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Research Article

Modeling and Analysis for Wear Performance in Dry Sliding of Epoxy/Glass/PTW Composites Using Full Factorial Techniques

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The dry sliding friction and wear behavior of epoxy hybrid composites reinforced with glass fibers and a varying amount of potassium titanate whiskers (PTWs) fabricated by vacuum hand layup method were studied. The influence of normal load, sliding velocity, and whisker content on both friction coefficient and specific wear rate was investigated on a pin-on-disc machine. The tests were conducted at ambient conditions based on the 3×3 (3 factors at 3 levels) full factorial design. Analysis of variance (ANOVA) was performed to obtain the contribution of control parameters on friction coefficient and wear rate. The density and hardness of the composites were found to be enhanced with the PTW loading. The friction coefficient and wear resistance of the hybrid composites were found to be improved with the whisker content and were also greatly influenced by normal load and sliding velocity. A correlation between dry sliding wear behaviors of composites with wear parameters was obtained by multiple regressions. The worn out surface of selected samples was observed under scanning electron microscope (SEM) to identify wear mechanisms. This study revealed that the addition of the ceramic microfillers such as PTW improves the wear performance of the epoxy/glass polymer composites significantly.

1. Introduction

Polymer matrix composites (PMCs) are nowadays considered as novel materials in many engineering applications due to the combination of advantages such as high strength to weight ratio, high stiffness to weight ratio, ease in processing, cost reduction, and excellent performance [1]. A traditional route followed from several decades to widen the scope of PMCs is by means of adding micro- or nanofillers into polymeric systems having the fibrous reinforcement. The combinative effects of adding the fibers and the fillers into polymers have shown encouraging results in terms of improvements in mechanical, thermal, and tribological properties [2]. The fillers employed for modifying the tribological behavior of polymers are mostly inorganic compounds. Among the several inorganic ceramics, potassium titanate whisker (PTW, $K_2O{\cdot}6TiO_2$) is the only multicomponent ceramic which has gained a widespread use as a friction material. These relatively cheap whiskers have good thermal durability, chemical resistivity, and dispersibility and have been used as reinforcement material in plastics, ceramics, heat insulating paints, and automotive brake linings [3]. These whiskers have very small diameters; hence, they are free from any internal flaws or imperfections. Because of their attractive mechanical properties such as high strength and very high modulus, they have been used as reinforcement for many polymers in recent years.

The synergistic effect of PTW with other fillers in case of PMCs is studied by many researchers [4–9]. Zhu et al. [4] compared the tribological performance of PTW, magnesium borate, and calcium sulfate whisker-filled nonmetallic friction materials and observed that wear resistance was maximum in case of PTW modified friction material. Hee and Filip [5] have observed that the presence of PTW in phenolic matrix-based brake lining material has offered simultaneous benefits such as fade reduction, stabilized friction coefficient, and wear improvements. The significant improvement in the overall performance was attributed to the formation of the Ti and K-oxide containing friction layer during frictional testing. The positive effect of compounding nanoscale PTW with the microscale ceramics fibers in automotive brake linings was demonstrated by Wu et al. [6]. They observed that

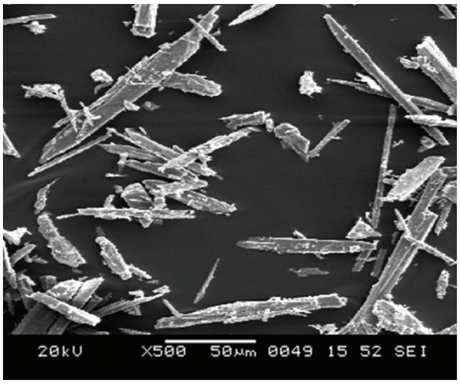


Figure 1: SEM picture of PTW fillers.

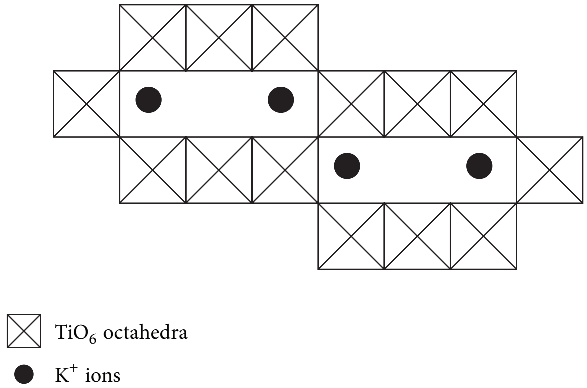


Figure 2: Tunneling structure of potassium titanate whiskers.

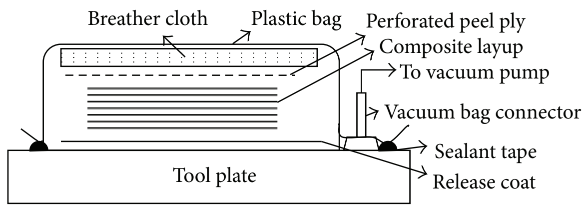


Figure 3: Schematic of the vacuum bag molding.

composites with both these fillers have shown improved wear resistance, higher impact strength, thermal stability and friction stability, when compared to those with only one type of filler. Long et al. [7] added silane-treated PTW into polypropylene/ramier fiber composites and observed significant improvement in the mechanical properties of the composites. Xie et al. [8] studied the effect of adding PTW into PEEK/carbon fiber composites under water-lubricated sliding conditions and noticed that PTW effectively protected the carbon fiber and also confined the fatigue failure of the PEEK material. Kumar et al. [9] have prepared composite friction materials based on synergistic ternary combination of PTW, aramid fiber, and graphite and characterized for friction braking performance. They found that friction build-up and friction decay was more consistent in composites with ≥7.5 wt% of aramid fibers whereas absolute friction effectiveness remained higher in the composites with ≥25 wt% of PTW.

