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Research Article

Tribological Characterization of Epoxy Hybrid Composites Reinforced with Al_2O_3 Nanofiller

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The addition of fillers to polymer composites induces a positive influence on the mechanical and tribological properties of the hybrid composites. These properties can be validated for possible uses such as automobile, construction, shipping, aerospace, sports equipment, electronics, and biomedical domains. In the present research, epoxy matrix reinforced with nylon-6 fibers and glass fibers were prepared using the solution blend technique. Alumina nanoparticles are added as fillers to enhance the properties of epoxy hybrid composites. The large surface area of interaction of nanofillers exhibits better adhesion between matrix and fibers of composites, and it significantly affects the various properties of composites. The tribological characteristics of fabricated epoxy hybrid composites were evaluated under various parameters and conditions. The results revealed that the addition of nanofiller significantly reduces the wear loss of epoxy hybrid nanocomposites. The wear resistance of epoxy hybrid composites increased with increase in addition of nanofiller up to 1.0%, and it slightly decreased with the further addition of filler. The Taguchi analysis was carried out for the least coefficient of friction and specific wear rate. The analysis found that the specific wear rate and coefficient of friction mainly depend on load, followed by speed and nanofiller. The fractured and worn surface of Al_2O_3-filled epoxy hybrid composites was analysed using SEM.

1. Introduction

In recent years, polymer composites with more than one reinforcement have been used in various mechanical and structural applications due to their tailored mechanical properties. Hybrid polymer composites derive the advantages of both primary and secondary reinforcements to enhance the properties of polymer composites. Therefore, these materials are chosen as possible replacements for the components used to make aircrafts, automobiles, and wind turbines and their components. In addition, the inclusion of particles as fillers in hybrid composites achieves better mechanical properties because the fillers govern the interface quality between the matrix and reinforcements [1]. The mechanical properties of hybrid polymer composites also depend on the type, size, and quantity of particles used as filler. Nanoparticles have an incredibly excessive surface to volume ratio which generally makes adjustments in their properties as compared to their bulk form equivalents [2]. The interaction between nanoparticles and the polymer material is high due to the higher surface to volume ratio. Also, the nanoparticles and polymer form a good bond between them, which may influence the polymer properties to a great extent. Nanosized particles exhibit better properties that cannot be obtained by conventional filler. The energy dissipation by wear damages intensely to the material property and effectively decreasing the control of wear is always desired [3, 4].

Wear properties of any engineering materials mainly contingent on load, speed, material hardness and existence of cross link material, also operating temperature and condition [5]. The load and sliding velocity during pin-on-disc testing method are the main parameters which effect the wear rate of composites, and the aluminium hybrid composites shows low wear rate compared to the composite with low weight percentage of the silicate particle reinforcement [6]. Polymer based composite have widespread application in the agricultural field and industries. In these places abrasive wear contributes to principal mode of failure in various applications such as conveyors, gears, bearings, bushes, seals etc. are some [7]. Low cost and easily available fillers should improve the mechanical characteristics of the composites. Addition of nanofiller improves the mechanical properties, thermal and tribological characteristics of polymer matrix composites due to the good dispersion of fillers in the matrix, the addition of a lesser amount of nanofillers in polymer matrix will lead to be more optimal to increase the properties of composites [8, 9].

Type of filler and polymer plays the critical role on tribological properties of FRP with microsize fillers. The study of frictional parameters and contact resistance of the materials revealed that load applied, track radius on disc, testing time and operating temperature are considered as parameters to regulate the test atmosphere [10–12]. Under adhesive wear condition, either thermoplastic or thermoset will not exhibit any general wear or frictional tendency. However, the majority of thermoplastic polymers produce a film transfer on the metal counterface, it leads to improve the frictional and wear properties of materials. In thermoset polymers, the frictional and wear properties of materials is determined by the wear track modification occurred in counter material. The addition of fillers or fibers improves the surface strength of polymers, which improves the tribological behaviour of the polymer, especially the thermoplastic [13]. The nano-SiO_2 amplified the maximum elongation of the glass-fiber-PA6 composites, whereas the tribological properties of Polypropylene (PP) composites also influenced with addition of secondary filler [14]. Addition of Al_2O_3 as reinforcement in Nylon-6 composites shows improved structural and mechanical properties. With increase in addition of Al_2O_3 to higher percentage leads to reduction in frictional coefficient and wear loss of material [15].

Various concentrations of Al_2O_3 nanoparticles in the polymer matrix increases tribological properties without compromising the mechanical properties is essential. Hence an attempt is made to increase the tribological properties using nanohybrid composites. The resin matrices offer physical characteristics and nanomaterials, which increase surface area the research has potential to enhance the property of a composite.

2. Materials and Methods

The materials and methods used to conduct this study is explained in the following sections.

