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Research Article

Effects of the Interfacial Bonding Behavior on the Mechanical Properties of E-Glass Fiber/Nanographite Reinforced Hybrid Composites

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The nanoparticles are incorporated into the composite to mark their unique properties. This work investigates the hybrid epoxy nanocomposite and the impact of nanographite reinforcement. The composite was prepared by using a mechanical stirring technique. The amount of nanographite was added in different volumes, i.e., 1.0, 1.5, and 2.0 wt.%. Results of mechanical and dynamic loading properties were analyzed in accordance to the quantity of nano-G. The fiber and matrix interfacial bonding enrichments were evident in high-resolution SEM images-tensile fracture surface. Finally, the optimum content of nanoparticle which impacts the sample greatly was found to be 1.5 wt.%.

1. Introduction

Epoxy adhesive is being used in many areas. Epoxy is well known for their outstanding features. The fiber was included as reinforcement into the epoxy matrix for the application purpose [1–5]. Glass fiber is chosen for its distinctive property like low cost, thermal stability, and easy malleability. In recent, it has been proven that the inclusion of nanosized filler can improve the quality of the composite material [6–10]. Nanographite (nano-G) is a suitable nanoparticle for its different properties. The nano-G is used in the electrode, fuel cell, radar-absorbent, corrosion-resistant, aerospace, and many other structural applications [11, 12]. The nanoparticles are incorporated into the composite to mark their unique properties. It aids in enhancing the material property and, in turn, it is quality [13]. The increasing demand for the excellent quality structural materials pays the way for making the nanocomposites significant.

There are a variety of composites categorized based on their matrix material. Thermoset composite of epoxy and glass fiber was expansively studied by many researchers [14, 15]. Addition of the nanocontent have reduced the volume of jute polymer composite [16]. The behavior of SC fiber toughened polypropylene composite [17]. Energy is

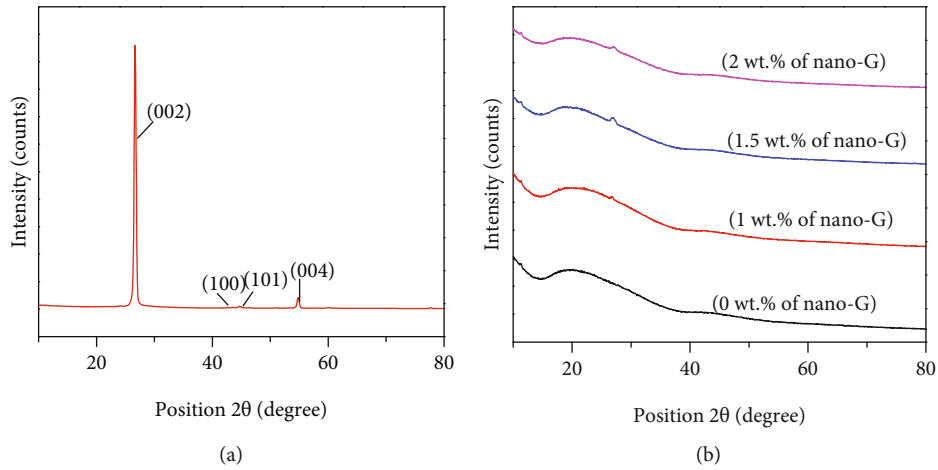


Figure 1: XRD pattern of nanographite (b). XRD pattern of nanocomposite.

