ANALYSIS OF MECHANICAL PROPERTIES OF COMPOSITE NANOFIBERS CONSTRUCTED ON ROTATING DRUM AND COLLECTOR PLATE

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Abstract. The methods of deposition of nanofibers on a rotating drum and a stationary plate, as well as analysis of mechanical properties of the nanofibers from both collectors, are proposed in this article. The deposition of nanofibers on collectors is crucial, as it is the successful development of nanofibers with various types of collectors, as well as the evaluation and demonstration of their strength and other mechanical properties. The most popular method for producing continuous nanofibers is electro spinning, which involves jetting polymer solutions in high electric fields to produce continuous nanofibers with diameters ranging from 200 to 600 nm. These results were compared using ANSYS, and the material behavior of biaxial nanofibers collected from the spinning collector was identified. The rotating drum collector's spinning speed causes the fibers to stretch, resulting in alignment and a decrease in diameter. The rotating drum collector adds force to the strong shear and elongation forces that arrange the chains and align the lamellae in the fiber axis direction during the electro-spinning process. As a result, the nanofibers on the rotating drum are aligned uniaxial. It indicates that by altering the collector design, the alignment and mechanical properties of nanofibers can be improved. The results showed that the nanofibers collected from the spinning drum were more consistently aligned (biaxial arrangement) than those obtained from the stationary plate and had Young's modulus of composite 5.01 GPa and 4.4 GPa respectively, ~9% more strength than the nanofibers collected from flat plate.

Keywords: electro spinning, nanofibers, ANSYS, random fibers, biaxial fibers.

Introduction

Nanofibers bring us a wide range of opportunities with new features by physically and chemically changing them during or after the production process [1; 2]. Electro spinning is a one of the popular methods for producing continuous nonwoven nanofiber mats [3; 4]. Nanofiber deposition on the collector is extremely important [5; 6]. To evaluate the strength and other mechanical properties, composite nanofibers must be developed and collected on a rotating drum and stationary plate.

Fabricated and deposited on a fast-rotating drum and stationary plate to simulate random and biaxial nanofiber alignment on this collector. These results are compared to those obtained from nanofibers gathered at random on a stationary plate collector. Better understanding of dynamic nano-fibre interactions with the electric field and collectors should lead to improved collector devices and one-step integrated nano fabrication of designer nano-filamentary assemblies and architectures [7; 8].

One of the biggest technological challenges of the last decade has been to come up with and mass-manufacture more efficient materials in all kinds of industries. We can make this material stronger and more durable by adding short, discontinuous fibers [9-12]. A lot of people are looking for new metal-matrix composites that have a lower density for automotive and aerospace applications [13]; new metal-ceramic composites with unique designs [14; 15]; and new metal-crystal-polymer composite fibers that can protect people from electromagnetic fields in the office [16-18].

Polymer matrix-based nanocomposites have been extensively employed, analysed, and explored across all engineering disciplines and in several industrial sectors, including defence, automotive, and space. Epoxy polymer composites reinforced with nanoparticles, in particular, have received increasing attention due to their unique and enticing qualities, as well as their unique uses in a variety of industrial fields [19]. Nanomaterials increase the mechanical characteristics and performance of epoxy polymer composites significantly. The qualities of epoxy polymer nanocomposites are determined by the chemistry of the matrices, the nature and uniformity of the nanomaterials contained inside the matrices, and the manner by which they are configured to achieve the required mechanical and physical properties [19].

A collector or a collecting surface is used to collect electro spun fibers. The collector is supported by an insulated stand, which provides for future regulation. For electro-spinning setups, various collectors such as a flat piece of metal, a screen, or even a rotating drum, known as a frame collector, have been devised for textile application [20; 21]. A rotating drum collector adds force to the strong

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shear and elongation forces that arrange the chains and align the lamellae in the fibre axis direction during the electro-spinning process [21; 22]. Fibre alignment tends to decrease because of fibre rupture and turbulent air flow around the circumference of the revolving collectors caused by excessive rotational velocity. Also, the collector rotating speed, which is inversely related to the rotating speed, might impact the diameter of nanofibers [23]. Rotating drum speeds that are increased typically result in decreased fibre diameters [24]. The rate of solvent evaporation is also increased, resulting in nanofibers with smaller diameters and higher crystallinity formed on the drum collectors [25; 26].