2.1. Materials and Fabrication. The epoxy hybrid polymer composite used in present investigation the epoxy (Resin-Araldite LY-556 and Hardener-HY 951 in 10 : 1 ratio) as a matrix material with reinforcement of glass fibers and nylon fibers. The Al_2O_3 nanoparticles (size range 30–50 nm) were used as filler materials. The investigating epoxy hybrid composites were fabricated using open moulding technology. A mould of 250 mm × 250 mm x 4 mm was coated with mould releasing agent were used for composite manufacture. The amount of epoxy resin was selected as per rule of mixture and it preheated about 80°C to 90°C and required amount of Al_2O_3 nanofillers dispersed uniformly in epoxy matrix using ultrasonic mixing technology along with 15 wt.% of Glass fiber and 15 wt.% of nylon fiber. EDS scanning results show that composition of a material predominantly consisted of aluminium from the large peaks, and it also contains copper and gold from the sputtering process shown in Figure 1. The size of the Al_2O_3 nanofillers 30–50 nm and density is 3.9 gm/cc (* from manufacturer's catalogue).

In present investigation, epoxy hybrid composites 0.5, 1.0, and 2.0 wt.% of Al_2O_3 was used as filler. The higher weight percentage of fibers/filler leads to agglomeration of fibers/filler, which leads to decreases the potential improvement of mechanical properties of polymer composites, because of the reduction in interfacial area [16]. The uneven dispersion and reduction in interfacial bonding of fibers/fillers in the matrix causes the decrease in overall strength of polymer matrix composites and nanofiller loses its effectiveness [17].

The sonicated mixture was poured into mould, which has been coated with releasing agent and compression loading is applied on mould for uniform pressure distribution show in Figure 2.

The mould is allowed for curing under applied pressure for 24 hours at room temperature and followed by post-curing at 100 ± 5°C for 2 hours using hot air circulated furnace Postcuring is helpful to complete the polymerization process and complete the incomplete bonding of polymers [18, 19]. The fabricated composites plate of 4 mm thickness was cut into required size of 10 mm × 10 mm as per ASTM standards. The composition of fabricated composites is shown in Table 1.

2.2. Experimental Procedure

2.2.1. Hardness Test. Hardness of fabricated composites were determined using Barcol Hardness tests according to ASTM D 2583 shown in Figure 3. The specimen dimension of 20 mm × 20 mm × 4 mm is used for the measurement according to the ASTM standard.

2.2.2. Impact Test. Impact strength of epoxy hybrid composites were determined according to ASTM D256 using computerized impact testing machine shown in Figure 4.

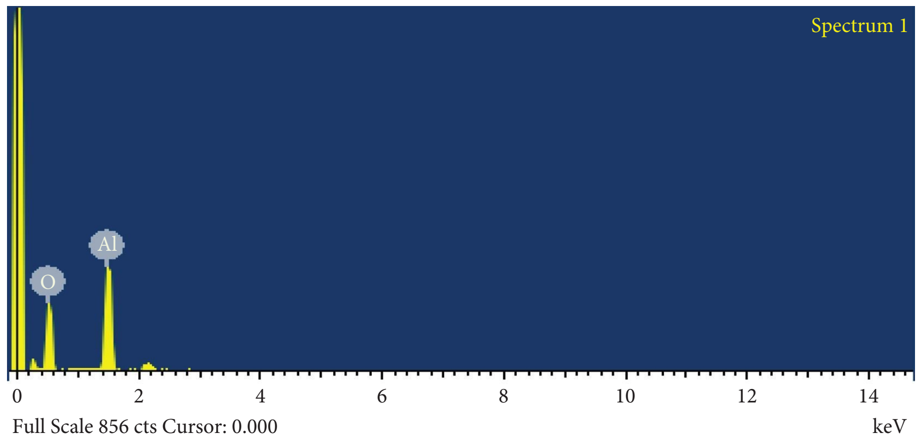


Figure 1: Elemental composition present in Al_2O_3 nanofiller.

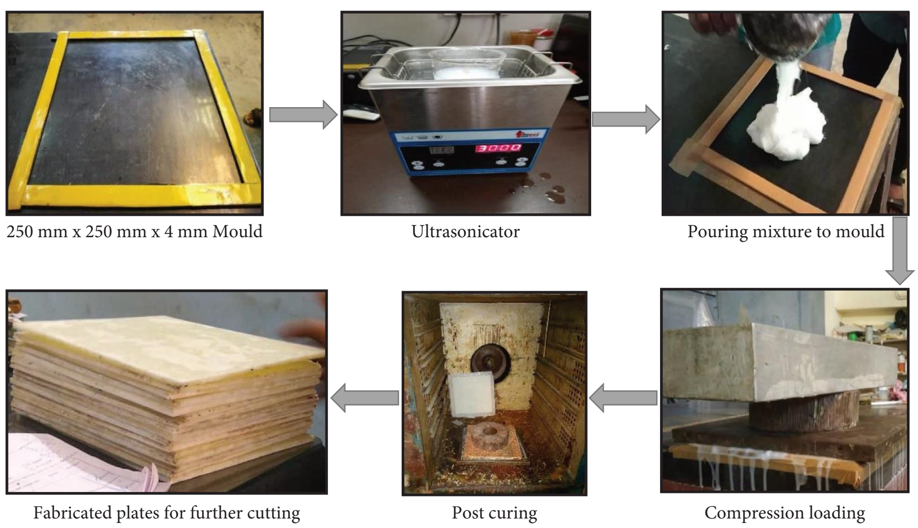


Figure 2: Fabrication process of epoxy hybrid composites.