However, to date, no effort has been directed towards the development of epoxy/glass/PTW composites. Keeping this in mind, the present work is aimed at studying the dry sliding wear behavior of epoxy/glass composites modified with PTW fillers using full factorial experimentation.

2. Materials and Methods

2.1. Materials. The matrix system (epoxy resin LY556 plus hardener HY951) was commercially obtained from Huntsman advanced materials India Pvt. Ltd., Bengaluru. The main reinforcement used was plain-woven fabric type E-glass fibers of 212 GSM and was purchased from Arun fabrics, Benagaluru. The secondary reinforcement of PTW fillers was supplied by Hangzhou Dayangchem Co. Ltd., Hong Kong. The SEM picture of these whiskers is presented in Figure 1. Some selected properties of these whiskers are listed in Table 1. These whiskers possess a tunneling structure (Figure 2) which makes them more stable in terms of physical and chemical properties [3].

2.2. Fabrication of Composites. The hybrid composites with different percentage of PTW fillers were fabricated by vacuum bagging technique. The essential steps in the process involve layup, preparing bagging materials, and applying the vacuum. The tool plate was first coated with a releasing agent to facilitate the easy removal of the laminates. The layup sequence involves coating the glass fabrics with the epoxy-whisker mixture. The 12 layers of glass fabrics were adopted in the study to get a laminate thickness of around 3 mm. The completed layup was covered with a perforated peel ply, breather cloth and plastic bag. A vacuum was drawn on the layup for 2 hours and a maximum pressure of 600–640 Hg-mm was achieved with this method. Applying the vacuum helps in removing the entrapped air and the excess resin from the layup. The layup was allowed to cure at room temperature and removed from the mold after 24 hours. The laminates, so prepared, were postcured at 100°C for 2 hours, and wear test samples of size $10 \times 10 \times 3$ mm were prepared using a high-speed cutter. A schematic of the vacuum bagging is presented in Figure 3. The compositional details of the fabricated composites are presented in Table 2.

2.3. Mechanical Testing. Density of the developed composites was determined using the Archimedes principle as per ASTM D792-08 [10]. The Rockwell hardness was measured on the M-scale as per ASTM D785-08 [11]. The values reported for density and hardness are the average of at least five samples.

2.4. Sliding Wear Testing. The dry sliding wear tests were performed on high-speed and high-stress pin-on-disc tribometer (Model TR-20E-PHM-400, Ducom, Bengaluru) as per ASTM G99-05 (reapproved 2010) [12]. The pin-on-disc schematic is illustrated in Figure 4. Wear test samples of precut size were glued to the steel pins of 10×10 mm cross section and 30 mm length. The test surface was successively polished against 400, 600, and 800 grade SiC abrasive paper to ensure the proper contact with the steel disc (diameter 165 mm,

Table 1: Some selected properties of potassium titanate whiskers.

Diameter (μm)	0.2–2.5	Tensile modulus (GPa)	280
Length (μm)	10–100	Hardness (Mohs)	4
Density (g/cc)	3.185	Melting point (°C)	1350–1370
Tensile strength (GPa)	7	Heat resisting temperature (°C)	1200

Table 2: Details of the composite samples.

Material designation	Epoxy (wt%)	Glass fibers (wt%)	PTW fillers (wt%)
C1	47.5	50	2.5
C2	45	50	5
C3	42.5	50	7.5

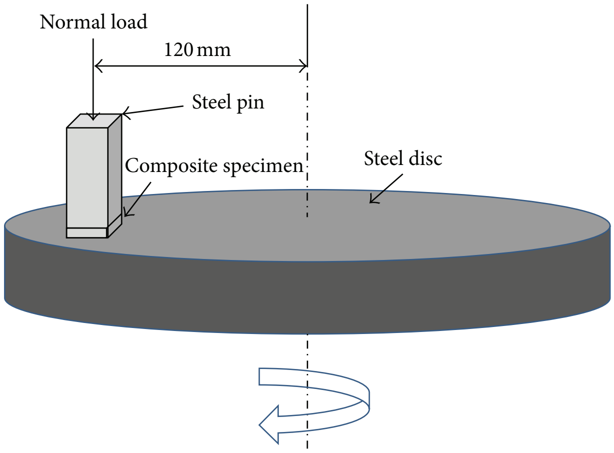


Figure 4: Pin-on-disc configuration.

Table 3: Control factors and their levels used in the experiment.

Control factor	Level I	Level II	Level III	Units
A: Sliding velocity	2.5	5	7.5	m/s
B: Normal load	30	60	90	N
C: Filler content	2.5	5	7.5	Wt %

Table 4: Density and hardness of hybrid composite samples.