absorbed under the varying load of glass fiber-epoxy nanocomposite with response to quantity of nanoparticle [18]. Impact of the toting up of graphene oxide in the epoxy matrix in mechanical and interface properties. Many studies revealed the advantage of adding nanoparticles and explained how it enhanced the material novelty [19, 20]. It was studied that the interfacial bonding into the matrix was improved. The delamination between the matrix was also studied with the inclusion of nanoparticles. Jeyabalaji et al. [10] investigated the nanocomposites dispersed with layered silicates and showed the improvement in the dynamic mechanical analysis. The use of mixed oxide obtains material with admirable properties. Sabeel Ahmed et al. [15] studied with the titanium oxide as nanofiller. Farzi et al. [12] studied the preparation and properties of nanocomposite. The other works also studied the addition of natural fibers and the effects of filling the nanodust. The confidence limit for the graphical analysis is studied by various techniques. In order to analyze the graphical data with interval limits and measurement errors, the statistical approach is carried out. The statistics on measurement errors and the confidence intervals can be insight analyzed using the graphical theory and statistical approach [32, 33]. There was inadequate research on the methodology of reinforcing chopped glass fiber into an epoxy matrix with nanographite.

In the current work, the epoxy matrix is made reinforcement with glass and nanographite nanoparticles. The laminates are processed by mechanical method. Mechanical tests are analyzed comparatively. Field emission scanning electron micrographs (FESEM) are captured to observe the nanoparticle dispersion and morphology.

2. Methodology

2.1. Equipment. E-glass fiber (GF) of type chopped strand mat has been bought. Epoxy adhesive, diglycidyl ether of bisphenol-A (DGEBA) is mixed with tri-ethylene tetraamine- (TETA-) HY951 hardener to form a matrix. Nanographite nanoparticle (<100 nm, 99% of purity) provided by Sigma Aldrich, United States, was used as filler.

2.2. Experimental. The reinforced nanocomposites were made with the required dimension by mechanical lay-up technique using a magnetic mechanical stirrer. The glass fibers have been purchased commercially. The nanoparticles are mixed into the matrix, and this plays the role of intermediate structure between the fibers. The chopped strand mat GF was used in the reinforcement. The nanographite of nanoscale was used in small weight fraction into the epoxy. To make certain, even distribution of nanomaterial stirrer was employed [20–24]. The composite was left to cure two days, postcured at 180°C for 4 hours in a void oven. For the present study, four different composites with different quantity of nanographite are processed (0%, 1.0%, 1.5%, and 2.0%).

2.3. XRD Analysis. The structure of hybrid nanocomposites has been subjected to characterization using X-ray diffraction (XRD) (analytical, Netherland) with copper radiation sources of 1.54A°, 40 kV, and 15 mA. The samples were subjected to XRD at two thetas (2° to 60°).

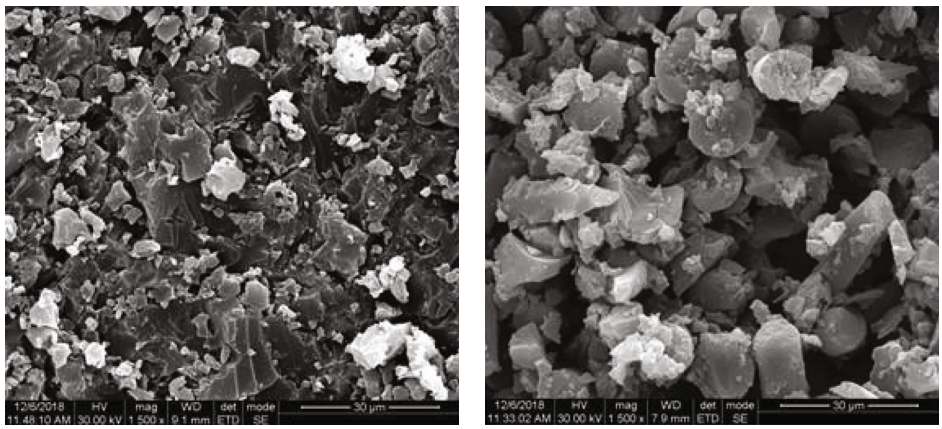
2.4. Micrograph Study. The high-resolution microscope (field emission scanning electron microscope—FESEM), of making "Quanta FEG 200," 1.2 nm resolution, gold particle separated on a substrate of carbon, was utilized for surface morphology analysis. The sample was gold plated to improve conductivity.

