EGTRIB Journal

JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 15, No. 4, October 2018, pp. 26 - 36 **ISSN 2090 - 5882**

(Received June 26. 2018, Accepted in final form August 15. 2018)

FRICTION AND WEAR OF EPOXY REINFORCED BY POLYAMIDE FIBERS

Zahraa F. and Ali W. Y.

Production Engineering and Mechanical Design Dept., Faculty of Engineering,
Minia University, El-Minia, EGYPT.

ABSTRACT

The present work investigates experimentally the effect of reinforcing epoxy matrix by polyamide fibers of different diameters on the friction and wear at dry sliding against steel surface.

The experiments showed that, friction coefficient displayed by the tested composites drastically decreased as the polyamide content increased, while it significantly increased up to maximum then drastically decreased with increasing polyamide fiber diameter. Wear increased up to maximum then slightly decreased with increasing fiber diameter. At constant content of polyamide fibers to epoxy matrix, fibers of relatively low diameter showed the lowest wear. Wear mechanism of the tested composites is based on the triboelectrification of the sliding surfaces, where the contact area is charged by double layer of electrostatic charge (ESC) of different charge. Consequently, layers of epoxy can transfer and adhere to the steel counterface, where the contact will be epoxy/epoxy rather than epoxy/steel. Those contact materials are responsible for the friction increase. The transfer and transfer back of polymeric materials that accumulated to form film adhered to the steel surface are representing the prevailed wear mechanism.

KEYWORDS

Friction coefficient, wear, epoxy, polyamide fibers, reinforcement and electrostatic charge.

INTRODUCTION

Reinforcing polymers by fibers has tremendously increased to strengthen the brittle matrix by incorporating high strength fibers. Laminates of fiber reinforced composites are applied in automotive and aerospace applications. Besides, woven hybrid composites have high resistance to failure, compression and impact [1 - 2]. The wear of glass fiber reinforced epoxy resin filled with aluminium powder was investigated, [3]. The results showed that wear increased linearly with increasing load and velocity. Besides, wear mechanism was observed as a function of fiber orientation. Polymer based composites are used in different engineering applications such as automotive, construction and sport materials. The reinforcements in polymers are organic and inorganic. They are added to enhance the mechanical and tribological properties of the composite, [4, 5]. Carbon

fibers (CF) reinforced epoxy composites have wide applications due to their light weight, high mechanical strength and chemical resistance, [6 - 8]. The drawback of CF is the weak interface between fiber and epoxy matrix, [9]. TO overcome that difficulty, CF were treated by titanium dioxide nanorods, [10 - 13], where the interfacial shear strength and impact strength of the composites could be increased.

Nano-silica (NS) particles were added to woven fiber reinforced carbon/Kevlar/epoxy. The tensile, flexural, vibration and damping characteristics were examined, [14]. It was shown that NS particles improve interfacial stress. Epoxy resin is extensively used due to its relatively high stiffness and chemical resistance, [15]. Reinforcing and fibers such as glass, carbon and Kevlar are commonly used in fiber reinforced composites, [16 - 18]. It was showed that the incorporation of Kevlar fibers increase the ductility and toughness of the epoxy composites. Surface of fibers reinforcing epoxy treated by sodium carbonate was discussed, [19]. It was observed that tensile and flexural modulus increased due to the increase of the superficial roughness of the fibers. The treatment is very useful for natural fibers. The low Young's modulus, ultimate tensile strength and fracture toughness of epoxy can be improved by incorporating multi-walled carbon nanotubes (MWCNTs), [20 – 22]. In general, addition of a small amount of MWCNTs into epoxy matrix could enhance the mechanical properties.

