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DRY SLIDING OF POLYESTER COMPOSITES FILLED BY NANOPARTICLES AGAINST STEEL

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ABSTRACT

In the present experiments, friction coefficient and wear of polyester composites reinforced by nanoparticles of iron, copper, aluminum, and aluminum oxide and dry sliding against steel were investigated to develop new engineering materials with low friction coefficient and high wear resistance which can be used as bearing materials. Experiments were carried out at dry sliding. Cylindrical test specimens of 10 mm diameter and 30 mm length of polyester resin filled by nanoparticles were tested. Pin on disc tribometer was used to perform friction and wear experiments under the application of electric direct current of 0, ± 1.5, ± 3 and ± 4.5 volts.

Experiments showed that, when the test specimens were negative charged, friction coefficient increased with increasing electric voltage for composites filled by aluminium, while at no voltage, friction coefficient decreased with increasing aluminium content. As the electric voltage increased wear decreased. The lowest wear values were displayed by polyester filled by 6 – 10 wt. % aluminium content. Polyester composites filled by copper displayed relatively lower friction than that observed for composites filled by aluminium. In condition of applying electric voltage friction coefficient increased with increasing copper content.

As for positive charged test specimens, application of electric voltage showed significant wear decrease. Wear resistance when applying negative voltage was better than that observed for positive voltage. Besides, friction coefficient showed relatively higher values than that observed for composites of negative voltage. Wear showed the same trend observed for composites of negative voltage. Composites filled by 10 wt. % copper at 4.5 volt showed the lowest wear value.

INTRODUCTION

The field of nanotechnology is extending the applications of engineering and technology. The polymer based nanoparticles/nanocomposites are the fast growing field of research for developing the materials, [1]. There is an increasing demand to develop materials based on thermosetting polymers due to the relatively high thermal stability and environmental resistance as well as the good tribological performance. Thermosetting

polymer composites are used as substrate, coating, and plastic bearings as well as in the automotive, railway and transport industries, [2]. The major drawback is their relatively poor wear resistance. While many thermoplastic materials show self lubricating behaviour, , [3], while the lubricating properties of thermosetting polymers need to be modified by solid lubricants or by the addition of nanoparticles of selected materials in particular ZnO nanoparticles. It was found that, for oil lubricated sliding of negative charged test specimens, friction coefficient displayed by sliding of polyester filled by aluminium of negative voltage against steel slightly increased with increasing aluminium content, [4]. As the applied voltage increased friction coefficient significantly increased. At no electric voltage wear slightly decreased with increasing copper content. Application of electric voltage increased wear. As for oil lubricated sliding of positive charged test specimens, friction coefficient showed no change with increasing aluminium content. Wear increased with increasing both aluminium content and electric voltage.

Silica nanoparticle filled polypropylene (PP) and PP blends were studied. Mechanical property improvement was the major, [4 - 6]. It is well known that the intrinsic properties of semi-crystalline polymer material, including the mechanical properties, are determined by the microstructure of the final products, which is in turn dependent on the thermal or mechanical history that the material experiences during processing. There are not as many reports on the non-isothermal crystallization behaviour of PP/silica nanocomposites as there are on the mechanical properties. Silicon nitride (Si_3N_4) is a ceramic material with high strength and toughness. It has been used in many industrial applications, such as engine components, bearings, springs, high temperature automobile components and cutting tools. Si_3N_4 nanoparticles exhibit high potential for the reinforcement of polymers.

There exists a great interest in the development of new polymer-clay nanocomposites in the expectation of improved physicochemical and mechanical properties with respect to the pure polymers and conventional composites, with the use of a relatively low filler proportion, [7 - 9]. Polycarbonate is an amorphous engineering thermoplastic which combines good thermal stability, transparency, impact resistance and the ability to be processed on conventional machinery. Thus, the surface properties are important for many applications such as medical, optics, automobile, etc., since problems related to scratching or wear on the surface are of interest in the case of this thermoplastic. New polycarbonate nanocomposites are being developed in order to improve the thermal, mechanical, electrical or optical properties of the base polymer.

The effect, of silane treatment of Fe_3O_4 on the magnetic and wear properties of Fe_3O_4/epoxy nanocomposites, was investigated, [10]. The results showed that the specific wear rate of surface-modified Fe_3O_4/epoxy nanocomposites was lower than that of unmodified Fe_3O_4/epoxy nanocomposites. The decrease in wear rate and the increase in magnetic properties of surface-modified Fe_3O_4/epoxy nanocomposites occurred due to the improved dispersion of Fe_3O_4 into the epoxy matrix.

Many authors became interested in magnetic nanopowder reinforced polymer composites because magnetic nanoparticles have shown great potential for applications, including aircraft, spacecraft, magnetic hard disks, and the magnetic bars of credit card.

These applications can take advantage of both the magnetic properties and wear properties of these compositions, [11]. Among the composites, one can produce magnetic nanopowder reinforced polymer nanocomposites that exhibit magnetic properties and wear properties superior to those of other composites. On the microscale of filling materials reinforcing polyester composites, several research works were carried out, [12]. Friction coefficients and wear rates of polyester composites reinforced by graphite fibre with different diameters and impregnated by vegetable oils (corn, olives, and sunflower oil) were measured to develop new engineering materials with low friction coefficients and high wear resistance which can be used in industrial applications as bearing materials. Corn and sunflower oil display good tribological behavior of the polyester composites.

Several works were carried out to develop polyester composites to be used as self lubricated bearing material in different engineering applications. Polyethylene and glass fibres were used to reinforce polyester in order to increase wear resistance of the tested composites. Paraffin, glycerin, almond, olives, cress, sesame and baraka oils were added to polyester during molding to produce self lubricated composites, [13 - 15]. It was found that increasing oil content and polyethylene fibres decreased friction content. The highest friction and wear were displayed by composites free of oil. Composites containing olive oil displayed higher friction and lower wear than that containing almond oil. Impregnating polyester matrix by paraffin and glycerin oils caused significant reduction in friction coefficient and wear.

Friction of polymers is accompanied by electrification. During frictional interaction chemical and physichemical transformations in polymers promote increases in the surface and bulk states density. Electrification in friction is a common feature, it can be observed with any mode of friction, and with any combination of contacting surfaces, [16]. The potential difference generated by the friction of polymeric coatings against steel counterface has been measured. The effect of sliding velocity and load on the generation of electric charge on the friction surface has been investigated, [17]. The results indicated that, at dry sliding condition the potential generated from friction increases rapidly with increasing both of sliding velocity and load at certain values then decreases due to the rise of temperature which causes molecular motion and reorientation of the dipole groups in the friction direction and leads to the relaxation of space changes injected during friction.

The triboemission characteristics of both negatively and positively charged particles from various materials such as metals, ceramics and glass were studied, [18]. The results obtained during scratching the tested materials showed increasing emission intensity with increasing electrical resistance of the materials, [19]. Mechanisms of polarization and relaxation of dielectrics were used to provide explanation of the friction and wear behaviour of insulators.