2.5. Mechanical Properties

2.5.1. Tensile Testing. Specimens of dimension $165 \times 3 \times 3$ mm^3 were performed under tensile test (ASTM-D-638), universal testing machine (UTM) Associated Scientific Engg. Works, New Delhi, of making Auto Instruments-Kholapur, at 5 mm/min.

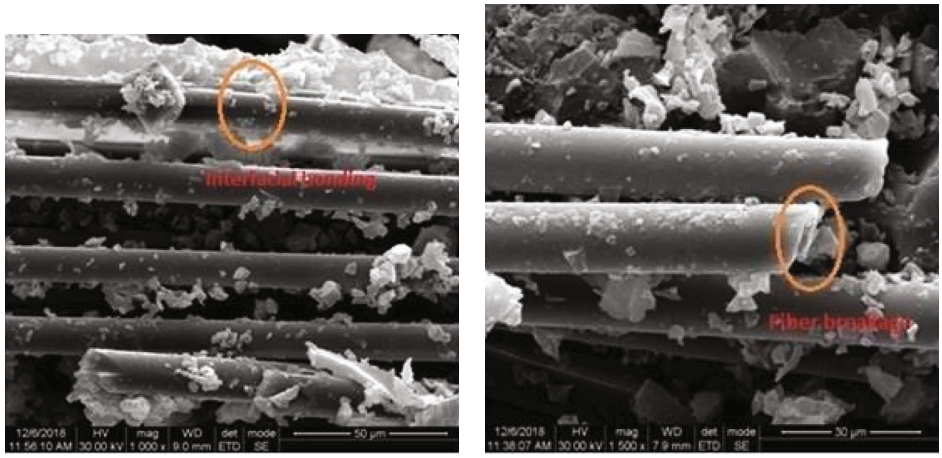
2.5.2. Flexural Testing. The samples of standard dimension were subjected to the above test at three-node bending using the UTM concerning ASTM-D-790, 1 mm/min.

2.5.3. Impact Testing. The impact strength was analyzed from the sample, $63.5 \times 12.7 \times 3$ mm^3. The test was carried



(a) (b)

Figure 2: FESEM micrographs. (a) 1.5 wt.%. (b) 2 wt.%.



(a) (b)

Figure 3: Tensile fracture surface micrograph. (a) 1.5 wt.%. (b) 2 wt.%.

in an Impactometer XJJU-50, India, as per ASTM_D-256 with a notch angle (45°).

2.5.4. Dynamic Mechanical Analysis. It was performed in SEIKO DMAI-DMSC 6100, which is a dynamic mechanical analyzer. The test was made at bending mode of three nodes and different frequencies. The experiment was performed in a nitrogen atmosphere with temperature from area temperature up to 200°C and 1°C/min.

2.5.5. Wear Analysis. This has been carried out using the pin-on-disk instrument (Ducom TR 20). The experiment was carried out at ASTM-G99 standard. Load of 2 kg was given at velocity and sliding distance of 2.5 m/s, 5000 m. The specific wear rate was evaluated.

$$\text{Specific wear rate} = \frac{{}^{v}\text{m}^3/\text{Nm}}{L * D}. \quad (1)$$

Table 1: Tensile property of nanoparticle reinforced epoxy composites.

Nanoparticle content (wt.%)	Tensile strength (MPa)	Tensile modulus (MPa)
0	80.93	5036.09
1.0	88.79	6627.18
1.5	97.19	7787.44
2.0	95.23	7422.17

3. Result and Discussion

3.1. XRD Analysis. Morphological characteristics and dispersion of nanoparticles in epoxy resin were examined by performing the XRD test. The XRD pattern for nanographite shown in Figures 1(a) and 1(b) shows the XRD pattern of different laminates. Braggs law ($2d\text{Sin}\theta = n\lambda$) was used to calculate d001 spacing. It has been clear from Figure 1(a) that nanographite exhibits 2.01 Å d-spacing. In the pattern

