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FRICTION AND WEAR OF EPOXY REINFORCED BY POLYESTER 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 continuous polyester fibers of different diameters on the friction and wear at dry sliding against steel surface.

It was observed that epoxy composites reinforced by polyester fibers showed drastic decrease in friction coefficient, where the highest value was observed for epoxy free of fibers. Besides, friction coefficient significantly increased with increasing fiber diameter. Wear of the tested composites decreased with increasing polyester content, while wear remarkably increased with increasing fiber diameter. It is recommended to test polyester fibers of lower diameter than that tested in the present work to specify the composites of the lowest friction coefficient and wear.

KEYWORDS
Friction coefficient, wear, epoxy, polyester fibers, reinforcement, electrostatic charge.

INTRODUCTION
The increased use of fiber reinforced epoxy composites for the low costs as well as high mechanical and tribological properties accelerates their development. The effect of reinforcing epoxy matrix by polyamide fibers of different diameters on the friction and wear, at dry sliding against steel surface, was studied, [1], where friction coefficient displayed by the tested composites drastically decreased as the polyamide content increased and 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 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.

Epoxy composites reinforced by fibers are applied in different industrial applications, [2 - 3]. Glass fiber reinforced epoxy resin showed wear increase with increasing load and velocity, [4], where fiber orientation affected wear mechanism. The reinforcements are reinforcing epoxy matrix to develop the strength and increase lifetime, [5, 6]. Carbon

fibers (CF) reinforced epoxy composites have light weight, high mechanical strength and chemical resistance, [7 - 14]. Woven fiber reinforced epoxy was filled by Nano-silica particles, [15, 16] to enhance interfacial stress. Fibers of glass, carbon and Kevlar were commonly used to reinforce epoxy composites, [17 - 20], where Kevlar fibers increased the mechanical property. Besides, multi-walled carbon nanotubes can improve the tensile strength of epoxy, [21 – 23]. 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 polyester 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.

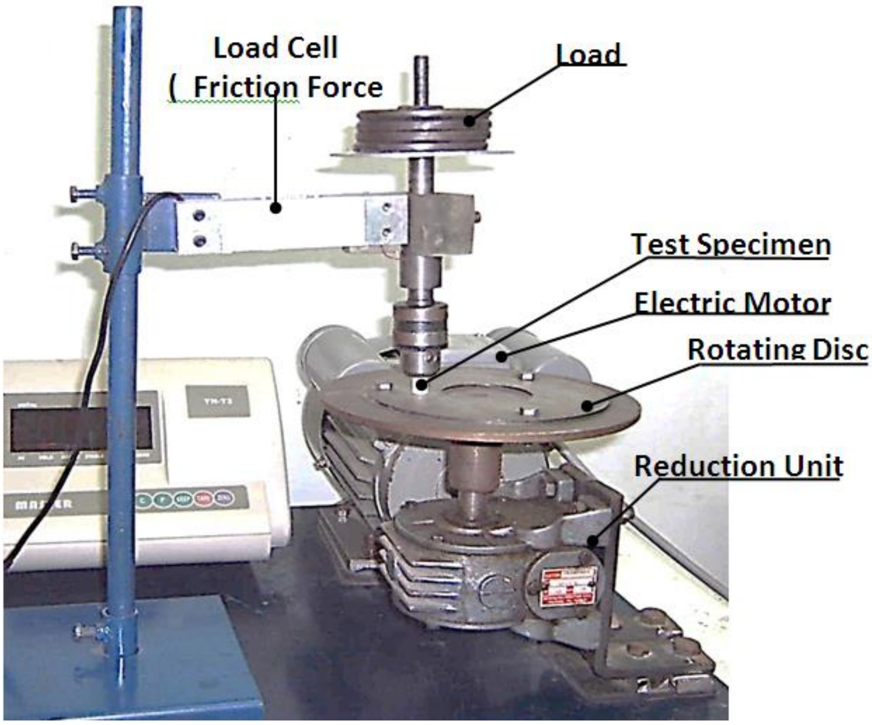


Fig. 1 Arrangement of the test rig.

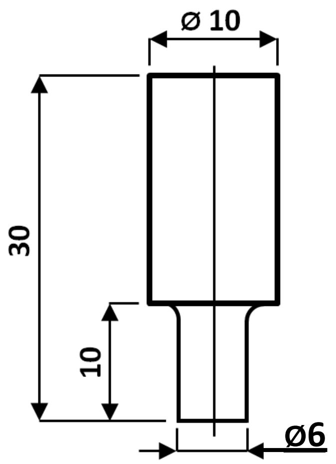


Fig. 2 Dimensions of the tested composites.