Unfilled and filled PA6 coatings by metal powders as well as high density PE, PA6, polypropylene coatings, reinforced by copper wire, were tested. Increasing the concentration of metal powder can reduce the effect of the applied voltage on friction and wear. Reinforcing PA6 and polypropylene coatings by copper wires increased the

wear resistance and reduced the friction, [20]. The application of an electric field, however, is considered to promote the breakdown of EHL film formed, [21]. The influence of applying electric field on the tribological behaviour of steel in a vertical magnetic field produced by an AC or DC electric current was investigated. The effect of a magnetic field on both oxidation and concentrations of dislocations on the surface is presented, [22]. Experiments showed that a magnetic field applied through the sliding contact decreased wear rate.

Voltage generated as a result of the friction caused by the sliding of the tested polymers against each other as well as steel surface was measured, [23]. The test results showed that friction coefficient displayed by the sliding in salt water represented maximum values due to the relatively high value of voltage generated as a result of friction. Triboelectrification of metallic and polymeric surfaces was investigated at dry and lubricated sliding conditions. The effect of sodium chloride (NaCl), gasoline, diesel fuel, and hydrochloric acid (HCl) as contaminants in the lubricant on voltage and friction was discussed, [24]. The test results showed that relatively high voltage generated due to sliding of metallic surfaces against each other in salt water and oil dispersed by ethylene glycol while sliding of PA6 against steel surface produced the highest values of voltage at oil lubricated condition. In the presence of NaCl in water, relatively high value of voltage due to friction was observed accompanied by high value of friction coefficient. It was found that a correlation between friction coefficient and voltage generated was found for polymers sliding against themselves and against steel in water and salt water lubricated conditions, [25]. Wear of the tested polymers decreased with increase of sand particle size down to minimum because of the sand embedment in the polymeric surface. Further increase in sand particle size increased wear due to the removal of sand from the polymeric surface.

The aim of the present work is to investigate the influence of the addition of nanoparticles to polyester composites on the friction and wear. Different positive and negative electrostatic charges are applied by connecting the terminals of the D. C. battery to the test specimen and the counterface at dry sliding. Two sets for experimental work were used, namely, dry sliding of negative and positive charged test specimens. Friction coefficient and wear are measured.

EXPERIMENTAL

Experiments were carried out using pin on disc tribometer. It consists of a rotary horizontal steel disc driven by a variable speed motor. The details of the pin on disc are shown in Fig. 1. The test specimen is held in the specimen holder that fastened to the loading lever. Through load cell, where strain gauges are adhered, friction force can be measured. Friction coefficient was determined through the friction force measured by load cell. The load is applied by weights. The counterface in form of a steel disc, of 100 mm outer diameter, was fastened to the rotating disc. Its surface was a smooth surface. Test specimens were prepared in the form of cylindrical shape with cross section of 10 mm diameter and 30 mm length. The test specimens were loaded against counterface of the carbon steel disc.

Test specimens were prepared by mixing the polyester by nanoparticles of aluminium, copper, aluminium oxide and iron of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 wt. % content. Electric current of 0, 1.5, 3 and 4.5 volts was applied. Two sets were carried out, the first when the test specimens were negative charged, and the second when the test specimens were positive charged. Friction coefficient was determined through the friction force measured by the deflection of the load cell divided on the normal load, while wear was measured by the difference between the weight of specimen before and after test using a digital balance of 1.0 mg accuracy.

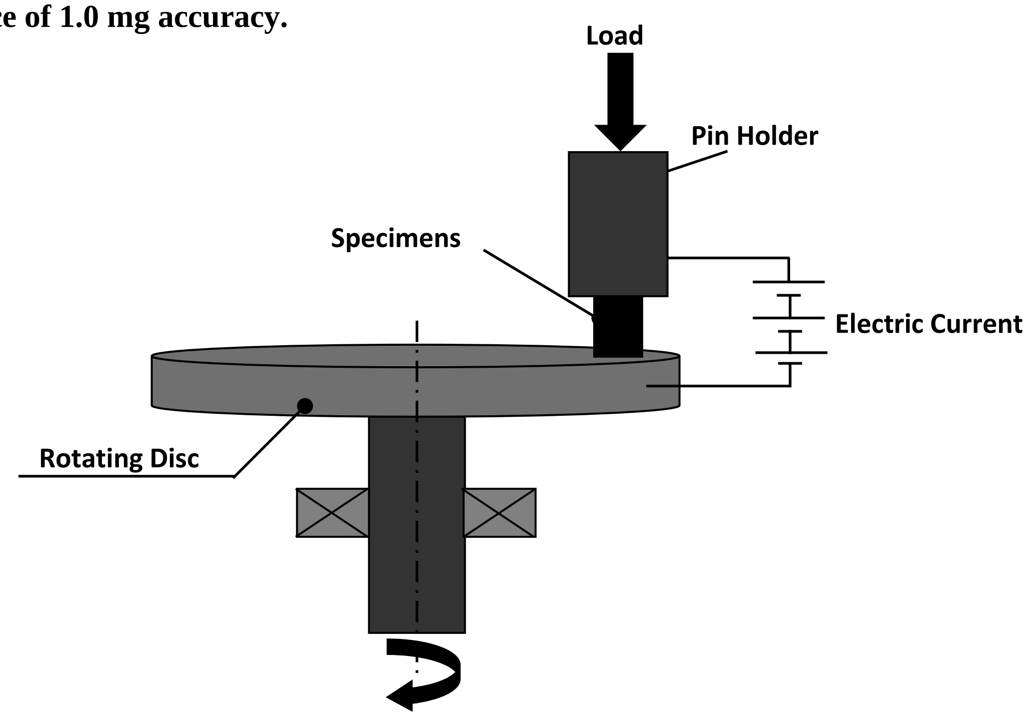

Fig. 1 Arrangement of the test rig.

RESULTS AND DISCUSSION

Friction coefficient displayed by test specimens filled by aluminum of negative charge is shown in Fig. 2. For zero voltage, friction coefficient decreased with increasing aluminum content. This decrease can be attributed to the ability of aluminum particles to reduce the adherence of polyester into the steel surface. Friction coefficient displayed by polyester free of aluminum was significantly influenced by the electric voltage, where it decreased with increasing the voltage. It seems that increasing electric voltage caused an increase in the contact temperature and consequently polyester layer adhered into the steel surface softened and became more plastic. As aluminum content increased friction coefficient increased with increasing the electric voltage. Presence of aluminum in polyester helped to conduct the electric current from the polyester to the steel surface. Thus the polyester layer adhered to the steel surface was slightly influenced by the electric current.