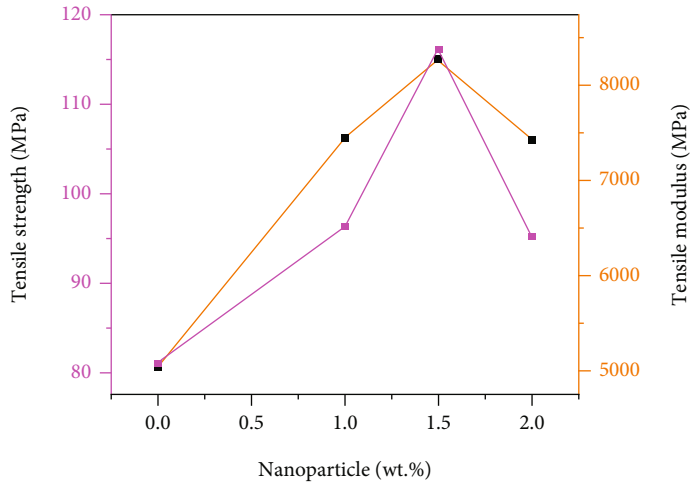


Figure 4: Mechanical properties of the epoxy nanocomposites.

of neat epoxy and nanoparticle reinforced composites, characteristic basal reflection was not shown as examined in Figure 1(b). Hence, from observation, the nanoparticle was dispersed uniformly into matrix and diffraction peak resulted in a better structure. This also depended on reinforced nanoparticles in the matrix. The 2% nanoparticle reinforced composite Figure 1(b) shows a broad peak indicating intercalated structure. This could be due to dispersion difficulty and exfoliated structure and agglomeration on increasing filler quantity further than a specific value. The peak shown in the XRD discloses the dispersion of nanoparticles. Since the 2% sample shows a broad peak comparatively, it can be suggested for intercalated structure. On increasing the volume fraction of nanoparticles, the structure tends to change is described in this scenario.

3.2. Morphology. Nanographite circulation into the composite is shown in Figure 2. The FE-SEM micrograph of the fracture area with nano-G content by weight % was reported in Figure 3. FESEM images supported the effects of nanoparticle addition on mechanical properties [25, 26]. The nanoparticle has been dispersed evenly, shown in Figure 2. There is a hint of decreased matrix bonding for the neat epoxy composite, which was observed in Figure 3, due to the pulling-out nature of the fiber. However, when the nano-G particle of 1.5 wt.% was added, the improved bonding strength has been seen in Figure 3(b). This can be inferred due to the better dispersive nature of the nanoparticle in the matrix system. And also, the components are in excellent interaction [27, 28].

3.3. Tensile Testing. The property mentioned above of the glass fiber reinforced hybrid nanocomposites is displayed in Table 1, Figure 4. Observation reveals that the ratio of stress and strain increases with the addition of nano-G to the epoxy matrix [29, 30]. The tensile strength increases and reaches the maximum value (97.19 MPa) at 1.5 wt.%. Nano-G and glass fiber reinforced epoxy composite show markedly maximized results because of the fortification of integrity between filler and matrix, which has allowed composite phases with good stress distribution [31]. Similarly, it has been investigated for mechanical properties of clay-induced nanocomposite reinforced with glass fabrics. With the increase in nano-G, there was a slight decrease in values from 1% to 1.5%.

The nanocomposite gave maximum tensile strength by around 16.8%, and the composite containing 2% nano-G recorded tensile strength hardly 11% better than bare composite. The filler-filler interaction that resulted in agglomeration could be attributed to this decrease in tensile strength. The agglomerates make weak points which may tend to pull out easily. Thus, composites at higher nano-G loading (2%) revealed a decline in tensile strength and modulus—the fine structure for 1.5 wt.% of the nanoparticle is due to improved matrix-fiber adhesion between fiber and matrix, which has been evident from Figure 5. When a matrix has been made with high particle content (2%), the quantity of pulled-out fiber was increased comparatively which was in agreement with the formation of agglomerates.

