

EFFECTS OF SINGLE-WALLED CARBON NANOTUBE ADDITION ON THE MECHANICAL PROPERTIES OF CARBON FIBER STRUCTURAL COMPOSITE

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Abstract – Different concentrations of single-wall carbon nanotubes were added to a carbon fiber composite with an epoxy matrix to evaluate its mechanical properties. The dispersion of the nanoparticles exhibited good quality and the flexural strength in the 90-degree direction showed an increase of over 10% with a concentration of only 0.0087% of nanotubes in the composite.

Keywords: Carbon Nanotube, Nanocomposite, Carbon Fiber Composite, Hierarchical Composite, Filament Winding

Introduction

Material strength is one of the technological limitations of various projects, where performance is constrained by the strength-to-mass ratio. As a result, the demand for materials with higher strength and lower density will remain constant in many industries.

One example of this is wind turbine blades, where larger dimensions result in higher energy generation efficiency [1]. By utilizing materials with greater mechanical strength and lower density, it becomes possible to manufacture larger blades. Thus, the advancement of materials is directly related to the viability of wind energy generation.

For many applications in industries such as aerospace, automotive, chemical, oil and gas, several components are transitioning to composite materials, which offer the best strength-to-mass ratios. Therefore, improving the properties of current composites enables technological advancements in various sectors.

Although composite materials, by definition, involve the multifaceted combination of any material classes, including two or more materials from the same class [2, 3], this study will specifically delve into polymer matrix composites reinforced with ceramic fibers, particularly those reinforced with carbon fibers (CFRP - Carbon Fiber Reinforced Polymer).

CFRP composites are commonly utilized in applications demanding high performance. In these composites, epoxy resin-based matrices are the predominant choice, which will be the focus of the study. Given that carbon fiber and epoxy resin are widely used in the market this study holds significant relevance for both the scientific community and industry.

Among the various potential failures that occur in composites, one of the most frequent and severe is interlaminar fracture (or delamination), which essentially refers to matrix failure between layers of fibers with different orientations. This failure occurs precisely in a region considered one of the "weak points" of laminated composites [2].

Carbon fibers and polymer matrices used in CFRP composites possess significantly different mechanical strengths. For example, Toray T300 carbon fiber has a tensile strength of 3500 MPa,

while the epoxy resin-based matrix Huntsman™ GY260 has a tensile strength close to 50 MPa, according to manufacturer data. Consequently, regions of the composite where the matrix experiences higher loads become potential areas of failure.

Therefore, methods that increase the matrix's stress limits are essential for enhancing the strength of a composite, thereby enabling technological advancements limited by the strength of existing materials. Increasing the matrix strength is one of the objectives of developing composites with dispersed nanoparticle additions in addition to traditional reinforcements.

The technology of CFRP composites with nanoparticles is still in its early stages, recently transitioning from specific structural applications such as wind turbines and high-performance aircraft to more mainstream products, as evidenced by their adoption by major automobile manufacturers. A significant expansion is expected in the coming years [4].

Given that delamination failure is very common in composites, the development of methods to prevent or at least reduce its occurrence is of great relevance. In this study, nanoparticles were tested to reinforce the matrix and enhance resistance to delamination.

Experimental

Test specimens were fabricated using a polymer matrix consisting of the following Huntsman™ products: epoxy diglycidyl ether bisphenol A (DGEBA) resin LY 5052, methyl tetrahydrophthalic anhydride (MTHPA) hardener HY 2918, and benzyl dimethyl amine-based accelerator DY 062, reinforced with Tenax™ HTA40 carbon fiber without the addition of nanotubes, to be used as a reference, using the filament winding process (Fig.1), set to a high ratio of carbon fiber. The curing process was carried out according to the following cycle: a plateau at 100°C for one hour, a ramp from 100°C to 145°C over 3 hours, a plateau at 145°C for 8 hours and cooling from 145°C to 25°C over 4 hours. The resulting sheet was used to produce specimens according to ASTM D7264/D7264M-21 standard.