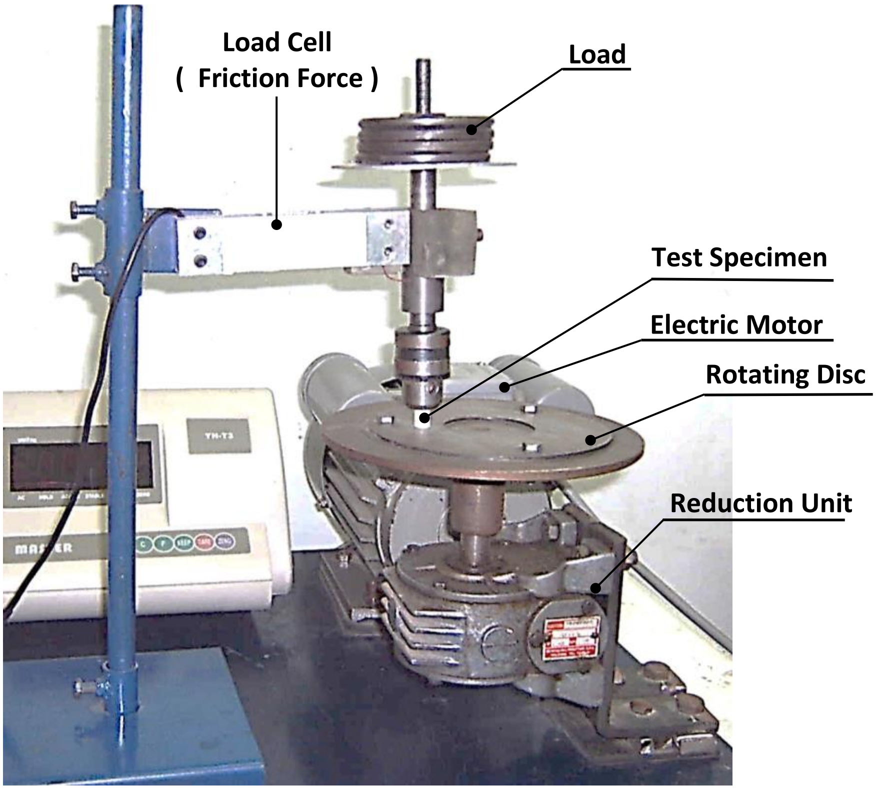
The mechanisms of triboelectrification are electron transfer, ion transfer and material transfer, [23 – 25]. For polymers, the electron transfers only happen on their surfaces, [27 – 29]. According to the triboelectric series the polarity of the charge that is transferred from one surface to another can be to predicted, [30]. At relatively high load the prevailing mechanism is material transfer, where the sign of ESC charge is frequently changed. Engineering materials including polymers can be arranged in a ''triboelectric series'' which lists the materials in the order of their relative polarity. In the triboelectric series the higher positioned materials will acquire a positive charge when contacted with a material at a lower position along the series, [31]. The triboelectric series can be used to estimate the relative charge polarity of the materials.

In the present work, effect of reinforcing epoxy by polyamide continuous fibers on friction coefficient and wear when sliding against steel is investigated. The effect of the fiber diameter is discussed.

EXPERIMENTAL

Experiments were carried out using pin-on-disc wear tester. It consists of a rotary horizontal steel disc driven by variable speed motor. The details of the wear tester are shown in Fig. 1. The pin made of the tested composites is held in the specimen holder that fastened to the loading lever. Friction force can be measured by means of the load cell, fastened to the rotating disc.

Friction tests were carried out under constant sliding velocity of 2.0 m/s, normal applied loads of 8, 10, 12, 14 and 16 N and lasted for 30 minutes. All measurements were performed at 25 ± 5 ºC and 30 ± 10 % humidity. The test specimen, in the form of a cylinder, is 10 mm diameter and 30 mm height. The diameter is reduced to 6 mm to contact the steel disc, Fig. 2. The polyamide continuous fibers of 0.25, 0.28, 0.45, 0.6, 0.7 and 0.8 mm diameter of volumetric content up to 72 vol. % were used to reinforce the epoxy matrix (KEMAPOXY 150A).



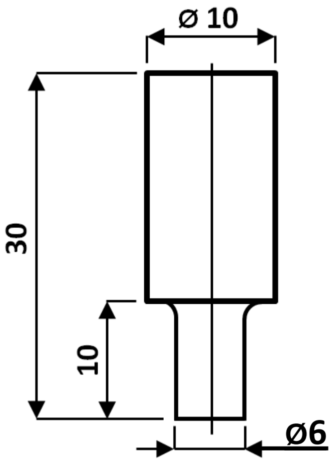


Fig. 2 Dimensions of the tested composites.

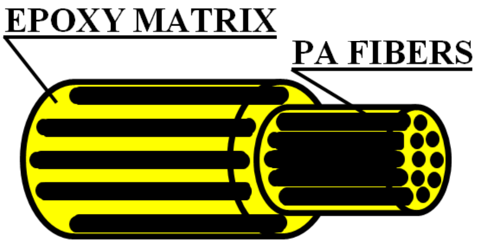


Fig. 3 Distribution of polyamide fibers in the tested composites.

RESULTS AND DICUSSION

Friction coefficient displayed by the tested composites reinforced by polyamide fibers of 0.8 mm diameter drastically decreased as the polyamide volumetric content increased, Fig. 4. The highest value of friction coefficient was observed for epoxy free of fibers due to the easy transfer of epoxy to the steel counterface, where the friction was between epoxy and epoxy. It seems that polyamide fibers might abrade epoxy layer transferred to the counterface. Friction coefficient decreased as the applied load increased. This behavior can be explained on the fact that load increase would increase the plasticity of the contact area of epoxy asperities so that the shear strength decreased causing the decrease of friction coefficient. The accumulation of the layers of the transferred polymers may produce the relatively high friction coefficient. At the beginning of the experiment the tested composites experienced relatively lower values of friction coefficient. As the epoxy transfer film deposited on the steel surface, friction coefficient increased indicating that both epoxy and steel suffered from severe stick-slip.