3.4. Flexural Testing. Flexural strength for glass fiber and nano-G included epoxy composite was given in Table 2 and Figure 6. The strength of the reinforcement dominated flexural strength. There has been improvement in flexural strength comparatively, with the inclusion of nano-G. This could be most likely due to the inappropriateness of nano-G mixing within the matrix. Nanoparticle reinforced composite revealed growing flexural properties at all compositions of the nanoparticle. Hybrid nanocomposite composed with 1.5% nano-G exhibited better results. The bending strength improved to 13.8%. This enhancement in flexural strength has been attributed to the exfoliated structure, which means lowering the polymer deformation.

3.5. Impact Testing. The values of impact strength were given in Table 3, and dissimilarity concerning nanoparticles was shown in Figure 7. Fiber and matrix deformity, fracture, and pull-out influence the impact. A crack could propagate towards an impoverished interfacial region for the sample

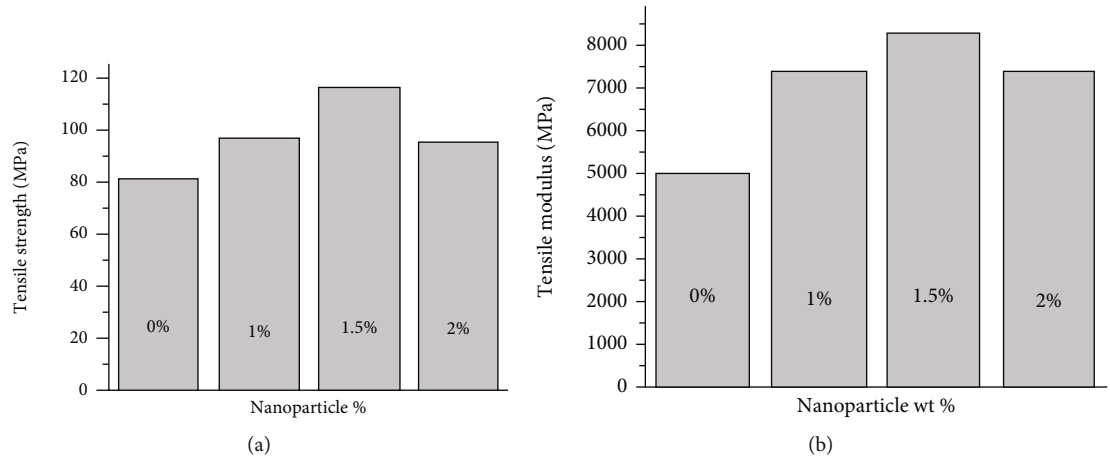


Figure 5: Mechanical properties of the nanocomposite: (a) tensile strength and (b) tensile modulus.

Table 2: Flexural property of nanocomposites.

Nanoparticle content in epoxy glass fiber reinforced composite (wt.%)	Flexural strength (MPa)
0	15.37
1.0	21.87
1.5	22.79
2.0	19.63

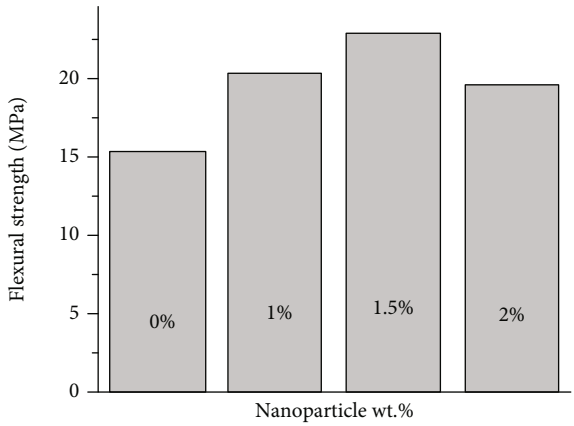


Figure 6: Flexural strength of the epoxy nanocomposites.

Table 3: Impact properties of nanoparticle reinforced epoxy composites.

