Research Article

Journal of Environmental Nanotechnology

Wear Performance of Polymer Matrix Composites Reinforced with Aramid Fibers and Modified with Ceramic Nano-powders

M. Sudheer[1], B. Ravikiran Kamath[2], Raja Yateesh Yadav[3], Vidyasagar Shetty[2*], Rajath[2], P. Akshara[2], Chidambar Kadoli[2], G. Sanjay Pai[2] and Akash Vishwanath[2]

[1]Department of Mechanical Engineering, St Joseph Engineering College, Vamanjoor, Mangaluru, KA, India
[2]Department of Mechanical Engineering, Nitte (Deemed to be University), NMAM Institute of Technology (NMAMIT), Nitte, Karkala, KA, India
[3]Department of Mechanical Engineering, Shri Madhwa Vadiraja Institute of Technology and Management, Bantakal, KA, India
Received: 02.06.2025 Accepted: 21.06.2025 Published: 30.06.2025
*vidyasagar.shetty@gmail.com

ABSTRACT

Tribology is a field that focuses on the study of lubrication, wear and friction occurring between contacting surfaces in relative motion. Polymer composites have gained attention particularly in situations where mating parts are subjected to increased wear and friction. In this work, epoxy polymer matrix is reinforced with an aramid fiber namely Kevlar and is modified with ceramic nano powders namely potassium titanate whiskers. The composites are prepared by hand lay-up followed by compression. The fabricated samples are subjected to pin-on-disc wear test as per ASTM G99-17. Experiments are designed and analyzed using MINITAB 22 following a Taguchi L9 orthogonal array with four parameters at three levels each. Density and specific wear rate of the specimens are evaluated. The density test results revealed slight improvement in the composite's density with the increase in the nano powder content from 0 wt. % to 4 wt. %. The experimental values of specific wear rate and the S/N ratios obtained from Taguchi analysis indicated that the minimum specific wear rate was achieved for sliding velocity(A) of 2.5 m/s, normal load (B) of 90 N, powder content (C) of 4 wt. % and sliding distance (D) of 3000 m. ANOVA results indicated that the sliding distance had the most significant impact on the wear of the composites followed by sliding velocity, normal load and percentage powder content.

Keywords: Kevlar; Epoxy; Potassium titanate whiskers; Hand lay-up; Polymer matrix composites.

1. INTRODUCTION

Polymer matrix composites (PMC) are the composite materials comprising of a variety of short or continuous fibers bound together by a matrix of organic or synthetic polymers. The fibers may be naturally occurring or synthetic. Synthetic fibers are usually preferred over natural fibers due to its enhanced properties like durability, strength and reduced weight (Ahmad and Zhou, 2022). On the other hand, polymers offer a number of advantages like lower cost, easier fabrication, faster curing and their ability to be molded into complex shapes. Fillers, when used in the preparation of composite materials, enhance their mechanical strength, stiffness, wear resistance and hardness (Yadav *et al.* 2023). Carbon, glass and aramids have been utilized in the past as synthetic reinforcements, while epoxy has been quite popular as a polymer matrix material. Whiskers are a type of short and fiber shaped crystals with a large aspect ratio. They are nearly free of defects which are generally present in other materials and with a highly ordered arrangement of atoms, they possess excellent mechanical properties. The commonly used whiskers include calcium carbonate, alumina and silicon carbide. These ceramic whiskers are commonly preferred as fillers because when added, they are seen to improve wear resistance (İpek and Çuvalcı, 2017).

Tribology is a field of study of wear and friction. This study is crucial with regard to mechanical parts in relative motion and are in contact. In usual practice, the fabricated composite specimens are subjected to wear and friction test using a pin-on-disc tribometer and parameters like specific wear rate and coefficient of friction are determined. Sudheer *et al.* (2012) conducted research on the wear performance of potassium titanate whiskers (PTW)-reinforced epoxy composites fabricated by vacuum casting considering various parameters like sliding velocity, normal load, filler content and sliding distance. Dry sliding wear tests were carried out using Taguchi's orthogonal arrays and the optimal combination of parameters to minimize the wear rate was determined. Pihtili and Tosun, (2002) conducted wear test on glass and aramid reinforced composites at different speeds and loads for varying sliding distances. The results revealed that wear is more influenced by the applied load than by speed. Kim *et al.* (2014) conducted a study to examine the synergistic effects of PTW, barite, phenolic resin,

molybdenum disulfide and aramid pulp for the formulation of friction materials. The results indicated that PTW and aramid pulp significantly contributed to the friction characteristics. Harshavardhan *et al.* (2024) conducted dry sliding wear test of short carbon fiber reinforced polyether sulfone composites filled with PTW on a pin-on-disc tribometer. It was demonstrated that the composites filled with PTW showed the highest coefficient of friction and the least amount of wear.