Material designation	Density (g/cc)	Rockwell hardness (M scale)
C1	1.6132	96
C2	1.6468	97
C3	1.6778	99

thickness 8 mm, EN 31 grade material hardened to 60 HRc, ground to 1.6 μm Ra). The test surfaces were cleaned with soft cotton soaked in acetone after each run on the machine to remove any wear debris. The sliding tests were performed on wear track diameter of 120 mm for a constant sliding distance of 4.2 km under ambient conditions. The tests were conducted for different loads 30–90 N and sliding velocities 2.5–7.5 m/s. The sliding wear loss was measured as weight loss of the samples using the high precision digital weighing scale (Shimadzu, Japan, AY220, 0.1 mg accuracy). One value reported was an average of two to four samples. Weight loss of the test samples was converted into volume loss using the density data of the specimen. The specific wear rate was then calculated as

$$W_s = \frac{\Delta V}{(L \times d)}, \quad (1)$$

where ΔV is the volume loss in mm^3, L is the load in Newton, and d is the sliding distance in m.

During the tests, the frictional force was measured directly from the friction monitor attached to the machine. The coefficient of friction (COF) was calculated as a ratio of the frictional force to the applied normal load as

$$\text{COF} = \frac{\text{Tangential frictional force}}{\text{Normal load}}. \quad (2)$$

2.5. Worn Surface Morphology. A scanning electron microscope (Joel JSM-6380LA, made in Japan) was used to study the worn out surfaces of some selected samples. The sample surfaces were gold coated (Joel JFC-1600, auto fine coater) before examination under SEM. Worn microstructure of the hybrid composites was studied to reveal the effect of maximum sliding conditions on dry sliding wear of composites.

2.6. Experimental Design. The wear tests were conducted as per the full factorial design matrix. Three parameters, namely, sliding velocity (A), normal load (B), and filler content (C) each at three levels, are considered in the study. Control parameters and their levels are indicated in Table 3. A statistical analysis of variance (ANOVA) was performed to identify the control parameters and their interactions that are statistically significant. Finally, a polynomial model was developed for both wear rate and friction coefficient using regression analysis, and results are compared with the experimental values. The statistical analysis was performed using MINITAB 14 [13] statistical software package.

3. Results and Discussion

3.1. Density and Hardness. The density and the hardness of the hybrid composites are listed in Table 4. It can be observed that the inclusion of the whiskers has contributed to improve the density and the hardness of the composites. This is an expected behavior that ceramic fillers being denser and

Table 5: Matrix for 3 × 3 full factorial design and corresponding test output.

Test number	Sliding velocity (A) in m/s	Normal load (B) in Newton	Filler content (C) in Wt%	W_s ($\times 10^{-5}$ mm^3/Nm)	COF
1	2.5	60	2.5	1.00854	0.417
2	2.5	90	5	0.77110	0.431
3	5	30	2.5	1.77110	0.414
4	2.5	90	2.5	0.96755	0.409
5	7.5	90	2.5	1.41032	0.392
6	5	30	7.5	1.04067	0.446
7	2.5	60	5	0.77110	0.438
8	2.5	30	2.5	1.22993	0.431
9	2.5	90	7.5	0.64648	0.436
10	5	60	5	1.08435	0.418
11	7.5	60	7.5	1.15893	0.443
12	7.5	90	5	1.20484	0.415
13	7.5	30	2.5	2.41067	0.419
14	7.5	90	7.5	0.99336	0.430
15	7.5	30	7.5	1.56100	0.448
16	5	60	7.5	0.87511	0.438
17	5	90	2.5	1.11514	0.390
18	5	60	2.5	1.25453	0.408
19	5	30	5	1.44581	0.425
20	2.5	30	7.5	0.70955	0.451
21	5	90	5	0.97994	0.411
22	2.5	60	7.5	0.63859	0.443
23	7.5	30	5	1.97593	0.434
24	7.5	60	2.5	1.59891	0.406
25	2.5	30	5	0.91568	0.445
26	7.5	60	5	1.42171	0.422
27	5	90	7.5	0.75685	0.432

harder phase will obviously improve the density and hardness of the base composites. An interesting aspect of higher hardness is that generally higher hardness is accompanied by better resistance to wear.

3.2. Effect of Control Parameters on Wear Rate. The design matrix for three control factors each at three levels along with the results of the wear tests are presented in Table 5. The influence of each control factor on the wear behavior can be analyzed with the main effects plot and interaction plot. The best combination of the control factors to optimize the performance output can be easily evaluated from this plot. In the main effects plot, if the line for a particular parameter is nearly horizontal, the parameter has a little effect. A parameter for which the line that has the highest inclination has a greater effect [14]. The main effects plot for the parameters affecting the wear rate of hybrid composites are shown in Figure 5(a). The main effects plot shows that sliding velocity is the most significant parameter, while normal load and filler content have relatively less significant influence. It is evident from the plot that wear rate of the composites increases with the increase in sliding velocity, but decreases with the normal load and filler content.