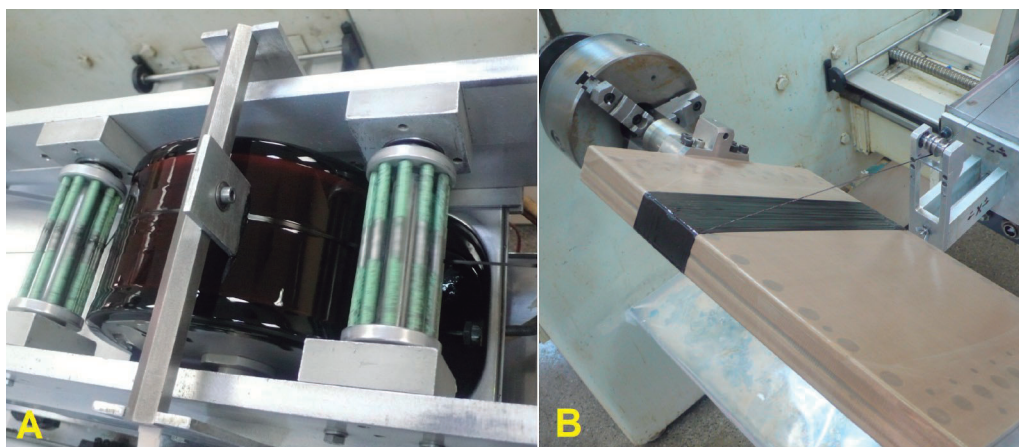


Figure 1 – Filament winding process: (A) Resin bath and (B) rotating mold

Subsequently, test specimens were fabricated and characterized under conditions similar to the reference samples, with the addition of the commercial product TUBALL™ MATRIX 301 (a compound pre-dispersed with 10% single-walled carbon nanotubes in epoxy matrix) at concentrations of 0.046% and 0.087%, using a Thinky Mixer ARE310 planetary mixer. The final composition of the specimens are presented in Table 1.

Table 1 – Composition of specimens

Specimen	Carbon fiber	Resin LY 5052	Hardener HY 2918	Accelerator DY 062	TUBALL™ MATRIX 301
0 wt% TUBALL™ MATRIX 301	718.1 g (77.00 wt%)	100.0 g (10.72 wt%)	114.0 g (12.22 wt%)	0.5 g (0.05 wt%)	-
0,046 wt% TUBALL™ MATRIX 301	719.5 g (77.00 wt%)	100.0 g (10.70 wt%)	114.0 g (12.20 wt%)	0.5 g (0.05 wt%)	0.428 g (0.046 wt%)
0,087 wt% TUBALL™ MATRIX 301	763.5 g (78.00 wt%)	100.0 g (10.22 wt%)	114.0 g (11.65 wt%)	0.5 g (0.05 wt%)	0.856 g (0.087 wt%)

The quality of dispersion was assessed using an FESEM JEOL JSM-7401F scanning electron microscope, a Discovery.V8 stereomicroscope and a simple method recommended by the manufacturer by depositing the dispersed resin on white paper (Fig. 2).



Figure 2 – Simple method recommended by the manufacturer: (A) Quality control procedure / (B) Example of poor quality dispersion / (C) Example of good quality dispersion (source: TUBALL™ MATRIX 300 series Processing Guide)

The mechanical property was evaluated using a flexural mechanical test, following the ASTM D7264/D7264M-21 standard (Fig. 3), which is a suitable method for assessing the strength of laminated composite matrices [5-7].

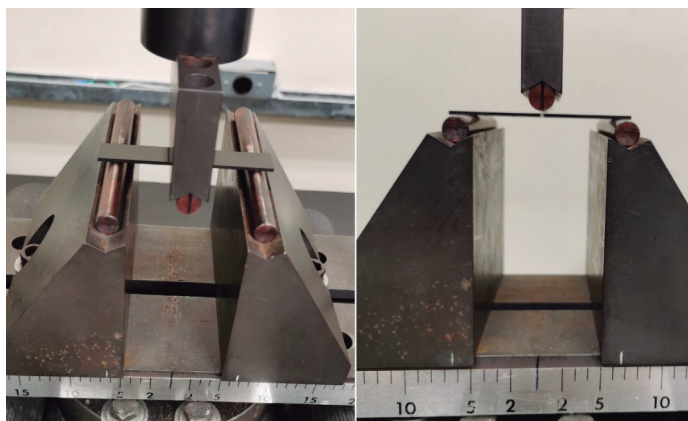


Figure 3 – Flexural mechanical test according to ASTM D7264/D7264M-21 standard

Results and Discussion

The duration of 30 minutes at 2000 rpm in the Thinky Mixer ARE310 proved to be suitable for dispersing the nanotubes in the epoxy resin matrix.

Small agglomerates were observed in the dispersion of TUBALL™ MATRIX 301 in the LY 5052 resin (without the addition of hardener and accelerator) using the stereo microscope (Fig. 4).

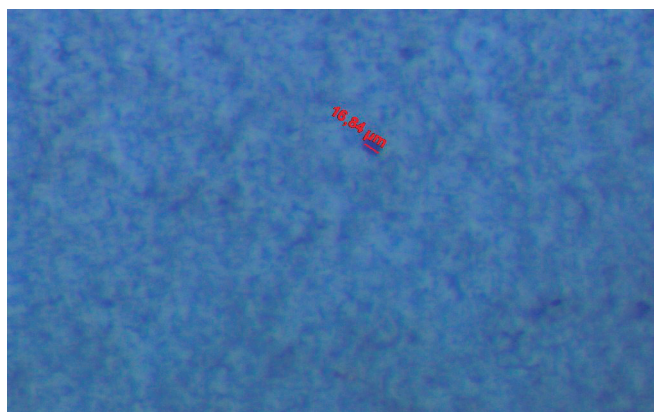


Figure 4 – Dispersion of TUBALL™ MATRIX 301 in LY 5052 resin: a cluster measuring 16.84 μm was identified (magnification 80X)

As observed in Figure 4, the dispersion of nanotubes, which is a critical step in the fabrication of nanocomposites [8-9], exhibited only small and rare clusters, indicating excellent dispersion quality.