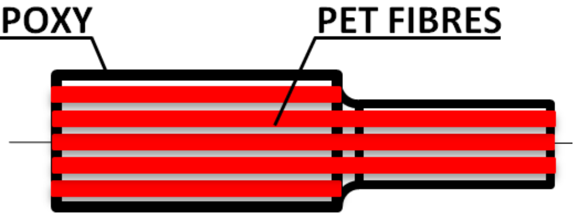


Fig. 3 Distribution of polyester fibers in tested composites.

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 polyester continuous fibers of 0.08, 0.10, 0.16 and 0.20 mm diameter of volumetric content up to 8.0 vol. % were used to reinforce epoxy matrix (KEMAPOXY 150A).

RESULTS AND DICUSSION

Drastic decrease in friction coefficient displayed by the tested composites reinforced by polyester fibers of 0.20 mm diameter as the polyester 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. Reinforcing epoxy by polyester fibers might reduce 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 epoxy may display the relatively high friction coefficient. It was observed 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.

Friction coefficient displayed by the tested composites reinforced by different diameters of polyester fibers significantly increased with increasing fiber diameter, Fig. 5. It seems that when the diameter of polyester fibers increases, the contact area of steel will be adhered by polyester wear particles where the contact will be epoxy/polyester and polyester/polyester instead of epoxy/steel and polyester/steel. This observation can give specific information about the proper fiber diameter that can be applied in epoxy reinforcement. The friction values observed at relatively lower diameter of polyester fibers recommends the application of those composites to be used as bearing materials in guide and slide ways. Besides, it is worthy to test polyester fibers of lower diameter than 0.2 mm.

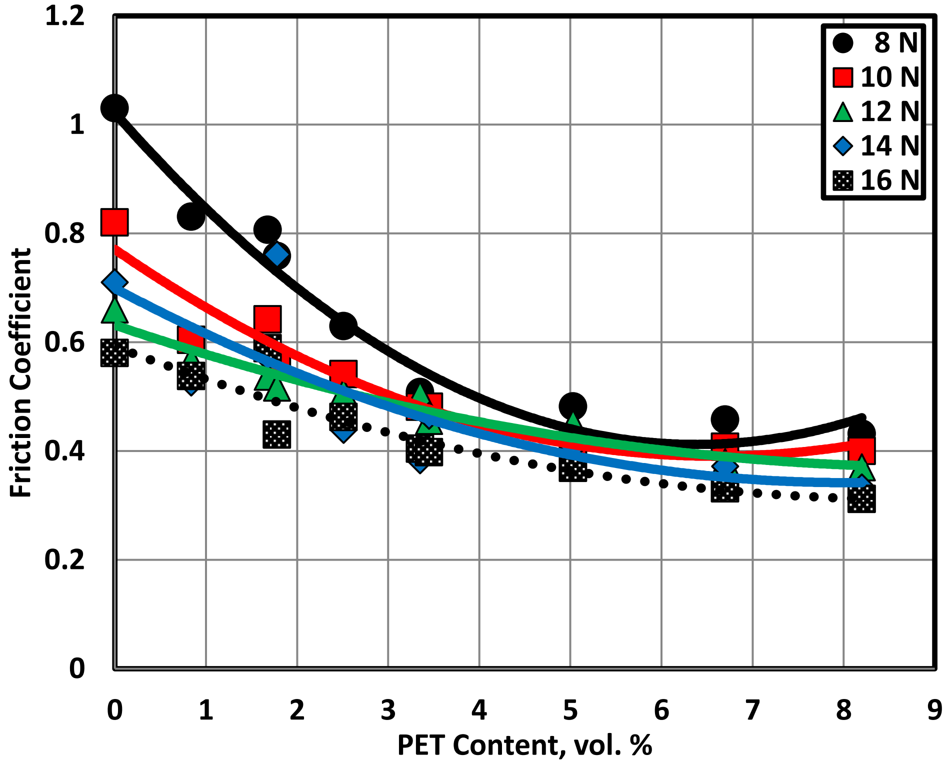


Fig. 4 Friction coefficient displayed by tested composites reinforced by polyester fibers of 0.20 mm diameter.

