Structural optimization of connectors based on 3D printing modified polyester composites

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ABSTRACT

The function of the connector on the mountain bike is to connect the two sides to ensure the stability in the driving process, but wear often occurs in daily use. First of all, this paper carries on the lightweight treatment to the bicycle connector, after the topology optimization, has realized the weight reduction 54%. Then carbon fiber modified polyester composites were used to improve the materials. The optimum aspect ratio of carbon fiber and the proportion of carbon fiber were determined through a series of experiments, and then its mechanical properties, thermophysical properties and friction properties were analyzed. Conclusion it is proved that the material has the advantages of light weight, good thermophysical properties and strong mechanical properties compared with steel structure. The connectors of different materials are explored by finite element analysis. Through the finite element analysis and comparison of the stress of different materials, the strength of carbon fiber modified polyester composite is obviously higher than that of medium carbon steel, the deformation of carbon fiber modified polyester composite is less than that of medium carbon steel, the service life of the connector is increased, and the safety hidden danger in the process of riding is reduced.

Keywords: 3D printing, mountain bike connectors, finite element analysis, composite materials, processing methods

1. INTRODUCTION

The mountain bike connector is a part located on both sides of the tire, which plays a connecting role and is an important part of the bike. In the process of use, the connector will be damaged due to bumps, impact, friction and other factors. When the connector is damaged, it will cause the danger of vehicle falling apart, reduce the maneuverability, and pose a threat to the safety of drivers. The material of mountain bike connector is generally medium carbon steel. in order to prevent cracks or local brittleness in the welding part, it is preheated to 200 ℃-250 ℃ before welding, and then cooled slowly in hot sand or asbestos powder. The picture of the connector is shown in Fig. 1.

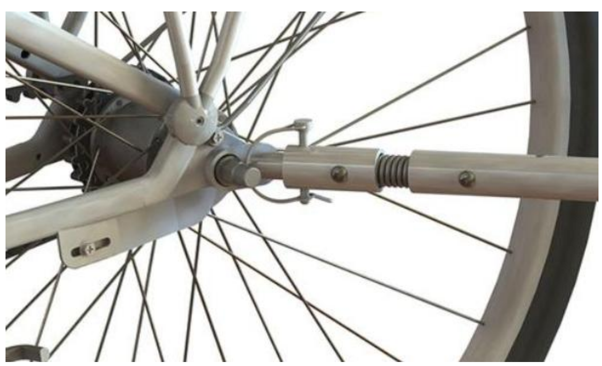

Figure 1. Mountain bike connector.

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In order to reduce the probability of damage to the connector, it is necessary to improve it with materials with better strength and wear resistance. Compared with the traditional composite process, the technological process of 3D printing technology is simpler, the utilization rate of materials is higher, and the manufacturing cost is lower [1]. Compared with forging and other methods, 3D printing can realize the integrated forming of continuous fiber reinforced complex materials without die.

At present, there has been a lot of research on the reinforcement of composite materials. Meng et al studied the tensile behavior of SiCf/TC11 composites [2] and tested that the tensile strength of SiCf/TC11 composites is 133% higher than that of TC11 titanium alloys. Ding et al studied Effect of carbon fiber preform structures on the mechanical properties of Cf@PyC/SiC composites [3]. The results show that the composites have better mechanical properties. Huang et al carried out low-speed impact on epoxy resin / glass fiber / carbon fiber hybrid composite board [4], and examined its damage, which proved that the toughness of glass fiber was higher than that of other composites; Wang S et al studied the modification of mechanical properties of composites by Ti/Ta material [5], and pointed out that the mechanical properties can be adjusted by adjusting the thickness ratio between Ti and Ta.