Nano particle content in epoxy glass fiber reinforced composite (wt.%)	Impact strength (J/m^2)
0	4.0
1.0	8.4
1.5	9.2
2.0	6.1

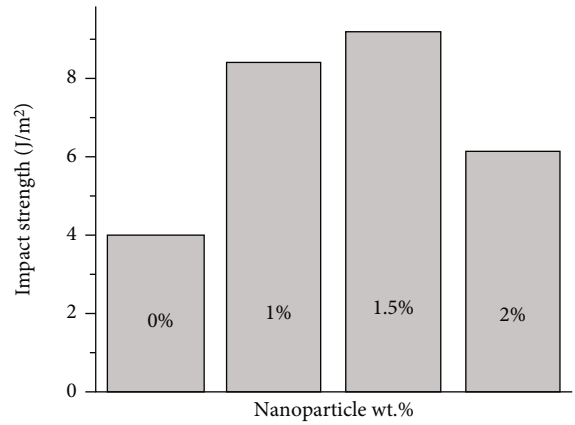


Figure 7: Impact strength of the epoxy nanocomposites.

with minimum fiber-matrix bonding. Whereas mobility of the particles has been hindered that results in a brittle nature. From Table 3, impact strength has been higher than bare epoxy. This was because crack propagation is subdued by reinforced glass fiber during impact load. After all, glass fibers check the crack, and power is used to pull out glass fiber from resin at the time of impact. This decrease in energy has shown improved impact strength. Also, it is because of the effect of nanosized particle reinforcement and intercalating structure. The hybrid epoxy nanocomposite made at 1.5% of nano-G content exhibited maximum strength. Around 15% increase in impact strength was achieved. This confirms the effective dispersion and adhesion of nanoparticle in matrix.

4. Dynamic Mechanical Analysis

4.1. Storage Modulus. The storage modulus gives the capacity of a composite to withstand load (E1) is. Variation of E1 concerning heat is shown in the figure. E1 for neat epoxy composite increased when nano-G was reinforced, which is seen in Figure 8. The storage modulus increases to the maximum extent of 75% for epoxy composite with

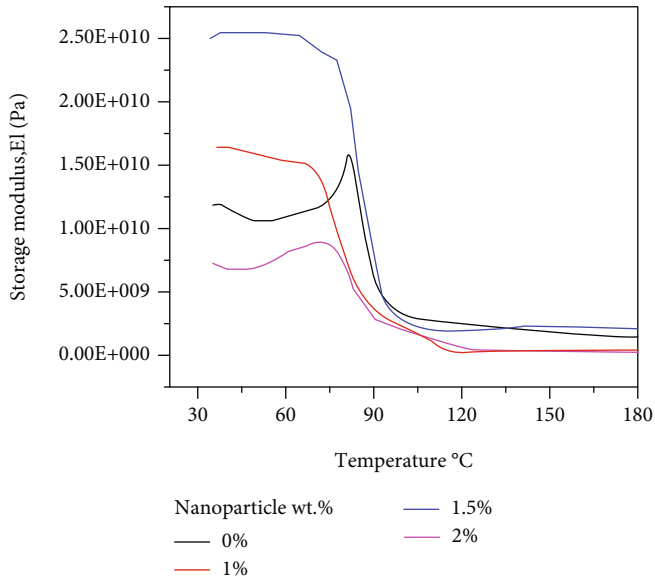


Figure 8: Storage modulus vs. temperature plot for the epoxy nanocomposites.

