Integration 3D printing of bionic continuous carbon fiber reinforced resin composite

Qian Zhao, Chang Liu, Yunhong Liang, Zhaohua Lin, Zhiwu Han and Lei Ren
The Key Laboratory of Bionic Engineering, Ministry of Education, Jilin University, Changchun 130025, People’s Republic of China
E-mail: linzhaohua@jlu.edu.cn

Keywords: bionic design, integration 3D printing, continuous carbon fiber, mechanical strength, layered spiral structure

Abstract
Inspired by microstructure characteristics of mantis shrimp propodus with high mechanical strength, the bionic continuous carbon fiber (CF) reinforced acrylonitrile butadiene styrene (ABS) resin composite with layered spiral structure was prepared successfully via self-built integration 3D printing. Combined with integration 3D printing demands of continuous carbon fiber reinforced ABS resin, bionic structure model was divided into 10 layers with cylindrical entities which spiralled from 0° to 45°. The 3D printed continuous carbon fibers realized designed specific arrangement direction in ABS matrix, which reappeared the layered spiral structure of mantis shrimp propodus. The existence of bionic layered spiral structure led to the higher tensile strength and impact toughness of bionic composite than that of ABS matrix and ABS/CF composite with unidirectional continuous carbon fiber arrangement via the mechanisms of fracture and pull-out of continuous carbon fibers. The high mechanical properties of integration 3D printed bionic composite proved the effectiveness and feasibility of 3D printing method and bionic layered spiral structure design, which extended the preparation method and application fields of carbon fiber reinforced thermoplastic resin composite in engineering materials.

1. Introduction
Carbon fiber reinforced thermoplastic resin composite combined the tensile and fatigue resistance properties of carbon fiber and mechanical and recoverable properties of thermoplastic resin, which has been treated as high strength engineering material in aerospace, artificial limb and so on [1–3]. Mechanical strength is the important application base of carbon fiber reinforced thermoplastic resin composite. In the categories of carbon fiber, short carbon fiber exhibits extensive application on the base of preparation convenience [4–6]. But, the relatively low isotonicity of carbon fiber in resin matrix restricts the improvement of corresponding mechanical properties of composites. Compared with the short carbon fiber, the continuous carbon fiber owns the property to enhance the holistic mechanical strength of composite via controlling carbon fiber distribution direction. Therefore, the adoption of continuous carbon fiber becomes an important research direction of carbon fiber reinforced thermoplastic resin composites [7, 8]. In the categories of thermoplastic resins, acrylonitrile butadiene styrene (ABS) owns steady corrosion and wear resistance and high impact resistance, which has been used in fields of automobile, aerospace and so on [9–11]. Compared with the carbon fiber reinforced thermosetting resin composite, the carbon fiber reinforced thermoplastic resin composite exhibits relatively high fracture toughness, creep resistance and recoverable property. Therefore, the combination of the continuous carbon fiber and ABS thermoplastic resin composite extends the improvement selection of corresponding mechanical strength [12, 13].

In the preparation methods of continuous carbon fiber reinforced ABS thermoplastic resin composite, molding method owns high operability. But, the relatively low molding precision and complicated preparation process increase the application difficulty. Moreover, compared with the short carbon fiber, the location stability of continuous carbon fiber in thermoplastic resin matrix enhanced the mechanical strength stability of
composite, which highlights the preparation method applicability of continuous carbon fiber reinforced thermoplastic resin composite. Facing effect of preparation method on application of continuous carbon fiber reinforced thermoplastic resin composite, the characteristics of high molding precision and preparation efficiency of 3D printing technology provides a kind of effective preparation selection \[14, 15\]. Moreover, considering physicochemical property of ABS, 3D printing of the fused deposition modelling (FDM) can realize the corresponding complicated molding of ABS. Combined with the length advantage of continuous carbon fiber, the integration FDM 3D printing of thermoplastic resin and continuous carbon fiber can effectively extend the corresponding application of composites from the point view of preparation method \[16, 17\]. Besides the advantages of 3D printing of continuous carbon fiber reinforced ABS composite, the disadvantages of relatively low mechanical strength resulted from printed structure and bonding strength restrict the extensive application. Even though many methods including liquid-phase oxidation \[18\] of carbon fiber and improvement of 3D printing machine effectively enhanced mechanical property of 3D printing of continuous carbon fiber reinforced ABS composite, but the enhancement of mechanical strength can be investigated further.

