torque of the motor is input to the shearing tool by synchronous belt transmission, and the motion synchronization is realized as shown in Fig. 8. The motor used in the device is a gear motor with a torque of 0.917N·m. Under the installation condition, the maximum shear force it can provide is 53.9N. In this way, the carbon fiber composite can be cut off steadily.

In the device, the distance between the shearing position and the nozzle is an important parameter, which directly determines the shortest continuous printing length of the carbon fiber. Based on front-end shearing mode, the remaining carbon fiber in the nozzle should be completely extruded after it was sheared off. Then the next shearing and jump can be done after the bonding of second carbon fiber composites. Therefore, the shorter the distance between the cut-off point and the nozzle, the shorter the interval between the two shear or jump, which means that the continuous printing accuracy of carbon fiber is higher. In this design, based on the front-end shearing mode, the combinatorial assembling of the shearing device and the nozzle structure can minimize the distance between the cut-off point and the nozzle.
The device has compact structure and reasonable space distribution, and greatly reduces the volume of the device. By controlling the motor, the action of the shearing tool can be controlled synchronously. The shearing device is a detachable structure. Without affecting other structures, shearing tools can be replaced quickly.

5. Experimental verification of continuous carbon fiber 3D printing

5.1 3D printing device for continuous carbon fiber

The equipment used in this experiment is an independently developed desktop 3D printer based on FDM principle. Based on the traditional desktop 3D printer, a special feeding device and nozzle structure are equipped for the continuous carbon fiber composite. As shown in Fig. 9, the printer includes frame, three-axis motion structure, feeding device, nozzle structure, shearing device, working platform, etc. The nozzle structure is the core of realizing carbon fiber 3D printing, and the shearing device is the key to the continuous fiber material complexly modeling.

The raw materials of the experiment are T700 1K carbon fiber tow and PLA particles. The carbon fiber tow is infiltrated in the melted PLA, and the carbon fiber composite with a diameter of 0.6mm is prepared by pulling out through a small hole. The printing temperature is 200°C.

5.2 Single layer printing experiment

The path jump of continuous carbon fiber 3D printing can be divided into two cases: intra layer jumping and inter layer jump. The effectiveness of intra layer jump processing is the foundation for completing multi-layer printing. For the parts with complicated outlines, the accuracy and stability of the shearing device can be effectively verified by testing the effect of shearing and jumping in single layer.
Figure 10 shows a model for single layer experiment. It is a flange plate used for pipe connections. There are multiple independent components in the model, which indicates that there will be multiple path jump. After processing model with slicing algorithm and shearing algorithm, the driver file for carbon fiber 3D printing is obtained, and the first layer is taken as the experimental object. The result of the path simulation shown in Fig. 11, ‘1-9’ in the figure shows the shearing position and ‘1-1X’ indicate the jump position. Dark blue lines and light blue lines in the figure show the printing path before and after shearing, respectively. The red lines represent the path of the jump. The simulation results show that the jump position always lag behind a certain distance of the shearing position and distribute regularly according to different components.

After the simulation results are successfully verified, the driving files are imported into the control system for printing test. The results of the experiment are shown in Fig. 12. The experimental results, in the range of error permissible, are basically consistent with the simulation results.
5.3 Multi layers printing experiment

After verifying the stability of the shearing system, the experiment of multilayer printing based on single layer forming foundation is carried out to find out whether the system can complete the forming of complex parts, which lays a theoretical foundation for the industrialization of continuous carbon fiber 3D printing. The height $\delta$ of each layer is an important parameter in the multi-layer forming process of the model. It not only determines the number of layers of the model, but also has an important influence on the forming quality. Through theoretical reasoning and experimental correction, the value of the height delta is determined to be 0.25mm.

The model used in the experiment as is shown in Fig. 13 is a wrench built on the basis of physical objects, and then reduced in proportion as a verification part. The number of printed layers is 10, and the thickness of the final model is 2.59mm as is shown in Fig. 14, which conform to the theoretical value within the allowable range of error.

![Figure 13](image1.png)

(a) Wrench model  (b) 3D printing part

Fig. 13 Multi layer printing experiment

![Figure 14](image2.png)

Fig. 14 Thickness of part

This model is a complex single component model, which can reduce or eliminate intra layer jump by path optimization. In the processed path, there is inter layer jump but no intra layer jump. In the experiment, the shearing device can accurately cut off the composite in the identified position and the nozzle jumps to the initial contour of the next layer.