It is well known that tribological behavior of polymers and polymer composites can be associated with their viscoelastic and temperature related properties. Sliding contact of two materials results in heat generation at asperities and hence increases the interface temperature, which influences the viscoelastic property in the response of material stress, adhesion, and transferring behaviors [15]. The increase in the sliding velocity increases the temperature at the friction surface and this could seriously deteriorate the mechanical properties of the composites and result in serious material loss. Thus, the wear rate increases with the sliding velocity for given load and material conditions. However, the increase in the normal load could result in early formation of transfer films, and further increase of the load could pack together the transfer films. These compressed and cohesive tribofilms are conducive to the reduction of the wear rate [16]. Thus, wear rate showed a declining trend for the range of loads (30–90 N) considered in the present study. It is also observed that a sharp decrease in the wear rate occurs when the load is

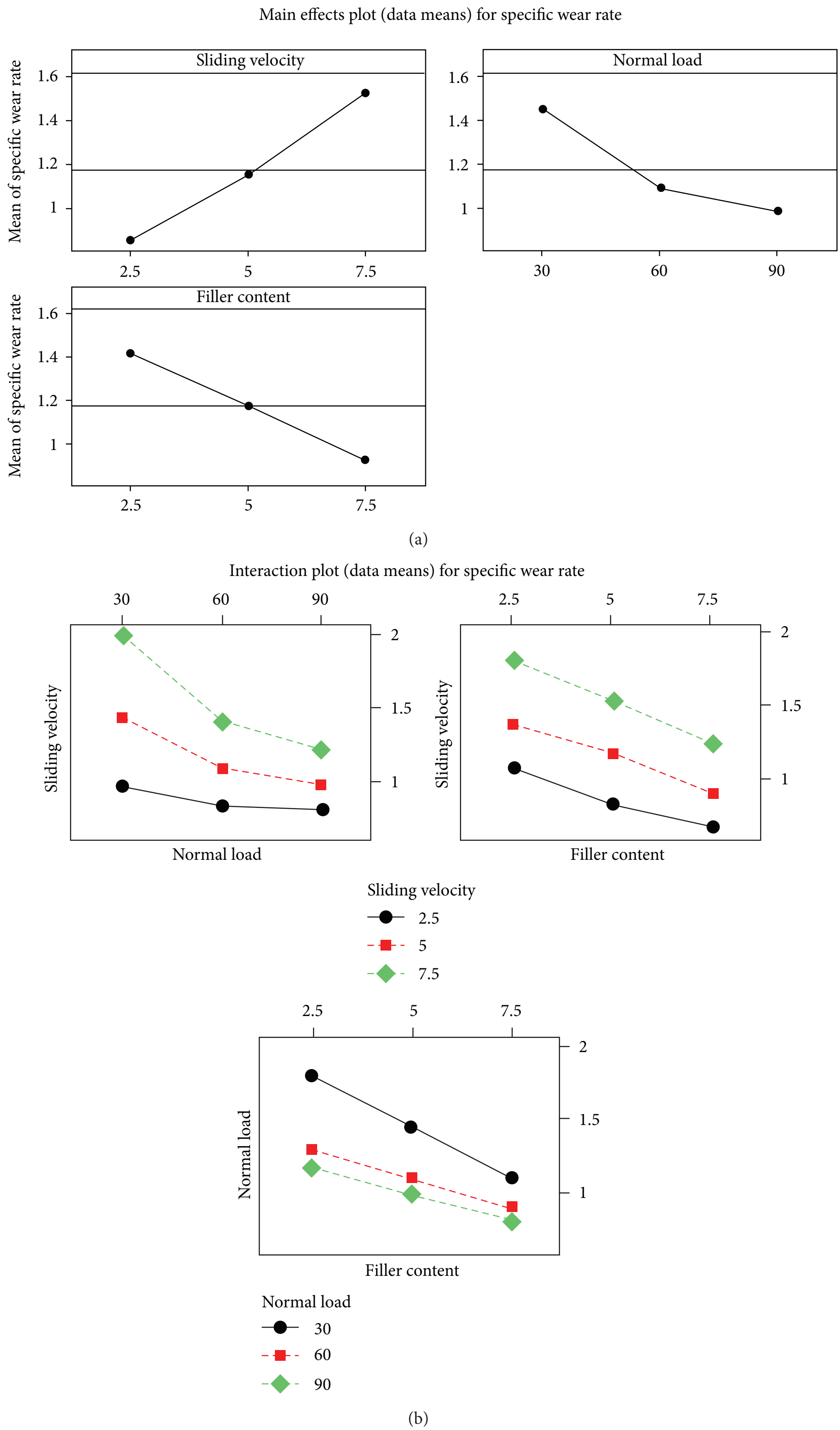


FIGURE 5: (a) Main effects plot for wear rate of epoxy/glass/PTW composites. (b) Interaction plot for wear rate of epoxy/glass/PTW composites.

increased from 30 to 60 N, whereas a gentle decrease in wear rate is seen when the load is increased from 60 to 90 N. This trend may be due to back transferring of the wear debris to the sample surface when load is increased from 60 to 90 N. It is clear from the main effects plot that PTW fillers improve the wear resistance property of the composites. These ceramic whiskers being a good heat resistant material could withstand the severe sliding condition and protect the epoxy matrix and glass fibers from rigorous damage or failure. This argument is further supported by the SEM pictures and is discussed in Section 3.6. The reduction in the wear rate with the inclusion of the PTW fillers is a widely reported phenomenon [4–9]. In our earlier investigation [17] of dry sliding wear study on epoxy/PTW composites (without the glass fibers), similar results were observed.