Kumaresan *et al.* (2011) conduced a research on carbon fabric-reinforced epoxy composites, with and without silicon carbide filler, formed by hand lay-up and then compressed into shape. The pin-on-disc wear experiments were conducted at a fixed sliding distance by varying the sliding velocity and applied weight. Wear loss was found to increase with increasing load and sliding velocity. However, with silicon carbide as filler, excellent wear characteristics were achieved. Sudheer *et al.* (2014) conducted a study in which two distinct micro-fillers, namely graphite and potassium titanate whiskers, were incorporated into an epoxy/glass composite using the vacuum bagging technique. Dry sliding wear behaviour of epoxy/glass composites was investigated. The results revealed that adding graphite lubricant as a secondary filler improved the composite's tribological qualities. Kumar *et al.* (2018) examined the impact of silicon carbide content on the wear behavior in glass fiber reinforced vinyl ester composites fabricated by hand lay-up. The findings showed that the composite wear was less sensitive to changes in sliding velocity and more sensitive to changes in sliding distance. Sharma and Sharma (2023) experimentally evaluated the tribological behavior of fly ash filled E-glass fiber reinforced epoxy composites processed by hand lay-up, employing a Taguchi L16 orthogonal array. A pin-on-disc wear testing machine was employed to investigate the wear behavior under dry sliding conditions at ambient temperature. The findings revealed that the sliding distance had the most significant impact on the composite wear.

Wang *et al.* (2020) carried out a research on the tribological performance of PTFE/Kevlar fabric composites under heavy loading. The results revealed the formation of a double-layer transfer membrane. This membrane holds significant promise for various engineering applications, including heavy machinery and the aerospace industry. Casing wear remains a significant challenge in oil and gas drilling operations, necessitating the development of innovative, wear-resistant materials to prevent casing failures. In this connection, Fouad *et al.* (2024) studied the wear characteristics of zirconia-toughened epoxy/Kevlar-honeycomb composite lining for drilling casing. The findings indicated that the specific wear rate increased with speed across all side loads and the epoxy/Kevlar-honeycomb composite lining exhibited significant wear resistance, even under dry sliding conditions. Li *et al.* (2022) studied the tribological properties of polytetrafluoroethylene (PTFE)/Kevlar fabric composites at various orientations, contact pressures and sliding velocities. The findings revealed that different wear mechanisms associated with various twill orientations resulted in changes in the tribological properties. Wang *et al.* (2024) demonstrated that incorporating PTW into carbon fiber reinforcements improved the wear resistance of the composites. Wei *et al.* (2018) focused on optimizing the content and dispersion of ceramic fillers in fiber reinforced epoxy matrices to achieve the desired properties.

It is evident from the literature review that Kevlar-Epoxy composites are well known for their exceptional mechanical and wear properties. However, there exists only limited studies on employing ceramic whiskers as fillers in Kevlar-Epoxy system. The incorporation of these whiskers could further enhance these properties making it a potential material for advanced engineering applications.

2. MATERIALS AND METHODS

In this study, the synthetic reinforcement used is a high strength, high modulus aramid fiber namely Kevlar 49 having plain weave form, an aerial density of 220 GSM and a filament diameter of 12 microns (M/s CF composites, New Delhi). The density, tensile strength and tensile modulus of the fibre were 1.44 g/cc, 3097 MPa, and 105 GPa, respectively.

The matrix material used belongs to polymer category, namely epoxy resin LY556, along with HY951 hardener. The resin and hardener were procured from M/s Herenba Instruments & Engineers, Chennai. The resin had a density of 1.15 g/cc and a Young's modulus of 3 GPa. The resin and the hardener were mixed in the proportions 10:1 by weight, as provided by the supplier. The nano powder material used in the study, potassium titanate whisker is a cost-effective ceramic powder having a diameter of 500─2500 nm, tensile strength of 7 GPa, and length range of 10000─1000000 nm, density of 3.185 g/cc and a tensile modulus of 280 GPa. It was procured from Hangzhou Dayangchem Company Limited, Hong Kong.

