Experimental Study on Preparation and Mechanical Properties of CF Knitted Fabric Composites for Nut Lining

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Abstract. To solve the problem of preparing composite screw nut lining, a preparation method of lining by the CF knitting stretch fabric was discussed. The effects of vacuum treatment and secondary reinforcement of chopped fiber on the mechanical properties of CF woven fabric and knitted fabric composite were studied. The results showed that the compressive strength of composites increased by 8.86% and 8.08% after vacuum treatment, and the impact strength increased by 15.55% and 9.43% respectively. The secondary reinforcing effect of chopped fibers was obvious, and the compressive strength increased by 9.91% and 22.52% respectively. The actual application showed the composite nut lining prepared by using the CF tubular knitted stretch fabric could better solve the defects of insufficient strength and partial peeling.

1. Introduction
Transmission screw pairs are important functional elements for machineries. In heavy load and low velocity conditions, the lubrication will be worse and wearing of the friction pairs become serious, reducing transmission efficiency and shortening service life. A new type of transmission screw nut has been developed with the structure of SB/CF-EP lining. This nut is made of steel backing (SB) with carbon fiber reinforced plastic (CFRP) composite lining composed by epoxy resin (EP) as matrix and some self-lubricants as additives. This structure has both advantages of heavy bearing capacity and excellent tribological behaviors, increasing transmission efficiency by 35-50% [1]. This nut lining structure is usually prepared by the CF fabric laying process, and the spiral surface is not easily formed, resulting in the composite nut being not widely used in engineering practice: The nut lining structure prepared by using the chopped fiber as the reinforcing body and by injection molding is another way of preparation [2], but this nut has poor mechanical strength and affects the nut transmission efficiency. In this study, a spiral single-layer CF knitted fabric was used to prepare the lining structure. The lining layer had a complete thread structure without lap joints, which could effectively solve the problem of strength discontinuity in the fiber layup process. At the same time, the CF knitted fabric had a grid-like skeleton support structure, which could compensate for the defects such as insufficient strength of the chopped fiber injection molding lining and easy local peeling. In this paper, the mechanical properties and preparation processes were studied.

2. Fabrication of Samples

2.1. Experimental Materials
Carbon fiber (CF) reinforcement material: plain woven fabric, T300-1K, produced by Toray Co. Japan, the detailed specifications are shown in Table 1 and Table 2; Resin and additives: Epoxy resin E51,
industrial grade, produced by Yueyang Baling Petrochemical Co., Ltd.; Curing materials: 4-4’ diamino Diphenylmethane (DDM), analytical grade, Light yellow crystalline flake at room temperature, produced by Aladdin Reagent Co.; Other materials: Epoxy reactive diluent 501; deputy phthalate; Solid lubricating components: graphite, MoS2, analytical grade, produced by Tianjin Damao Chemical Reagent Factory; Talc powder, commercially available. According to previous studies, a formula for CF/PTFE composite was shown in Table 3.

| Table 1. The essential property of T300-1K carbon fiber. |
|---|---|---|---|---|---|
| Type | Tow | Tensile strength(Gpa) | Elongation | Linear density (g/km) | Monofilament diameter (μm) |
| T300-1K | 1000 | 3530 | 1.5% | 66 | 5~7 |

| Table 2. The product specification of Japan Toray 1K carbon fabric cloth. |
|---|---|---|---|---|---|
| Warp yarn | Weft yarn | Weaving type | Thickness (cm) | Width(cm) | Density(g/m²) |
| T300-1K | T300-1K | Plain | 0.15 | 100 | 119 |

| Table 3. Composite matrix material formula (%). |
|---|---|---|---|---|---|---|---|
| NO. | Epoxy | DDM | Active diluent | Plasticizer | Graphite | MoS₂ | French chalk | Chopped Fiber |
| No.1 | 50 | 12.5 | 2.5 | 5 | 6 | 9 | 15 | / |
| No.2 | 50 | 12.5 | 2.5 | 5 | 3.25 | 5 | 8.25 | 13.5 |

2.2. Fabrication of Samples

2.2.1. Preparation of the CF Knitted Stretch Fabrics. The basic sample of the CF knitted stretch fabrics was manually knitted by the flat knitting machine. The knitting parameters were as follows: the elastic scale value was 4, the machine number was 7 stitches per inch, and the T300-1000/3000 type fiber bundle was used. Fabric thickness was about 1.2mm; Stretch rate of the CF knitted fabrics is 69.1%.