The main effects plot (Figure 5(a)) indicates that optimal values of the parameters for minimizing the wear rate occurred when the sliding velocity is at level 1 and normal load and the filler content are at level 3. The interaction plot for specific wear rate is illustrated in Figure 5(b). It is well understood that interactions do not occur when the lines on the interaction plots are parallel and strong interactions occur when the lines cross [18]. An examination of Figure 5(b) yields a small interaction between the test parameters.

3.3. Effect of Control Parameters on Coefficient of Friction. The main effects plot for COF of hybrid composites is depicted in Figure 6(a). This plot indicates that filler content is the most influential parameter affecting the COF followed by normal load and sliding velocity. It is clear that COF shows a decreasing and then increasing trend with the change in the sliding velocity. However, COF decreases with the normal load and increases with the whisker content as expected. The variation of coefficient of friction with applied load follows

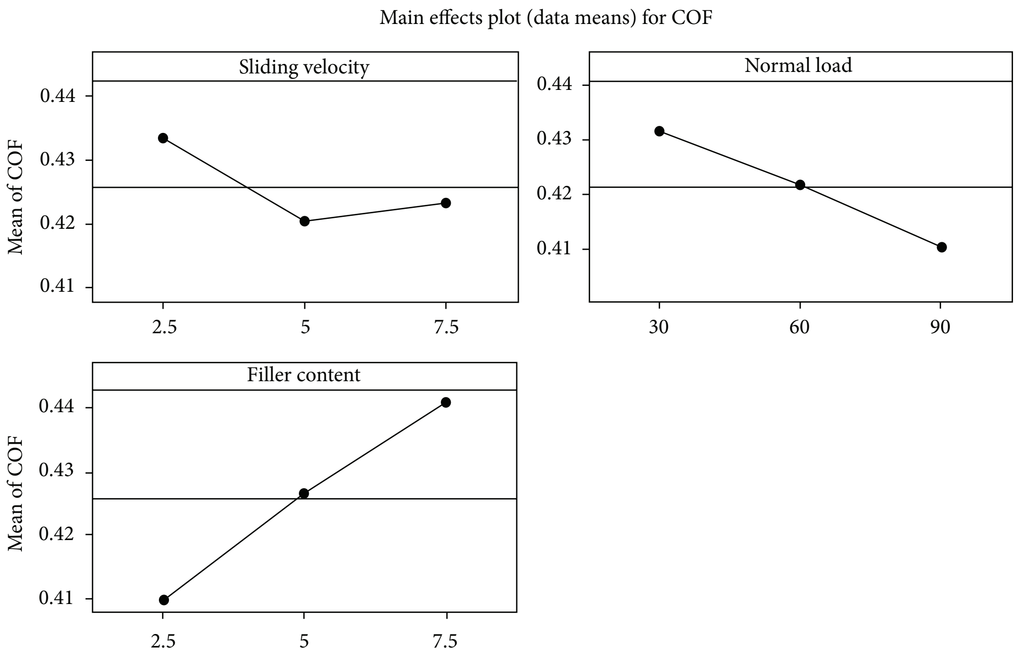
$$\mathrm{COF} = K \cdot N^{(n-1)}, \tag{3}$$

where K is a constant that depends on several factors including the shape and distribution of the asperities and the bulk properties of the polymer, N is the applied load, and n is also a constant, its value remains $0.66 < n < 1$ [15]. According to this equation, the coefficient of friction decreases with the increase in applied load, and the same trend is observed in the present study for the selected range of normal loads. Quaglini and Dubini [19] also demonstrated the inverse relationship between COF and the applied pressure in case of different polymers rubbing against smooth stainless steel sheet. The factors that are anticipated to reduce the wear rate with the load also acted to reduce the COF with the normal load.