With the development of bionics, advantages of biological materials provided excellent structure and function models for preparation of composites. Mantis shrimp is a kind of typical ambush predatory marine crustaceans with speedy and efficient predation equipment of spearer \[19\]. Inspired by the mechanical strength resulted from layered spiral structure of mantis shrimp propodus in our previous study \[20\], a serious kind of bionic composites with high mechanical strength were prepared via 3D printing \[21, 22\], which proved the feasibility of bionic design of mantis shrimp propodus and adaptability between bionic design and 3D printing. Considering mechanical strength improvement of continuous carbon fiber reinforced ABS composite, the bionic model of mantis shrimp propodus provides a new effective solution.

In this paper, inspired by effect of microstructure characteristic of mantis shrimp propodus on mechanical strength, the bionic integrated continuous carbon fiber reinforced ABS composites were prepared via self-built 3D printing. Based on microstructure of bionic model, the 3D printing path was designed and used for preparation of bionic composites. Besides investigation of mechanical strength of bionic composite, the corresponding enhancement mechanisms were also disclosed.

2. Materials & methods

2.1. Materials
ABS resin which was used for FDM 3D printing was purchased from Sanweicube Co., Ltd, China. Continuous carbon fiber with specification of 1 K (consisted of one thousand monoradicular continuous carbon fiber) was purchased from Yixing Siweiqi Carbon Fiber Products Co., Ltd, China. ABS and continuous carbon fiber were used as received. The fresh mantis shrimps were purchased from the aquatic product market of Changchun, China. After removing from noumenon, the spearer propodus of mantis shrimp was washed and dried at room temperature for 3 days.

2.2. Preparation of bionic composite
3D printing of bionic continuous carbon fiber reinforced ABS resin composite was prepared via the self-built 3D printing machine. Figure 1 shows the proximal extrusion structure and preparation mechanism. The proximal extrusion structure was composed of extruder, heating head and subuliform nozzle with diameter of 0.8 mm. ABS resin was squeezed into the heating head with temperature of 240 °C via the driving gears. After squeezing into heating head, the continuous carbon fiber was wrapped by ABS resin. Under the sequential squeeze of ABS
resin, the continuous carbon fiber wrapped ABS resin was extruded to the printing platform. The printing precision was 0.1 mm. The mass fraction of continuous carbon fiber in ABS matrix was about 10 wt.%. The sample structure was designed by SolidWorks. The corresponding STL file was used for 3D printing of composites. After slicing via the Slic3r software offered by Alessandro Ranellucci, the G code file was obtained. Attributed to the specific structure design of bionic composites, the G code file was self-written. The software of Repetier-Host was used to preview and modified G code files. In order to prove the validities of bionic structure design and role of continuous carbon fiber, the bionic composite, the ABS/CF composite with paralleled continuous carbon fiber arrangement and pure ABS matrix were prepared, respectively.

2.3. Characterization of bionic composite
2.3.1. Microstructure
In order to build the bionic structure model, microstructure of spearer propodus were analysed by a scanning electron microscope (SEM; Model Evo18 Carl Zeiss, Oberkochen, Germany). The arrangement direction of continuous carbon fiber in ABS resin matrix was also observed by SEM to disclose the feasibility of integration 3D printing of reinforcement and matrix of composite.

2.3.2. Tensile strength
The tensile strength sample with dimension of 75 mm × 10 mm × 2 mm (length × width × thickness) was 3D printed directly. The stress and strain were calculated by the following equations.

\[
\sigma = \frac{F}{A},
\]

\[
\varepsilon = \frac{1 - l_0}{l_0}.
\]

where \(\sigma\) and \(\varepsilon\) represented stress and strain, respectively. \(F\) was maximum force. \(A\) was sectional area of sample. \(l\) and \(l_0\) were actual and original length, respectively. The universal mechanical machine (Model C43, MTS Criterion, USA) with constant loading rate was 1 mm min\(^{-1}\) was used. The average value of the stress and strain were obtained from five individual tests. The tensile fracture morphology was observed via SEM to analyse the anti tensile mechanism.