Dispersion was evaluated using the method recommended by the manufacturer. As shown in Figure 5, the dispersion pattern is deemed suitable, according to the manufacturer's manual (Fig. 2).

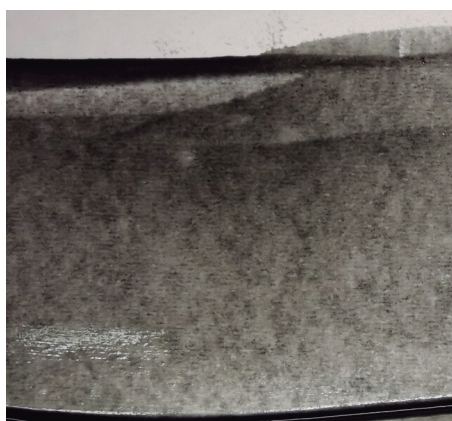


Figure 5 – Result of simple test recommended by the manufacturer: a high-quality dispersion is observed

The detail of the dispersed nanotube can be observed in the image obtained from the FESEM JEOL JSM-7401F scanning electron microscope (Fig. 6), on the fracture surface of the specimen containing carbon nanotubes.

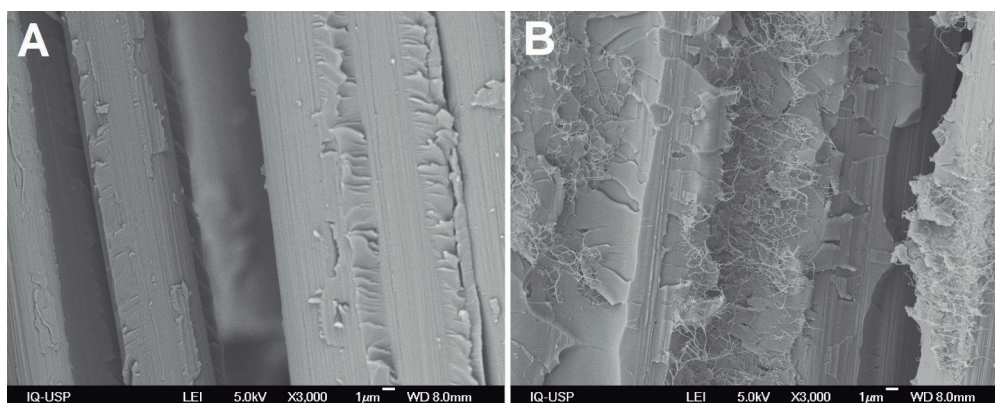


Figure 6 – Fracture surface observed using an FESEM JEOL JSM-7401F scanning electron microscope: (A) with 0 wt% TUBALL™ MATRIX 301 and (B) with 0.087% wt% TUBALL™ MATRIX 301, showing the nanotubes well dispersed in surface

The flexural test with the carbon fiber oriented at 90 degrees yielded the following results (Table 2).

Table 2 – Results of the flexural tests

Composition (details on Table 1)	Flexural strength (MPa)	Number of Specimens
0% wt% TUBALL™ MATRIX 301	93±4	10
0.046 wt% TUBALL™ MATRIX 301	101±2	9*
0.087 wt% TUBALL™ MATRIX 301	103±4	9*

* One outlier specimen was discarded

As can be seen in Table 2, the addition of 0.046% of TUBALL™ MATRIX 301, which corresponds to 46 ppm of carbon nanotubes, increased the transverse flexural strength from 93 to 101 MPa, representing an 8.6% improvement. The addition of 0.087% of TUBALL™ MATRIX 301, which corresponds to 87 ppm of carbon nanotubes, increased the strength from 93 to 103 MPa, corresponding to a 10.7% increase. The improved mechanical properties achieved corroborate the behavior already established in the literature [4, 8-10].

Conclusions

The presented results demonstrate that the commercial product TUBALL™ MATRIX 301 can be successfully dispersed in the resin using a planetary mixer. The addition of 0.046% of the product increased the transverse flexural strength by 8.6%, while the addition of 0.087% resulted in a 10.7% increase. This suggests a nonlinear relationship between the nanotube concentration and strength enhancement but tests are needed on additional compositions to confirm this hypothesis.

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