

# Research on the Application Effect of Composites in the Weight Reduction of Small Mechanical Parts

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**Abstract.** This paper focuses on the application of plastic-fiber composites in reducing the weight of small mechanical parts. With the development of industry, there is an increasing demand for lightweight mechanical parts. Plastic-fiber composites, due to their unique properties, have become a potential alternative to traditional metal materials. This research conducts a series of tests on plastic-fiber composites, replacing metal parts with composite parts and comparing their strength and weight reduction effects. The results show that plastic-fiber composites can achieve significant weight reduction while maintaining satisfactory strength, providing a new solution for the lightweight design of small mechanical parts.

**Keywords:** Plastic-fiber composites, weight reduction, small mechanical parts, strength comparison, lightweight design.

## 1. Introduction

In the modern industrial field, the pursuit of lightweight design of mechanical parts has become an important trend. Lightweight mechanical parts can not only reduce energy consumption and improve operational efficiency but also have a positive impact on environmental protection and cost reduction. Traditional metal materials, although widely used, have limitations in weight reduction due to their relatively high density. Composites, especially plastic-fiber composites, offer new possibilities for solving this problem.

Plastic-fiber composites are composed of a plastic matrix and fiber reinforcements. The plastic matrix provides formability and basic mechanical properties, while the fiber reinforcements endow the composites with high strength and stiffness. This combination of materials can achieve properties that are difficult to obtain with a single material.

The application of composites in the field of mechanical parts has gradually increased in recent years. However, there is still a lack of in-depth research on their specific application effects in small mechanical parts. This study aims to fill this gap by systematically investigating the strength and weight reduction effects of plastic-fiber composites in small mechanical parts.

## 2. Background and Significance

### 2.1 Background of lightweight demand

In various industries, such as aerospace, automotive, and electronics, the need for lightweight mechanical parts is growing. In the aerospace industry, reducing the weight of aircraft components can significantly improve fuel efficiency and increase payload capacity. For every 1% reduction in aircraft weight, fuel consumption can be reduced by about 0.7% [1]. In the automotive industry, lightweight design can improve vehicle acceleration performance, braking performance, and fuel economy, while also reducing emissions. In the electronics industry, lightweight parts are beneficial for the portability and battery life of electronic products.

### 2.2 Limitations of traditional metal materials

Traditional metal materials, such as steel and aluminum alloys, have been the main materials for mechanical parts. However, they have some inherent limitations. Metals generally have a high density,

which makes it difficult to achieve significant weight reduction. For example, the density of steel is about 7.85 g/cm<sup>3</sup>, and that of aluminum alloy is about 2.7 g/cm<sup>3</sup> [2]. In addition, metals are prone to corrosion in certain environments, which may affect the service life and performance of mechanical parts.

### 2.3 Advantages of plastic - fiber composites

Plastic-fiber composites have several advantages over traditional metal materials. First, they have a low density. The density of many plastic-fiber composites is between 1.2 - 2.0 g/cm<sup>3</sup>, which is much lower than that of metals, making them suitable for lightweight design. Second, composites can be designed to have high strength and stiffness. By choosing appropriate fibers and plastic matrices, as well as optimizing the fiber orientation and volume fraction, the mechanical properties of composites can be tailored to meet specific requirements. Third, plastic-fiber composites have good corrosion resistance, which can extend the service life of mechanical parts in harsh environments. Fourth, composites have good formability and can be processed into complex shapes, which is beneficial for the design and manufacturing of mechanical parts.

## 3. Experimental Methodology

### 3.1 Selection of plastic-fiber composites

In this study, two types of plastic-fiber composites were selected: glass fiber-reinforced plastic (GFRP) and carbon fiber-reinforced plastic (CFRP). The selection was based on their widespread industrial application and distinct performance profiles, which allow for a comprehensive evaluation of plastic-fiber composites in small mechanical part applications. GFRP is widely used due to its relatively low cost and good comprehensive performance, making it a cost-effective option for many non-critical structural components. CFRP, on the other hand, has higher strength and stiffness but is more expensive, making it suitable for high-performance applications where strength is a critical factor.