Wear displayed by the dry sliding of polyester filled by aluminum of negative voltage against steel is shown in Fig. 3. Polyester test specimens displayed the highest wear at no voltage. Wear increased with increasing aluminum content. It seems that aluminum

particles decreased the strength of polyester matrix. As the electric voltage increased wear decreased. The lowest wear values were displayed by polyester filled by 6 – 10 wt. % aluminum content. Wear decrease may be attributed to the strong adhesion of polyester layer into the steel surface and the contact would be polyester/polyester. In that condition polyester transfer into the steel surface followed by transfer back into the polyester test specimen so that wear decreased.

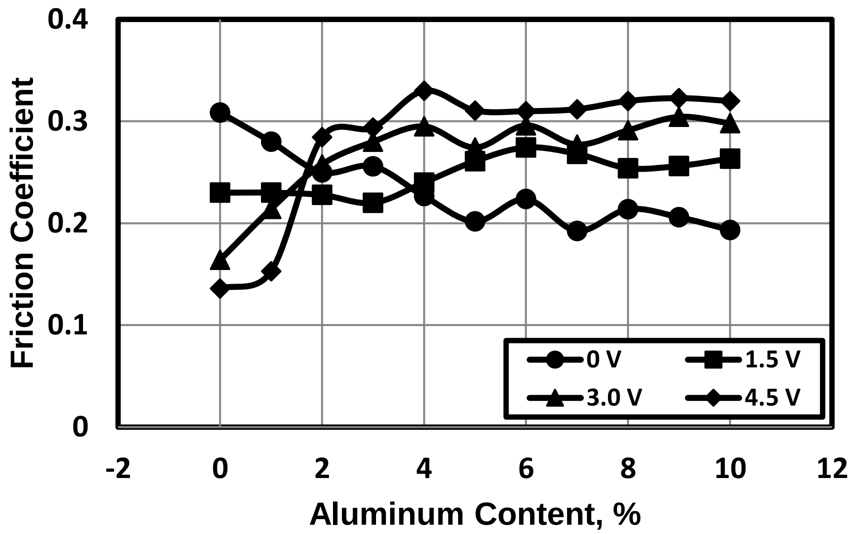

Fig. 2 Friction coefficient displayed by the dry sliding of polyester filled by aluminum of negative voltage against steel.

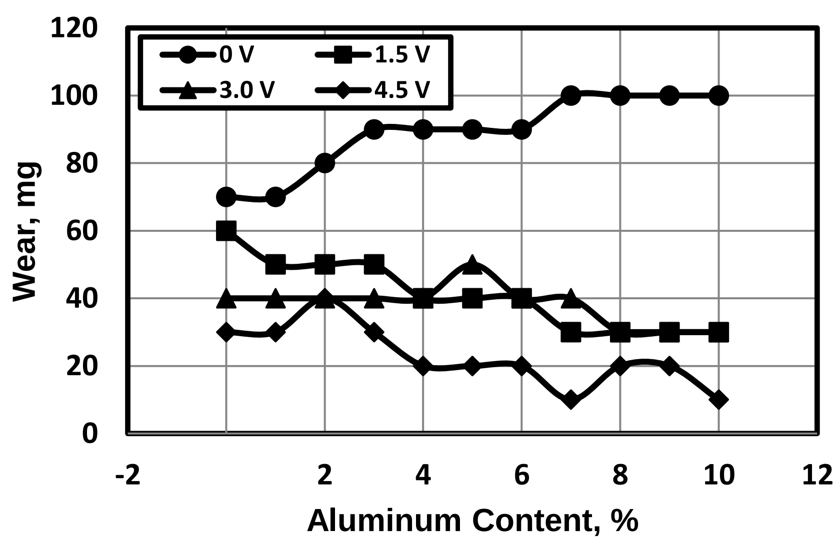

Fig. 3 Wear displayed by the dry sliding of polyester filled by aluminum of negative voltage against steel.

Friction coefficient displayed by test specimens filled by copper of negative charge is shown in Fig. 4. Polyester composites filled by copper displayed relatively lower friction than that observed for composites filled by aluminum. Unfilled polyester

showed a decreasing trend of friction coefficient with increasing copper content. In condition of applying electric voltage, friction coefficient increased with increasing copper content. The friction increase was proportional to the value of the electric voltage.

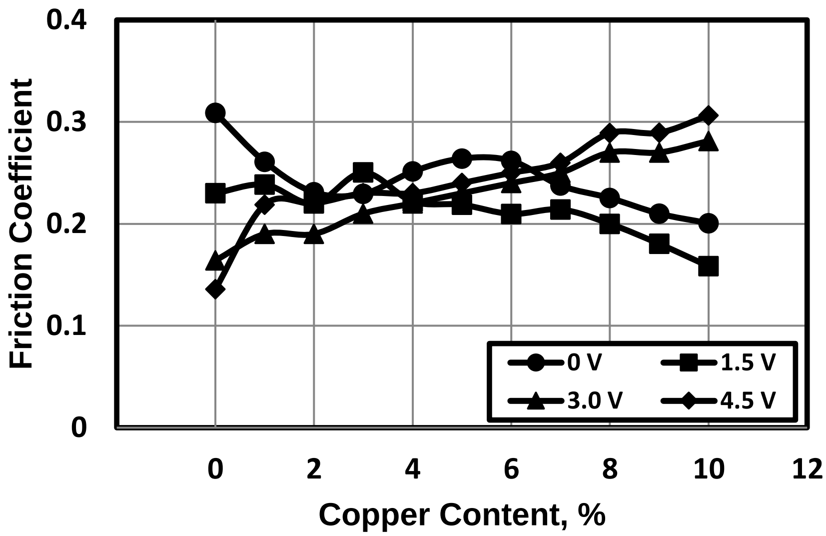

Fig. 4 Friction coefficient displayed by the dry sliding of polyester filled by copper of negative voltage against steel.

Wear displayed by dry sliding of polyester filled by copper of negative voltage against steel is shown in Fig. 5. At no voltage, wear significantly increased with increasing copper content. When the voltage was applied, friction coefficient decreased with increasing copper content, where the lowest values were observed at 4.5 volts. Friction of polymers is accompanied by electrification. The basic mechanism of solid triboelectrification implies processes, which can be described in terms of surface conditions. During frictional interaction chemical and physichemical transformations in polymers promote increases in the surface and bulk states density. Ionization and relaxation of those states lead to electric fields of the surface and bulk charges. Electrification in friction is a common feature, it can be observed with any mode of friction, and with any combination of contacting surfaces. Because of triboelectrification, the charged surfaces can interact with each other due to the direct electrostatic forces. Since these forces are strong and effective, they contribute a major part of the adhesion force. Based on the triboelectrification theory, particles of copper and polyester gained negative charge while steel surface gained positive charge. These charges were imposed on the charges gained from the electric voltage. Then both copper and polyester particles transferred and strongly adhered to the steel surface, where the force of adherence increased with increasing applied voltage. The adhered layer changed the electric state of the surface and decreased material transfer into the steel surface.