Table 1: Composition of fabricated composites.

Composite designation	Epoxy (wt %)	Glass fiber (wt %)	Nylon fiber (wt %)	Al_2O_3 (wt %)
0	70	15	15	0
0.5	69.5	15	15	0.5
1	69	15	15	1
1.5	68.5	15	15	1.5
2	68	15	15	2

Figure 3: Barcol hardness tester.

The pendulum, which was set to a specific height, tripped and collided with the specimen on the other side of the notch, resulting in a shattered specimen. According to the Joule unit, absorbed energy had to produce the fracture surfaces. The specimen dimension of 63 mm × 12 mm × 3 mm is used for the measurement according to the ASTM std.

2.2.3. Wear Test. Tribological properties are wear loss; specific wear rate and coefficient of friction of fabricated composites were carried out as per ASTM G99-17 using pin-

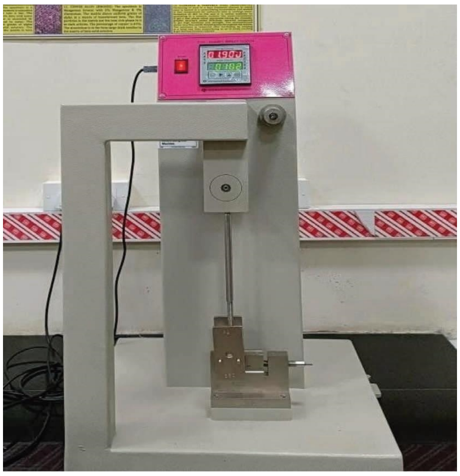


Figure 4: Impact testing machine.

on-disk apparatus under abrasive wear condition [20, 21]. The prepared specimen attached to pin at on surface and disc surface covered with abrasive paper (Grit number 320) to achieve the abrasive wear condition. The specimen attached pin abraded against abrasive disc under different loading conditions such as 20 N, 40 N, and 60 N and various speeds of 1200, 1500 and 1800 rpm at constant time of 10 minutes and track diameter of 100 mm.

Figure 5(a) shows the pin-on-disc apparatus, and Figure 5(b) shows the specimen holder. The initial weight and final weights were analysed for the samples to find the wear loss. Average value of three tests conducted for each specimen is recorded. Wear volume (FV) and specific wear rate (K_s) were calculated from equations (1) and (2):

$$\Delta V = \frac{\Delta m}{\rho}, \tag{1}$$

$$K_s = \frac{\Delta V}{L d}, \tag{2}$$

where "Δm" represents mass loss in g, "ρ" represents density of the test material in g/cc, "ΔV" represents the volume loss in m^3, "L" is the load in Newton, and d is the sliding distance in meters.

The densities of the composites were calculated by an experimental method. The wear study is done using three parameters, coefficient of friction (COF), wear loss, and specific wear rate for various nanofiller percentages, different speeds, and load conditions.

2.3. Wear Mechanism. Adhesive wear occurs when the asperities experience significant plastic deformation as a result of the combined action of adhesion between surfaces and sliding motion. When dissimilar materials are in contact, adhesive wear causes the particle transfer from cohesively weaker of the material to stronger. Equation (3) shows Archard's equation, which describes the phenomena of adhesive wear processes:

$$V = K\frac{WL}{3H}. \tag{3}$$

Archard's equation consists of the material hardness as the only material property. Archard's wear coefficient K depends on several parameters, such as type of material, type of wear, and relative motion between surfaces.

3. Results and Discussion

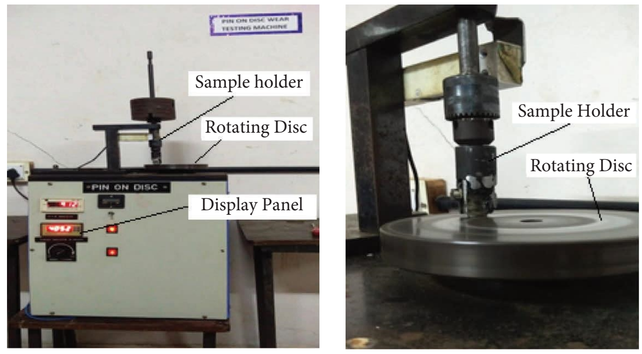
The results and discussion are discussed as follows.