These materials are applied to a variety of specific objects. For example, Dudzik Krzysztof applies Gfrp composites to marine and aviation structures [6], and detects its safety load range; Wu et al use glass fiber reinforced materials to improve the fan blade [7] to improve the power generation efficiency of the fan; Alanazi Ahmed T et al apply the hybrid composites of conductive polymer and plasma nanomaterials to catalysis and sensing [8], proving that the materials have good catalytic and sensing efficiency. However, in the connectors and other important parts, these composite materials are not used, and the traditional steel structure is still used for parts processing. Connectors need to achieve the goal of lightweight on the basis of meeting the functional requirements. In this paper, firstly, the topology of the parts is optimized to reduce the weight of the parts. Because the material of the connector requires wear resistance, impact resistance and high strength, carbon fiber modified composites with higher strength are used in this paper. By comparing this material with other composite materials and medium carbon steel, the service life of the connector is improved, thus the handling performance is improved.

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2. OPTIMAL DESIGN OF MOUNTAIN BICYCLE CONNECTOR

2.1 Part properti

The mountain bike connector is located at the back of the bike to play a connecting role. The model diagram of the connector is shown in Fig. 2.

Figure 2. Connector model diagram.

As can be seen from the model diagram, the whole of the connector part is not complex. The traditional casting method has many labor departments and long working hours, but the method of integral forming the parts by 3D printing can ensure the accuracy of the parts and reduce the difficulty of operation at the same time. In order to increase the strength, ribs are set in the middle of the parts.

2.2 Lightweight optimization design of parts

In order to get lighter parts, reduce the weight of parts, so that the rider has a better cycling experience. First of all, this paper lightens the weight of the part, taking the main part of the part as the design space and the other through holes as the non-design space. Then the shape control of extrusion is added to the parts, and the lightweight parts are obtained through software analysis. Then the results are fitted automatically, and after the fitting operation, the results are adjusted manually. The final design result is shown in Fig. 3.

Figure 3. Lightweight design result

Through lightweight design, the connecting structure of mountain bike has been reduced by 54%. Through the software fitting analysis, compared with the original parts, the strength has not decreased. The maximum mises equivalent stress is 10.91 MPa, the maximum displacement 0.7021mm and the minimum safety factor 4.1, which can meet the actual strength requirements. And the lightweight parts have the advantage of reducing consumables in 3D printing.

2.3 Compound material

In order to obtain materials with higher strength and ensure the integration and efficiency of molding, carbon fiber is used to composite polyester in this paper. The melt deposition molding technology is to melt the material at high temperature, then extrude it through the nozzle, and then print the extruded wire in a layer-by-layer stack [9]. Carbon fiber is mainly composed of carbon elements, and the carbon content is generally more than 90%. The strength and wear resistance of the material can be increased by compounding with the matrix. Thermoplastic materials are widely used in 3D printing, but the shear strength between the two layers of wire is low. The printed parts are prone to shear deformation, and after adding carbon fiber reinforcement, a connecting layer can be formed between the layers, thus enhancing the strength of the printed parts [10]. In this paper, polyethylene terephthalate is used as polyester substrate, and the finished silk can be obtained by blending after adding compatibilizer and toughening agent.

2.4 Compound mode

The reinforced modification of polyester generally includes chemical modification and physical modification. Chemical modification is to change the molecular chain segment through a series of methods to make up for its defects, and physical modification is to add stabilizers and other materials to increase its stability [11]. The composite material used in this paper is polyethylene terephthalate. After adding 4 compatibilizer, 15 toughening agent is added. The toughening agent is based on the mass: EBA:AX8900=100:15:4. In order to determine the best carbon fiber content, the addition amount of carbon fiber was added to the same substrate according to 5, 10 and 15 respectively.

After adding raw materials, the added materials are mixed and compounded by twin-screw, and then the composite wires can be formed by single-screw extrusion. The wire was put in the drying oven and the temperature was set to 55 ℃. After drying for 4 hours, the wire with diameter of 1.75mm was obtained.

