EGTRIB Journal

JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 8, NO. 2, April 2011, 1 - 15

EFFECT OF MAGNETIC FIELD ON FRICTION AND WEAR OF STEEL

Abeer A. E.[1], Abu Elainin H. M.[1], Khashaba M. I.[1] and Ali W. Y.[1,2]

[1]Faculty of Engineering, El-Minia University, P. N. 61111, El-Minia, EGYPT.
[2]Current Address: Faculty of Engineering, Taif University, Al –Taif, K. S. A.

ABSTRACT

The present work discusses the effect of the magnetic field on the friction and wear of steel sheets scratched by a steel insert at dry, lubricated by vegetable oils and dispersed by polymeric particles such as polyethylene (PE), polyamide (PA6) and polymethylmethacrylate (PMMA)

Based on the experimental observations, it was found that friction coefficient displayed the highest values at dry sliding. Olive oil displayed the lowest values of friction coefficient followed by castor oil, almonds, maize, chamomile and jasmine oils. It seems that polar molecules of the tested vegetable oils can significantly improve the wear resistance developed by their strong adsorption on the sliding surfaces. Application of magnetic field on the sliding surface caused significant friction reduction at dry sliding. This behaviour may be from the magnetization of the steel which is known to be accompanied by reduction of plasticity and increasing the brittleness. Besides, magnetic field enhanced the ability of the oil molecules to orient themselves in relatively long chain adhered to the steel surface and thus decreased the friction and wear.

Besides, the addition of polymeric particles such as PE, PA 6 and PMMA particles caused slight friction decrease as a result of the adhesion of those particles into the contact area. Further friction decrease was observed in condition of application of the magnetic field. Dry sliding gave the highest wear. The best wear resistance was observed for olive, maize, jasmine, castor, camomile and almonds oils. The polarity of oil molecules enhanced the oil to form a thick layer on the friction surface and consequently reduced the interaction of the insert into the scratch area. Under application of the magnetic field, wear slightly increased as a result of the reduction of plasticity and the increase of the brittleness, where the material removed from the groove scratched by the insert increased, while the material deformed in front and side ridges decreased. Presence of polymeric particles significantly decreased wear due to the ability of those particles to adhere into the insert/scratch track forming protective layer from excessive wear. In the presence of the magnetic field wear increased for polyethylene and polyamide. Magnetic field strengthened the adherence of PMMA particles into the cutting edges of the steel insert.

KEYWORDS
Friction, wear, steel, magnetic field.

INTRODUCTION

It has been observed that friction and wear behavior of two components sliding against each other can be greatly influenced by an externally applied electrostatic field or electric current. Under boundary lubrication conditions in a ball-on-disk machine, [1], during sliding of steel pairs in the presence of an additive-free mineral oil, the friction coefficient decreased but the ball wear increased when the disk was at a higher potential than the ball compared to the condition when no current passed. The decrease in friction coefficient was concluded to be due to the formation of a thin passivation layer on the disk surface. With continued sliding, damage to the passivation layer led to increased friction coefficient. However, when the ball was at higher potential than the disk, no decrease in friction coefficient was observed, and the ball wear was lower than that obtained when no current passed through the contact.

The effect of an applied electric field on the running-in operation of a roller bearing was investigated, [2, 3]. In the mixed lubrication regime, when the bearing was the anode, the friction coefficient increased and also the bearing temperature increased and showed signs of seizure. The bearing surface was oxidized as would be expected, because of an anodic reaction. However, when the bearing was cathode, the friction coefficient rapidly decreased and so did the bearing temperature. The effect of additives in highly refined paraffinic base stocks on wear under the influence of an electric current was also investigated, [4]. The addition of a sulfur compound decreased wear on the cathodic surface but increased wear on the anodic surface. However, addition of a phosphate compound (tricresylphosphate) decreased wear of both cathodic and anodic surfaces. These effects were explained by electrochemical reactions of additives on sliding surfaces.

The influence of electric field has also been observed to reduce friction and wear for sliding of two dissimilar materials [5, 6]. The friction and wear behavior of a steel pair when an electric current was passed through the contact in the presence of fully formulated engine oils was discussed, [7]. The passage of electric current changed friction coefficient only to a small degree but the wear was impacted significantly.