Triboelectric charging is a well-known effect that occurs when two particles come into contact with each other (i.e., rubbing). Studies have shown that there are two different

types of charge transfer. One is when dissimilar materials interact with one particle gaining electrons from the other material resulting in a negative and positive final state for the different materials. The exact nature of the charge transfer depends on where the materials are located on the triboelectric series, and the physical nature of the samples including oxidation of surfaces, surface roughness, temperature, and relative humidity. The other case occurs when similar materials rub against each other; the larger particles tend to lose high-energy electrons to the smaller particles which become negatively charged. These phenomena will occur at greater intensities in the cold and dry nature of the ambient environment. For dissimilar material, which particle becomes negative and which becomes positive depends on the relative tendencies of the materials involved to gain or lose electrons. Some materials (e.g., polyethylene and teflon) have a greater tendency to gain electrons while others (e.g., glass and aluminum) tend to be electron donors.

Friction coefficient displayed by dry sliding of polyester filled by aluminum oxide of negative voltage against steel is shown in Fig. 6. Friction coefficient slightly decreased with increasing aluminum oxide for 0, 1.5 volts. The friction decrease might be from abrasive action of aluminum oxide particles which abraded the polyester layer adhered into the steel surface. As the electric voltage increased the polyester layer strongly adhered to the steel and caused significant friction increase.

Wear displayed by dry sliding of polyester, filled by aluminium oxide of negative voltage against steel, showed significant increase for sliding free of electric current, Fig. 7. As the electric voltage increased wear decreased. The application of electric voltage strengthened the adherence of polyester composite layer into the steel surface and consequently polyester transfer back to polyester composites occurred. The significant influence of electric voltage on wear decrease may be from the electric charge generated on the aluminum oxide particles due to the oxide layer existed on the surface. Besides, the presence of aluminum oxide particles enhanced wear resistance of both composites and layer adhered into the steel surface.

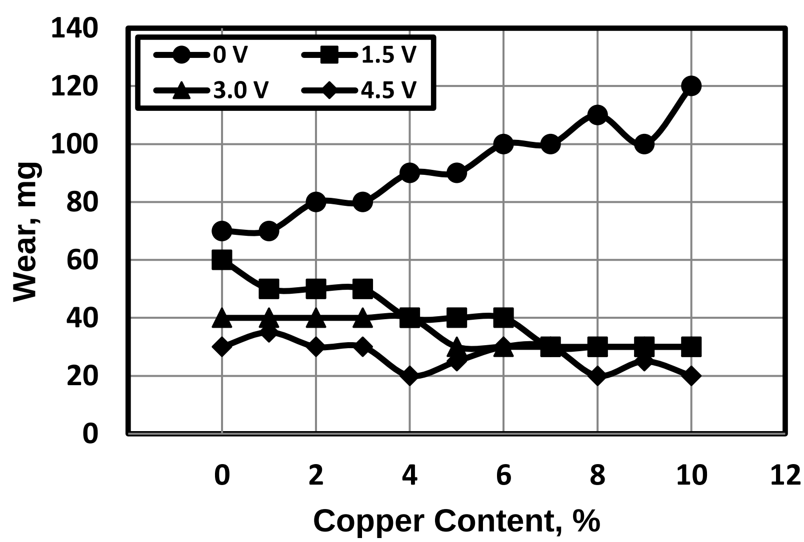

Fig. 5 Wear displayed by the dry sliding of polyester filled by copper of negative voltage against steel.

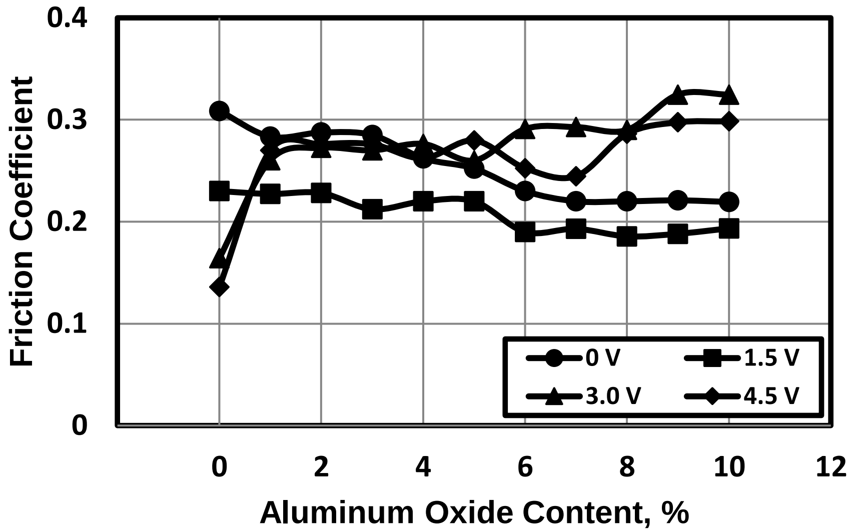

Fig. 6 Friction coefficient displayed by the dry sliding of polyester filled by aluminum oxide of negative voltage against steel.

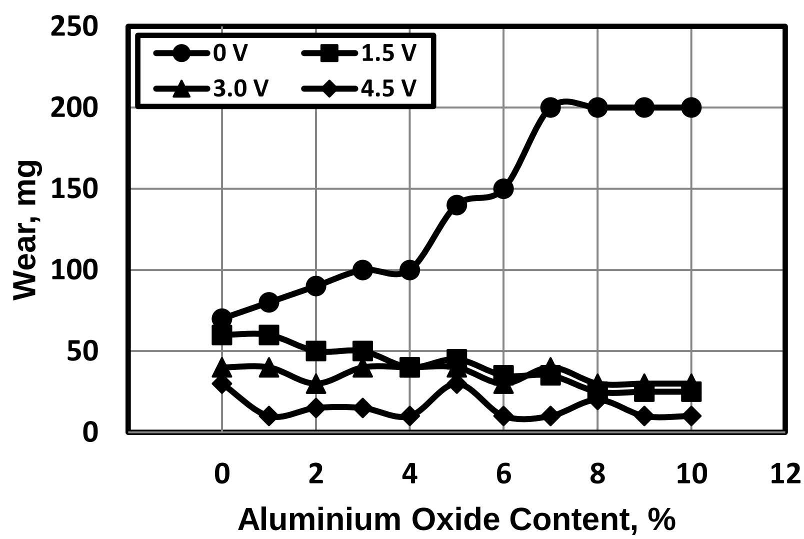

Fig. 7 Wear displayed by the dry sliding of polyester filled by aluminum oxide of negative voltage against steel.

The influence of adding iron nanoparticles into polyester composites on friction coefficient is shown in Fig. 8. Presence of the electric voltage caused significant friction increase. The same trend was observed for composites filled by aluminium, copper and aluminium oxide.