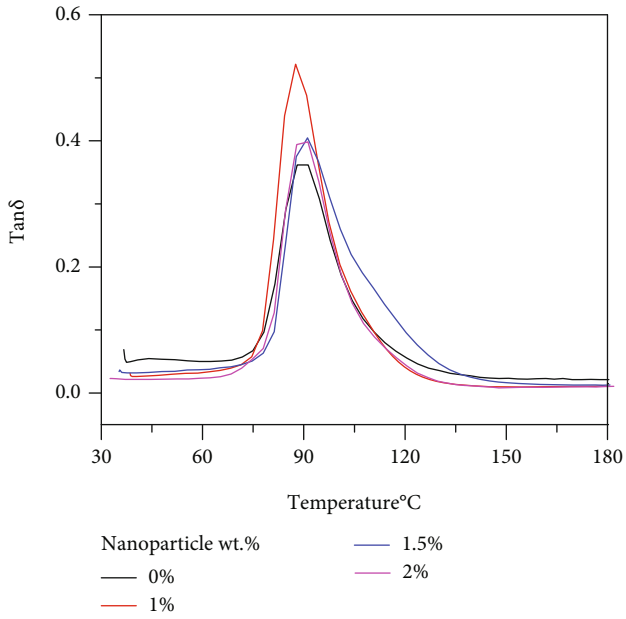


Figure 9: Tanδ vs. temperature plot for the epoxy nanocomposites.

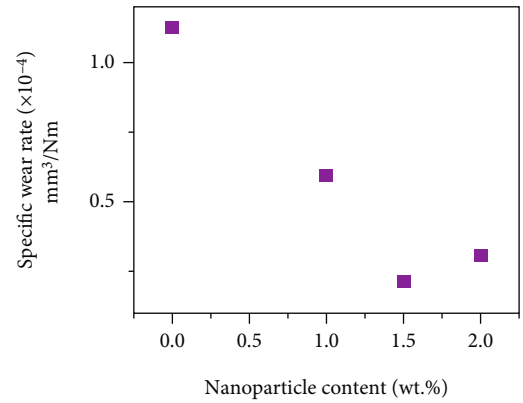
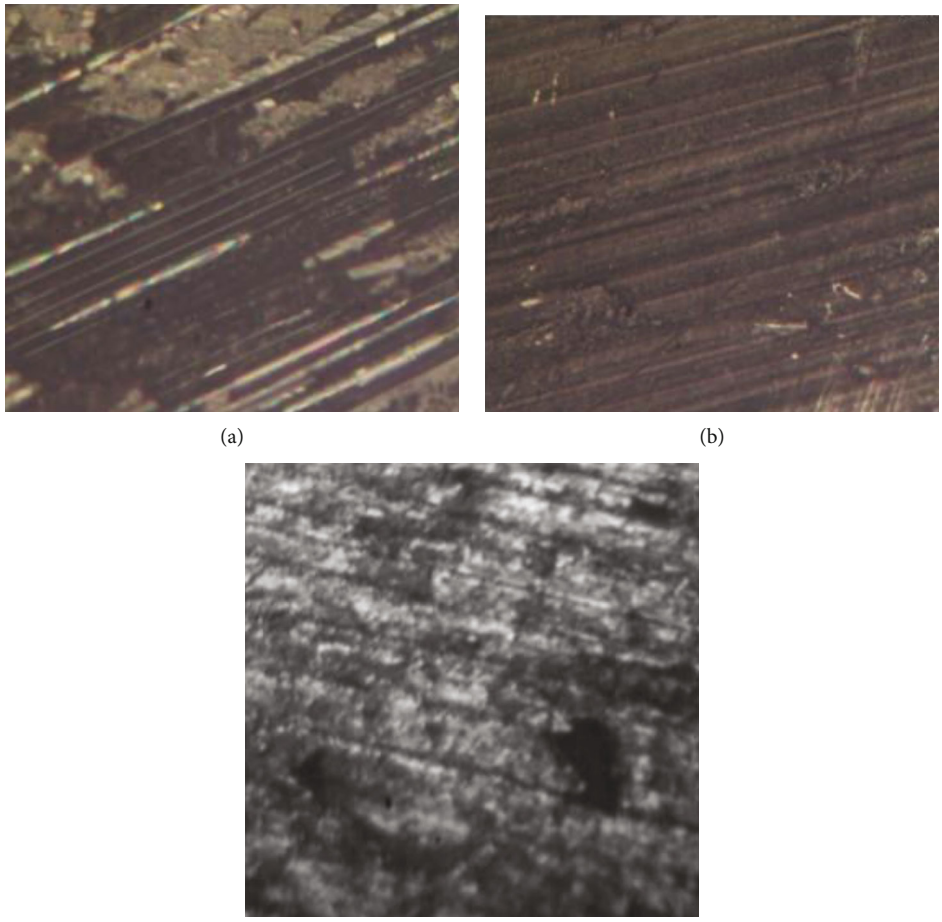