Tool wear is fully recognized as an important factor in materials cutting, [8]. Nevertheless, application of external electromotive force (EMF) sources (e.g. magnetic field) during cutting of material may accomplish this role. The possible use of external electromotive force (EMF) sources for improving tool life was discussed. Experiments showed that the presence of electric current and magnetic field around the tribocontact modifies the mechanical properties of the surface and subsurface, [9]. The mean friction coefficient changes from 0.16 without electric current and magnetic field to 0.26 with them, and its variation reduces considerably. The worn surfaces were smoother with magnetic field application than that without it, and the modification of subsurface structure was observed.

It is known that, during friction on metals or dielectric couples, part of the energy consumed turns into electrical energy. Because of triboelectrification, the charged surfaces can interact with each other due to the direct electrostatic forces, [10]. Since these forces are strong and effective, they contribute a major part of the adhesion force.

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, [11]. 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.

It was 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, [12]. Presence of water or oil on the friction surface, oil impregnation of PA 6 coating and filling PA 6 by molybdenum disulphide reduce the potential difference while filling the coatings by graphite increases that potential. The electrification of polymer surface can be controlled by using composites of different polymers.

Friction and dielectric measurements performed on sapphire and alumina samples were correlated, [13]. Mechanisms of polarization and relaxation of dielectrics were used to provide explanation of the friction and wear behaviour of insulators. Experiments were carried out to investigate the influence of the applied voltage on the friction and wear of polymeric coatings sliding against steel. Unfilled and filled PA 6 coatings by metal powders as well as high density PE, PA 6, 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 PA 6 and polypropylene coatings by copper wires increased the wear resistance and reduced the friction, [14]. This improvement may be attributed to the strengthening effect of the copper wire and its ability to leak some of the electric charge formed on the friction surface.

The effect of an electric field applied between rubbing surfaces on friction and wear characteristics was examined using a ball-on-disc testing apparatus under different lubrication conditions, [15]. By applying an electric field between the rubbing surfaces, the oxidation of the rubbing surface at anode side is enhanced, and suppressed on the cathode side surface.

Voltage generated as a result of the friction caused by the sliding of the tested polymers such as polyamide, polytetrafluoroethylene, polyethylene terephthalate, and polymethyl methacrylate against each other as well as steel surface was measured, [16]. 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 salt water (NaCl), gasoline, diesel fuel, and hydrochloric acid (HCl) as contaminants in the lubricant on voltage and friction was discussed, [17]. The test results showed that relatively high voltage was generated due to sliding of metallic surfaces against each other in salt water and oil dispersed by ethylene glycol, while sliding of PA 6 against steel surface produced highest values of voltage at oil lubricated condition.

It was found that a correlation between friction coefficient and voltage generated was found for polymers sliding against polyethylene terephthalate and against steel in water and salt water lubricated conditions, [18]. Wear of the tested polymers decreased with increase of sand particle size down to minimum because of the sand embedment in the polymeric surface. It was found that, application of magnetic field decreased friction coefficient at dry sliding due to its influence to decrease the adherence of polyethylene worn particles into the steel counterface, [19]. Besides, the magnetic field favored the formation of oxide film on the contact surface, where it played a protective role in dry friction, modified the friction and changed wear from severe wear to mild.

In the present work, the effect of the magnetic field on the friction and wear of steel sheets scratched by steel insert at dry, lubricated by vegetable oils and dispersed by polymeric particles such as polyethylene (PE), polyamide (PA6) and polymethylmethacrylate (PMMA) is discussed.

EXPERIMENTAL

The test rig, used in the experiments was top scratching tester equipped with an insert to produce a scratch on a flat surface with a single pass. The details of the test rig are shown in Fig. 1. The insert, used in experiments, was a square insert (12 × 12 mm) of TiC of tip radius of 0.1 mm and hardness of 2800 kp/mm^2. The scratch force was measured by the deflection of load cell. The ratio of the scratch force to the normal force was considered as friction coefficient. Wear was considered as the wear scar width of the scratched wear track. The width was measured by optical microscope with an accuracy of ± 1.0 μm. The tested surface was ground by an emery paper (500 grade) before testing. The load was applied by weights. The test speed was nearly controlled by turning the power screw feeding the insert into the scratch direction that was adjusted to be 2 mm/s. The applied load values were 2, 4, 6, 8 and 10 N. All measurements were performed at 28 ± 2 º C and 50 ± 10 % humidity. The vegetable oils used in the experiments were castor, maize, olive, almonds, jasmine and camomile oils. The polymers used in the experiments were polyethylene (PE), polyamide (PA6) and polymethylmethacrylate (PMMA).