The methodology involved in the fabrication of the composite samples is hand lay-up followed by compression. The detailed procedure of the hand lay-up process is explained elsewhere (Basavarajappa and Ellangovan, 2012; Kim *et al.* 2001; Kim *et al.* 2014; Yurohman *et al.* 2024). In this work, the composite samples were prepared keeping the fiber and resin proportions in the ratio 50:50 by weight and varying the nano powder proportions in the order of 0%, 2% and 4% by weight. Fig. 1 presents the various stages of the fabrication process. Composites fabricated without powders are designated as KEP_0, while the composites with 2% and 4% powders are designated as KEP_2 and KEP_4, respectively.



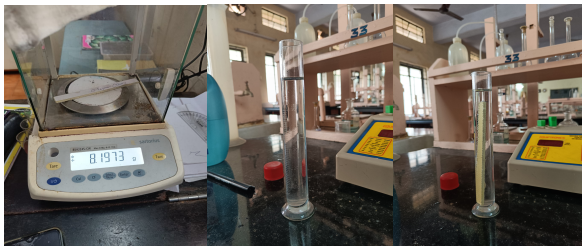
Layers cut from the roll | The layers are weighed | Powder quantity weighed



Powder preheated in hot air oven | Mixing of powder into the resin, followed by hardener | Hand lay up

Fig. 1: Various stages of hand lay-up process

The fabrication was followed by removing the excess resin and machining the samples to the required dimensions of 12 × 12 × 3 mm according to ASTM G99-17. The machining was carried out at M/s Mangala Switch Board Makers, Mangaluru, India. An attempt to improve the surface finish of the machined specimens was carried out by subjecting them to filing and successively abrading against a silicon carbide sand paper of grit sizes 1000 and 320.



Specimen is weighed | Measuring jar used | Specimen immersed in the jar filled with distilled water

Fig. 2: Density test

Density of the composites was determined using Archimedes principle as per ASTM D792. Distilled water was used as the medium at room temperature. The mass of the specimen was accurately measured using a precision digital balance (Sartorius BSA224S-CW, 0.1 mg accuracy). Measurements of the level of water in the measuring jar were noted before and after immersing the specimen, and the difference between these readings was determined. The density of the specimen was calculated as shown in Equation (1). Fig. 2 depicts the images of density test.

$$\rho = \frac{Mass}{Volume\ loss} \quad \ldots (1)$$

The surface roughness of the disc and specimen was measured using Taylor Hobson Talysurf surface roughness tester. The test was conducted over a sampling length of 2.5 mm. The average surface roughness of the carbon steel disc was in the range 0.2–0.4 microns and that of the specimen was 0.4 microns.

Table 1. Control factors and levels used in the experiment

Control factors	Level I	Level II	Level III
Sliding velocity(m/s) (A)	2.5	5.0	7.5
Normal load (N) (B)	30	60	90
Powder content (%) (C)	0	2	4
Sliding distance (m) (D)	1000	2000	3000

Design of experiments (DOE) is a well-organized and effective method to study the relationship between multiple input variables and key output variables. Taguchi's orthogonal array is a statistical technique used for designing experiments in an efficient manner. It decreases the number of trials desirable to study several factors by making use of a matrix structure where factors are tested independently. This structure helps to discover optimal settings while minimizing noise, making the process robust. Taguchi's L9 orthogonal array was designed for four control parameters with three levels each using MINITAB 22. The four parameters chosen in the study were sliding velocity (A), normal load (B), powder weight percent (C) and sliding distance (D). The levels chosen for A are 2.5, 5 and 7.5 m/s, for B are 30, 60, 90 N, for C are 0, 2, 4 wt.

%, and for D are 1000, 2000, 3000 m. Table 1 presents the various control factors and their levels used in the study.

Dry sliding wear test was conducted using a pin-on-disc tribometer (Magnum Engineers, Bengaluru). Wear track diameter was kept constant at 80 mm. The specifications of the test set up is illustrated in Table 2.