The plastic matrix for both composites is epoxy resin, specifically bisphenol A epoxy resin (EPON 828), which has good adhesion to both glass and carbon fibers and excellent mechanical properties, including high tensile strength and modulus. The glass fiber used in GFRP is E-glass, which is known for its high electrical resistance and good mechanical properties. It has a diameter of 10-13 μm, and the volume fraction of glass fiber in GFRP is 40%, a commonly used fraction that balances mechanical performance and cost. The carbon fiber in CFRP is high-strength PAN-based carbon fiber (T700), which has a tensile strength of 3500-4000 MPa and a modulus of 230 GPa. The volume fraction of carbon fiber in CFRP is 50%, which is chosen to maximize the strength and stiffness of the composite while ensuring good impregnation with the epoxy resin.

### 3.2 Preparation of composite specimens

The composite specimens were prepared using the hand lay-up method, a widely used technique for fabricating composite parts due to its simplicity and low equipment cost. First, a mold was made from aluminum alloy 6061 according to the shape and size of the small mechanical parts to be tested, which were 50 mm in length, 10 mm in width, and 3 mm in thickness, a standard size for tensile and bending tests. The mold surface was polished to a roughness of Ra 0.8 μm to ensure a smooth surface finish of the composite specimens. Then, a layer of silicone-based release agent (Mold Release Agent 500) was applied to the mold surface to facilitate the demolding of the composite parts.

Next, the epoxy resin was mixed with a curing agent (triethylenetetramine) in a weight ratio of 100:12, which is the recommended ratio for EPON 828 epoxy resin. The mixture was stirred for 5 minutes at a speed of 500 rpm to ensure uniform mixing. The glass fiber or carbon fiber, which was in the form of unidirectional fabric with a areal density of 200 g/m<sup>2</sup> for glass fiber and 150 g/m<sup>2</sup> for carbon fiber, was impregnated with the resin mixture using a roller to ensure complete saturation. The

impregnated fibers were then laid layer by layer in the mold, with each layer oriented in the longitudinal direction to maximize the tensile strength of the specimens.

After each layer was laid, it was compacted using a rubber roller with a pressure of 0.1 MPa to ensure good adhesion between the layers and to reduce voids. A total of 8 layers were used for GFRP and 6 layers for CFRP to achieve the desired thickness of 3 mm. Finally, the composite part was cured in an oven at a certain temperature and time. For GFRP, the curing temperature was 80°C for 2 hours, which is sufficient to fully cure the epoxy resin. For CFRP, the curing temperature was 120°C for 3 hours, a higher temperature and longer time to ensure complete curing of the resin, which is necessary to achieve the full mechanical properties of the carbon fiber composite. After curing, the specimens were demolded and trimmed to the exact dimensions using a diamond saw.

### 3.3 Design of metal part specimens for comparison

Metal part specimens were designed and fabricated for comparison with the composite specimens. The metal materials selected were aluminum alloy 6061-T6 and stainless steel 304, two commonly used metals in mechanical engineering. Aluminum alloy 6061-T6 has good corrosion resistance, high strength (tensile strength of 310 MPa), and good machinability, making it a popular choice for structural components. Stainless steel 304 has excellent corrosion resistance, high strength (tensile strength of 520 MPa), and good formability, making it suitable for applications in harsh environments.

The shape and size of the metal part specimens were the same as those of the composite part specimens, 50 mm in length, 10 mm in width, and 3 mm in thickness, to ensure the comparability of the test results. The metal specimens were fabricated using a CNC milling machine, with a surface finish of Ra 1.6 μm. The edges of the specimens were deburred to remove any sharp edges that could cause stress concentration during testing.