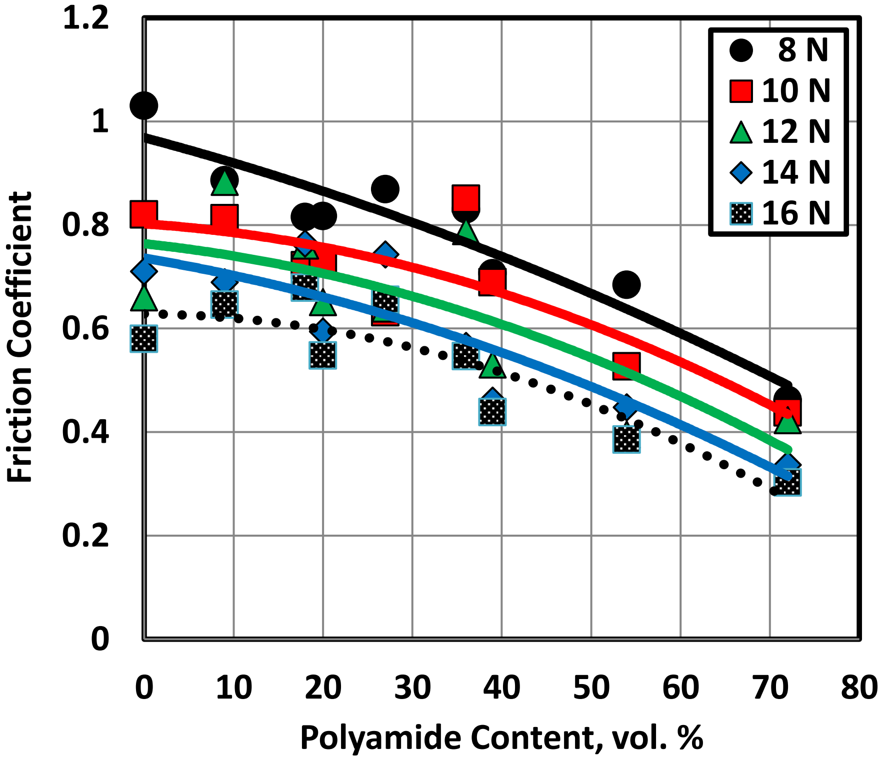


Fig. 4 Friction coefficient displayed by tested composites reinforced by polyamide fibers of 0.8 mm diameter.

Wear of the tested composites reinforced by polyamide fibers of 0.8 mm diameter increased with increasing applied load, Fig. 5, and decreased with increasing polyamide content. The observations in wear tests confirmed the role of polyamide fibers that have relatively higher wear resistance than epoxy in decreasing wear. The wear mechanism observed in the present work, can be explained on the basis of material transfer onto the steel counterface forming an adherent layer of transferred polymers. During friction, the relatively softer polymers transfer to the steel counterface. The deposit then back transfers fractionally to the tested composites. An equilibrium state appears to be reached as far as the amount of transfer in both directions is concerned. The accumulation of the layers of the transferred material may produce the relatively big

wear particles which were adhered to the counterface by the action of the contacting asperities then removed from the surface when the shear stress exceeds the adherence between the transferred layers and the steel counterface. Transferred materials are mainly epoxy and polyamide contaminated by tiny steel particles.

Formation of polymeric film on the steel counterface was observed as result of the electrostatic force generated from the triboelectrification. At the applied contact stresses a "roof-tile laminates" may be observed. Several layers of epoxy formed a composite roof-tile laminates as a result of the flattening of the substrate asperities in the direction of motion because of plastic yielding, [32 – 33]. As the sliding motion proceeds, back transfer occurred sequentially until a critical number of layers was deposited. Thereafter, one layer or more might be removed as wear particles, while the other layers might be bonded to the tested composites surface, back transferred to the steel counterface or released as wear particles. The deposited layers were held by the electric force generated from ESC. The surface of the steel disc after the test revealed small flattened islands of epoxy which adhered strongly by electric static force. These particles were elongated in the direction of sliding, they were found on only a very small proportion of the steel surface.