2.2.2. Preparation of resin and Additives Colloid. Before being used, Weighed the EP, curing agent, modified components, etc. according to the specific formula ratio, The EP and the modified component were mixed and stirred uniformly at room temperature, and the DDM curing agent was heated to 120°C to melt, in order to prevent the liquid DDM from cold crystallization again, the other
components were pre-baked at low temperature for 20 min, and then DDM was evenly mixed. Finally, the vacuum defoaming treatment was carried out at room temperature for 30 min.

2.2.3. Preparation of CFRP Composite Samples. The prepared knitted fabric or purchased woven fabric was cut into a certain size, and pre-treated according to the sequence of: acetone cleaning, nitric acid heating oxidative, coupling treatment. Using hand lay-up method, uniformly coated the glue on the surface of the fabric, stacked and placed it in the mold. After been pressurized to the required thickness, the mold was placed in an oven and heated in accordance with the curing step of the resin body. After cured, it was naturally cooled, demolded, processed and polished.

2.2.4. Fabrication of SB/CF-EP Nuts. The SB/CF-EP nut molding procedures were as follows: Prepared the CF tubular knitted fabric and resin, Then coated the screw mandrel with wax of about 0.12 mm thickness, set the knitted CF tube on the screw mandrel, tightened the tube on grooves of the thread with thin CF band, dipped CF tube into resin matrix, then vacuumed, rotated the mandrel with CF tube into steel baking part and assembly the set. Replenished resin matrix through the hole of the steel backing, cured, demolded, post processed. Figure 3 showed the key processes and the sample screw nut of the standard trapezoid screw Tr32x8 [3].

![Figure 3. Key photos of SB/CF-EP Nut molding procedures.](image)

2.3. Experimental Equipment
CMT5504 Microcomputer Control Electronic Universal Tensile Machine, Shenzhen Xinsansi Material Testing Co., Ltd.; Hot pressing mold, homemade; S-3400N scanning electron microscope, Japan Hitachi Co.; Vacuum drying oven, Shenzhen Kuaike Manufacturing Technology Co., Ltd.; MR5000 inverted metallographic microscope, Nanjing Jiangnan Yongxin Optical Co., Ltd.

2.4. Test Methods

2.4.1. Impact Strength. The impact strength test of the CFRP composites was carried out according to the national standard "GB/T 1843-2008 Plastic cantilever beam impact strength measurement". The sample size was 80×10×4mm, and the unnotched impact sample was adopted. Support plane of sample was attached to the support block of the tester; the impact edge was aligned with the center of the sample.

2.4.2. Compressive Strength. The compressive strength test of CFRP composite was carried out according to the national standard "GB/T 1448-2005 FRP compression performance test method". To avoid the instability, the sample size was 10×10×10mm, and the error range was 0.5mm. The upper and lower end faces of the sample were required to be parallel to each other, and the non-parallelism was less than 0.1% of the height value. Loading speed was 2 mm/min. The direction of compression was perpendicular to the lamination direction of the fabric, and the maximum load at the moment of destruction of the specimen was recorded.

2.4.3. Resin Mass Percentage of Composite. The experiment was carried out according to the national standard "GB/T 3855-1983 CFRP resin content test method", the content of CFRP resin was determined by sulfuric acid digestion method, the method was suitable for the CFRP which could
completely decompose the resin colloid under certain conditions and did not excessively corrode the fiber.

3. Experiment results and Analysis

3.1. Effect of Vacuum Treatment Process on Mechanical Properties

Table 4 showed the mechanical properties in compression and impact strength and the resin mass percentage prepared by vacuum or non-vacuum treated to the CF plain woven and knitted fabric sample. Compared to non-vacuum process, it could be seen that the compression performance of the vacuum-treated CF plain woven and knitted fabric was improved by 8.9% and 6.1%, and the impact performance was improved by 15.6% and 9.6%, respectively. The addition of chopped CF (No.2) increased the compressive strength of CF plain woven and knitted fabric sample by 9.91% and 22.52%, respectively. However, the impact strength of the two showed a different degree of decline, which decreased by 29.34% and 17.97%, respectively. The resin mass percentages of the CFRP were changed by the vacuum treatment. The resin mass percentage of the CFRP vacuum treated of CF plain woven fabric and the CF knitted stretch fabric was 19.9% and 21.8% higher than the non-vacuum treated.

| CFRP Sample type       | Impact strength (KJ/m²) | Compression strength (Mpa) | Resin content (%) |
|------------------------|-------------------------|----------------------------|------------------|
| woven fabric /non-vacuum| 55.3                    | 453.3                      | 29.42            |
| woven fabric /vacuum    | 63.9                    | 493.5                      | 35.27            |
| woven fabric-chopped /vacuum | 45.2                | 542.4                      | /                |
| knitted fabric / non-vacuum| 21.8                | 248                        | 59.68            |
| knitted fabric /vacuum  | 23.9                    | 263.1                      | 72.69            |
| knitted fabric-chopped /vacuum | 19.6                | 293.4                      | /                |