3.1. Hardness. Hardness is the key factor influencing the wear resistance of the material. Higher hardness of the material shows the better wear resistance property. The hardness of the fabricated hybrid composites is mainly dependent on the surface of the material, which consists of glass and nylon fibers along with Al_2O_3 nanofillers.

The variation of hardness of epoxy hybrid composites with different weight percentages of Al_2O_3 nanofillers is shown in Figure 6. The hardness of epoxy hybrid composites is improved significantly with increase in amount of Al_2O_3 nanofillers. From the results, it is found that the addition of 2 wt.% of Al_2O_3 nanofillers to epoxy hybrid composites results in better hardness than unfilled epoxy hybrid composites. From the results, it is observed that the intensification of hardness is directly related to the amount of addition.

3.2. Impact Strength. The impact strength of the epoxy hybrid composites is largely governed by the toughness of individual constituents of the composites as well as other various factors such as the length of short fibers, aspect ratio of fibers, size and shape of Al_2O_3 nanofillers, filler loading, and interfacial bonding strength between matrix-fiber-filler. Short fiber-reinforced polymer composites exhibit higher impact strength at high aspect ratio of fibers. The higher aspect ratio of fiber causes an increase in the surface area to volume ratio, which leads to an increase in the interfacial strength between the fiber and matrix and hence affects the toughness and impact strength of composites [22]. The experimental results it is shown that the impact strength of epoxy hybrid composites improved with the addition of Al_2O_3 nanofillers. Figure 7 shows a progressive improvement in the impact strength of epoxy hybrid composites with the addition of Al_2O_3 nanofillers up to 2 wt.%. Glass and nylon fibers played an important role in improving the impact strength of the epoxy hybrid composites. The interfacial bond between the epoxy matrix and fibers improved with the addition of Al_2O_3 nanofillers. Due to this enhanced load transfer and better quality of interfacial adhesion between matrix and fiber, more energy was required to pull the fiber from the epoxy matrix.

3.3. Coefficient of Friction (μ). The coefficient of friction measures the resistance to the friction, which is associated to the effect of surface roughness. The force of friction between two bodies and the forces acting together are functions of the type of constituents used. The coefficient of friction of



(a) (b)

FIGURE 5: Pin-on-disc apparatus.

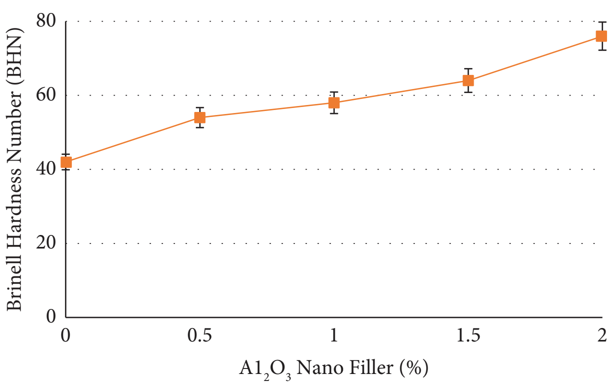


FIGURE 6: Hardness of epoxy hybrid composites.

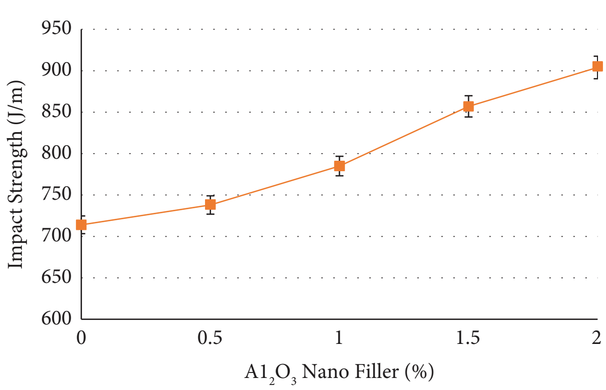


FIGURE 7: Impact strength of epoxy hybrid composites.

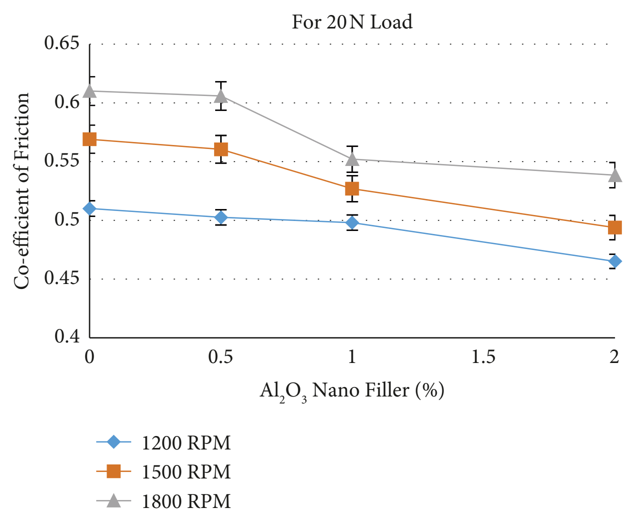


FIGURE 8: Coefficient of friction of epoxy hybrid composites at 20 N load.