2.5 Material strength analysis

2.5.1 Effect of carbon fiber length on mechanical properties of composites

The material silk is printed with the printing nozzle of 0.4mm to print the bending spline. in order to determine the carbon fiber of different length to modify the polyester material, this paper uses three kinds of carbon fiber material whose length increases sequentially, and their aspect ratio is 5, 13 and 18 respectively. First of all, the effect of carbon fiber length on the mechanical properties of materials was analyzed, and when the addition of carbon fiber was 5, it was consistent with polyester. The tensile strength, bending strength and notched impact strength are compared [12]. The results are shown in Table 1:

Table 1. Effect of carbon fiber length on mechanical properties of composites.

Types of carbon fiber	**Tensile strength (MPa)**	**Bending strength (MPa)**	**Notched impact strength (kJ/m^2)**
Polyester control group	25.82	46.34	8.23
a	27.84	42.84	5.34
b	26.79	38.41	10.45
c	26.96	47.49	4.12

Through the experiment, it can be found that the tensile strength of all materials is improved to a certain extent after adding carbon fiber. It is proved that the tensile strength can be improved by adding carbon fiber. Among them, the strengthening effect of carbon fiber with an is better, which is 8.02%, while when the aspect ratio of carbon fiber is increased to b, the tensile strength decreases, and when it is increased to c, the tensile strength increases slightly.

In the aspect of bending strength, the bending strength decreased in varying degrees when adding shorter carbon fiber particles, and increased when the ratio of length to diameter was c. According to the material characteristics, it is speculated that the addition of carbon fiber will affect the bonding ability of each printing layer in the printing process, and then lead to the decrease of bending strength. According to the experimental results of impact strength test, it can be seen that when the length of carbon fiber is added, the impact strength of the notch is obviously stronger than that of the control group.

There was a significant decrease in group an and group c. The results show that the aspect ratio has an effect on the mechanical properties of the composites. According to the experiment, the impact strength of group b is the highest, and the impact strength of group an and group c decreases.

2.5.2 Effect of carbon fiber content on mechanical properties of composites

As can be seen from the previous section, the strength test result under group an is the best. In order to further explore the effect of carbon content on mechanical properties, 5, 10 and 15 of carbon fiber were added in case an above, and mechanical tests were carried out. In the process of printing the test sample, the nozzle was blocked in the group with more toner added. In order to reduce caking, the latter two groups were recombined repeatedly, and the unclogged wire was finally obtained.

The results are shown in Table 2:

Table 2. Effect of carbon fiber content on mechanical properties of composites.

Carbon fiber content	**Tensile strength (MPa)**	**Bending strength (MPa)**	**Notched impact strength (kJ/m^2)**
0	25.89	45.24	8.23
5	27.84	42.84	5.34
10	26.29	35.21	5.32
15	21.56	22.49	3.94

As shown in the table, when the content of carbon fiber increases gradually, the tensile strength increases at first, and then decreases. When 5 and 10 of carbon fiber were added, the tensile strength of the material increased to a certain extent, but with the increase of carbon fiber addition, the tensile strength decreased gradually. Until it was increased to 15, the tensile strength decreased to a certain extent compared with that without addition. It shows that the addition of carbon fiber content can promote the increase of tensile strength to a certain extent, but the tensile strength will decrease when the content exceeds a certain threshold. According to the material properties, it is inferred that when the content of carbon fiber increases, the strength decreases due to the uneven local mixing. The uniformity of the wire also affects the result of the print.

In terms of bending strength, with the increase of carbon fiber content, the bending strength of the material gradually decreased, at most by more than 50%. From the analysis of the previous section, it can be seen that with the increase of carbon content, the bonding effect of each layer of the print decreases, resulting in a decrease in bending strength. And delamination occurs when 15 is added, which leads to caking due to excessive fiber content, resulting in structural cavitation, which affects the mechanical properties of the material.