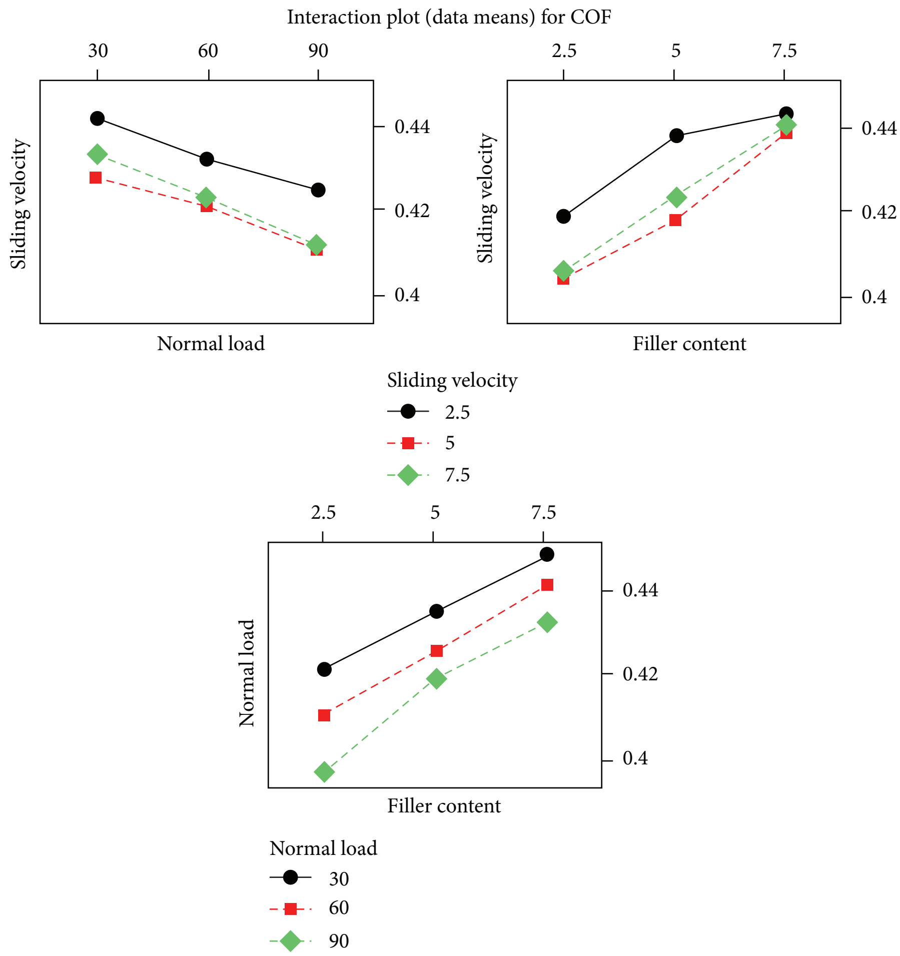
The relationship observed between sliding speed and COF is more complex. The COF first decreases with the increase in the velocity from 2.5 m/s to 5 m/s and later slightly increases when the sliding velocity increased to 7.5 m/s. The reason for this trend could be explained as follows. With the increase of the velocity up to 5 m/s, the plastic deformation of the epoxy matrix dominates and forms a thin transfer layer between the sliding materials. The broken glass fibers along with the PTW fillers aid in the retention of the friction film for a longer time. This results in the easy shear during the sliding and reduces the frictional force. With the further increase of the speed, material loss from the composite surface increases, which is obvious from the specific wear data, and this results in the increase of the abrasive force due to the presence of more glass fiber fragments and ceramic whiskers at the interface. This contributes to increase the friction coefficient values. The decreasing and then increasing trend in the frictional force with the sliding velocity is also explained in the literature [20]. It is well recognized that inorganic fillers always increase the abrasive force during the friction process [21]. Thus, COF is expected to increase with the increase in the PTW contents, which is also the observation made in the present study.

The two-way interaction plot for COF is presented in Figure 6(b). This plot shows that the interaction effect of sliding velocity and filler content is the highest. Other parameters show less interaction effects. The main and interaction effect plots aid to visualize the impact of each factor and its combination on output performance and recognize which factors are most influential. However, a statistical hypotheses test is needed in order to determine if any of these effects are significant. Analysis of variance (ANOVA), which consists of simultaneous hypothesis tests to find out if any of the effects are significant, is performed on the output data.

3.4. Statistical Analysis of Variance (ANOVA). ANOVA is a statistical design method used to break up the individual effects from all control factors. The percentage contribution of each control factor is employed to measure the corresponding effect on the quality characteristic [17]. Tables 6 and 7 show the results of the ANOVA with the specific wear rate and COF of the hybrid composites. The last column in Tables 6 and 7 show the percentage of contribution of each parameter and their interactions. Table 6 shows that the sliding velocity ($P = 44.19\%$), the normal load ($P = 23.22\%$), and the filler content ($P = 22.91\%$) are the controlling factors on the wear of the composites. Thus, load and filler content have shown nearly an equal degree of influence on the wear rate. The interaction between velocity and normal load ($P = 6.62\%$) and that between load and filler content ($P = 2.20\%$) are the significant interaction model terms. The interaction effect between velocity and filler content is only marginal, and the error contribution in the ANOVA for wear rate is only 0.26%. It can be observed from Table 7 that filler content ($P = 61.40\%$), normal load ($P = 21.64\%$), and sliding velocity ($P = 12.07\%$) are the factors that control COF values of hybrid composites. The interaction between the velocity and filler content ($P = 2.95\%$) is the predominant interaction model term, and other interaction models are less significant, and the error contribution in the ANOVA for COF is only 0.47%. It is clear that sliding velocity and filler content are the predominant factors that control wear rate and the COF of the hybrid composites, respectively. The present analysis indicates that control parameters selected in the study and also their interactions have both statistical and physical significance (the percentage contribution > error) in the dry sliding performance of the epoxy/glass/PTW composites.