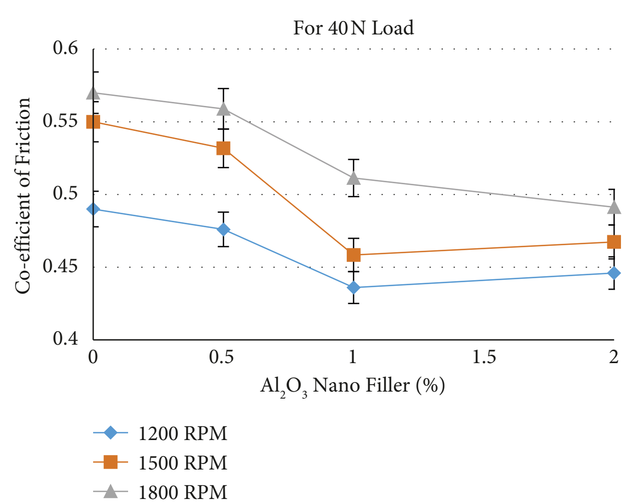


FIGURE 9: Coefficient of friction of epoxy hybrid composites at 40 N load.

fabricated epoxy hybrid composites with 0, 0.5, 1.0, and 2.0 wt.% of Al_2O_3 nanofiller was tested under different load and speed environments. The effects of nanofiller, load, and speed on the coefficient of friction of epoxy hybrid composites were studied.

Figure 8illustrates the effect of Al_2O_3 nanofiller and speed on the coefficient of friction of epoxy hybrid composites at 20 N load. The graph shows the coefficient

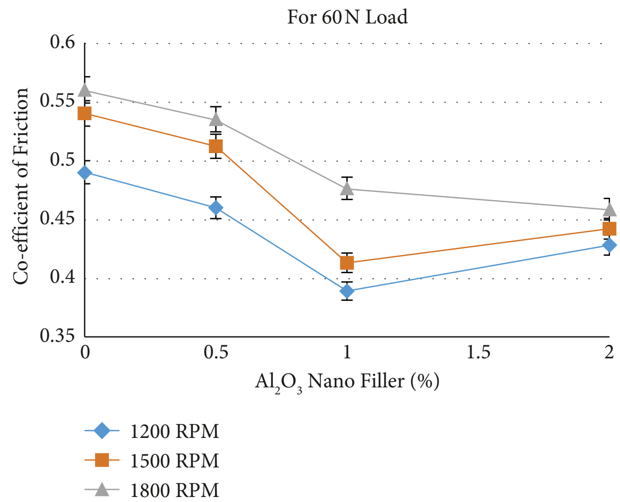


Figure 10: Coefficient of friction of epoxy hybrid composites at 60 N load.

Table 2: Response table for signal-to-noise ratios for coefficient of friction.

Level	Al_2O_3 (%)	Load (N)	Speed (rpm)
1	5.594	5.589	6.853
2	6.546	6.288	6.242
3	6.576	6.839	5.621
Delta	0.982	1.25	1.232
Rank	3	1	2

of friction of the epoxy composites decrease with upsurge in addition of Al_2O_3 nanofiller and it increases with increase in speed. Similarly, Figures 9 and 10 show the effect of Al_2O_3 nanofiller and speed on the coefficient of friction of composites at 40 N and 60 N load, respectively. In both the loads coefficient of friction of composites increases with upsurge in speed. The coefficient of friction of epoxy hybrid composites decreases with the addition of Al_2O_3 nanofiller up to 1.0 wt%. Further increases in the addition of Al_2O_3 nanofiller up to 2.0 wt.% filler lead to a decrease in the coefficient of friction. The coefficient of friction reduces as the speed increases for all loads, and it also reduces as loading increases for all speeds. The temperature at the interface increases as the applied load increases. Also, at 1800 rpm speed shows low coefficient of friction of composites than other speeds. The increase in load and speed causes the increase in temperature of interface of the material and disc under dry sliding environments. The increase in temperature in the composites leads to a reduction in the interface bonding between fiber and matrix due to the softening of epoxy at high temperatures. Also, the increased temperature due to dry sliding significantly affected the bonding of fiber and matrix, which led to debonding and failure of fiber due to shear [23].

3.4. Design of Experiments for Coefficient of Friction. The L27 array design is used as the experimental design using the Taguchi method. The experimental investigations are studied using "signal-to-noise ratio" values. The "signal-to-noise ratio" for the minimum coefficient of friction is examined as a "smaller is better" characteristic.

Table 2 shows the response values for "signal-to-noise ratio" for coefficient of friction for the hybrid composite specimens. The rank based on delta values shows load plays an important role followed by speed and Al_2O_3 nanofiller in the hybrid material plays the least important role.