This collecting module is made comprised of a spinning drum unit with a translational linear motion emitter. At low spinning rates, the fibers are randomly deposited onto the surface of the drum. When the rotational speed of the drum is at 800 rpm, fibers are deposited on the surface in an aligned pattern. The purpose of this research is to compare the mechanical properties of nanofibers collected from the rotating drum and stationary plate, and the numerical simulation of the results.

Materials and methods

Nylon 6 is abrasion-resistant, with high tensile and impact strength, and flexible. Its absorption capacity increases as it absorbs more moisture. Nylon 6 is a non-toxic material that can be mixed with glass or carbon fibers to improve the performance. This is the reason to choose Nylon 6 as the subject of this study.

In this research, experiments are performed by using nanofibers produced by electrospinning and fabricated on a rotating drum and stationary plate. Nanofibers align unidirectionally on the rotating drum, resulting in improved mechanical properties than randomly collected nanofibers. Then, using the rule of mixtures, we intend to compare the numerically estimated mechanical characteristics of biaxial alignment nanofibers.

The centrifugal force imposed on the spinning fluid when it is placed in a revolving nozzle tip may be defined by formula [3]:

$$F_{centrifugd} = \frac{m\omega^2 D}{2}, \tag{1}$$

where m – mass of the fluid, kg·m^{-3};
ω – rotating speed of the drum, RPM;
D – diameter of the drum, m.

The frictional force imparted to the liquid jet may still be estimated after it ejects from the nozzle tip by equation:

$$F_{friction\ force} = \frac{\pi C \rho A \omega^2 D^2}{2}, \tag{2}$$

where C – drag coefficient;
ρ – air density, kg·m^{-3};
ω – rotating speed of jet, RPM;
A – cross sectional area of jet, m^2;
D – diameter of the drum, m.

Consider Figure 1 of the composite material fibre and matrix aligned unidirectionally. When the tensile force F_C is applied unidirectionally, then the ΔL elongation is on the composite material.

Equation (3) determines longitudinal elastic modulus of the composite, which is also known as the rule of mixture. It will be implemented in numerical simulation.

$$E_C = F_f V_f + E_m V_m. \tag{3}$$

The two forces balance each other at equilibrium in the electrospinning process, as shown by the following equation:

$$\frac{1}{8P\varepsilon_0}\frac{Q^2}{R^2}=8P\sigma_s R, \tag{4}$$

where Q – charge on the droplet surface, C;
R – droplet radius, m;
ε_0 – vacuum permeability, $H \cdot m^{-1}$;
σ – surface tension coefficient, $N \cdot m^{-1}$.

Table 1

Experimental process parameters

Process parameters	Parameters used
Solution	PA6 + Formic acid
Polymer solution concentration (wt%)	PA6 20
Flow rate (ml/hr)	0.60
Applied voltage (KV)	20
Tip to collector distance (cm)	25
Syringe (ml)	1
Needle (Gauge)	30
Collector	Plan plate, rotating drum

Figures 1 and 2 represent both types of collectors which are used in the experiment.

Fig. 1. **Stationary plate collector**

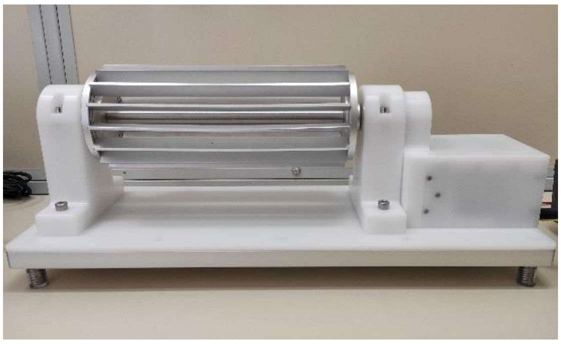

Fig. 2. **Rotating drum collector**

The stationary plate produces nanofibers in form of a non-woven mat and the rotating drum collects nanofibers. Given Figures 3 and 4 represent the alignment of the nanofibers collected in the stationary plate and rotating drum, images are captured in TM300 Tabletop Microscope SEM, Hitachi, x 1500; vacuum 10-2 Torr, Ion coater, 6 mA, Gold cover, coating thickness 10 nm.