Table 2. Specifications of pin-on-disc setup

Normal load range	Upto 200N
Frictional force range	Upto 200 N with resolution of 1 N
Wear measurement range	±2 mm with tare facility
Disc speed	100 to 2000 rpm
Wear disc diameter	Ø165 mm × 8 mm thickness
Wear disc track diameter	Ø 10 to 140 mm
Specimen pin diameter	Ø3 mm to Ø12 mm
Pin Length	25 to 30 mm

Initially, the samples were abraded against fine sized 1000 grit silicon carbide sandpaper to make sure an appropriate contact between the specimen and disc was made. The specimen and disc were cleaned with a cotton soaked in acetone to keep it free from contaminants. The initial mass of the specimen was noted using a precision weighing scale, having 0.1 mg accuracy. The disc was placed on a rotating platform and the specimen was mounted vertically above the disc, ensuring that it can be pressed down onto the disc surface. Then, a specific load was applied to create contact pressure between the specimen and the disc. The duration of the test was calculated and the disc was rotated at a predetermined speed. The wear of the specimen was monitored in the computerized facility. After the run time is completed, the specimen was removed and cleaned in acetone to remove any wear debris. It was again weighed and the mass loss was measured. From the mass loss values, volume loss of the specimen was determined using density data. Specific wear rate was determined using Equation (2).

$$Ws = \frac{V}{Ld} \quad \ldots (2)$$

where, V = volume loss in mm^3, L = applied normal load in N and d = sliding distance in km.

The analysis of the experimental results was carried out using MINITAB 22 and the experimental findings were converted into a signal-to-noise ratio (S/N). "Smaller the better" was used as the characteristic, since it is desirable to achieve minimum specific wear rate. ANOVA (Analysis of Variance) statistical analysis was implemented to investigate which control factors substantially influence the specific wear rate. The optimum combination of parameters which yield minimum specific wear rate was predicted using ANOVA and S/N ratio values.

3. RESULTS AND DISCUSSION

Table 3 presents the density values of various composites. From the obtained results, it can be observed that the density of the composite increases with the powder content. However, the composite density is remarkably lesser than the density of the Kevlar fiber (1.44 g/cc), making it a light weighted material.

Table 3. Results of the density test

Composite Designation	Density (g/cc)
KEP0	1.2149
KEP2	1.2393
KEP4	1.2561

The specific wear rate (Ws) and S/N ratios for the various experimental runs as an outcome of the pin-on-disc wear test using Taguchi's L9 array are presented in Table 4. One specific wear rate value reported in the table refers to the average value obtained from two to three trials.

Table 4. Results of wear test

Sliding Velocity A (m/s)	Normal Load B (N)	Powder Content C (wt. %)	Sliding Distance D (m)	Specific Wear Rate (W_s) (mm^3/Nkm)	S/N Ratio (dB)
2.5	30	0	1000	0.026730	31.4600
2.5	60	2	2000	0.013446	37.4281
2.5	90	4	3000	0.009731	40.2369
5.0	30	2	3000	0.015060	36.4435
5.0	60	4	1000	0.019578	34.1646
5.0	90	0	2000	0.015768	36.0445
7.5	30	4	2000	0.029178	30.6989
7.5	60	0	3000	0.017833	34.9755
7.5	90	2	1000	0.024195	32.3291

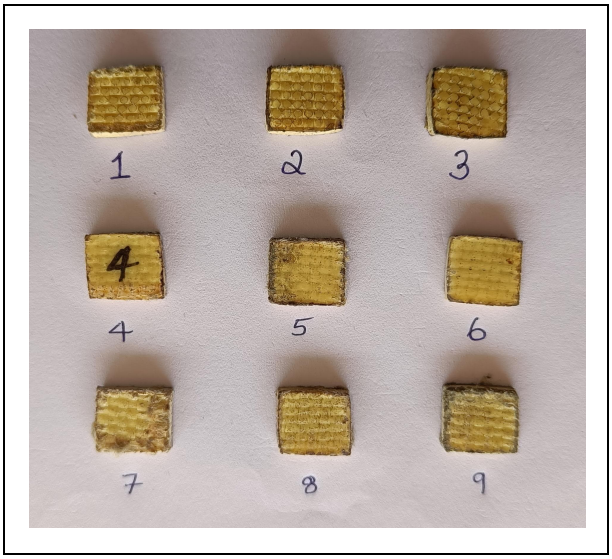


Fig. 3: Sample worn out specimens

It is a well-known fact that the control factor with the highest S/N ratio always yields optimum combination with least variance, i.e., least specific wear rate corresponds to the highest S/N ratio. Accordingly, it can be observed that the minimum specific wear rate was achieved for the factor-level combination of A1, B3, C3, D3, i.e., sliding velocity of 2.5 m/s, normal load of 90 N, powder content of 4 wt. %, and sliding distance of 3000 m. From Table 5, the mean S/N ratio of specific wear rate was observed to be 34.86 db.