Figure 4(a, b) showed that the CF knitted stretch fabric had a void percentage of 5.6% when not vacuum treated, and the void percentage was 1.0% after 60min vacuum treatment. The percentage of porosity before and after plain woven fabric treatment was 16.2% and 2.3%, respectively. It was indicated that vacuum treatment could effectively fill the resin between the reinforcements, greatly reducing the porosity (Figure 4(c, d)). It could be seen that the gas generated by the reaction between the air in the fabric and the resin was sufficiently discharged before the matrix resin was solidified under vacuum. The fiber bundle of the fabric was also completely wetted by the colloid resulting in a tight bond. There was almost no gap in the resin matrix, fabric layers and layers or grids, which greatly improved the bond strength and transferred load between the fabric reinforcement layers, and improved the bearing capacity [4]. The mechanical strength of the fabric was also improved.

Figure 4. The metallographic micrograph of CF knitted fabric composite.

3.2. Analysis of Fracture Morphology

It could be seen from the shape of the impact fracture sample as shown in Figure 5. In Figure 5(a), the CF plain fabric has a distinct impact fracture, and the fracture morphology was roughly a "V" shaped section. And near the surface of both sides of the sample, there was obvious delamination. It was
indicated that the bond strength between the layers of the multi-layer carbon plain fabric was not good. Secondly, during the impact process, the fibers in the middle part of the test piece first debond, and the transverse shear fracture breaks and spreads to both sides. In Figure 5(b), the knitted fabric has a relatively flat fracture, and some of the carbon filaments were pulled out. The cross-section fiber material was relatively less than the resin colloid. It was subjected to the impact load, and the fiber bundle acts as a discontinuous reinforcement effect, which was a typical brittle fracture phenomenon [5].

![Figure 5. Photos of impact fracture morphology.](image)

![Figure 6. Photos of compression fracture.](image)

![Figure 7. SEM photo of compression section.](image)

3.3. Analysis of Compression Morphology

Figures 7 and 8 showed the macro topography of the compressed sample and SEM photo of the compressed section. It could be seen from Figure 6 that, after the compression failure, the fiber fracture of the samples were relatively flat along the width of the test piece, and the fracture in the thickness direction was about 45°, which was a typical shear failure [6, 7]. It could be seen from the Figure 7(a) that the fiber bundles of sample by the woven fabrics were arranged very closely, and the fiber breakage at the fracture was clearly visible, that was, the fiber was fractured in a certain direction, indicated that the fiber was the main carrier during compression. The stress concentration between the layers caused the fibers to break in turn and spread the cracks to the next layer. The initial crack location was usually located where the fiber bond strength was weak, which was the inter-layer resin-poor zone. It could be seen from the Figure 7(b) that the main carrier of sample by the knitted fabric was an intermittent CF tow and resin matrix filler. The resin matrix had a lower load carrying capacity than the fiber. The CF fibers on the cross section of the knitted sample were discontinuous and the CF ratio was small, so the mechanical strength of the knitted sample was weaker than that of the plain woven structure. During the compression test, the load-displacement curve showed a linear
change before the fracture, which was a typical brittle fracture. However, the compression curve of the knitted sample had several fluctuations before the crack was generated to the final fracture, and the plain sample had a steep drop after the force reaches the maximum value, that was, a sudden crack phenomenon. It was indicated that the knitted fabric sample had small fiber content, and the load was mainly carried by the resin matrix. When the crack extends to the periphery of the fiber bundle, the matrix and the fiber were debonded, and then the fiber was broken by load.

4. Conclusion
Vacuum treatment causes the fibers of the CF plain woven fabric and knitted fabric to be completely wetted by the colloid, resulting in tight adhesion of the fibers. The composite compressive strength was increased by 8.86% and 8.08% compared with non-vacuum conditions, and the impact resistance was increased by 15.55% and 9.43%.

The chopped CF had a significant enhancement effect on the compressive strength of CF plain woven fabric and knitted fabric composites, which played a secondary strengthening role, and its value was increased by 9.91% and 22.52%, respectively, but the impact resistance was reduced to some extent.

The single-layer CF tubular knitted stretch fabric was integrally formed on the screw nut, the chopped CF was used as the secondary reinforcement to prepare the nut lining by vacuum treatment, the problem of inter-layer peeling in the CF fabric laying process could be avoided, and the defect that the strength of the chopped fiber injection molding liner was insufficient was also improved. The composite nut of this structure could basically meet the mechanical properties and preparation process requirements of the transmission nut under heavy duty and low velocity.

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