Figure 10: Specific wear rate for the CSM glass and nanographite reinforced epoxy nanocomposites.

reinforcement of 1.5 wt.% nanoparticles. The interfacial bonding of matrix imparted with the help of nano-G nanoparticles and higher transfer of stress. This behavior would be primarily attributed to the homogeneous dispersion of nanoparticles in the polymer. The shift in the glass transition temperature might be attributed to the restriction of the matrix on nanoparticle addition. This behavior explains the effect of the nanoparticle on the glass transition temperature and the material behavior.

4.2. Damping Factor (Tanδ). Tanδ of the material gave the phase equilibrium of the polymeric structure. The glass transition temperature, T_g of the samples is analyzed from max out tanδ. Figure 9 shows the strengthening of nano-G shifts T_g value higher. This trend might be due to the restraint of the matrix in the presence of nanoparticles. The glass transition temperature, T_g increase with nanoparticle addition to utmost of 89.5°C is obtained for 1.5 wt.%.

4.3. Wear Analysis. The specific wear rate of various composites has given in Figure 10. The epoxy polymer composite without nanocontent gives 0.6051×10^{-4} mm^3/Nm value. Figure 11 shows an optical microscopic view of worn-out surfaces. It was observed that few particles have left out from the surface resulting in voids. On adding a higher amount of nanoparticles, the value decreased. The most negligible value of 0.1928×10^{-4} mm^3/Nm is determined for 1.5 wt.% of nanoparticle content. Figure 11(b) reveals minimum worn had taken place. This could be due to better interfacial interactions. The clusters of nanoparticles could be easily removed in underwear. This could be figured out on the



(a) (b) (c)

Figure 11: Optical micrograph of wear rate of the CSM glass and nanographite reinforced epoxy nanocomposites. (a) 0 wt.%. (b) 1.5 wt.%. (c) 2 wt.% nanocontent.

addition of a higher quantity of nanoparticles. Figure 11(c) shows similar phenomena. The appropriate quantity of nanoparticles can avoid this.

5. Conclusion

Hybrid composite toughened with chopped strand mat, and nanographite was prepared mechanically at varying content of nano-G. Tensile, impact, and flexural strength were enhanced in variation with the content of nano-G. The XRD analysis showed fine dispersion nature in the composite. The most significant value of 97.19 MPa, 22.8 MPa, and 9.2 J/m^2 was obtained. The transition temperature (T_g) and damping factor amplified with the amount of reinforcement. The optimal E^1 and T_g of 1.44×10^4 MPa and 89.5°C have been achieved for composite reinforced with 1.5 wt.% nanographite. A minimum specific wear rate was obtained for 1.5 wt.% nanographite-reinforced laminate. FESEM aided significant improvement in properties of the nanocomposite. It visibly revealed the homogeneous interaction between nanoparticle, glass, and matrix. The results reveal the dispersion of nanoparticle plays a major role in the mechanical properties of the composites. The nanoparticles are significant as it greatly enhances the mechanical properties. Significant improvement in properties of the nanocomposite was aided by FESEM. It visibly revealed the homogeneous interaction between nanoparticle, glass, and matrix. Nanographite and chopped strand mat/epoxy silica composite showed maximum enhancement in mechanical properties over those of neat epoxy composite due to their better interfacial interaction between epoxy chains, glass fiber, and nanoparticle. In conclusion, nanographite and chopped strand mat/epoxy composite showed maximum enhancement in mechanical properties due to their enhanced interfacial contact between epoxy chains, glass fiber, and nanoparticles.

Data Availability

The data used to support the findings of this study are included within the article. Conflicts of Interest.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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