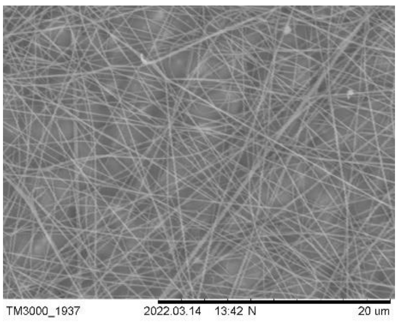

Fig. 3. **Morphology of nanofibers collected in stationary plate**

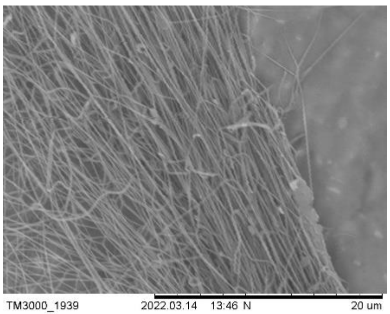

Fig. 4. **Morphology of nanofibers collected in rotating drum**

It can be seen in Figure 4 that nanofibers are arranged parallelly compared to Figure 3. The diameter of nanofibers has been measured using the ImageJ software (software version 1.53e, 2021, National Institutes of Health, Bethesda, MD, USA). Average diameter of nanofibers collected from the stationary plate is 153.83 ± 10 nm and average diameter of nanofibers collected from the rotating drum is 156.08 ± 10 nm. Histograms of the diameter of nanofibers are shown in Figures 5 and 6.

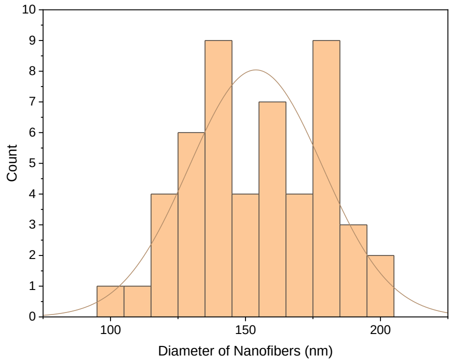

Fig. 5. **Diameter of nanofibers collected from stationary plate**

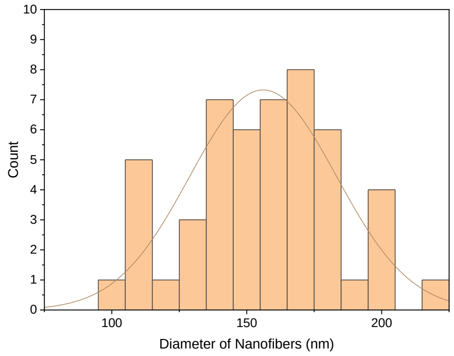

Fig. 6. **Diameter of nanofibers collected from rotating drum**

Figure 6 presents that there is more consistency in the diameter of nanofibers collected from the rotating drum. Table 2 represents the true stress and strain parameters of electro spun nanofibers depending on the diameter on nanofibers.

Table 2

Stress–strain parameters of typical as-spun composite nanofibers with various diameters [16]

Nanofiber diameter, nm	True stress, MPa	True strain, %
139	1800	60
260	700	78
400	200	44
810	100	40
1097	10	22

It shows the strength of nanofibers as well as reducing the diameter of nanofibers increases their strength. To perform numerical simulation of nano composites prepared from epoxy reinforced with nanofibers, the unit cell is considered, which is discussed in the section below.