2.3.3. Impact toughness
The impact resistance sample with dimension of 75 mm × 10 mm × 2 mm (length × width × thickness) was obtained directly via 3D printing. The impact toughness was calculated by the following equation.

\[
a = \frac{A}{bh},
\]

where \(a\) represented impact toughness. \(A\) was impact work. \(b\) and \(h\) were width and thickness of sample. \(A\) can be obtained from impact testing machine with pendulum of 7.5 J (Model JC-50D, Beijing Times Peak Technology Co., Ltd, China). The loading span for impact toughness tests was 40 mm. The average value of the impact toughness was obtained from five individual tests. The impact fracture morphology was observed via SEM to analyse the anti impact mechanism.

3. Results and discussion
3.1. Construction of bionic structure model
As shown in figure 2(a), the mantis shrimp propodus was composed of many compact mineralized chitin-protein fibers, which exhibited layered structure and rotated around the normal axis of the spearer propodus [20]. The layered spiral structure played an important role in mechanical strength of spearer propodus. Inspired by the microstructure characteristics of mantis shrimp propodus, the bionic layered spiral structure which was used for bionic composite design was constructed, as shown in figure 2(b). The bionic structure model was divided into 10 layers, which consisted of many cylindrical entities in specific layers. With the increase of height, the layers constituted of cylindrical entities spiralled from 0° to 45°, forming the bionic layered spiral structure. The bionic structure model reappeared the microstructure characteristics of mantis shrimp propodus, providing structure design reference for bionic continuous carbon fiber reinforced ABS resin composite. Based on 3D printing technology demands, the designed 3D printing bionic composite model with layered spiral structure was exhibited in figure 2(c). The 3D printing structure model realized the application of bionic structure model in sample structure design, which guided the 3D preparation of bionic composite.
3.2. Microstructure of bionic composite

According to bionic structure model with layered spiral structure, the bionic continuous carbon fiber reinforced ABS resin composite was successfully 3D printed, as shown in figure 3(a). The morphology of bionic composite in figure 3(a) exhibited the 45° arrangement direction of continuous carbon fiber, which was similar to bionic structure model in figure 2(b). The continuous carbon fiber in ABS/CF composite was parallel to the length direction of sample. The ABS/CF composite and pure ABS matrix were used to disclose the effectiveness of bionic design. Compared with the ABS/CF composite, the bionic composite realized the bionic arrangement of continuous carbon fiber in ABS matrix, as shown in figure 3(b). The continuous carbon fiber with fascicled state exhibited specific arrangement direction and coated with ABS matrix. Besides effectiveness arrangement direction, the excellent bonding state between continuous carbon fiber and ABS matrix proved the feasibility of 3D printing and bionic layered spiral structure, which built material base of mechanical strength test.

3.3. Mechanical properties of bionic composite

In order to investigate the effect of bionic layered spiral structure, mechanical properties including tensile strength and impact toughness of bionic composite, ABS/CF composite and pure ABS matrix were conducted, as shown in figure 4. The stress values of ABS matrix, ABS/CF composite and bionic composite were 30.15 MPa, 28.98 MPa and 31.99 MPa, respectively. The strain values of ABS matrix, ABS/CF composite and bionic composite were 25.24%, 18.67% and 18.59%, respectively. Compared with ABS matrix, the continuous carbon fiber without surface treatment resulted in the decreased stress of ABS/CF composite. The reinforcing role of continuous carbon fiber was restricted in the ABS/CF composite. But, under same material and preparation method, the existence of bionic layered spiral structure led to the higher stress of bionic composite than that of ABS matrix and ABS/CF composite. Attributed to the existence of continuous carbon fiber, the strain values of ABS/CF composite and bionic composite were reduced. Under the reinforcing role of arrangement direction of continuous carbon fiber in ABS/CF composite, the impact toughness was higher than that of ABS matrix. The
existence of bionic arrangement of continuous carbon fiber led to the highest impact toughness, as shown in figure 4(b). The mechanical properties in figure 4 exhibited the effectiveness of bionic layered spiral structure. Moreover, the integration 3D printing of continuous carbon fiber and ABS matrix provided an efficient and feasible preparation method for the realization of bionic design.