Wear of the tested composites reinforced by polyester fibers of 0.2 mm diameter increased with increasing applied load, Fig. 6, and decreased with increasing polyester content. The observations in wear tests confirmed the role of polyester 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 epoxy transfer onto the steel counterface forming an adherent layer. During friction, the relatively softer epoxy and polyester transferred to the steel counterface. The deposit then back transferred 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 form the layer that was 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 layer and the steel counterface. Transferred materials are mainly epoxy and polyester contaminated by tiny steel particles.

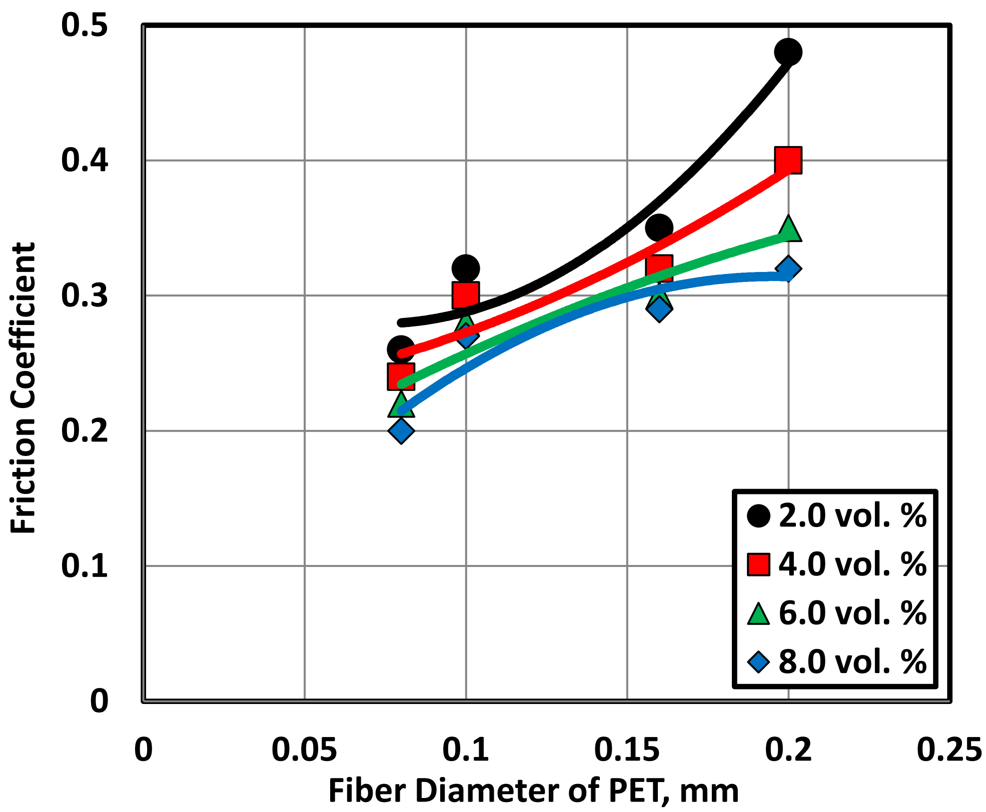


Fig. 5 Friction coefficient displayed by tested composites reinforced by polyester fibers of different fiber diameter.

The relationship between wear of the tested composites and polyester fiber diameter reinforcing epoxy is shown in Fig. 7. Wear remarkably increased with increasing fiber diameter. At constant content of polyester 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 formed thin layer. During sliding, relatively hard steel asperities penetrated the surface of the tested composites, where the stresses at the point of contact were high and caused localized plastic deformation. Then, sliding of the contacting materials was accompanied by repeated extensive deformation of the thin surface layer of epoxy 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 polyester. The transfer film of epoxy was accumulated to form thicker film adhered to the steel surface and followed by excessive shear stress that caused considerable plastic flow of the deposited film.

ESC generated on steel counterface displayed relatively high values for epoxy reinforced by polyester fibers. Generally, ESC increased proportional to the sliding distance. The generation of ESC is from the contact of the sliding surfaces that 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, Fig. 8, one surface would gain negative charge while the other would gain positive charge.