Wear displayed by the dry sliding of polyester filled by iron of negative voltage against steel is shown in Fig. 9. Significant wear reduction was observed when the electric voltage was applied. Wear reduction increased with increasing the voltage. Wear depended mostly on the adherence of the polyester composites into the steel surface, where the adherence increased with increasing the electric voltage.

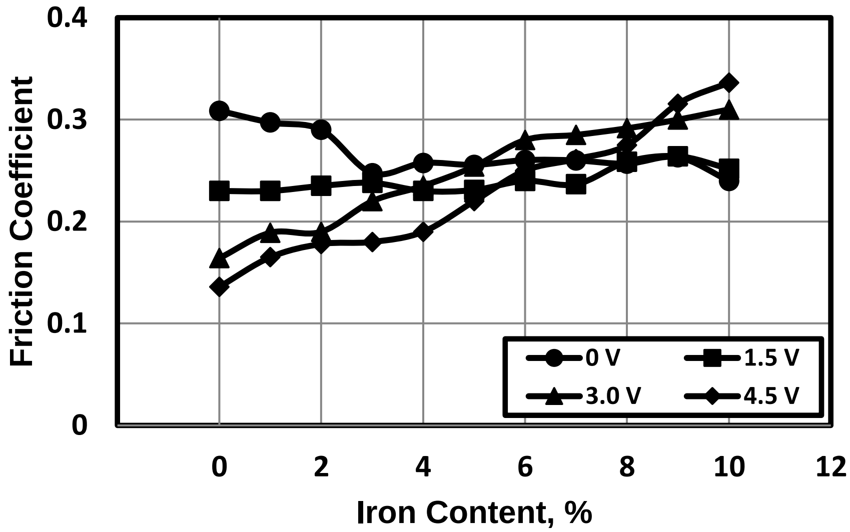

Fig. 8 Friction coefficient displayed by the dry sliding of polyester filled by iron of negative voltage against steel.

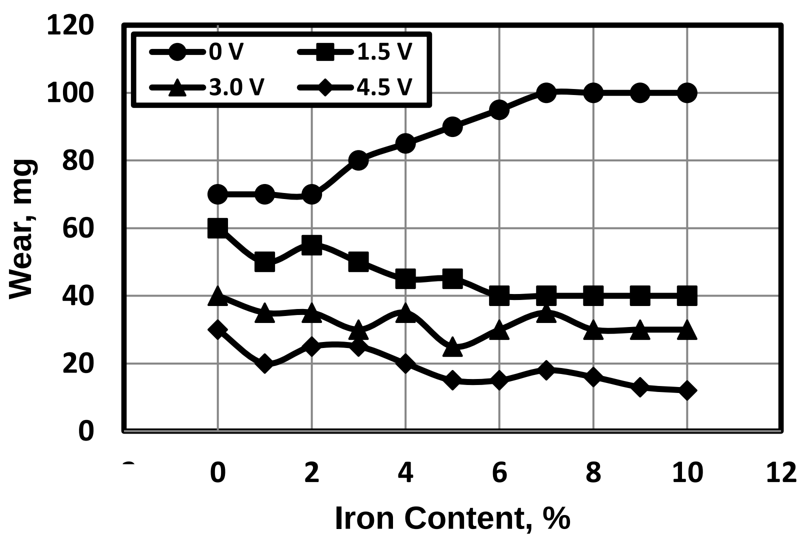

Fig. 9 Wear displayed by the dry sliding of polyester filled by iron of negative voltage against steel.

The influence of application of the electric voltage of positive charge on the tested composites on the friction and wear is shown in Figs. 10 – 17. In the presence of electric voltage friction coefficient increased with increasing aluminium content. As the voltage increased friction coefficient increased. At 10 wt. % aluminum content, friction

coefficient displayed the highest value when the voltage approached 4.5 volts, Fig. 10. Composites free of aluminum and working under no voltage showed relatively higher friction coefficient. As the electric voltage was applied, friction coefficient decreased because polyester gained positive charge from the voltage as well as negative charge from friction against steel so that the adherence of polyester into the steel surface was not enough strong and consequently friction decreased. Presence of aluminum which gained positive charge from voltage imposed on the positive charge gained from friction against steel would lead to strong adherence of composites material transferred from the test specimens into the steel surface.

Wear displayed by dry sliding of polyester filled by aluminum of positive voltage against steel is shown in Fig. 11. Application of electric voltage showed significant wear decrease. This may be attributed to the relatively strong adherence of composites materials and consequently material transfer back to the test specimens. Generally, wear resistance when applying negative voltage was better than that observed for positive voltage.

Friction coefficient displayed by polyester filled by copper of positive voltage against steel showed relatively higher values than that observed for composites of negative voltage, Fig. 12. This observation was clear as the copper content increased. Wear displayed by the dry sliding of polyester filled by copper of positive voltage against steel showed the same trend observed for composites of negative voltage, Fig. 13. Composites filled by 10 wt. % copper at 4.5 volts showed the lowest wear value.

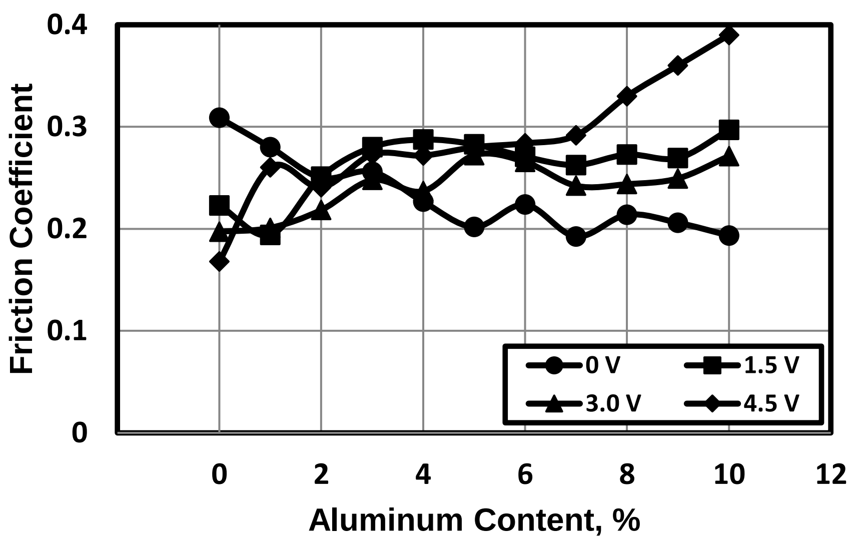

Fig. 10 Friction coefficient displayed by the dry sliding of polyester filled by aluminum of positive voltage against steel.