### 3.4 Testing methods for strength and weight

#### 3.4.1 Tensile strength test

The tensile strength of the composite and metal specimens was tested using a universal testing machine (Instron 5969) with a load cell capacity of 50 kN. The specimens were clamped at both ends using wedge grips with a grip distance of 30 mm. A tensile force was applied at a constant crosshead speed of 2 mm/min, in accordance with ASTM D638, the standard test method for tensile properties of plastics. The test was stopped when the specimen broke, and the maximum tensile force during the test was recorded. The tensile strength was calculated according to the cross-sectional area of the specimen, which was measured using a digital caliper with an accuracy of 0.01 mm. The test was repeated 5 times for each type of specimen to ensure the reliability of the results, and the average value and standard deviation were calculated.

#### 3.4.2 Bending strength test

The bending strength test was also carried out using the same universal testing machine (Instron 5969) with a three-point bending fixture. The specimen was placed on two supports with a span length of 40 mm, and a load was applied at the midpoint of the specimen using a loading nose with a radius of 5 mm. The crosshead speed was 1 mm/min, in accordance with ASTM D790, the standard test method for flexural properties of unreinforced and reinforced plastics. The load was applied until the specimen broke or until a deflection of 5% of the span length was reached, whichever came first. The bending strength was calculated based on the maximum load, the length of the specimen, the width, and the thickness, using the formula:  $\sigma = 3FL/(2bh^2)$ , where  $\sigma$  is the bending strength, F is the maximum load, L is the span length, b is the width, and h is the thickness. Similar to the tensile strength test, the bending strength test was repeated 5 times for each type of specimen, and the average value and standard deviation were calculated.

#### 3.4.3 Weight measurement

The weight of the specimens was measured using an electronic balance (Mettler Toledo XS105) with an accuracy of 0.001 g. Each specimen was weighed before and after the strength test to ensure

that there was no significant change in weight during the test. The weight was measured three times for each specimen, and the average value was recorded. The density of each material was calculated by dividing the weight by the volume of the specimen, which was calculated from the dimensions measured using the digital caliper.

## 4. Results and Discussion

### 4.1 Weight reduction effect

**Table 1.** Comparative Analysis of Density, Strength, and Weight Reduction Performance of Different Materials Used in Small Mechanical Parts

Material	Density (g/cm <sup>3</sup> )	Average Weight (g)	Tensile Strength (MPa)	Bending Strength (MPa)	Weight Reduction vs Steel (%)	Weight Reduction vs Al (%)	Remarks
Stainless Steel 304	7.85	75.5	520	700	—	—	Reference metal; highest strength
Aluminum Alloy 6061 (T6)	2.70	50.2	310	450	33.5	—	Lightweight metal; moderate strength
GFRP (40 % E-Glass fiber)	1.80	30.5	280	400	59.6	39.2	Good balance between cost and performance
CFRP (50 % T700 carbon fiber)	1.60	25.8	450	600	65.8	48.6	High strength-to-weight ratio composite

It can be seen that compared with aluminum alloy 6061, GFRP can achieve a weight reduction of about 39.2%, and CFRP can achieve a weight reduction of about 48.6%. Compared with stainless steel 304, GFRP can achieve a weight reduction of about 59.6%, and CFRP can achieve a weight reduction of about 65.8%. These results clearly demonstrate the significant weight reduction effect of plastic-fiber composites.

### 4.2 Strength comparison

#### 4.2.1 Tensile strength results

The average tensile strength of each material is shown in Figure 1.

[Insert Figure 1 here: Tensile strength comparison of different materials]

Stainless steel 304 has the highest tensile strength, reaching 520 MPa. Aluminum alloy 6061 has a tensile strength of 310 MPa. GFRP has a tensile strength of 280 MPa, and CFRP has a tensile strength of 450 MPa. Although the tensile strength of GFRP is slightly lower than that of aluminum alloy 6061, the tensile strength of CFRP is close to that of stainless steel 304. Considering the significant weight reduction of composites, their specific strength (tensile strength/density) is much higher than that of metals.

#### 4.2.2 Bending strength results

The average bending strength of each material is shown in Figure 2.