Analysis is made by means of minitab-17 software in order to find the numerical implications of factors like speed, load, and nanofiller content on various wear characteristics as shown in Figure 11 and Table 1. The delta value suggests that even Al_2O_3 nanofillers have the same impact as speed and loading conditions. The coefficient of friction almost shows a reduced trend above the 1.0% of nanofiller content in the hybrid composite.

3.5. Wear Loss. The effect of addition of Al_2O_3 on wear loss of investigating epoxy hybrid composites were carried out using the pin-on-disc method under abrasive wear condition at different load and speed. Figure 12 shows the effect of the addition of Al_2O_3 nanofiller and speed on wear loss of composites at 20 N load. The graph shows speed significantly effect on the wear loss of composites; wear loss is at high speed than the low speed. Also wear loss of epoxy hybrid composites reduces with addition Al_2O_3 nano filler. The addition nanofillers enhances the wear resistance of epoxy composites and leads to a reduction in wear loss.

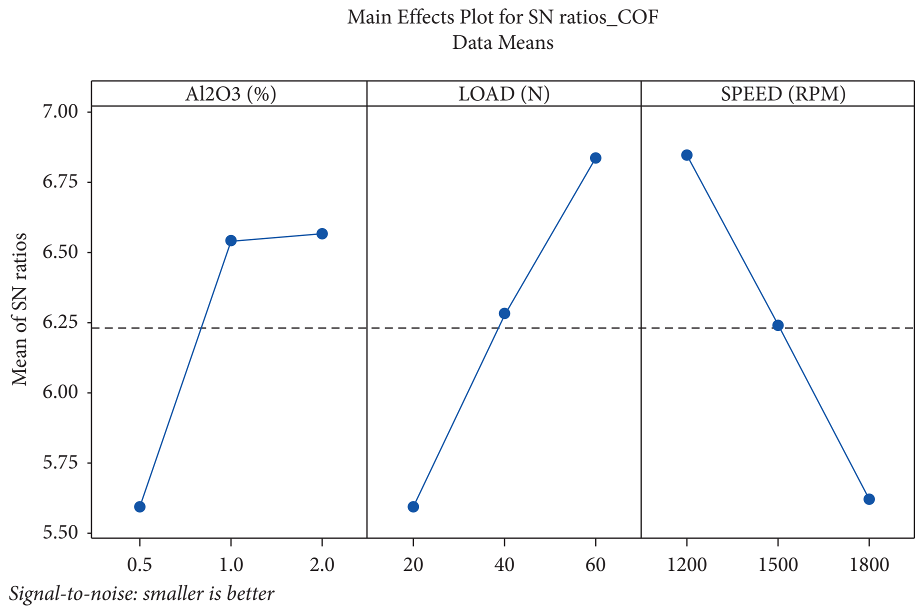


Figure 11: Main effect plot for signal-to-noise ratios for coefficient of friction.

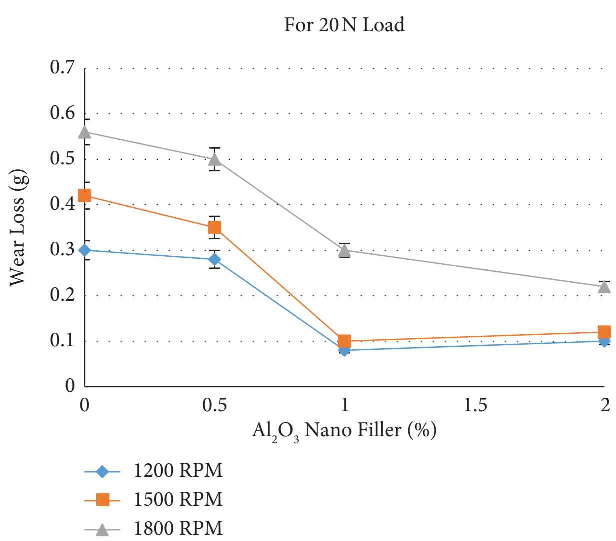


Figure 12: Wear loss of epoxy hybrid composites at 20 N load.

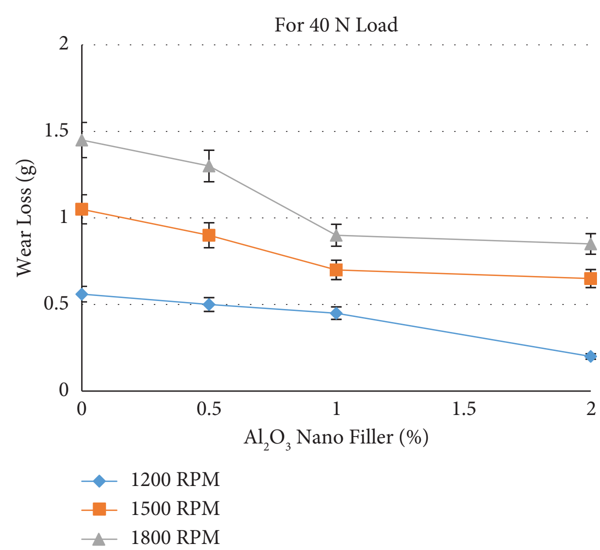


Figure 13: Wear loss of epoxy hybrid composites at 40 N load.