Friction coefficient displayed by the dry sliding of polyester filled by aluminum oxide of positive voltage against steel is shown in Fig. 13. Generally, values of friction coefficient slightly increased with increasing aluminium oxide content. The values were ranging between 0.17 and 0.32. The influence of aluminum oxide on friction coefficient was dominant, where its ability to abrade the composites layer formed on the steel surface was the reason for the relatively lower friction values.

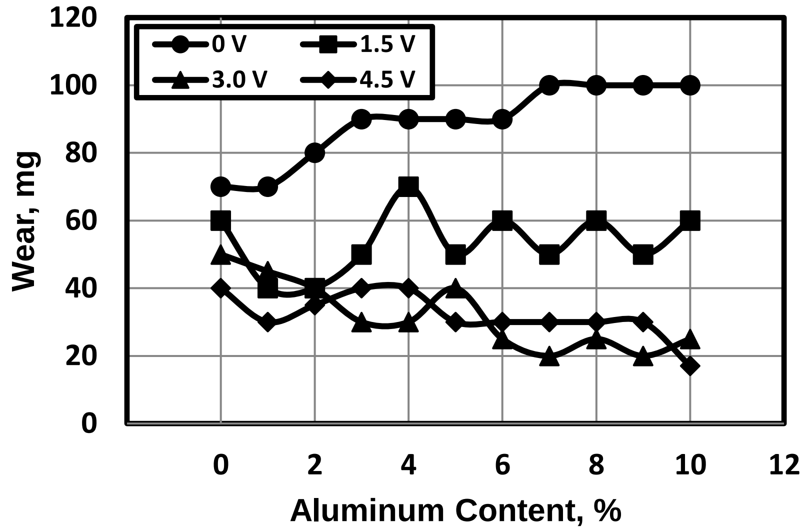

Fig. 11 Wear displayed by the dry sliding of polyester filled by aluminum of positive voltage against steel.

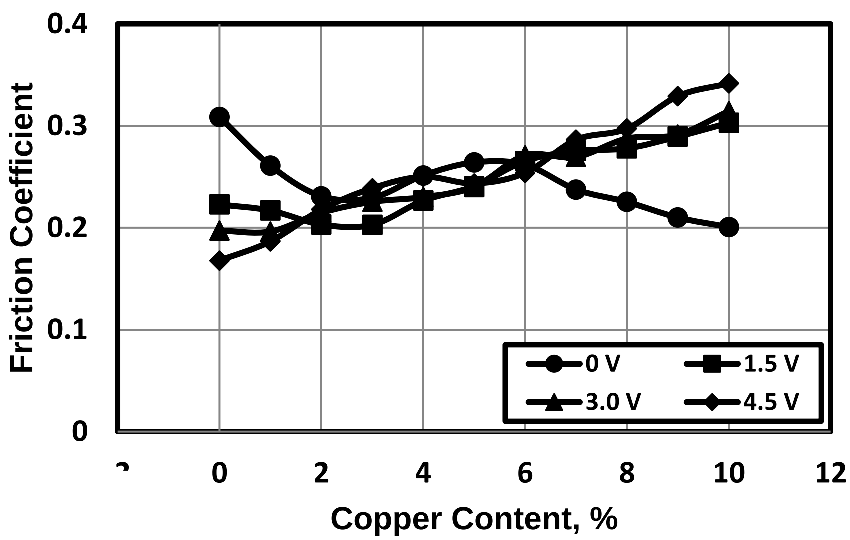

Fig. 12 Friction coefficient displayed by the dry sliding of polyester filled by copper of positive voltage against steel.

The friction between two surfaces can result in the transfer of materials from one to the other, which can be fragments of the two surfaces as well as contaminated dusts or impurities. For instance, when a metal slides over a polymer surface, a certain amount of polymer will transfer to the metal surface and the metal can also transfer to the polymer. If the transferred material carries charge, it is expected that charge transfer will occur. When brittle particles impact on a metal wall, elements of particles are easily transferred on the metal. The presence of the oxide layer on the particles of aluminum oxide enables the particles to keep the charge formed as a result of the electric voltage.

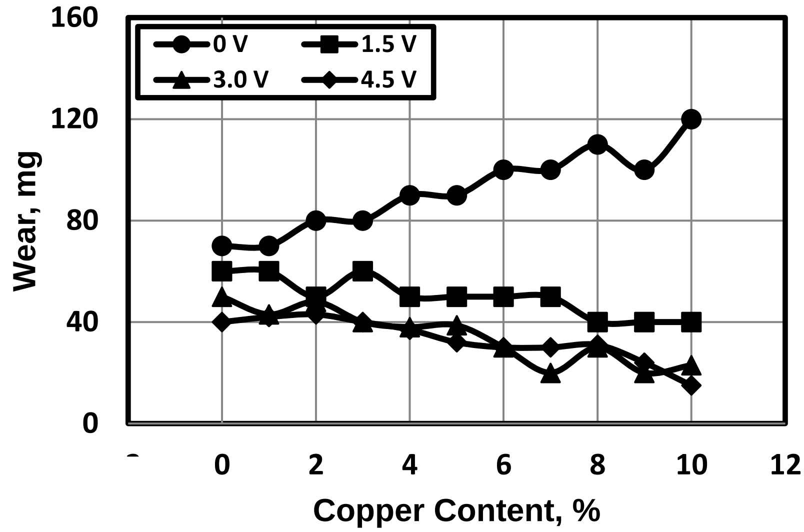

Fig. 13 Wear displayed by the dry sliding of polyester filled by copper of positive voltage against steel.

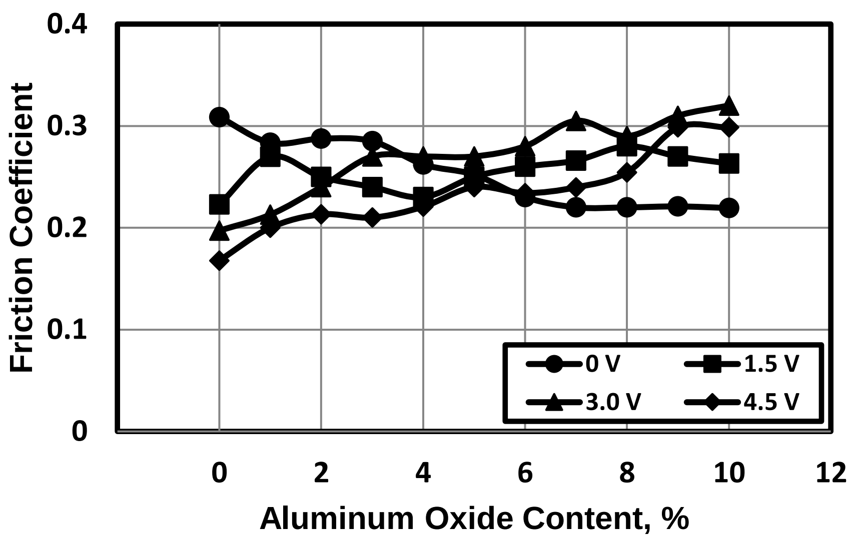

Fig. 14 Friction coefficient displayed by the dry sliding of polyester filled by aluminum oxide of positive voltage against steel.