2.5.3 Effect of carbon fiber parameters on tribological properties of composites

As the working environment of mountain bicycle connectors requires better friction properties, it is necessary to analyze the wear resistance of the composites [13]. The friction coefficient can reflect the performance of the material. When carbon fiber modified polyester material is used in friction experiment, different aspect ratio and different carbon content will affect the results. As can be seen from the previous section, it is better to add 5 or 10 copies. In this paper, the effect of aspect ratio on mechanical properties was studied by adding the same carbon content in group an and different carbon fiber content in group a. The experimental results are shown in Table 3.

Table 3. Effect of carbon Fiber parameters on friction Properties of Composites.

Carbon fiber	Carbon fiber content (parts)	Friction coefficient	Wear mark width / mm	Volume wear / cm^3
Control group	0	0.17	8.13	9.32×10^{-3}
a	5	0.22	10.18	1.84×10^{-2}
b	5	0.20	10.03	2.23×10^{-2}
c	5	0.23	9.51	2.01×10^{-2}
a	10	0.19	12.44	3.87×10^{-2}
a	15	0.18	14.38	7.36×10^{-2}

It can be seen from the table that when carbon fibers with different aspect ratios are added, the friction coefficient of the material will increase. From the characteristics of carbon fiber, it can be known that in friction, polyester is softer than carbon fiber and is worn off first. Then the carbon fiber is convex to increase the friction. When the ratio of length to diameter is not high, the bump is not obvious and the adhesion is good, but when the bump increases, the wear rate decreases due to the lubrication of carbon fiber.

When the carbon fiber content is gradually increased, the friction coefficient of the composites increases at first and then decreases. When added to 5, the friction coefficient is the highest, and then the friction coefficient decreases. When the carbon content is low, the adhesion of carbon fiber is more obvious, and the wear resistance of the material is stronger. When the content of carbon fiber powder increases, the coincidence between the composites decreases, which leads to the decrease of friction coefficient.

2.6 3D print composite settings

In this paper, FDM equipment can be used to print the material. Firstly, the printer parameters are set according to the characteristics of the material [14]. Set the initial printing temperature to 260C and the printing speed to 60mm/s. In the printing process of the connector, the parameters in the slicing process need to be set in order to improve the printing quality of fused deposition. According to the characteristics of the material, in order to prevent the excessive size of carbon fiber particles from blocking the nozzle, it is necessary to repeatedly composite the material to obtain more uniform composites. Setting the slice thickness to 0.2mm, the wall thickness to 2.4mm, and the filling rate 75% can reduce the printing time and reduce the material consumption at the same time. Because the structure of the connector is not complex, the support angle is set to 55 °and the support density is set to 15%. After printing, the real object of the carbon fiber modified polyester composite connector is obtained.

3. STRUCTURE AND STRENGTH ANALYSIS

3.1 Fatigue life analysis of connectors

In order to compare the actual fatigue life of the connector with that of the improved material, the simulation software is used to add load to the connector, and then the stress equation time is derived.

$$\sigma_i(t) = \sigma_i F_p(t) \quad (1)$$

In the formula: σ_i (t) is the stress time equation of the connector, σ_i is the net stress of the connector, and $F_p(t)$ is the time experienced by the force on the connector. According to the calculation, the maximum stress of the joint is 121MPa, which is less than the yield strength of the material, and then the profit fatigue analysis theory is used to analyze the fatigue life of the joint. Use the power function formula to express the curved stress cycle curve:

$$\sigma^m N = C \quad (2)$$

In the formula, σ is the amplitude of stress and N is the number of stress cycles. In the analysis of fatigue life, the curve of the material is generally obtained when the damage rate of the part to be tested is 50%. In order to reduce the large fitting deviation caused by the cyclic load for a long time, the performance of the gearbox becomes worse. In this paper, according to the GL specification, the success standard of the component is set to complete the test when it is higher than 97.7%. The curve is modified by the reduction coefficient on the stress amplitude.