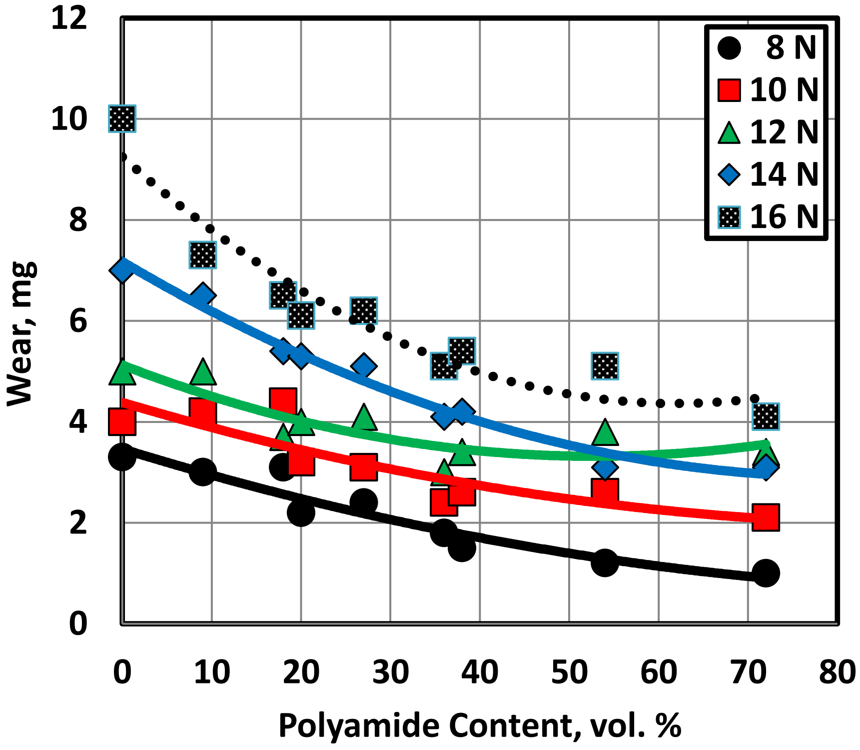


Fig. 5 Wear of the tested composites reinforced by polyamide fibers of 0.8 mm diameter.

Friction coefficient displayed by the tested composites reinforced by different diameter of polyamide fibers significantly increased up to maximum at 0.6 mm fiber diameter then drastically decreased with increasing fiber diameter, Fig. 6. It seems that when the diameter of polyamide increases the contact area of steel will be adhered by polyamide wear particles where the contact will be epoxy/polyamide and polyamide/polyamide instead of epoxy/steel and polyamide/polyamide. Further increase of polyamide fiber diameter decreases the contact area adhered by epoxy that leads to the decrease of friction coefficient. This observation can give specific information about the proper fiber

diameter that can be applied in epoxy reinforcement.

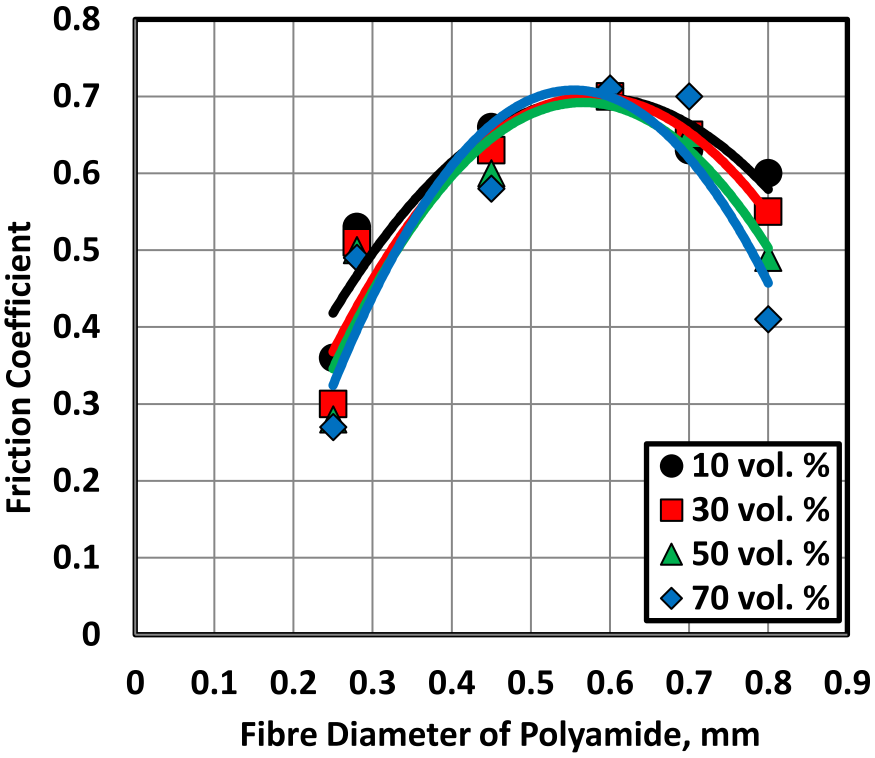


Fig. 6 Friction coefficient displayed by tested composites reinforced by different diameter of polyamide fibers.