Fig. 4 presents the main effects plot for S/N ratios, while Fig. 5 for means. It is evident from the plots that the conditions of sliding have greatly impacted the wear performance of the composites. Wear rate increased with the increase in sliding velocity, which is obvious from the increased rubbing between the counterparts at higher speeds. Also, the wear rate has shown decreasing and increasing trend with the nano powder weight percentage, suggesting the necessity to maintain an optimum content for enhancing wear resistance of the composites. When both normal load and sliding distance are increased, the wear rate decreases, with the domination of the influence of normal load over sliding distance on the wear rate. Previous research (Ray and Gnanamoorthy, 2007) revealed the possible wear mechanisms such as formation of transfer layer, cracking etc. in polymeric composites that provided protection against wear. Wear behavior of filled polymer composites is regulated by the dominance of one control parameter over the other. In the current study, PTW, owing to their splinter shape and brittleness, alter the wear behavior of the composites.

Table 5 presents the responses for signal-to-noise ratios. It is clear from the table that sliding distance is the most influential parameter followed by sliding velocity, normal load and powder weight percentage. Fig. 6 shows the interaction plots between the factors normal load (B), powder content (C) and sliding distance (D) for wear rate. It is observed that there exists a small interaction between the control parameters since the lines are crossing each other.

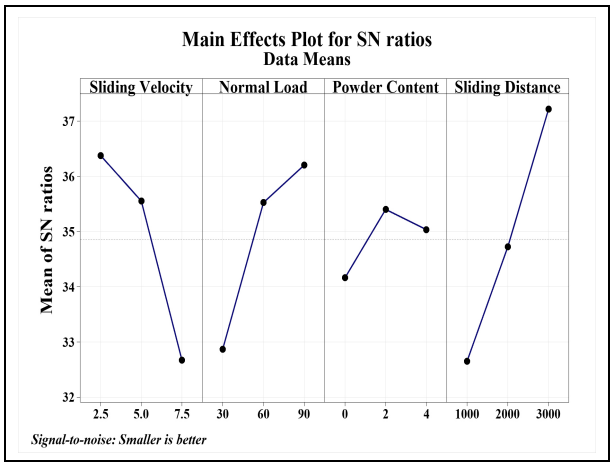


Fig. 4: Main effects plot for S/N ratios

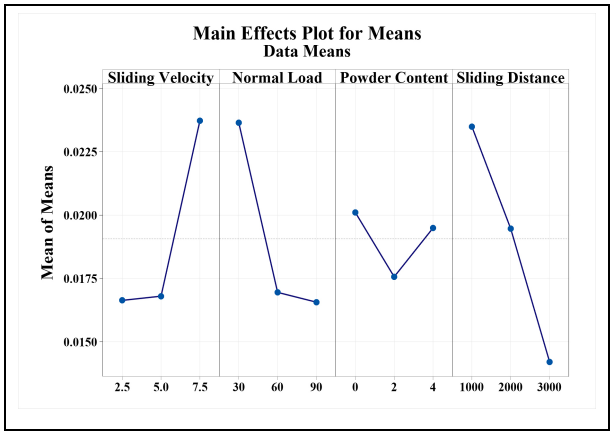


Fig. 5: Main effects plot for means

ANOVA was conducted for justifying the least influential parameter on the specific wear rate and is presented in Table 6. A 5% level of significance was employed in the analysis. From the table, it can be observed that the sliding distance contributes the maximum (38.92%), followed by sliding velocity (29.43%), normal load (28.49%) and nano powder content (3.16%) on the specific wear rate. It is also observed that the interactions between the factors B×C, C×D and B×D exhibit lesser contribution on the specific wear rate.