Wear displayed by the dry sliding of polyester, filled by aluminum oxide of positive voltage against steel, showed significant increase for sliding free of electric current, Fig. 15. As the electric voltage increased wear decreased. The significant influence of electric voltage on wear decrease might be from the electric charge generated on the aluminum oxide particles due to the oxide layer existed on the surface. Besides, the presence of aluminum oxide particles enhanced the wear resistance of both the composites and the layer adhered into the steel surface.

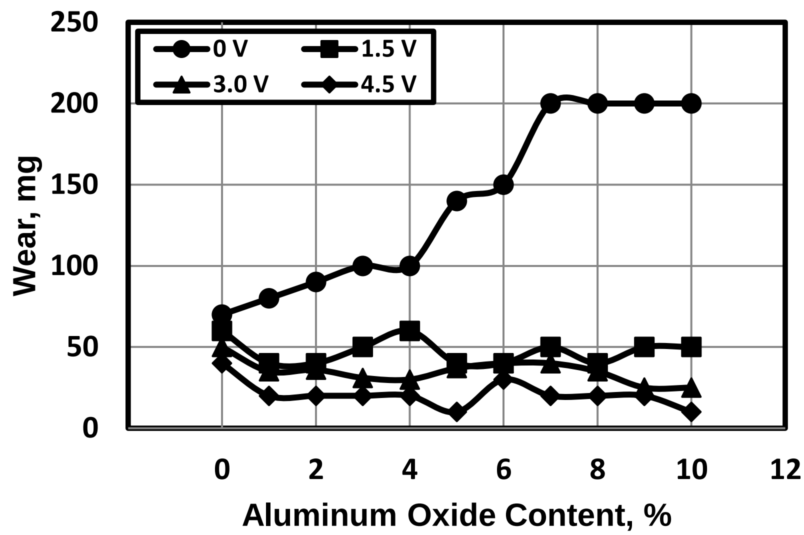

Fig. 15 Wear displayed by the dry sliding of polyester filled by aluminum oxide of positive voltage against steel.

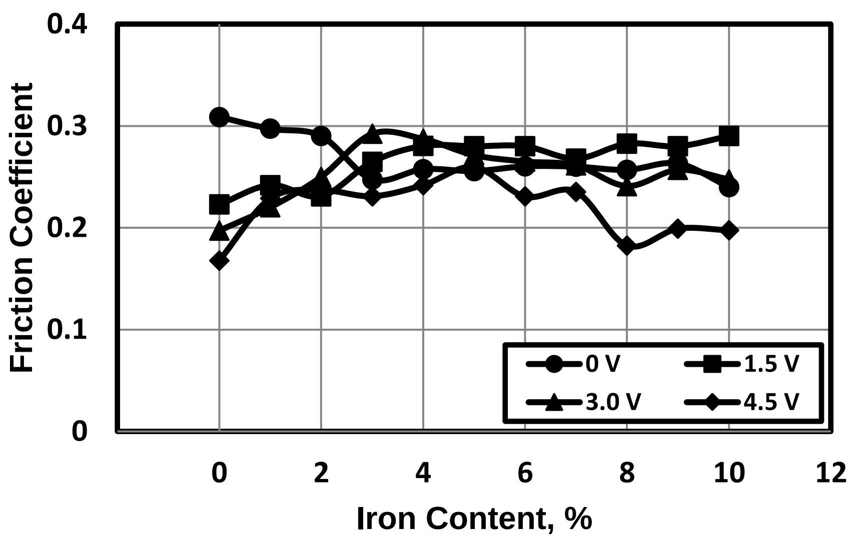

Fig. 16 Friction coefficient displayed by the dry sliding of polyester filled by iron of positive voltage against steel.

The effect of addition of iron nanoparticles into polyester matrix on the friction coefficient is shown in Fig. 16. Friction coefficient slightly increased with increasing iron content for 1.5 and 3.0 volts, while for 4.5 volts friction increased up to maximum then decreased with increasing iron content. It seems that polyester positive charge gained from the electric voltage would be normalized by the negative charge gained from friction.

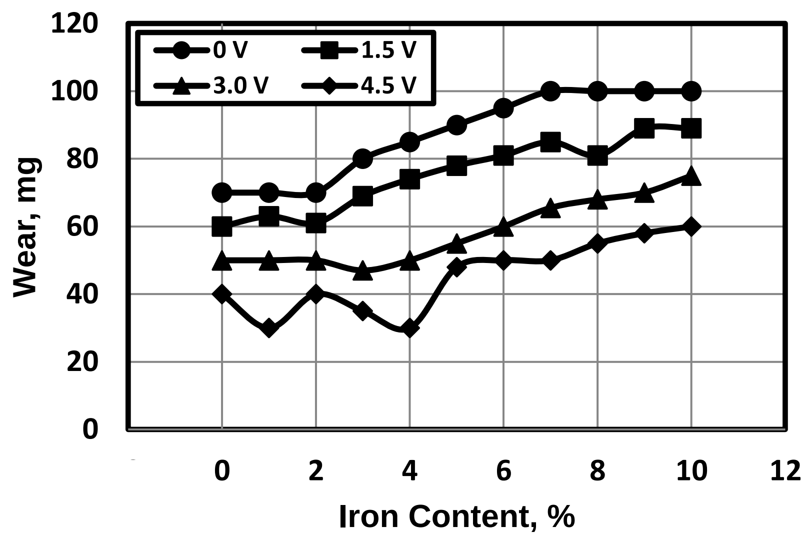

Fig. 17 Wear displayed by the dry sliding of polyester filled by iron of positive voltage against steel.

Wear displayed by polyester filled by iron of positive voltage against steel is shown in Fig. 17. Significant wear decrease was observed when the electric voltage was applied. Generally, wear increased with increasing electric voltage. Wear depended mostly on the adherence of polyester composites into steel surface, where the adherence was disturbed by the positive charge of iron particles and the transfer back of the composite layer into the tested composites decreased.

CONCLUSIONS

I. Negative charged test specimens

1. At no voltage, friction coefficient decreased with increasing aluminium content. Increasing the electric voltage increased friction coefficient.

2. As the electric voltage increased wear decreased. The lowest wear values were displayed by polyester filled by 6 – 10 wt. % aluminium content.

3. Polyester composites filled by copper displayed relatively lower friction than that observed for composites filled by aluminium. Polyester composites showed a decreasing trend of friction coefficient with increasing copper content. In condition of applying electric voltage friction coefficient increased with increasing copper content.

II. Positive charged test specimens

1. Application of electric voltage showed significant wear decrease. Wear resistance when applying negative voltage was better than that observed for positive voltage.