Figure 9 illustrates the distribution of ESC on the contact area for relatively big diameter of polyester fibers reinforcing epoxy matrix. It is shown that most of the contact area is charged by double layer of ESC of different charge due to the position of polyester fiber in the triboelectric series. Consequently, layers of epoxy and polyester can transfer and adhere to the steel counterface, where the contact will be epoxy/epoxy and polyester/polyester rather than epoxy/steel or polyester/steel. That contact condition was responsible for the friction increase. Polyester is ranked as negative charged material. Although epoxy is negative charged one slides against steel it gains positive ESC when contacts steel. 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.

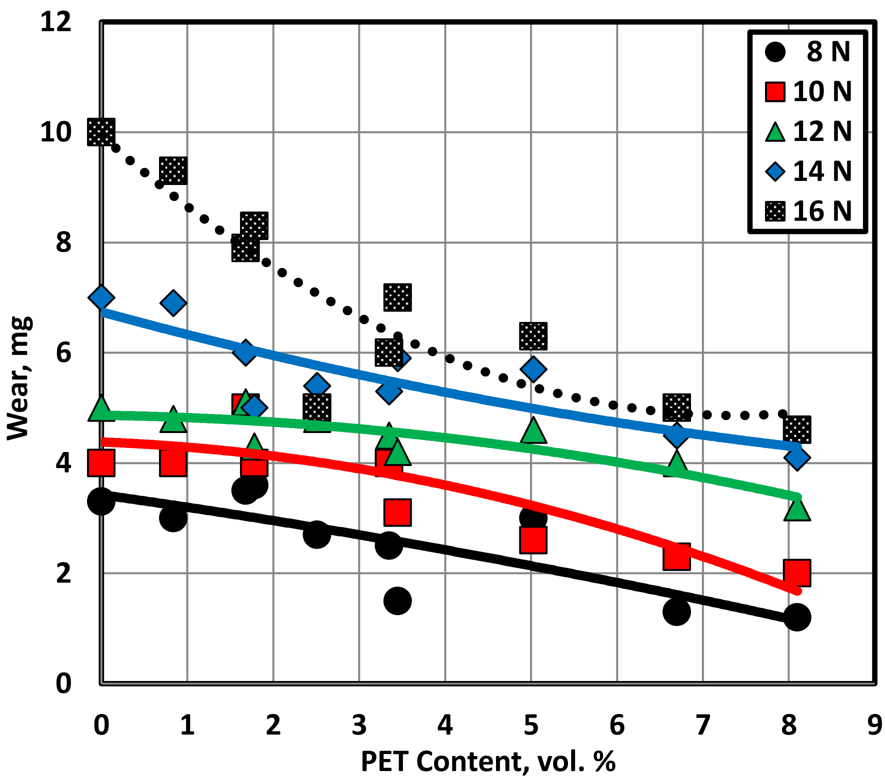


Fig. 6 Wear of the tested composites reinforced by 0.20 mm diameter polyester fibers.

When the diameter of polyester fiber increases, higher fraction of the contact area of steel will be electrified by negative charge. It is expected that ESC generated from the friction of polyester and steel will be higher than that generated from steel and epoxy. This behaviour could be attributed to the fact that epoxy, polyester 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 (steel) and that in the lower position to be charged negatively (polyester and epoxy). 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, polyester wear particles in form of film 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 polyester and epoxy into the steel counterface both friction coefficient and wear increased. The distribution of ESC on the contact area for relatively smaller diameter of polyester fibers reinforcing epoxy matrix is shown in Fig. 10. The increase of polyester fibers influenced the sign of ESC built up on steel counterface, where the resultant showed lower charge than that observed for relatively big diameter.

