Synthesis of Carbon Fiber Composites and Different Methods to Improve its Mechanical Properties: A Comprehensive Review

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Abstract. Efficient and innovative products can be made using high strength and lighter weight (almost half the steel weight) in modern-day automobile industries. One such material is Carbon Fiber, and it is used as its composites made with the help of epoxy resins. Carbon Fibers applications are increasing in use, in both the aerospace and automobile industries. The corrosion resistance and damping properties of the material can be put to better use in constructions that are heavily strained. The paper aims to review the manufacturing of Carbon fiber composites and their mechanical properties (tensile & flexural strength), which ultimately deals with their applications in the automobile industry. Also, it deals with a review of a few methods or substances used to improve the mechanical properties of carbon fiber composites.

Keywords: Carbon fibers, Automobile Industry, Carbon footprints, Additive Manufacturing, Carbon Fiber Reinforced Polymers

1. INTRODUCTION

World environment conditions haven't been decent in the past few years; some of the many things can be held responsible for it. For instance: To some extent, it is the Automobile Industry responsible for pollution and scarcity of fossil fuels. The complete industry runs on petrol, diesel, and natural gases and constitutes a substantial amount of the world's air pollution. The bar graph makes it easier to understand how much GHGs in 2018, leading car companies emitted \([1–3]\). So now, as we know world environment is facing a crisis, majorly because of the automotive industry, we need to find a solution. The best solution can be something that helps in reducing fuel usage and hence reducing CO\(_2\) emissions. And the provided solution we have is using a lighter material than steel or aluminum, which will minimize the fuel consumption. But what material?
The material is Carbon Fiber Composite. Parts made by carbon fiber are 50% lighter than steel and 30% lighter than aluminum. Also, a study shows that reducing a car's weight by 10% reduces its fuel consumption by 7% [4–6]. We choose weight reduction to be the best option because it reduces fuel consumption and improves the car's acceleration and braking forces. Also, it lightens the Electric Vehicles' weight and Carbon fiber composite is way stronger than steel and aluminum combined [7]. That's why this study deals with a review of the best manufacturing methods of carbon fiber composites and reviewing the methods to improve its mechanical properties like tensile strength, flexural strength, fracture toughness, fatigue, impact, or collision toughness [8,9], see figure 1.

![Fig 1: GHG emitted in the year 2018 by leading car companies around the globe](image)

### 2. FABRICATION OF CARBON FIBER COMPOSITES

There are two methods of fabricating carbon fiber composites: 1) Molding & 2) 3D printing. Molding: Sheets of carbon fiber cloth are layered in the mold by spreading epoxy resin between the progressive layers of fiber. Epoxy resin is the thing that converts the cloth into a rigid composite [10–13].

Vacuum Bagging: This technology is much similar to molding, except it uses a vacuum bag, in the end, to seal the carbon fiber to the mold and make it a bit stronger as it removes the trapped air makes the epoxy stick properly with the carbon fiber.

Additive Manufacturing: Added substance producing (AM) is a procedure of joining materials to make three-dimensional objects from a PC-supported software (CAD) mode.

It has a few types: Power liquid 3D printing technology, Stereolithography apparatus, Laminated object manufacturing (LOM), Selective laser sintering (SLS), Fused deposition modeling (FDM)

Compression molding: Two pieces of molds are used in this method, one male and another female. The fiber is placed between the two with epoxy resin between them and then the two molds are pressed together [14].

RTM: Dry fiber cloth is placed between the two molds, i.e., male & female, and the molds are pressed together, and then the resin injection starts at very high pressure. By this process, the soft fabric turns into a hard composite in just 30-60 minutes [15–18].
For our study, we should choose the better methods for lab production for easy testing and low costing. For that, we will consider: The molding method by hand layup technique
  - AM & Compressed molding by 3D printing

3. Fabricating the Samples and Analysing their Mechanical Properties

3.1 Using 3K Carbon - 200 Gsm Bidirectional

Fabricated test samples of bidirectional carbon fiber using a 250g epoxy resin solution consisting of 15% hardener of type 6%. Then the epoxy and hardener mixture was spread uniformly in the die and the carbon fiber sheet is placed over it. This procedure is repeated to get the required number of layers of carbon fiber. After that, the fabricated composites were cut into samples of ASTM standards. Results of tensile and flexural strength are as follows [19,20], see table 1.