2. Friction coefficient showed relatively higher values than that observed for composites of negative voltage.

3. Wear showed the same trend observed for composites of negative voltage. Composites filled by 10 wt. % copper at 4.5 volts showed the lowest wear value.

REFERENCES

1. Sanes J., Carrion F.J., Bermudez M.D., " Effect of the addition of room temperature ionic liquid and ZnO nanoparticles on the wear and scratch resistance of epoxy resin", Wear 268 1295–1302 (2010).

2. Kumar A. P., Depan D., Tomer N. S., Singh R. P., "Nanoscale particles for polymer degradation and stabilization—Trends and future perspectives", Progress in Polymer Science 34, pp. 479 – 515, (2009).
3. Brostow W., Chonkaew W., Menard K. P., Scharf T. W., "Modification of an epoxy resin with a fluoroepoxy oligomer for improved mechanical and tribological properties", Mater. Sci Eng. A 507, pp. 241 – 251, (2009).
4. Magda S., Khashaba M. I. and Ali W. Y., "Oil Lubricated Sliding of Polyester Composites Filled by Nano-Scale Particles Against Steel", Journal of the Egyptian Society of Tribology Vol. 9, No. 2, April 2012, pp. – , (2012).
4. Hao W., Yang W., Cai H., Huang Y., "Non-isothermal crystallization kinetics of polypropylene/silicon nitride nanocomposites", Polymer Testing 29, pp. 527 – 533, (2010).
5. Martin G., Barres C., Sonntag P., Garois N., Cassagnau P., "Co-continuous morphology and stress relaxation behaviour of unfilled and silica filled PP/EPDM blends", Mater. Chem. Phys. 113 (2e3), p. 889, (2009).
6. W.H. Ruan, Y.L. Mai, X.H. Wang, M.Z. Rong, M.Q. Zhang, "Effects of processing conditions on properties of nano-SiO_2/polypropylene composites fabricated by pre-drawing technique", Compos. Sci. Technol. 67 (13), p. 2747, (2007).
7. Carrión F. J., Arribas A., Bermúdez M. D., "Physical and tribological properties of a new polycarbonate-organoclay nanocomposite", European Polymer Journal 44, pp. 968 - 977, (2008).
8. Liu A., Xie T., Yang G., "Comparison of polyamide 6 nanocomposites based on pristine and organic montmorillonite obtained via anionic ring-opening polymerization", Macromol Chem Phys, 207, pp. 1174 – 81, (2006).
9. Yoo Y., Choi K. Y., Lee J. H., "Polycarbonate/montmorillonite nanocomposites prepared by microwaved aided solid state polymerization", Macromol Chem Phys;205, pp. 1863 - 1868, (2004).
10. Park J. O., Rhee K. Y., Park S. J., " Silane treatment of Fe_3O_4 and its effect on the magnetic and wear properties of Fe_3O_4/epoxy nanocomposites", Applied Surface Science 256, pp. 6945 - 6950, (2010).
11. Birsan I. G., Circiumaru A., Bria V., Ungureanu V., "Tribological and electrical properties of filled epoxy reinforced composites", Tribol. Ind. 31, pp. 33 - 36, (2009).
12. Ibrahim R. A., Ali W. Y., “Tribological performance of polyester composites filled by vegetable oils”, Mat.-wiss. u. Werkstofftech. 41, No. 5, pp. 1 – 6, (2010).
13. Abd El-Aal U. M., Hasouna A. T. and Ali W. Y., “Experimental Study of Abrasive Wear Resistant Polyester Composites”, Journal of the Egyptian Society of Tribology, Vol. 7, No. 3, July, pp. 26 – 38, (2010).
14. Abdel-Jaber G. T., Mohamed M. K. and Ali W. Y., "Friction and Wear of Polyester Reinforced by Polyethylene Fibres and Filled by Vegetables Oils", 47. Tribologie - Fachtagung, Septembe, pp. 33/1 – 33/11, (2008).
15. Abdel-Jaber G. T., Mohamed M. K. and Ali W. Y., “Friction and Wear of oil impregnated polyester–glass fibre composites”, 47. Tribologie - Fachtagung, 25 – 27 September, pp. 33/1 – 33/9, (2006).
16. Bely, V. A., Pinchuk, L. S., Klimovich, A. F. and Guzenkov, S. I., “Tribological Aspects of Electret State Generation in Polymers”, Proceedings of The 5th Int. Congress on Tribology, EUROTRIB 89, Vol. 2, June 13 - 16, Espo, Finland, pp. 276 - 281, (1989).

17. Ali, W. Y., " Experimental Study of the Potential Generated by Friction of Polymeric Coatings", 4th Conference of the Egyptian Society of Tribology, EGTRIB'95, Jan. 4-5, Cairo, Egypt, (1995).
18. Nakayama, K. and Hashimoto, H., "Triboemission From Various Materials in Atmosphere", Wear, 147, pp. 335 - 343, (1991).
19. Fayeulle, S., Berroug, H., Hamzaoui, B. and Treheux, D., "Role of Dielectric Properties in the Tribological Behaviour of Insulators", Wear, 162 - 164, pp. 906 - 912, (1993).
20. Ali, W. Y., "Influence of Applied Voltage on Friction and wear of Polymeric Coatings Sliding Against Steel", Tribologie und Schmierungstechnik, 43. Jahrgang, March/April, pp. 83 - 87, (1996).
21. Yamamoto, Y., Ono, B. and Ura, A., "Effect of Applied Voltage on Friction and Wear Characteristics in Mixed lubrication", Proceedings of the VI Int. Congress on Tribology, Vol. 5 EUROTRIB'93, Budapest, Hungary, pp. 82 - 89, (1993).
22. Nery, H., Zaidi, H., Pan, L. and Paulmier, D., "Influence of Magnetic Field on Steel in Sliding Contact", Proceedings of the VI Int. Congress on Tribology, Vol. 5 EUROTRIB'93, Budapest, Hungary, pp. 70 - 75, (1993).
23. Youssef, M. M., Ezzat, F. M., and Ali, W. Y., "Triboelectrification of Polymeric Materials", PEDD 6, Proceedings of the 6th International Conference on Production Engineering and Design for Development, Cairo, Egypt, February 12 – 14, (2002).
24. Youssef, M. M., "Triboelectrification of Metallic and Polymeric Materials" Bulletin of the Faculty of Engineering, El-Minia University, Vol. 20, No. 1., July, pp. 31 – 41, (2001).
25. Youssef, M. M., Mahmoud, M. M. and Ali, W. Y., "Friction and Wear of Polymeric Materials Sliding Against Steel", Journal of the Egyptian Society of Tribology, Vol. 2, No. 1, April, pp. 18 – 31, 45. Tribologie-Fachtagung, 25th – 27th, September in Göttingen, pp. 9/1 – 9/14, (2004).