3.4. Mechanical mechanisms of bionic composite
The bionic composite owned relatively high mechanical strength, building application base for engineering materials. In order to disclose the mechanical mechanisms of bionic composite, the tensile fracture surface and impact fracture surface were observed. As shown in figure 5(a), many continuous carbon fiber and holes resulted from pull-out of carbon fibers existed on the rough tensile fracture surface. From the magnification of tensile fracture surface in figure 5(b), it can be found that the continuous fascicled carbon fibers were tensile failure and were exposed to ABS matrix surface. The residual ABS resin on continuous carbon fiber indicated the relatively high bonding strength between ABS resin and reinforcement. Moreover, the interlaced continuous carbon fiber layer arrangement was similar to the microstructure characteristic of mantis shrimp propodus, reappearing the bionic layered spiral structure characteristics. Figure 5(c) exhibited the mechanical mechanisms including fracture and pull-out of continuous carbon fibers in bionic composite for enhancing tensile strength. Compared with the tensile fracture surface, the impact fracture surface also exhibited rough morphology and fractured continuous carbon fibers in figure 5(d). But, the length of continuous carbon fibers which exposed on impact fracture surface was lower than that on tensile fracture surface. In the magnification of impact fracture surface, ABS resin also existed on the pull-out continuous carbon fibers, which indicated the relatively high bonding strength between matrix and reinforcement. Different fascicled continuous carbon fibers intersected on impact fracture surface, exhibiting the effective arrangement of bionic structure. The fracture and pull-out of continuous carbon fibers in bionic composite were also the main mechanical mechanisms of bionic composites.
Based on analysis of tensile and impact fracture surface, bionic composite exhibited relatively high mechanical strength via the mechanisms of fracture and pull-out of continuous carbon fibers. The bionic layered spiral structure enhanced the mechanical strength of bionic composite and maintained the reinforcing properties of continuous carbon fibers in ABS resin matrix. Inspired by structure characteristics of bionic model with high mechanical properties. Integration 3D printing of ABS resin and continuous carbon fiber provided an effective new preparation method for application of carbon fiber reinforced thermoplastic resin composite.

4. Conclusion

Inspired by the effect of microstructure characteristics of mantis shrimp propodus on the high mechanical strength, the bionic layered spiral structure of mantis shrimp propodus was treated as bionic design model for integration 3D printing of continuous carbon fiber reinforced ABS resin composite. The corresponding conclusions were listed as follows:

(1) The mantis shrimp propodus was characterized by layered spiral structure, which was treated as bionic model and built structure base for high mechanical strength. Based on layered spiral structure of mantis shrimp propodus and technology demands of 3D printing, the designed bionic structure model was divided into 10 layers which constituted of cylindrical entities spiralled from $0^\circ$ to $45^\circ$ with the increase of height of layers. The bionic layered spiral structure model reappeared the characteristics of bionic model and used for bionic composite preparation.

(2) The integration 3D printing of continuous carbon fiber and ABS resin was realized via the self-built 3D printing machine. The fascicled continuous carbon fiber exhibited designed specific arrangement direction and coated tightly with ABS matrix. The bionic composite realized the characteristics of bionic model, which proved the feasibility of 3D printing and bionic layered spiral structure.

(3) The 3D printing bionic continuous carbon fiber reinforced ABS resin composite exhibited high mechanical properties. The existence of bionic layered spiral structure led to the higher tensile strength and impact toughness of bionic composite than that of ABS matrix and ABS/CF composite via the mechanisms of fracture and pull-out of continuous carbon fibers. The bionic layered spiral structure enhanced the mechanical strength of bionic composite and maintained the reinforcing properties of continuous carbon fibers in ABS resin matrix, which provided new design and preparation method for application of carbon fiber reinforced thermoplastic resin composite.

Acknowledgments

The authors also wish to thank the reviewers and editor for kindly giving revising suggestions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Project of National Key Research and Development Program of China (2018YFA0703300, 2018YFB1105100, and 2018YFC2001300), the National Natural Science Foundation of China (51822504, 91948302, 91848204 and 52021003), Key Scientific and Techno-logical Project of Jilin Province (20180201051GX), Program for JLU Science and Technology Innovative Research Team (2017TD-04) and China Postdoctoral Science Foundation (2020M670845).
References

[1] Hernandez T P A, Mills A R and Nezhad H Y 2021 Shear driven deformation and damage mechanisms in high-performance carbon fibre-reinforced thermoplastic and toughened thermostet composites subjected to high strain loading Compos. Struct. 261 113289–97

[2] Lin M C, Lin J H and Bao L 2020 Applying TPU blends and composite carbon fibers to flexible electromagnetic-shielding fabrics: long-fiber-reinforced thermoplastics technique Compos Part A-App 138 106022–31