The similar wear loss behaviour exhibits in 40 N and 60 N loads shown in Figures 13 and 14. Wear loss of investigating composites in 40 N and 60 N at different wt.% of nanofiller loading and at different speeds shows similar behaviour such as wear loss at 20 N load. The addition of Al_2O_3 nanofiller reduces the wear loss of epoxy hybrid composites due to the addition of ceramic particle attributes that increase the toughness and hardness of the materials [24].

3.6. Design of Experiments for Wear Loss. The L27 array design is used as the experimental design for wear loss test results. The experimental investigations are studied using "signal-to-noise ratio" values. The "signal-to-noise ratio" for the least specific wear rate is observed under the "smaller is better" characteristic.

Table 3 shows the response values for "signal-to-noise ratio" for wear loss for the hybrid composite specimens. The rank based on delta values shows that load plays an important role followed by speed and Al_2O_3 nanofiller content in the hybrid material plays the least important role.

Figure 15 shows the main effect plot for "signal-to-noise ratios" for wear loss. From Figure 15, it is obvious that load plays an important role followed by speed and Al_2O_3 nanofiller content in the hybrid material. As the nanofiller percentage increases above 1.0%, the trend decreases. This type of behaviour in composites may occur due to the initial wear of the epoxy matrix from abrasion. The fibers that are exposed and the filler elements that

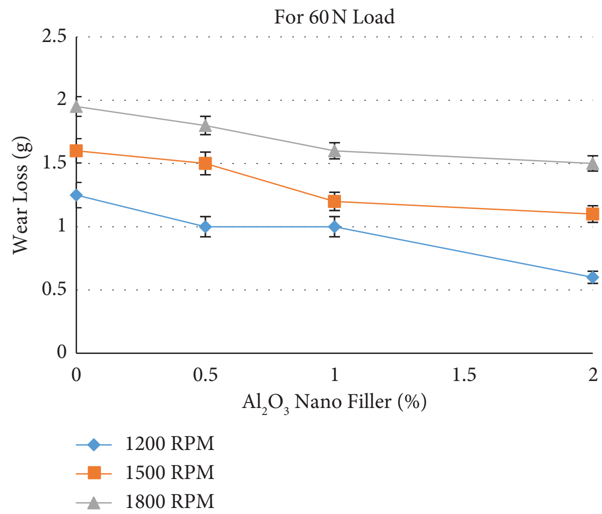


FIGURE 14: Wear loss of epoxy hybrid composites at 60 N load.

TABLE 3: Response table for signal-to-noise ratios for wear loss.

Level	Nano Al_2O_3 (%)	Load (N)	Speed (rpm)
1	2.470	14.462	9.374
2	6.409	3.860	5.484
3	7.865	−1.578	1.885
Delta	5.396	16.041	7.489
Rank	3	1	2

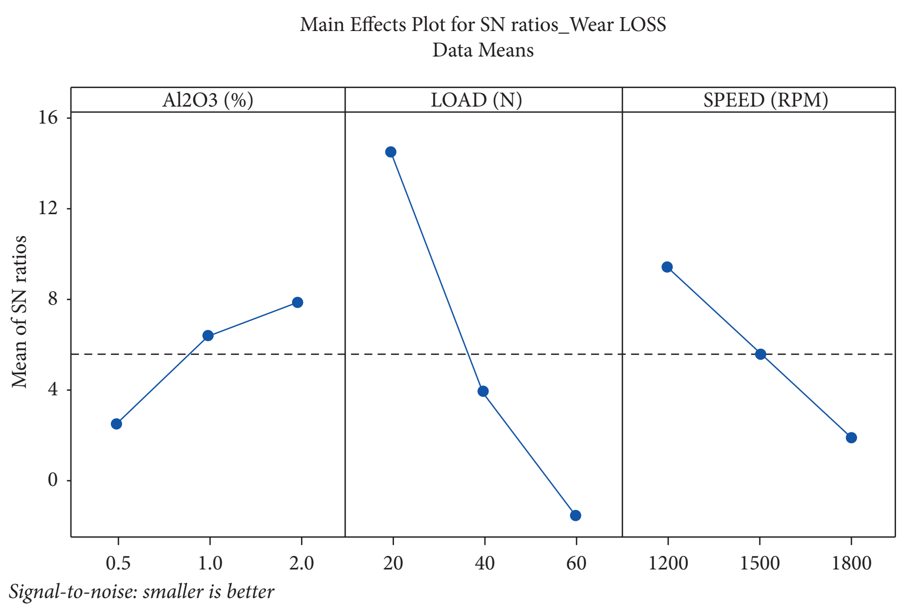
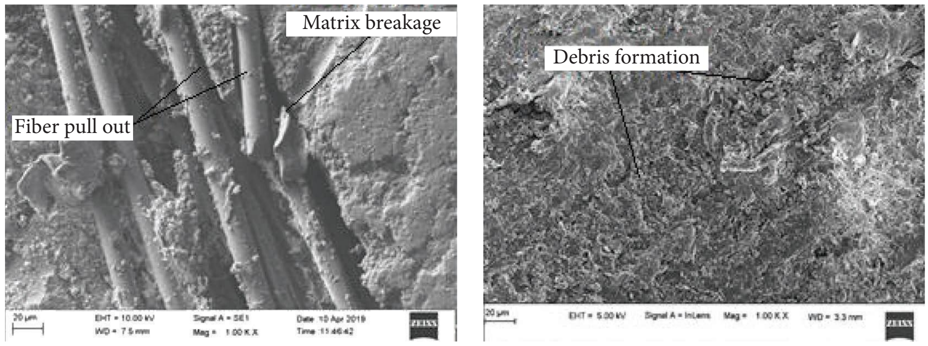