The relationship between wear of the tested composites and polyamide fiber diameter reinforcing epoxy is shown in Fig. 7. Wear remarkably increased with increasing fiber diameter up to 0.7 mm then slightly decreased. At constant content of polyamide fibers, relatively low fiber diameter showed the lowest wear due to the increased number of fibers reinforcing the matrix. During wear process, epoxy worn from the tested composites and adhered to the steel counterface forming thin layer. During sliding, relatively hard steel asperities penetrate the surface of the tested composites, where the stresses at the point of contact are high and cause localized plastic deformation. Then, sliding of the contacting materials is accompanied by repeated extensive deformation of the thin surface layer of polymer leading to the deformation of the surface layer and wear particles. The polymeric material transfers back to the parent composites. It is expected that the transfer film generated from epoxy is considerably thicker than those generated from polyamide. The transfer film of epoxy is accumulated to form larger film adhered to the steel surface and followed by excessive shear stress that caused considerable plastic flow of the deposited film.

When epoxy was reinforced by polyamide fibers, ESC generated on steel counterface displayed relatively high values. Generally, ESC increased proportional to the sliding distance. The generation of ESC is from the contact of the sliding surfaces which accelerates the electron exchange. ESC charge will be gained by each of the two contact surfaces. Based on the rank of the two sliding materials in the triboelectric series, one surface would gain negative charge while the other would gain positive charge.

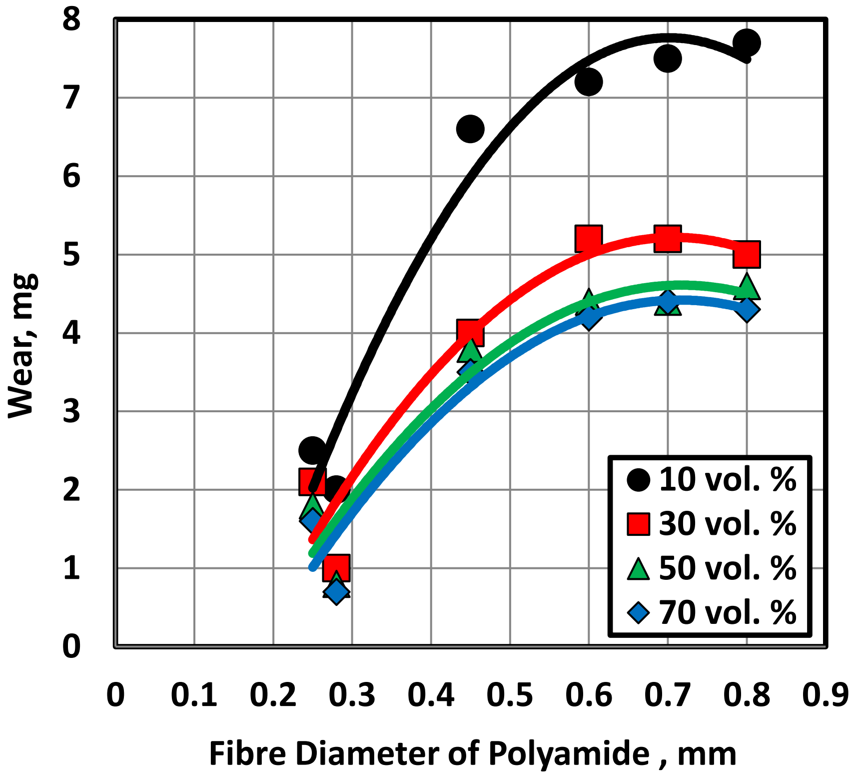


Fig. 7 Wear of the tested composites reinforced by different diameter of polyamide fibers.

Figure 8 illustrates the distribution of ESC on the contact area for low number of polyamide fibers reinforcing epoxy matrix. It is shown that most of the contact area is charged by double layer of ESC of different charge. Consequently, layers of epoxy can transfer and adhere to the steel counterface, where the contact will be epoxy/epoxy rather than epoxy/steel. That contact condition is responsible for the friction increase. Polyamide is ranked as positive charged material, while epoxy is negative charged one and the gap is relatively long in the triboelectric series, Fig. 9. This means that the voltage difference generated from triboelectrification increases. It is obvious that ESC plays major role in adhesion energy and alters friction by the effect of the trapped charges and, consequently on the presence of surface defects introduced during friction.

The distribution of ESC on the contact area for smaller diameter of polyamide fibers reinforcing epoxy matrix is shown in Fig. 10. The increase of polyamide fibers influenced the sign of ESC built up on steel counterface, where the resultant approaches zero. Practically, steel counterfce loses its ability to attract neither epoxy nor polyamide wear particles removed from the tested composite surface. In this condition, the contact will be epoxy/steel and polyamide/steel so that friction coefficient displays relatively lower values.