[3] Wang P, Zou B, Ding S L, Huang C Z, Shi Z Y, Ma Y S and Yao P 2020 Preparation of short CF/GF reinforced PEEK composite filaments and their comprehensive properties evaluation for FDM-3D printing Compos. Part B-Eng. 198 108175–87

[4] Nie H J, Xu Z, Tang B L, Deng C Y, Yang Y R, Zeng X L, Lin B C and Shen X J 2021 The effect of graphene oxide modified short carbon fiber on the interlaminar shear strength of carbon fiber fabric/epoxy composites J. Mater. Sci. 56 688–96

[5] Zhan Y X, Wang Y T, Wang M, Ding X Q and Wang X L 2020 Improving the curing and mechanical properties of short carbon fibers/epoxy composites by grafting nano ZIF-8 on fibers Adv. Mater. Interfaces 7 1901490–500

[6] Capela C, Oliveira S E and Ferreira J A M 2019 Fatigue behavior of short carbon fiber reinforced epoxy composites Compos. Part B-Eng. 164 191–7

[7] Obande W, Brádaigh C M Ó and Ray D 2021 Continuous fibre-reinforced thermoplastic acrylic-matrix composites prepared by liquid resin infusion-a review Compos. Part B-Eng. 213 108771–97

[8] Dong K, Sarmad M P, Cui Z Y, Huang X Y and Xiao X L 2021 Electro-induced shape memory effect of 4D printed auxetic composite using PLA/TPU/CNT filament embedded synergistically with continuous carbon fiber: a theoretical & experimental analysis Compos. Part B-Eng. 220 108994–9005

[9] Mura A, Adamo F, Wang H Z, Leong W S, Li X and Kong J 2019 Investigation about tribological behavior of ABS and PC-ABS polymers coated with graphene Tribol. Int. 134 335–40

[10] Milionis A, Languasco J, Loth E and Bayer I S 2015 Analysis of wear abrasion resistance of superhydrophobic acrylonitrile butadiene styrene rubber (ABS) nanocomposites Chem. Eng. J. 281 730–8

[11] Kumar S and Roy B S 2020 Tribological properties of acrylonitrile butadiene styrene rubber in self-mated contacts and against steel disc Mater. Today 26 2388–94

[12] Li J and Cai C L 2011 The carbon fiber surface treatment and addition of PA6 on tensile properties of ABS composites Curr. Appl. Phys. 11 50–4

[13] Yu N, Sun X Y, Wang Z, Zhang D J and Li J 2020 Effects of auxiliary heat on warpage and mechanical properties in carbon fiber/ABS composite manufactured by fused deposition modeling Mater. Design. 195 108978–86

[14] Luan C C, Yao X H, Zhang C, Fu J Z and Wang B 2020 Integrated self-monitoring and self-healing continuous carbon fiber reinforced thermoplastic structures using dual-material three-dimensional printing technology Compos. Sci. Tech. 188 107866–94

[15] Zhang H Q, Chen J Y and Yang D M 2021 Fibre misalignment and breakage in 3D printing of continuous carbon fibre reinforced thermoplastic composites Addit. Manuf. 38 101775–88

[16] Li N Y, Li Y G and Liu S T 2016 Rapid prototyping of continuous carbon fiber reinforced polyactic acid composites by 3D printing J. Mater. Process. Tech. 238 218–23

[17] Rarani M H, Afrani M R and Zahedi A M 2019 Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites Compos. Part B-Eng. 175 107147–53

[18] Zhang G X, Sun S H, Yang D Q, Dodelet J P and Sacher E 2008 The surface analytical characterization of carbon fibers functionalized by H2SO4/HNO3 treatment Carbon 46 196–205

[19] deVries M S, Murphy E A K and Patek S N 2012 Strike mechanics of an ambush predator: the spearing mantis shrimp J. Exp. Biol. 215 4374–84

[20] Zhao Q, Chang Y J, Lin Z H, Zhang Z H, Han Z W and Ren L Q 2021 Microstructure and in situ tensile strength of propodus of mantis shrimp Microsc. Res. Techniq. 84 415–21

[21] Ribbans B, Li Y J and Tan T 2016 A bioinspired study on the interlaminar shear resistance of helicoidal fiber structures J. Mech. Behav. Biomater. 56 57–67

[22] Sukaonpanya N, Yaraghi N A, Pipes R B, Kiszlig D and Zavattieri P 2018 Crack twisting and toughening strategies in bouligand architectures Int. J. Solids Struct. 150 83–106