5.4 Analysis of shearing error

The consistency between the experimental results and the simulation shows the feasibility and stability of the shearing algorithm and the device. However, there are errors between the printed path and the ideal path. Error analysis is of great significance to improve the accuracy of continuous carbon fiber 3D printing. Shearing error is caused by shearing off the carbon fiber when dealing with discontinuous paths. According to the source of error, it is classified as algorithm error and device error.
5.4.1 Algorithm error

The essence of the shearing algorithm is to find the shearing position through jump position. Its calculation method uses precise value operation, so the shearing algorithm itself will not produce errors. There are two sources of algorithm errors:

1. **Interpolation fitting:** When dealing with curve path, slicing software divides the curve into several small straight line segments. In the process of finding the shearing position according to the jump position, the length of the curve is simulated by the way of accumulating the distance of the straight line, which will cause minor errors. However, in the printing process, the movement of the nozzle is still printed by several linear interpolation instead of curves. This part of the error can be neglected.

2. **Parameter error:** The parameter $l$ in the algorithm is an important basis for finding the shearing position. Its theoretical value is the actual distance from the shearing position to the tip of the nozzle. The real value comes from the actual measurement. Measurement error is difficult to avoid.

5.4.2 Device error

The carbon fiber composite is sheared off before it is fed into the nozzle and melts. After the continuous carbon fibers are sheared off, the nozzle will continue to move forward from the shearing position to the jump position. Ideally, the length of residual carbon fibers in the nozzle is $l$, which is equal to the path length between the shearing position and the jump position, as shown in Fig. 15. As the nozzle moves, the residual carbon fibers should be pulled out vertically along the guide pipe in the nozzle and bonded tightly to the worktable.

Generally, in order to ensure the smooth extrusion of carbon fibers and the melted resin from the nozzle without blocking, the diameter of the guide pipe in the nozzle is larger than it of the carbon fibre composite. Therefore, in the printing process, the carbon fibers in the nozzle will not be in a vertical state. Moreover, due to the gap between the nozzle and the worktable, the carbon fiber will have a certain angle with the worktable under the influence of the pull force generated by the movement of the nozzle, as shown in Fig. 16. In this case, after shearing, the residual carbon fiber length in the nozzle is longer than the print path length.
Then we printed a set of simple patterns under the original parameter settings, as shown in Fig. 17. The results show that the starting point and the ending point of each pattern do not coincide completely. After the nozzle moves to the jump position, there will be surplus carbon fibers. Then the carbon fibers at the end warped up as the nozzle jumped.

![Fig. 17 Experiment based on original parameters](image1)

In order to obtain the surplus range, the same model was printed several times, and the measured residual was within 0.6mm-1.3mm. According to the distribution characteristics of the measured datas, the parameter $l$ of the shearing algorithm is compensated. Then print tests with the same model are performed, and the results are shown in Fig. 18. After compensating the parameters of the shearing algorithm, the starting point of the patterns is basically the same as the end point, and the surplus of carbon fibers is obviously reduced.

![Fig. 18 Experiment after parameter compensation](image2)

6. Conclusion

Continuous carbon fiber 3D printing technology has important application value in the industrial field. The preparation of CFRP from carbon fiber and thermoplastic resin can be well applied to 3D molding based on FDM. Because of the continuity of fiber, the complex model can not be formed under the condition that only a single component of continuous path can be printed. In order to solve this problem, a shearing device is designed to make the nozzle jump freely without affecting the quality of the molding, and complete the printing of the discontinuous path, which is of great significance to the industrialization application of continuous carbon fiber 3D printing. The following are the specific work done: (1) The front-end shearing algorithm is proposed, which can accurately position the shearing point by jumping point recognition. (2) The combined assembly structure of shearing device and nozzle structure for 3D printer is designed, which can minimize the shearing interval. (3) Based on the continuity of fibers, an intermittent feeding method is proposed, which works cooperatively with the shearing device and greatly improves the printing quality. (4) The carbon fiber printing equipment was carried out for single layer and multi layer molding experiments, which provided a theoretical basis for the rapid and high quality molding of continuous carbon fiber 3D printing. Through analysis and experiment, the parameters of shearing algorithm are compensated.
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