Table 5. Response table for S/N ratios

Level	Sliding Velocity A (m/s)	Normal Load B (N)	Powder Content C (wt. %)	Sliding Distance D (m)
1	36.38	32.87	34.16	32.65
2	35.55	35.52	35.40	34.72
3	32.67	36.20	35.03	37.22
Delta	3.71	3.33	1.24	4.57
Rank	2	3	4	1

Table 6. ANOVA table for specific wear rate

Source	Degrees of Freedom	Sequential Sum of Squares	Contribution	Adjusted Sum of Squares	Adjusted Mean Squares
Sliding velocity	2	0.000099	29.43%	0.000099	0.000049
Normal load	2	0.000095	28.49%	0.000095	0.000048
Powder content	2	0.000011	3.16%	0.000011	0.000005
Sliding distance	2	0.000130	38.92%	0.000130	0.000065
Total	8	0.000335	100.00%	-	-

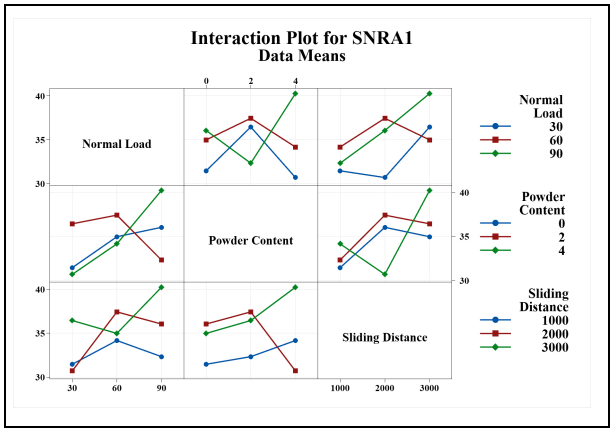


Fig. 6: Interaction plot between normal load, powder content and sliding distance for wear rate

4. CONCLUSION

In this study, Kevlar-Epoxy composites reinforced with PTW powders were fabricated using the hand lay-up technique and evaluated for their dry sliding wear behavior using a pin-on-disc apparatus. The composite density increased slightly with PTW addition, rising from 1.2149 g/cc for KEP0 to 1.2393 g/cc (2.008% increase) for KEP2 and 1.2561 g/cc (1.355% further increase) for KEP4. The optimal wear resistance was observed at a sliding velocity of 2.5 m/s, normal load of 90 N, powder content of 4 wt.%, and sliding distance of 3000 m. ANOVA revealed that sliding distance had the highest influence on the specific wear rate (38.92%), followed by sliding velocity (29.43%), normal load (28.49%), and powder content (3.16%).

ACKNOWLEDGEMENTS

The authors would like to thank all those who directly/indirectly contributed in conducting the work and framing the article.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

REFERENCES

Ahmad, J. and Zhou, Z., Mechanical properties of natural as well as synthetic fiber reinforced concrete: A review, *Constr. Build. Mater.,* 333, 127353(2022). https://doi.org/10.1016/j.conbuildmat.2022.127353

Basavarajappa, S. and Ellangovan, S., Dry sliding wear characteristics of glass–epoxy composite filled with silicon carbide and graphite particles, *Wear.,* 296(1-2), 491–496(2012). https://doi.org/10.1016/j.wear.2012.08.001

Fouad, Y., Merah, N., Azeem, M. A., Gasem, Z., Alqutub, A., Aleid, A. A., Osman, O., Shaarawi, A. and Aljohar, A., Wear characteristics of zirconia-toughened epoxy/Kevlar-honeycomb composite lining for drilling casing, *Heliyon.,* 10(17), e37333(2024). https://doi.org/10.1016/j.heliyon.2024.e37333

Harshavardhan, B., Ravishankar, R. Dixit, A. C. and Anandraj, D., Tribological behaviour of short carbon fibre reinforced polyether sulfone composites with PTW filler, *Tribol. Ind.,* 46(2), 217–235(2024). https://doi.org/10.24874/ti.1532.08.23.10

İpek, H. and Cuvalci, H., Wear behaviour of the glass fibre reinforced cast polyamide in pin-on-disc type wear machine, *Res. Eng. Struct. Mater.,* 3(1), 77 – 87 (2017). https://doi.org/10.17515/resm2016.39ma0216

Kim, S. J., Cho, M. H., Lim, D. S. and Jang, H., Synergistic effects of aramid pulp and potassium titanate whiskers in the automotive friction material, *Wear.,* 251(1), 1484–1491(2001). https://doi.org/10.1016/S0043-1648(01)00802-X