Numerical simulation

To determine the numerical simulation of Young's modulus or modulus of elasticity of pure epoxy, epoxy reinforced with nanofiber samples were gathered from both collectors. A 3D model is developed in SolidWorks as shown in Figures 7 and 8.

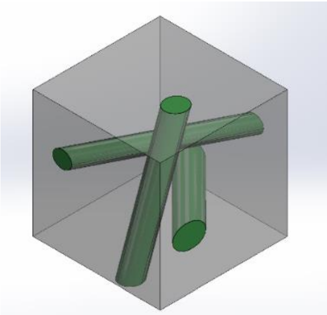

Fig. 7. **Randomly arranged nanofibers**

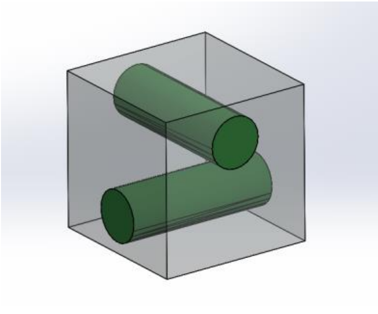

Fig. 8. **Biaxial aligned nanofibers**

The unit cell of the matrix of epoxy and fibers are randomly and biaxial arranged in the unit cell of the matrix. The matrix cube is considered of 700x700x700 nm, and nanofibers with the diameter of 150 nm. Table 3 summarises the elastic modules studied for nanofiber and epoxy.

Given below Figures 9 to 12 represent that the boundary condition of the model initial displacement is kept of $1\text{x}10^{-6}$ mm in longitudinal and transverse direction, while simulation and rest of the face are kept frictionless. Nodes on one of two opposing sides were confined to horizontal displacement in the plane of the unit cell, with the ability of rotation and orthogonal movement, whilst nodes on the other face were moved as a plane reactive 1x10^{-6} mm.

Table 3

Elastic modulus of materials

Type of material	Young's modulus (E) GPa
PA6 Nanofiber	6 [26]
Epoxy	3.75

The longitudinal Z-Axis (yellow face in Figure 9) and transverse Y-Axis (yellow face in Figures 10 and 12) were determined with a surface displacement of 1x 10^{-6} mm on the right face normal to the right plane.

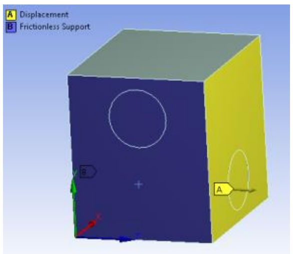

Fig. 9. **Boundary conditions in biaxial longitudinal model**

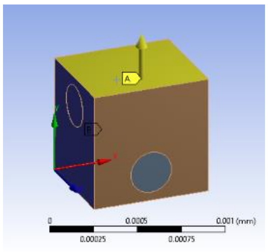

Fig. 10. **Boundary conditions in biaxial transverse model**

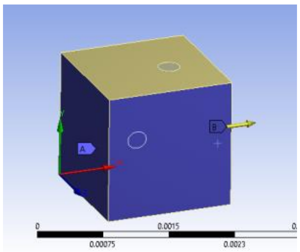

Fig. 11. **Boundary conditions in random fibre longitudinal model**

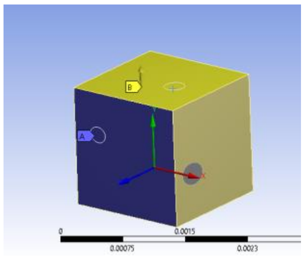

Fig. 12. **Boundary conditions in random fibre transverse model**

Results and Discussion

The Representative Volume Element (RVE) is used to determine the mechanical characteristics of polymer-based composites. Polymer-based composites predict reliable results with this method since the whole composite is made up of tiny repetitive micro-parts [27]. The Young's modulus of composite nanofiber aligned in a biaxial manner and randomly arranged is determined by using simulation results. The maximum and minimum stresses of composite from the unit matrix on longitudinal direction from that face are obtained by performing the static analysis and applying displacement under elastic deformation.