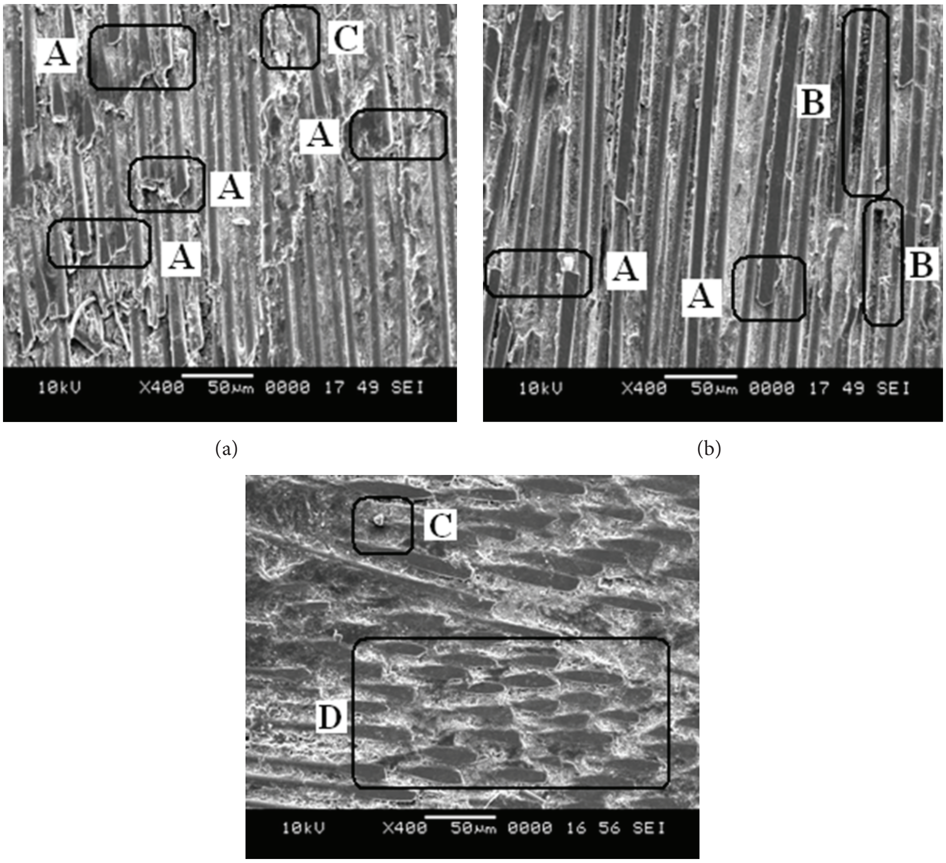


(a)



(b)

FIGURE 6: (a) Main effects plot for friction coefficient of epoxy/glass/PTW composites. (b) Interaction plot for friction coefficient of epoxy/glass/PTW composites.



(a) (b) (c)

Figure 7: SEM pictures of worn surfaces of (a) C1, (b) C2, and (c) C3 composite samples. (Test conditions: normal Load = 90 N, sliding velocity = 7.5 m/s, and sliding distance = 4.2 km).

3.5. Multiple Regression Models. The relationship between the control factors (sliding velocity (A), normal load (B), and filler content (C)) and the output performance (specific wear rate and friction coefficient) are obtained by multiple regression analysis. Ultimately, the following regression models are fitted to the wear rate and friction coefficient.

Specific wear rate $\left(\text{mm}^3/\text{N-m}\right)$,

$$\begin{aligned} W_s = {} & 1.00 + 0.293 \times A \\ & - 0.00300 \times B - 0.131 \times C - 0.00208 \times A \times B \\ & - 0.00660 \times A \times C + 0.00112 \times B \times C. \end{aligned} \tag{4}$$

Coefficient of friction,

$$\begin{aligned} \text{COF} = {} & 0.438 - 0.00324 \times A - 0.000381 \times B \\ & + 0.0024 \times C - 0.000014 A \times B + 0.000413 A \times C \\ & + 0.000029 B \times C. \end{aligned} \tag{5}$$

The coefficient of determination (R^2) for specific wear rate is 95.5% and for the COF is 89%. This is an expected result because epoxy/glass/PTW composite is a multiphase structure and friction, and wear data are usually scattered. From the individual regression equations, it appears that wear rate of the hybrid composites can be described more accurately than the COF. The low value of R^2 (89%) for COF is due to the changing contact conditions during sliding mainly because of the presence of two inorganic fillers (broken glass fibers and ceramic whiskers). The value of constant in the previous equations is the intercept of the plane and is a mean response value for the entire experiments conducted [22]. The value of this constant depends not only on the major parameters A, B, and C, which are considered in this study, but also with the experimental irregularities like machine vibrations, environmental conditions, and the surface finish of both the pin and the disc [23]. The coefficient of control variables and its interactions gives a measure of the effect of the corresponding factors on the test results. From (4), it is revealed that sliding velocity (A) has the highest effect, followed by filler content (C), then interaction effect between A and C ($A \times C$). The normal load (B) and the other interactions have less significant effect on the wear rate. Equation (5), again indicates that sliding velocity (A) followed by filler content (C), has significant influence on the COF of composites. However, other variables effects on COF are observed to be very small. The positive

Table 6: ANOVA table for specific wear rate.

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P-value	P (%)
Sliding velocity (A)	2	2.06212	2.06212	1.03106	669.36	0.000	44.19
Normal load (B)	2	1.08337	1.08337	0.54169	351.66	0.000	23.22
Filler content (C)	2	1.06880	1.06880	0.53440	346.93	0.000	22.91
$A \times B$	4	0.30911	0.30911	0.07728	50.17	0.000	6.62
$A \times C$	4	0.02761	0.02761	0.00690	4.48	0.034	0.60
$B \times C$	4	0.10280	0.10280	0.02570	16.68	0.001	2.20
Error	8	0.01232	0.01232	0.00154			0.26
Total	26	4.66613					100

$S = 0.0392474$, R-Sq = 99.74%, R-Sq (adj) = 99.14%.
DOF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares; Adj MS: adjusted mean squares; P: percentage of contribution.

Table 7: ANOVA table for coefficient of friction.