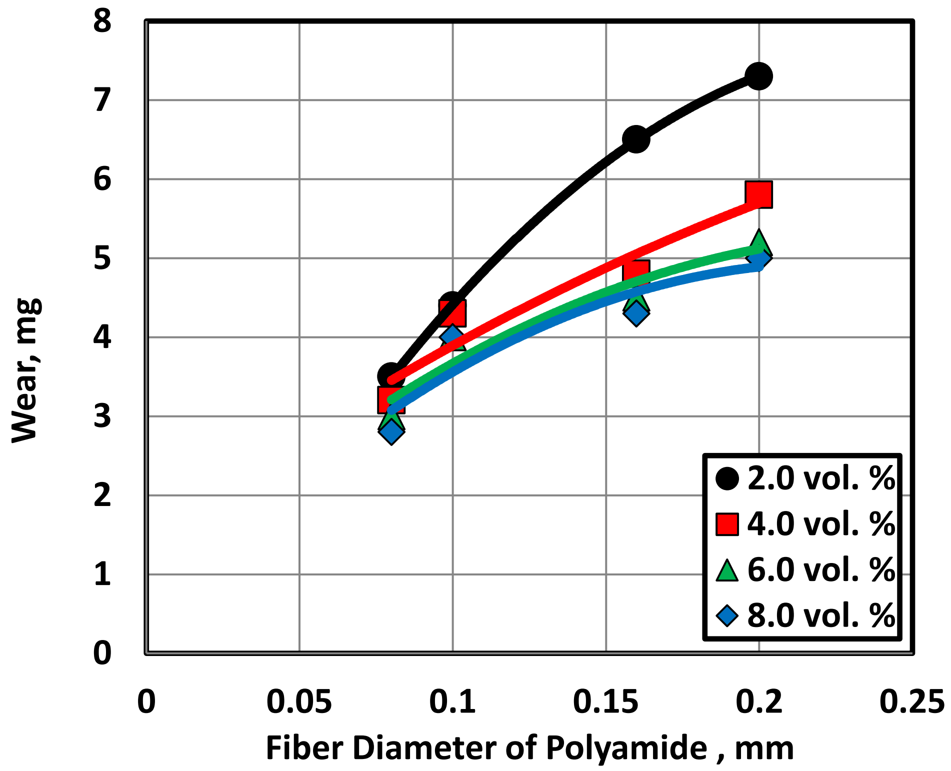


Fig. 7 Wear of the tested composites reinforced by polyester fibers of different fiber diameter.

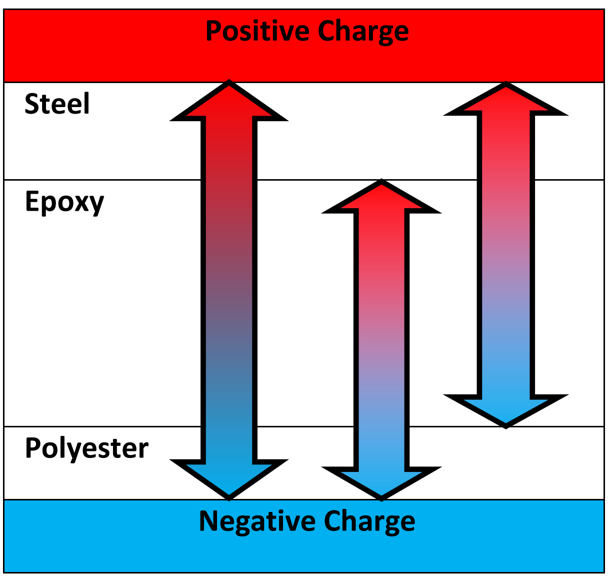


Fig. 8 Triboelectric series of the tested materials.

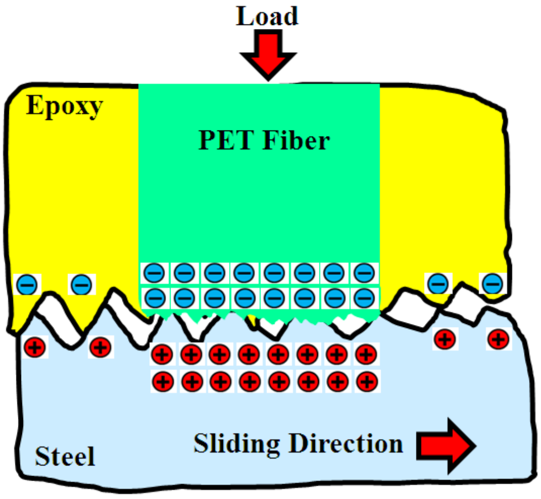


Fig. 9 ESC built up on the sliding surfaces for big polyester fiber diameter.