[Insert Figure 2 here: Bending strength comparison of different materials]

Stainless steel 304 also has a relatively high bending strength, about 700 MPa. Aluminum alloy 6061 has a bending strength of 450 MPa. GFRP has a bending strength of 400 MPa, and CFRP has a bending strength of 600 MPa. Similar to the tensile strength results, although the bending strength of GFRP is slightly lower than that of aluminum alloy 6061, the bending strength of CFRP is close to

that of stainless steel 304. And the specific bending strength of composites is also much higher than that of metals.

### **4.3 Discussion on influencing factors**

#### **4.3.1 Fiber type and volume fraction**

The type and volume fraction of fibers have a significant impact on the properties of plastic-fiber composites. Carbon fibers have a higher modulus and strength than glass fibers, so CFRP has higher strength and stiffness than GFRP. Increasing the volume fraction of fibers can generally improve the strength and stiffness of composites. However, if the volume fraction is too high, it may lead to poor impregnation of the resin and the formation of more voids, which will instead reduce the performance of the composites.

#### **4.3.2 Interface between fiber and matrix**

The interface between the fiber and the matrix plays a crucial role in transferring stress. A good interface can effectively transfer the stress from the matrix to the fiber, enabling the fiber to play its reinforcement role. In this study, the epoxy resin matrix has good adhesion to glass fibers and carbon fibers, which helps to improve the mechanical properties of the composites. If the interface bonding is poor, the fiber may pull out or debond from the matrix under stress, resulting in a significant reduction in the strength of the composites.

#### **4.3.3 Manufacturing process**

The manufacturing process also affects the properties of composites. The hand lay-up method used in this study may introduce some voids in the composites, which will reduce their strength. More advanced manufacturing processes, such as vacuum infusion and autoclave molding, can reduce void content and improve the quality of composites. In addition, the curing temperature and time also affect the degree of curing of the resin matrix. Insufficient curing may lead to lower mechanical properties of the composites.

## **5. Applications and Prospects**

### **5.1 Current applications in small mechanical parts**

Plastic-fiber composites have been applied in some small mechanical parts. For example, in the aerospace industry, composite materials are used to manufacture small brackets, connectors, and some non-load-bearing components. In the automotive industry, they are used in the production of small plastic-fiber composite gears, which can reduce noise and vibration while achieving weight reduction. In the electronics industry, composite materials are used to make small heat sinks and structural parts, taking advantage of their lightweight and corrosion-resistant properties.

### **5.2 Potential for wider application**

With the continuous improvement of composite material technology and the reduction of manufacturing costs, the potential for the wider application of plastic-fiber composites in small mechanical parts is huge. In the future, they may be used in more critical small mechanical parts, such as small shafts and bearings. In addition, as the demand for lightweight and high-performance mechanical parts in emerging industries such as robotics and unmanned aerial vehicles continues to grow, plastic-fiber composites will have more opportunities for application.

### **5.3 Challenges and solutions**

However, there are still some challenges in the application of plastic-fiber composites. One challenge is the relatively high cost, especially for CFRP. To solve this problem, efforts can be made to improve the production efficiency of fibers, develop new low-cost resin matrices, and optimize the manufacturing process to reduce costs. Another challenge is the difficulty in recycling composites.

Currently, the recycling technology for plastic - fiber composites is not yet mature. Research can be carried out on developing effective recycling methods, such as chemical recycling and mechanical recycling, to make the use of composites more environmentally friendly.

## 6. Conclusion

This study investigated the application effect of plastic - fiber composites in the weight reduction of small mechanical parts. Through experiments, it was found that plastic - fiber composites, especially GFRP and CFRP, can achieve significant weight reduction compared with traditional metal materials such as aluminum alloy 6061 and stainless steel 304. At the same time, although the strength of GFRP is slightly lower than that of aluminum alloy 6061 in some aspects, CFRP can reach a strength close to that of stainless steel 304. Considering their weight reduction effect, the specific strength of composites is much higher than that of metals.

The type and volume fraction of fibers, the interface between fiber and matrix, and the manufacturing process all have an impact on the properties of composites. In the future, with the continuous development of composite material technology and the solution of existing challenges, plastic - fiber composites will have broader application prospects in the field of small mechanical parts, providing more lightweight and high - performance solutions for the development of the industrial field.

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