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P value	P (%)
Sliding velocity (A)	2	0.0008650	0.0008650	0.0004325	102.88	0.000	12.07
Normal load (B)	2	0.0015503	0.0015503	0.0007751	184.40	0.000	21.64
Filler content (C)	2	0.0043983	0.0043983	0.0021991	523.15	0.000	61.40
$A \times B$	4	0.0000257	0.0000257	0.0000064	1.53	0.282	0.36
$A \times C$	4	0.0002117	0.0002117	0.0000529	12.59	0.002	2.95
$B \times C$	4	0.0000797	0.0000797	0.0000199	4.74	0.030	1.11
Error	8	0.0000336	0.0000336	0.0000042			0.47
Total	26	0.0071643					100

$S = 0.00205029$, R-Sq = 99.53%, R-Sq (adj) = 98.47%.

values of the coefficients suggest that the wear rate of the composites increases with the increase in the associated variables, whereas the negative values of the coefficients indicates an opposite effect. Thus, as per (4), wear rate of composites increases with the sliding velocity and decreases with the normal load and filler content. These observations agree well with the variations reported in the main effect plot for specific wear rate (Figure 5(a)). Similarly, (5) reveals that COF of composites decreases with the sliding velocity and normal load, but increases with the filler content. These also almost agree with the observations made in the main effects plot for COF (Figure 6(a)). The maximum deviation observed between the experimental values and that calculated from the previously regression equations is 12.46% for specific wear rate and 2.28% for coefficient of friction. Thus, multiple regression equations derived previously correlate the evaluation of the wear rate and COF with reasonable degree of approximation.

3.6. Worn Surface Morphology. The SEM morphologies of the worn surfaces of the composites are presented in Figure 7. These worn surfaces correspond to the C1, C2, and C3 composite samples under highest sliding conditions (90 N, 7.5 m/s, and 4.2 km). These SEM pictures clearly reveal the effect of PTW contents on the wear behavior of the composites. The worn surface of the C1 sample (Figure 7(a)) shows the different morphological patterns such as fiber breakage (marked as "A"), plastic deformation of the matrix, and exposure of the long fibers, and some wear debris attached to specimen surface (marked as "C"). The severe breakage of the fiber indicates the poor wear resistance property of the C1 composites. The SEM picture for C2 sample in Figure 7(b) illustrates the breakage of only a few fibers (marked as "A"). The impressions (marked as "B") left after the removal of the fiber due to the severe sliding conditions can also be witnessed in Figure 7(b). Less instances of the fiber breakage and retention of the long fibers in C2 samples indicate the positive effect of loading the PTW fillers. The worn feature of the sample C3 (Figure 7(c)) exhibits a comparatively smooth worn surface, where there are no instances of severe fiber damage/removal. Referring to Figure 7(c), it can be argued that the increase in the COF is mainly due to the rubbing action of the fibers (marked as "D") with the disc surface. The worn surface of C3 sample has shown less visible fibers compared to the C2 and C1 samples. This indicates that in C3 samples PTW fillers were able to take up the portion of the normal load applied. Moreover, the reinforcing effect of PTW fillers can reduce the fiber failure by reducing the stress concentration on the fibers [8]. The worn surface micrographs revealed that dominant wear mechanism in the C1 samples may be fatigue abrasion and has changed to adhesive abrasion in C3 samples. The wear mechanisms interpreted from the SEM images presented here are commensurate with the mechanisms proposed by Kishore et al. [24] in relation to studies on glass/epoxy composites with different ceramic fillers. The specific wear rate under the highest sliding conditions observed in the study is 1.41032×10^{-5} mm^3/Nm for C1 composites and 0.99336×10^{-5} mm^3/Nm for C3 composites. This means that wear rate has reduced by nearly 30% by increasing the filler content from 2.5 to 7.5 wt% in the glass/epoxy composites. However, COF values observed lie between 0.39 and 0.45, which is preferred range for friction materials [8].

It is always interesting to note the correlation between the tribological and the mechanical properties of polymer composites. In the present study, the improvement in the COF and wear resistance property of the hybrid composites can be attributed to the improvement in the hardness property of the composites with the PTW content (Table 4), thus validating the Archard equation of relating the wear rate and hardness of the materials [25].

4. Conclusions

The effect of PTW content on the wear rate and friction coefficient of hybrid composites was systematically investigated. From the observations made in the study, following conclusions can be drawn.

(1) The addition of the increased whisker content has increased the density, hardness, friction coefficient, and wear resistance of the epoxy/glass/PTW composites.

(2) The ANOVA results indicated that the most significant variables affecting sliding wear rate are the sliding velocity (44.19%), normal load (23.22%), filler content (22.91%), interaction effect of the sliding velocity with normal load (6.62%), and normal load with filler content (2.20%), within the selected range of parameters. ANOVA also showed that the most significant factors affecting the friction performance are filler content (61.40%), normal load (21.64%) sliding velocity (12.07%), and interaction effect of sliding velocity with filler content (2.95%), within the selected range of parameters.

(3) The results of the polynomial models developed by regression analysis agree well with the experimental values. The comparison between the experimental values and the regression model results indicated a maximum error of 12.46% for specific wear rate and 2.28% for coefficient of friction.

(4) SEM pictures of selected samples revealed a change in the wear mechanism from fatigue abrasion to adhesive abrasion with the loading of the PTW fillers and are in good agreement with the experimental findings.

The study showed that the use of PTW as hybrid reinforcement in epoxy/glass systems can effectively improve the dry sliding wear performance. This material can be adopted in the future for designing the components that are meant for low wear and moderate friction applications.

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