FIGURE 15: Main effect plot for SN ratios for wear loss.

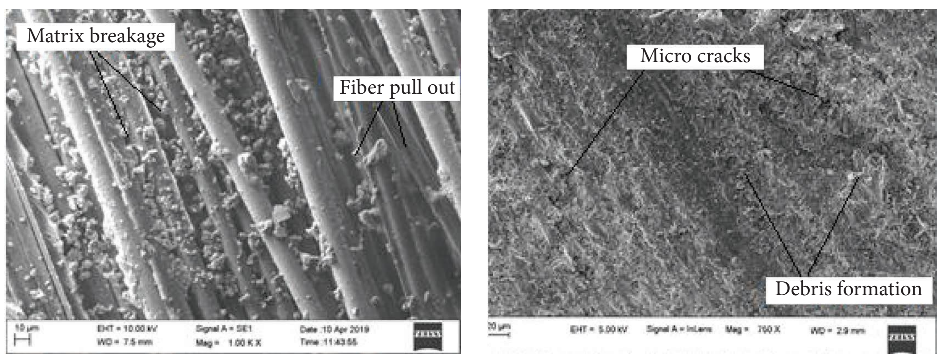
come into contact will reduce the further wear loss at higher nanofiller content.

Figures 16 and 17 show the SEM images of tested wear sample at 1.0% of nano Al_2O_3, 1200 rpm and 20 N load and 2.0% of nano Al_2O_3, 1500 rpm and 60 N load. The agglomeration of nano Al_2O_3 in the epoxy in Figure 16(a) is observed, and it leads to a weaker matrix filler interface and nonuniform dispersion of fillers at higher percentages of filler addition. After the preliminary abrasion of matrix material, the exposed fibers will wear out; further wear loss is being restricted. At higher loads, delamination between fiber and matrix caused severe damage to the fibers; crushed and fragmented fibers were observed. Figure 17(a) shows the fibers breakage but not being pulled out of the matrix



(a) (b)

Figure 16: SEM results of wear samples at 1.0% of Al_2O_3 nanofiller at 1500 rpm and 20 N load.



(a) (b)

Figure 17: SEM results of wear samples at 2.0% of Al_2O_3 nanofiller at 1500 rpm and 60 N load.

completely. Figures 16(b) and 17(b) show the debris formation in the samples may be due to heat produced by the surface.

4. Conclusion

The epoxy hybrid composites filled with different wt.% of Al_2O_3 nanofiller were fabricated using open moulding technology. The fabricated epoxy hybrid composites were tested for hardness, impact strength, and tribological properties under abrasive wear conditions using the pin-on-disc method. Experimental results have shown that the addition of Al_2O_3 nanofiller improves hardness, impact strength, and tribological properties such as wear loss and coefficient of friction. The addition of Al_2O_3 nanofillers significantly enhanced the hardness and impact strength of epoxy hybrid composites due to the fact that Al_2O_3 nanofillers have a higher stiffness than the epoxy matrix. The wear loss and coefficient of friction of investigating composites reduced gradually with upsurge in addition of nanofiller at lower loadings. At higher load conditions, the coefficient of friction of composites decreases up to 1.0 wt.% with the addition of nanofiller and increases further with the addition of nanofiller. Because of uniform distribution of Al_2O_3 nanofiller will be achieved up to 1% and further addition of fillers may leads to agglomeration and distribution of more particles in surface area is limited. In specific wear rate the load plays a significant role followed by Al_2O_3 nano filler content in the hybrid material and speed plays least role. The increased temperature at the interface reduces the bonding of fibers in the matrix, which leads to easier shear at higher axial thrust. From the coefficient of friction response, it is obvious that load plays an important role followed by speed, and filler content in the hybrid material plays the least important role.

Data Availability

No data were used to support the findings of the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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