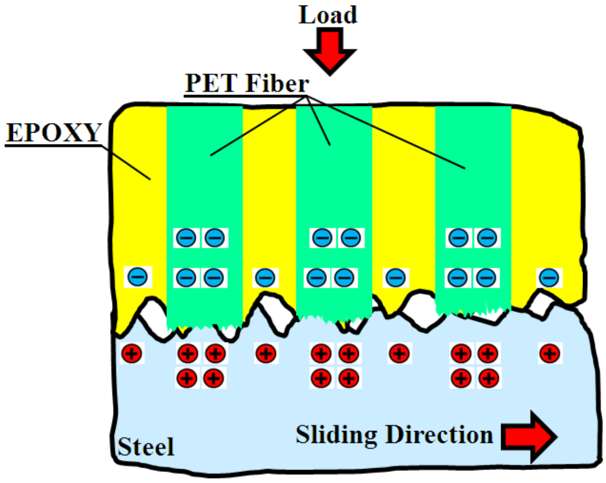
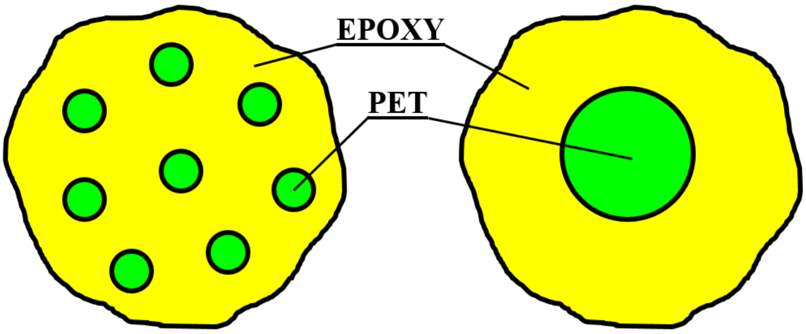


Fig. 10 Generation of ESC on the sliding surfaces for smaller polyester fiber diameter.



a. Contact area of composites reinforced by PET fibers of small diameter.	**b. Contact area of composites reinforced by PET fibers of big diameter.**

Fig. 11 Illustration of the contact area of the tested composites before sliding.

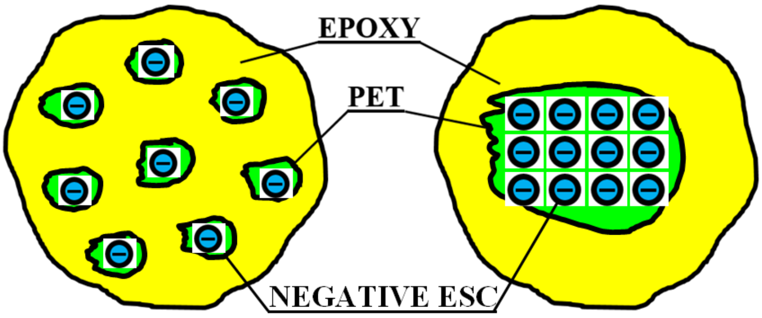


Fig. 12 Distribution of ESC on the contact area of the tested composites after sliding.

The dependency of friction coefficient and wear on the diameter of PET can be explained on the bases of epoxy and PET transfer and back transfer into the contact surfaces. Figures 11, a and 11, b illustrates the distribution of PET fibers inside the matrix of epoxy reinforced by relatively small and big PET fibers respectively. After sliding, Fig. 12, epoxy and PET transferred into steel surface, where friction coefficient depended on the area covered by epoxy and PET as well as the adhesion between both of epoxy and PET and steel surface. When epoxy matrix was reinforced by PET of relatively small diameter, epoxy transfer into steel would be easier leading to significant increase in the steel area covered by epoxy. In that condition, the contact would be between PET and epoxy, where the ESC would be lower

The attractive force between steel and PET is much higher than that expected for steel and epoxy due to the position of those materials in the triboelectric series, where the intensity of ESC controls the strength of the attractive force. Adhesion of PET into steel surface would be stronger than the adhesion of epoxy into steel. It is expected that friction force would increase with increasing adhesion between the two contact surfaces. As the surface area covered by PET increases, friction would increases more than that displayed surface area covered by epoxy. Proper distribution of fibers in epoxy matrix would control polymer transfer into steel surface, while concentration of fibers would disabled the homogeneity of the polymer distribution.

CONCLUSIONS

1. Epoxy composites reinforced by polyester fibers showed drastic decrease in friction coefficient. The highest value of friction coefficient was observed for epoxy free of fibers. Friction coefficient decreased as the applied load increased. Friction coefficient significantly increased with increasing fiber diameter.
2. Wear of the tested composites increased with increasing applied load and decreased with increasing polyester content. Wear remarkably increased with increasing fiber diameter.
3. It is recommended to test polyester fibers of lower diameter than that tested in the present work to specify the composites of the lowest friction coefficient and wear.

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