$$\Delta\sigma = \Delta\sigma S_{p_3} \quad (3)$$

According to the calculation, when the reduction coefficient is 0.66, the survival rate of the part is more than 97.7%. Because the steel structure includes casting defects such as cold hardening and cracks, the casting defect coefficient is:

$$S_l = (\frac{t}{25})^{-0.1} \quad (4)$$

In the case of considering the defect coefficient, the corresponding stress amplitude to ensure the high survival rate of the material is as follows:

$$\Delta\sigma^* = 2\Delta\sigma_A \frac{S_{P_u} S_t}{\gamma_m} \quad (5)$$

After the parameters are calculated, the stress curve can be fitted. After bringing the stress amplitude of the work in the fifth and sixth gear into the formula, the stress amplitude and the average stress can be obtained as follows:

$$\sigma_{\mathrm{A}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{L}}}{2} \quad (6)$$

$$\sigma_{\mathrm{M}} = \frac{\sigma_1 + \sigma_1}{2} \quad (7)$$

After the calculation is completed, the fatigue strength safety factor of the connector is calculated:

$$SF_A = \frac{\sigma_e}{\sigma_A} \quad (8)$$

According to the calculation, the minimum safety factor of the connector appears at the fracture of the failed part. The minimum value of steel structure 1.37 is lower than the fatigue safety factor 1.5. After the replacement of carbon fiber modified polyester material, the fatigue safety factor reaches 1.74, which is higher than the design requirements, which can meet the requirements of bicycles in long-term use.

3.2 Analysis of Thermophysical Properties of Composites

As the use of connectors due to the role of friction will generate heat, the material needs to have a certain degree of heat resistance to prevent melting in the process of use to threaten the safety of drivers. The thermal conductivity of carbon fiber modified polyester composites was measured by laser [15]. The test results are shown in Fig. 4:

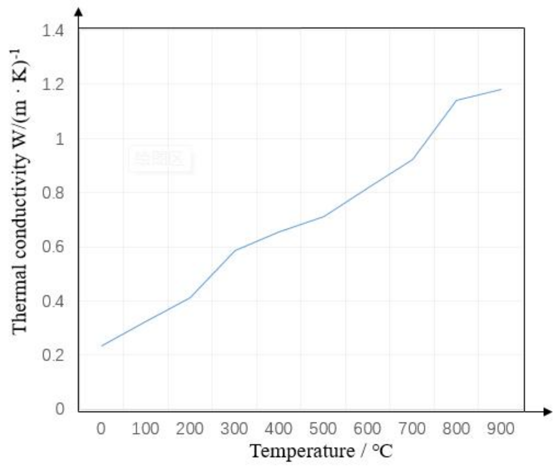


Figure 4. Relationship between thermal conductivity and temperature.

According to the test results, when the temperature is low, the thermal conductivity of the material is between 0.37 and 0.43W/ (MK). When the temperature continues to rise to 800C, the thermal conductivity of the material is less than 1.39W / (MK), which is significantly lower than that of 45W / (MK) of steel. The heat transfer methods of materials generally include solid heat transfer, convection heat transfer and radiation heat transfer. In the process of mountain bike connectors, the temperature of the material will not increase significantly. Therefore, the carbon fiber composite polyester material used in this paper has a great advantage over the traditional steel in terms of thermal conductivity.

Then the coefficient of thermal expansion of the material is tested and inferred from the characteristics of carbon fiber materials. in the case of high temperature, with the increase of temperature, the coefficient of expansion should remain stable, as shown in Fig. 5:

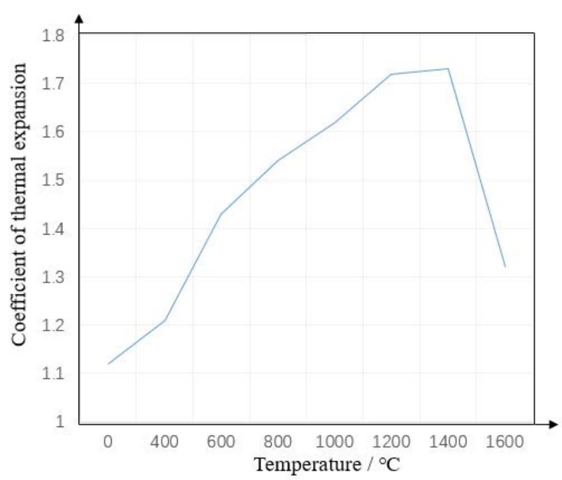


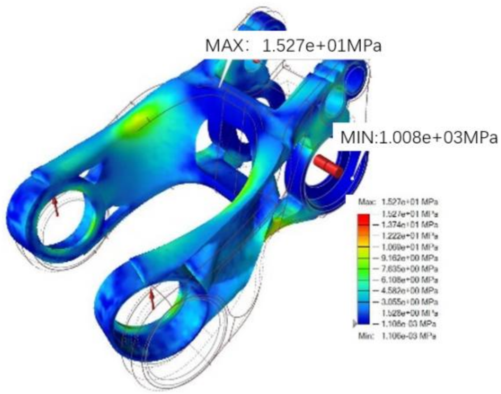
Figure 5. Temperature change curve.

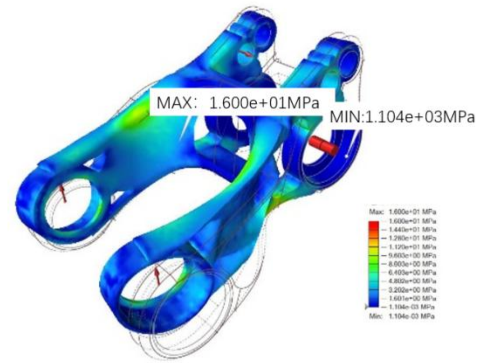
It can be seen from the diagram that the thermal expansion coefficient of the material does not change much with the temperature, and the thermal expansion coefficient of the material increases continuously when the temperature is less than 1000 ℃. When the temperature continues to increase, the coefficient of thermal expansion of the material decreases gradually. It is proved that the material can be stable at high temperature.

3.3 Simulation analysis of mechanical properties

In order to more intuitively reflect the performance of materials, and the differences between traditional steel structure and other materials, this paper compares four kinds of materials: carbon fiber modified polyester material, steel, SiCf/tc11 composite material and glass fiber composite material. In the process of testing, four materials are added to the connector. In the process of using the mountain bike connector, the maximum stress does not exceed 20MPa, but in the actual work, the force of the connector changes from three to two, resulting in a greater actual force. According to the calculation, the actual force of the connector fluctuates between 15 and 30MPa. The fatigue strength of the aluminum alloy used in the connector is 46MPa and the yield strength is 130MPa, and the actual stress does not exceed the risk of yield strength.

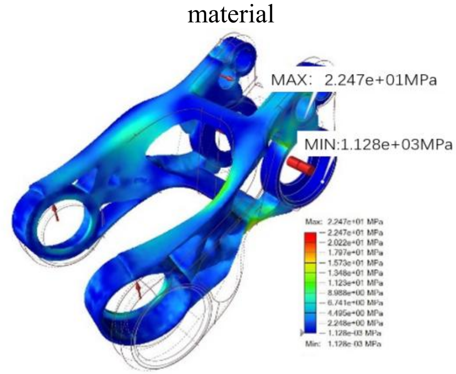
First of all, the model is gridded. In order to ensure the calculation accuracy and speed, we need to see the distribution of the load. In this paper, the average mesh element size is 0.1 as the fraction of the border length, and the minimum element size is 0.2 as the fraction of the average grid size. In order to better carry out the finite element analysis, the axial pressure is applied to the model socket and the rotating shaft is fixed to ensure the relative axial displacement unchanged. The stress distribution is shown in Fig. 6:

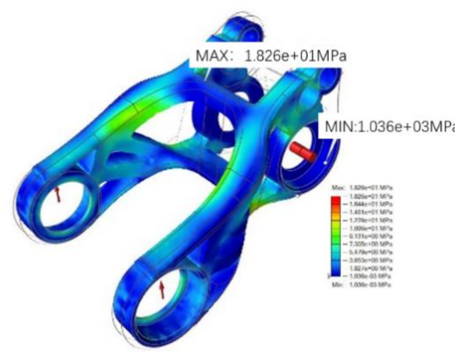




(a) stress 15.27MPa of carbon fiber modified polyester material

(b) stress 16.00MPa of glass fiber composites





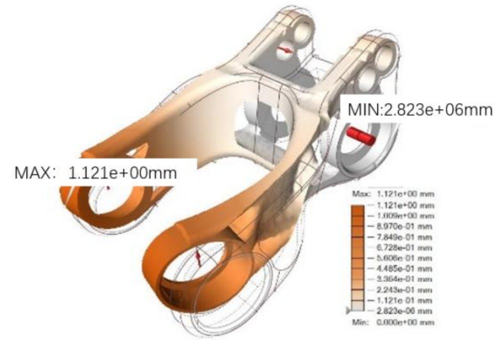
(c) stress 22.47MPa of SiCf/tc11 composites

(d) stress 18.26MPa of medium carbon steel

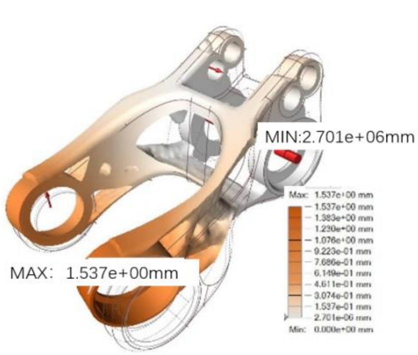
Figure 6. Stress analysis of different materials.

In terms of stress distribution, the stresses of the four materials are all within the standard range, which are the normal loads received by the connectors when they are working. Then the deformation under load is analyzed, and the displacement distribution of each material is shown in Fig. 7:

(a) shift 1.119mm of carbon fiber modified polyester material



(b) displacement 1.121mm of glass fiber composites



(c) SiCf/tc11 composite displacement 1.537mm

(d) displacement 1.263mm of medium carbon steel

Figure 7. Displacement simulation of different materials

As can be seen from the figure, all the four materials have produced a certain degree of displacement. The smallest carbon fiber modified polyester material is 1.119mm, while the largest is 1.537mm of SiCf/tc11 composite. The deformation is too large to be applied to mountain bike parts. According to the simulation results, the improved mountain bike connector using carbon fiber modified polyester composite material has obvious advantages over other materials and can be used in practical production.

4. CONCLUSION

In view of the fact that the medium carbon steel used in the connecting parts of mountain bikes may be damaged by bumps and frictions in practical work. In this paper, a kind of mountain bike connector based on 3D printing carbon fiber modified polyester composite is proposed. the polyester is modified by carbon fiber material to obtain higher strength and wear resistance. In this paper, the composite method of polyester material is verified at first, and then the material with more balanced tensile strength and bending strength is obtained through a series of experiments. Based on the experiments of notched impact and friction properties, it is determined that the optimum content of carbon fiber is 5 and the optimum aspect ratio of carbon fiber is 5.

Then through the calculation of life, it is proved that this material can be applied to practical use.

Then the thermophysical properties and mechanical properties are analyzed. Compared with other materials, it can be seen that the material used in this paper has obvious advantages and is suitable for mountain bike connectors. At the same time, the way of 3D printing can be used to realize integrated molding and reduce the working steps of processing.

And the 3D printing method does not need a mold, which can obviously reduce the difficulty of operation. In this paper, the scientific method is used to test the material, and the feasibility of the method is proved by simulation. The materials and processing methods can also be applied to the processing of other parts or key materials, which has a broad application prospect.

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