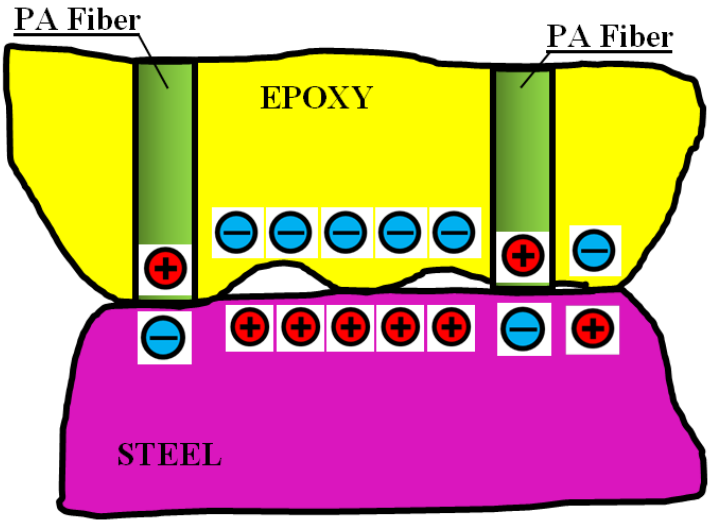


Fig. 8 Generation of ESC on the sliding surfaces.

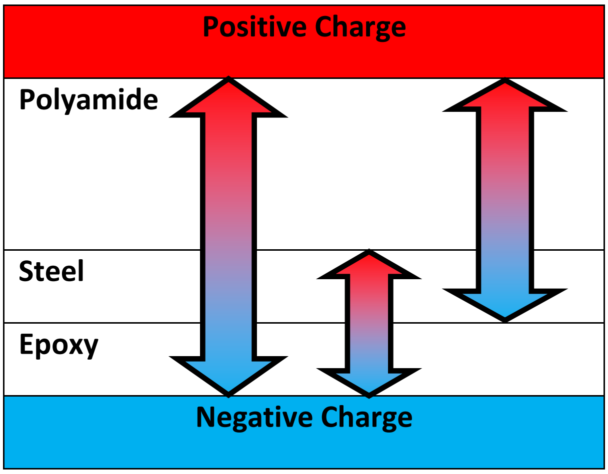


Fig. 9 Triboelectric series of the tested materials.

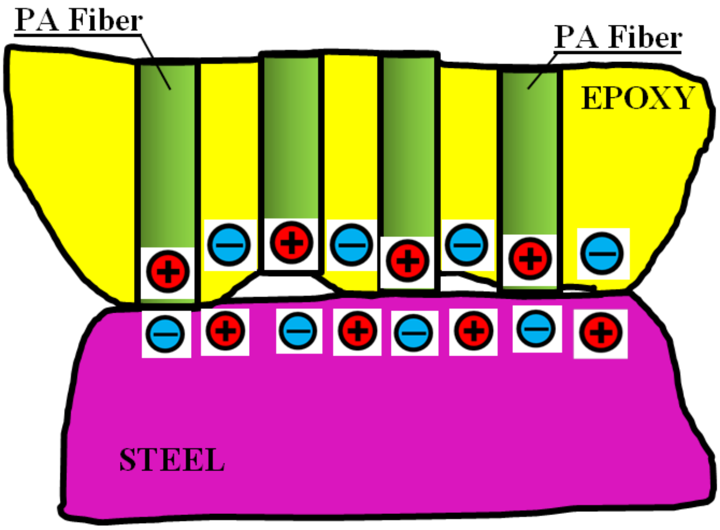


Fig. 10 Generation of ESC on the sliding surfaces for smaller polyamide fiber diameter.

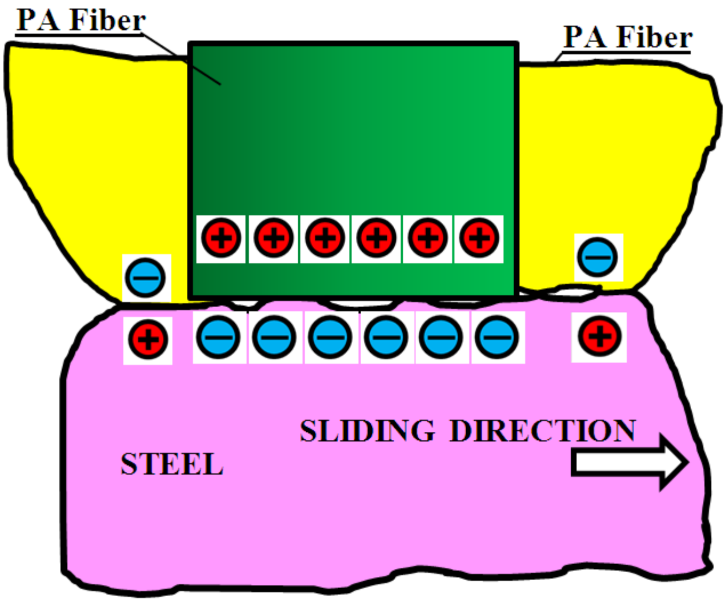


Fig. 11 ESC built up on the sliding surfaces for bigger polyamide fiber diameter.