Table 1: Results of tensile and flexural test of bidirectional carbon fiber composite.

| Sample                  | Tensile Strength(N/mm²) | Flexural Strength(N/mm²) |
|-------------------------|-------------------------|--------------------------|
| 1. Tensile test specimen| 84.588                  | ---                      |
| 2. Flexural test specimen| ---                    | 115                      |

3.2 Using Sikacarbodur S512

Fabricated composites of the Sikacarbodur S512 carbon fiber sheets of thickness 1.2mm. The epoxy resin used is sikadur 30. The molding technique was used for fabricating test specimens as per ASTM D638 standards. Tensile strength when tested comes out to be 3051 N/mm², see figure 2.

Fig 2: Carbon Fiber Reinforced Polymer, standard tensile test sample.
3.3 Using Bi-Woven Carbon Fiber

Fabricated the composites of bi-woven carbon fiber using the epoxy YD128 and hardener HY140. Three samples were prepared for each type of angle-oriented specimen with an orientation angle of 30°, 45°, 90°. The preparation technique used was simple molding and specimens fabricated were of ASTM standards. The result of the tensile and flexural strength test is shown below in figure 3:

![Result of Tensile & Flexural Tests](image)

Fig. 3: Result of Tensile and Flexural Tests

3.4 Using Printed Epoxy Carbon Fiber Composite

As shown in Table 2, fabricated carbon fiber composites by using 3D printing technology. They manufactured two specimens for testing, one with additive manufacturing and the other with compressed molding techniques. Five μm diameter AS type carbon fiber was used for composite and ink consisted of EPON resin 826, curing agent, and nanoclay (Garamite – 7305). AM tests samples were manufactured on a nSsryct 3Dn-500 printer. The ink was expelled through a Nordson-tightened spout with a 580 μm distance across. Target printing parameters were a testimony pace of 3.75 × 10−3 cc/s and a printing rate of 15mm/s, bringing about ostensible street width and layer stature of 500 μm. The fabricate plate was borosilicate glass secured with PTFE-covered aluminum foil.

Fig 4 and 5, 2 AM sample raster printing orientations: (a) 0°; (b) 90°; (c) ±45°; (d) Example of voids between raster and perimeter roads

For CM samples same ink was used. The inks were spread into 152.4 × 152.4 mm square molds 3 mm deep and pressed between two steel metal plates with 3000 N power. After the square plates were removed from the mold, a waterjet cutter was used to cut samples for the tensile tests.

Table 2: Test ink composition and mix time

| CF loading | Min mix time |
|------------|--------------|
| 0 pph (base ink) | N/A |
| 1 pph (0.6 vol%) | 2 min |
| 4 pph (2.3 vol%) | 4 min |
| 7 pph (3.9 vol%) | 6 min |
| 10 pph (5.5 vol%) | 8 min |

*a after addition of carbon fiber tape*
4. Methods to improve Mechanical properties of Carbon Fiber Composite

4.1 Using functionalized Carbon nanotubes

Four harness satin weaved carbon fabric, having identical warp, fiber type was IM7. A solvent spraying technique was used for the deposition of nanotubes. First, the functionalized CNTs were dispersed in organic ethanol solvent. The solvent is sprayed on both sides of the fabric; eventually, the solution evaporates, leaving the CNTs on the fabric surface. Fluorine functionalized CNTs and Amine functionalized Single wall CNTs were used for two specimens. Test results are shown below in figure 6 and 7:

![Test specimens fabricated for tensile test](image)