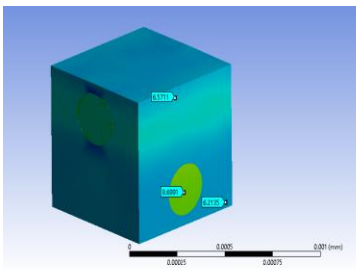

Fig. 13. **Bi-axial longitudinal direction**

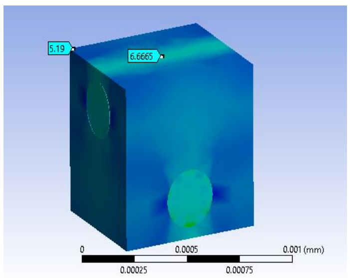

Fig. 14. **Biaxial transverse direction**

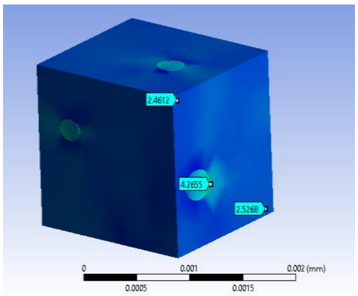

Fig. 15. **Random fibre longitudinal direction**

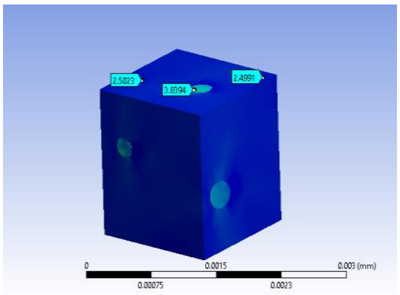

Fig. 16. **Random fibre transverse direction**

As it can be observed in Figures 13 to 16, the areas with the highest stress values are clearly focused on the outer face of the fibers. This indicates that the fibers carry the full force of the displacement tension. As a result, it concludes that this model distributes stress from epoxy resin to the biaxial reinforcing nanofiber in an appropriate manner.

From Table 4, randomly oriented composite nanofiber has lower strength than others. It only has 4.6 GPa, whereas biaxial aligned composites have 5.01 GPa, which is about 8.9% more than randomly oriented composites. Novelty of this research is that it helps predict the behaviour of composite structures with the nanofibers.

Table 4

Young's modulus of composite materials

Fibre Alignment	Young's modulus GPa (Longitudinal)	Young's modulus GPa (Transverse)
Random	4.6313	4.4247
Biaxial	5.0148	5.0148

Although nanofibers have a tendency of increasing the strength when the diameter is reduced and the electrospinning process is not much controlled that it can produce the same diameter of nanofibers, it produces a range of diameter as it is shown in Figures 5 and 6. Therefore, practical results may vary from this theoretical calculation.

Conclusions

1. The research indicates that nanofibers collected from a rotating drum have more superior mechanical qualities than those obtained from a stationary plate. The Young's modulus of nanofibers collected using spinning drum collectors is 8.9% more than that of nanofibers collected using stationary plate collectors, according to the experimental data.
2. Due to the drum rotational speed the fibers stretch, resulting in alignment and a reduction in the diameter. Consequently, the nanofibers aligned uniaxially on the revolving disc. This implies that by modifying the collector design, it is possible to enhance the alignment and mechanical characteristics of nanofibers.
3. When tensile stress is applied to biaxially aligned composite nanofibers from spinning drums, their longitudinal and transverse strengths are virtually identical (5.01 GPa).

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Author contributions:

Conceptualization, J.V.S. and A.G.A; methodology, J.V.S. and S.S.; software, J.V.S. and S.S.; validation, S.P.K.; formal analysis, J.V.S. and S.S.; investigation, J.V.S. and S.P.K.; data curation, S.P.K.; writing – original draft preparation, J.V.S. and S.P.K.; writing – review and editing, J.V.S.; visualization, J.V.S. and S.P.K.; project administration, J.V.S. and S.P.K.; funding acquisition, J.V.S. and S.P.K. All authors have read and agreed to the published version of the manuscript

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