When the diameter of polyamide fiber increases, higher fraction of the contact area of steel will be electrified by negative charge, Fig. 11. It is expected that ESC generated from the friction of polyamide and steel will be higher than that generated from steel and epoxy. This behaviour could be attributed to the fact that epoxy, polyamide and steel are different materials and according to the triboelectric series, friction between two surfaces causes the object in the upper position of the series to be charged positively (polyamide) and that in the lower position to be charged negatively (steel). It is known that different polarity means attraction. Also, it could be attributed to that, the long distance gives higher chance to exchange more electrons between the two different materials rubbing each other. Based on that, polyamide wear particles will be strongly adhered to the steel surface attracting layers of epoxy of negative charge to be accumulated to form thicker polymeric layer. In that condition due to the transfer of polyamide and epoxy into the steel counterface both friction coefficient and wear increases.

CONCLUSIONS

1. Friction coefficient displayed by the tested composites reinforced by polyamide fibers drastically decreased as the polyamide content increased.
2. Friction coefficient significantly increased up to maximum then drastically decreased with increasing fiber diameter.
3. Wear decreased with increasing polyamide content.
4. Wear remarkably increased with increasing fiber diameter up to maximum then slightly decreased.

REFERENCES

1. Kaw A., "Mechanics of composite materials", Vol. II. London, New York: Taylor and Francis Group; (2006).
2. Valenç S. L., Griza S., Oliveira V. G., Sussuchi E. M., Cunha F. G. C., "Evaluation of the mechanical behavior of epoxy composite reinforced with Kevlar plain fabric and glass/Kevlar hybrid fabric. Compos B Eng, 70, pp. 1 - 8, (2015).

3. Kumar S. T., Shivashankar G. S., Dhotey K., Singh J., "Experimental study wear rate of glass fiber reinforced epoxy polymer composites filled with aluminium powder", Materials Today, Proceedings 4, pp. 10764 - 10768, (2017).

4. Wang Q. H., Xue J., Shen W., Liu W., “An Investigation of the Friction and Wear Properties of Nanometer Si_3N_4 Filled PEEK,” Wear, Vol. 196, No. 1 - 2, pp. 82 - 86, (1996).

5. Rao S., Rao G.K., "An Emerging, Energy-Efficient Cure Process for Rapid Composite Manufacture. NAL, Bangalore, (2008).

6. Daniel P. C., Todd C. H., Frank G., Hu R. A., "Interphase mechanical behavior of carbon fiber reinforced polymer exposed to cyclic loading", Compos. Sci. Technol. 151, pp. 202 - 210, (2017).

7. Han W. B., Zhao G. D., Zhang X. H., Zhou S. B., Wang P., An Y. M., Xu B. S., "Graphene oxide grafted carbon fiber reinforced siliconborocarbonitride ceramics with enhanced thermal stability, Carbon 95, pp. 157 – 165, (2015).

8. Zhang Y., Zhang L. T., Liu Y. S., Liu X. Y., Chen B., "Oxidation effects on in-plane and interlaminar shear strengths of two-dimensional carbon fiber reinforced silicon carbide composites", Carbon 98, 144 - 156, (2016).

9. Ning H. M., Li J. H., Hu N., Yan C., Liu Y. L., Wu L. K., Liu F., Zhang J. Y., "Interlaminar mechanical properties of carbon fiber reinforced plastic laminates modified with graphene oxide interleaf", Carbon 91, pp. 224 - 233, (2015).

10. Ma L., Zhu 8.Y., Li X., Yang C., Han P., Song G., "The architecture of carbon fiber-TiO_2 nanorods hybrid structure in supercritical water for reinforcing interfacial and impact properties of CF/epoxy composites", Polymer Testing 66, pp. 213 - 220, (2018).

11. Gao B., Zhang R. L., Wang C. G., "Enhanced mechanical properties of carbon fiber composites by grafting different structural poly(amido amine) onto fiber surface", Polym. Test. 56, pp. 192 - 199, (2016).

12. Dong J. D., Jia C. Y., He J. M., Jiang Z. X., Huang Y. D., "Improved mechanical properties of carbon fiber-reinforced epoxy composites by growing carbon black on carbon fiber surface", Compos. Sci. Technol. 149, pp. 75 – 80, (2017).