Kim, S. Y., Shim, C. S., Sturtevant, C., Kim, D. and Song, H. C., Mechanical properties and production quality of hand-layup and vacuum infusion processed hybrid composite materials for GFRP marine structures, *Int. J. Nav. Archit. Ocean Eng.,* 6(3), 723–736 (2014). https://doi.org/10.2478/IJNAOE-2013-0208

Kumar, T. B., Haseebuddin, M. R., Raghavendra, N. and Mahesh, K. V., Influence of SiC on mechanical, thermal, fire and wear studies of vinyl ester/glass fibre composites, *Mater. Today Proc.,* 5(10), 22675–22686(2018). https://doi.org/10.1016/j.matpr.2018.06.644

Kumaresan, K., Chandramohan, G., Senthilkumar, M., Suresha, B. and Indran, S., Dry sliding wear behaviour of carbon fabric-reinforced epoxy composite with and without silicon carbide, *Compos. Interfaces.,* 18(6), 509–526(2011). https://doi.org/10.1163/156855411X610241

Li, J., Liu, J., Peng, S., Li, W., Du, S. and Zhang, Y., Tribological properties of PTFE/Kevlar fabric composites at different twill orientations, *Tribol. Int.,* 174, 107752(2022). https://doi.org/10.1016/j.triboint.2022.107752

Pihtili, H. and Tosun, N., Effect of load and speed on the wear behaviour of woven glass fabrics and aramid fibre-reinforced composites, *Wear.,* 252(11-12), 979–984(2002). https://doi.org/10.1016/S0043-1648(02)00062-5

Ray, D. and Gnanamoorthy, R., Friction and wear behavior of vinyl ester resin matrix composites filled with fly ash particles, *J. Reinf. Plast. Compos.,* 26(1), 5–13(2007). https://doi.org/10.1177/0731684407069945

Sharma, R. and Sharma, D., Synthesis and experimental evaluation of tribological behaviour of fly ash filled E-glass fibre reinforcement epoxy composites using Taguchi method, *Mater. Today. Proc*., 02, 136–142 (2023). https://doi.org/10.1016/j.matpr.2023.02.136

Sudheer, M., Hemanth, K., Raju, K. and Bhat, T., Enhanced mechanical and wear performance of epoxy/glass composites with PTW/graphite hybrid fillers, *Procedia Mater. Sci.,* 6, 975–987 (2014). https://doi.org/10.1016/j.mspro.2014.07.168

Sudheer, M., Prabhu, R., Raju, K. and Bhat, T., Optimization of dry sliding wear performance of ceramic whisker filled epoxy composites using Taguchi approach, *Adv. Tribol.,* 2012(1), 431903–431911 (2012). https://doi.org/10.1155/2012/431903

Wang, H., Qi, X., Zhang, W., Dong, Y., Fan, B. and Zhang, Y., Tribological properties of PTFE/Kevlar fabric composites under heavy loading, *Tribol. Int.,* 151, 106507(2020). https://doi.org/10.1016/j.triboint.2020.106507

Wang, Z., Guan, C., Sun, W., Tan, S., Duan, L. and Fang, X., Effect of carbon fiber and Potassium Titanate Whisker on the mechanical and impact tribological properties of Fe-based impregnated diamond bit matrix, *Mater.,* 17(11), 2645–2658 (2024). https://doi.org/10.3390/ma17112645

Wei, F., Jiang, B. and Pan, B., Frictional wear of potassium titanate whisker filled carbon fabric/epoxy composites, *Chem. Eng. Trans.,* 66, 115–120 (2018). https://doi.org/10.3303/CET1866020

Yadav, R., Singh, M., Shekhawat, D., Lee, S. Y. and Park, S. J., The role of fillers to enhance the mechanical, thermal, and wear characteristics of polymer composite materials: A review, *Composites, Part A.,* 175, 107775 (2023). https://doi.org/10.1016/j.compositesa.2023.107775

Yurohman, Ramadhoni, B., Prabowo, S., Jayatin, Winarto, D. A., Swasono, Y. A., Laksmono, J. A., Hidayat, M. I. P. and Ardhyananta, H., Mechanical properties of hand layup manufactured lightweight sandwich composites consisting of multilayer carbon fiber skin-reinforced micro balloon core, *J. Inst. Eng. India Ser. D.,* 105(1), 1–8 (2024). https://doi.org/10.1007/s40033-024-00704-w