Fig 6: Test specimens fabricated for tensile test

Tensile tests were performed considering ASTM standard D4762-04.
4.2 Using Graphite Powder as a Filler
Fabricated the composite using 3K bidirectional carbon fiber. First of all, the carbon fiber sheet was cut into dimensions of the dye set for the test specimens. Then 250 gm epoxy resin solution was prepared to add to it was 15% hardener of type 6% and then mixing filler i.e., graphite powder, the hardener is mixed at end stages of mixing. Then the epoxy and hardener mixture was spread uniformly in the die and the carbon fiber sheet is placed over it. This procedure is repeated to get the required number of layers of carbon fiber. Then it is left undisturbed to cure for 48 hours. Two Specimens were fabricated for tensile & flexural strength testing, each with different levels of graphite powder mixing, one with 5% graphite powder and the second with 10% graphite powder. Test results are shown below:

4.3 Using E-type glass fiber, Carbon fiber, Natural Fiber
Hand layup technique to fabricate the composites. The first step being was coating the mold with paraffin wax to avoid sticking. Then epoxy resin(Ly556) was applied and over that, the E-type glass fiber. Then another layer of epoxy resin was applied over the glass fiber and then carbon fiber was stacked over it. Similarly, natural fiber was stacked over carbon fiber, creating a three-layer composite with carbon fiber in the middle of E-type glass fiber and natural fiber. Dimensions of the composite formed were 300*400 mm with a thickness of 4 mm, as shown in fig 8 and 9.

Fig 7: Ultimate tensile strength of different specimens fabricated by varying the wt% of Fluorine functionalized carbon nanotubes (f- XD CNT) & Amine functionalized single-wall carbon nanotubes (a- SWCNT)

Fig 8: Tensile Specimen ASTM-D638 (All Dimension are in mm)
Fig 9: Tensile test results

5. RESULTS AND DISCUSSION
TENSILE STRENGTH
Table 3: Comparing the tensile strength of different specimens.

| S.NO. | COMPOSITE                           | METHOD                        | TESTING STANDARD | TENSILE STRENGTH*(N/MM²) |
|-------|-------------------------------------|-------------------------------|------------------|--------------------------|
| 1     | 3K CF BIDIRECTIONAL                 | CM                            | ASTM             | 84.588                   |
| 2     | ^SIKACARBODUR S512                  | MOLDING                       | ASTM D638        | 3051                     |
| 3     | BI-WOVEN CF                         | HAND LAYUP TECHNIQUE          | ASTM             | 341.6                    |
| 4     | CF: 5MM DIAMETER AS TYPE            | AM {3D PRINTED}               | ASTM D638        | 128                      |
| 5     | CF: 5MM DIAMETER AS TYPE            | CM {3D PRINTED}               | ASTM D638        | 100                      |

METHODS TO IMPROVE TENSILE STRENGTH

| S.NO. | COMPOSITE                           | METHOD                        | TESTING STANDARD | TENSILE STRENGTH*(N/MM²) |
|-------|-------------------------------------|-------------------------------|------------------|--------------------------|
| 6     | HIGH STRENGTH CF                   | NANOTUBE TECHNOLOGY {F- XD CNT} | ASTM D4762-04   | 801                      |
| 7     | HIGH STRENGTH CF                   | NANOTUBE TECHNOLOGY {A- SW CNT} | ASTM D4762-04   | 747                      |
| 8     | 3K CF BIDIRECTIONAL                | CM                            | ASTM             | 136                      |
| 9     | E-TYPE GLASS FIBER+ CARBON FIBER+ NATURAL FIBER | MOLDING | ASTM D638        | 219                      |

*taking the maximum value of tensile strength if any method has used more than one specimen in testing. AM – Additive manufacturing, CF – Carbon Fiber, CM – Compressed molding ASTM – American Society for Testing and Materials : Sikacarbodur S512 can be left as an exception because sheets of the fiber used to manufacture composites were 1.2 mm thick and no else fiber sheets were this much thick, see table 3.

FLEXURAL STRENGTH :
Bi - Woven carbon fiber didn't have a tremendous flexural strength but adding 10% graphite in the epoxy resin then fabricating it with compressed molding gave us good results. So we can infer that by using graphite flexural strength of carbon fiber composite can be increased, see fig 10.
Fig 10: Graph showing results in flexural strength of Bi-woven carbon fiber composite when the epoxy solution is added with graphite powder.

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