13. Lee H., Ohsaw I., Takahashi J., "Effect of plasma surface treatment of recycled carbon fiber on carbon fiber-reinforced plastics (CFRP) interfacial properties", Appl. Surf. Sci. 328, pp. 241 - 246, (2015).

14. Alsaadi M., Bulut M., Erkliğ A. , Jabbar A., "Nano-silica inclusion effects on mechanical and dynamic behavior of fiber reinforced carbon/Kevlar with epoxy resin hybrid composites", Composites Part B 152, pp. 169 - 179, (2018).

15. Gay D., Hoa S. V., Tsai S. W., "Composite materials, design and applications", Boca Raton, FL: CRC Press LLC; (2003).

16. Dorigato A., Pegoretti A., "Flexural and impact behaviour of carbon/basalt fibers hybrid laminates", J Compos Mater Apr, 48 (9), pp. 1121–1130, (2014).

17. Singh T. J., Samanta S., "Characterization of Kevlar fiber and its composites: a review. Mater Today, Proceedings, Jan 1, 2, (4 - 5), pp. 1381 – 1387, (2015).

18. Reddy M. I., Kumar M. A., Raju C. R. B., " Tensile and Flexural properties of Jute, Pineapple leaf and Glass Fiber Reinforced Polymer Matrix Hybrid Composites", Materials Today: Proceedings 5, pp. 458 – 462, (2018).

19. Santos J. C., Siqueira R. L., Vieirad L. M. G., Freire R. T. S., Mano V., Panzera T. H., "Effects of sodium carbonate on the performance of epoxy and polyester coir reinforced composites", Polymer Testing 67, pp. 533 - 544, (2018).

20. Quan D., Urdaniz J. L., Ivankovic A., "Enhancing mode-I and mode-II fracture toughness of epoxy and carbon fiber reinforced epoxy composites using multi-walled carbon nanotubes", Materials and Design 143, pp. 81 – 92, (2018).

21. Xu H., Tong X., Zhang Y., Li Q., Lu W., "Mechanical and electrical properties of laminated composites containing continuous carbon nanotube film interleaves", Compos. Sci. Technol. 127, pp. 113 – 118, (2016).

22. Zheng N., Huang Y., Liu H.-Y., Gao J., Mai Y.-W., "Improvement of interlaminar fracture toughness in carbon fiber/epoxy composites with carbon nanotubes/polysulfone interleaves", Compos. Sci. Technol. 140, pp. 8 – 15, (2017).

23. Lee L. H., "Dual mechanism for metal–polymer contact electrification", J. Electrostat. 32, 1 - 29, (1994).

24. Matsusaka S., Masuda H., "Electrostatics of particles" Adv. Powder Technol. 14, pp. 143 - 166, (2003).

25. Saurenbach F., Wollmann D., Terris B., Diaz A., "Force microscopy of ioncontaining polymer surfaces: morphology and charge structure" Langmuir 8, pp. 1199 - 1203, (1992).

26. Anderson J., "A comparison of experimental data and model predictions for tribocharging of two-component electrophotographic developers", J. Imag. Sci. Technol. 38, pp. 378 - 382, (1994).

27. Gutman E., Hartmann G., Triboelectric properties of two-component developers for xerography" J. Imaging Sci. Technol. 36, pp. 335 - 349, (1992).

28. Yoshida M., Ii N., Shimosaka A., Shirakawa Y., Hidaka J., "Experimental and theoretical approaches to charging behavior of polymer particles", Chem. Eng. Sci. 61, pp. 2239 - 2248, (2006).

29. Park C. H., Park J. K., Jeon H. S., Chun B. C., Triboelectric series and charging properties of plastics using the designed vertical-reciprocation charger", J. Electrostat, 66, pp. 578 - 583, (2008).

30. Meurig W. Williams, "Triboelectric charging in metal-polymer contacts - How to distinguish between electron and material transfer mechanisms", Journal of Electrostatics 71, pp. 53 - 54, (2013).

31. Diaz A. F., Felix-Navarro R. M., "A semi-quantitative tribo-electric series for polymeric materials: the influence of chemical structure and properties", Journal of Electrostatics 62, pp. 277 - 290, (2004).

32. Youssef, M., Balogh, I. and Ali, W., “Material Transfer During Starved Lubricated Sliding Of Metallic Surfaces”, MICATE’2002, Minia, EGYPT, 16 – 18 March, pp. 1179 – 1187, (2002).

33. Mansour H., El-Sherbiny, M. G. and Ali, W. Y., “Mechanism of Formation of Large Wear Particles During Starved Lubricated Sliding of Aluminium Alloy and Brass Against Steel Surfaces”, Journal of the Egyptian Society of Tribology, Vol. 1, No. 3, October, (2003).