The test specimens were fixed on the base and the magnet of 0.1 Mg (flux intensity) was assembled back to the test specimens, Fig 2. The tested materials were carbon steel (St. 34.11) sheets of 100 mm long, 30 mm wide and 1.0 mm thickness. The mechanical properties are shown in Table 1:

Table 1 Mechanical properties of the steel test specimens.

Carbon content, %	0.12
Ultimate tensile strength	340 – 420 MPa
Hardness B. H. N	950 – 1200 MPa
Surface roughness, R_a	3.6 μm

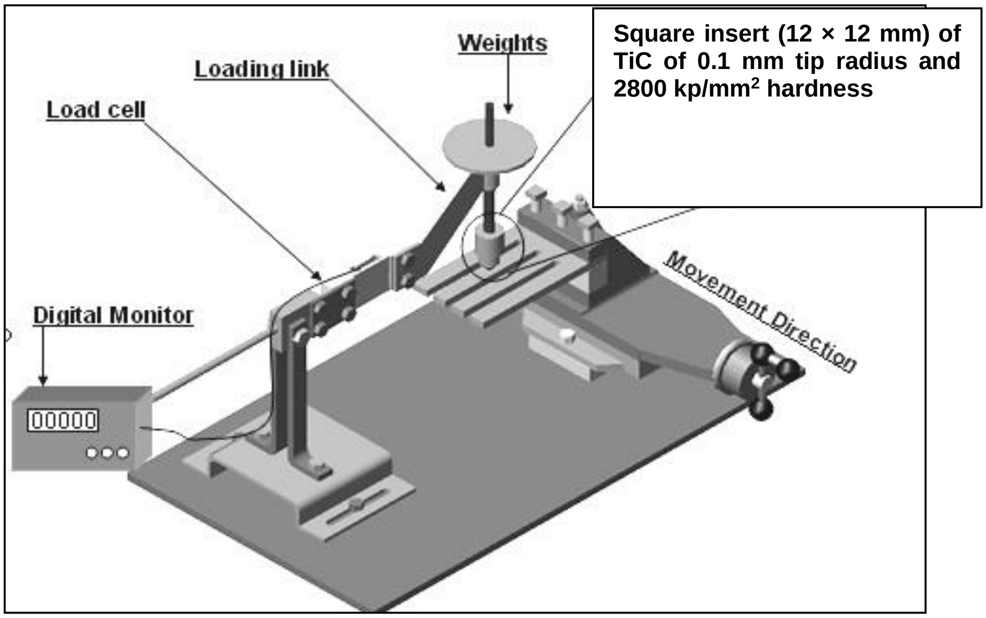

Fig. 1 The arrangement of the test rig.

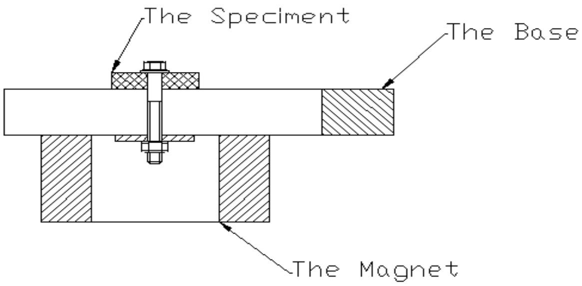

Fig. 2 The test specimen fixation.

RESULTS AND DISCUSSION

Friction coefficient and wear of steel at dry and oil lubricated conditions are illustrated in Figs. 3 and 4. At dry sliding, friction coefficient displayed the highest values, where a value of 1.37 was approached. Olive oil lubricated steel surface displayed the lowest values of friction coefficient followed by castor, almonds, maize, chamomile and jasmine oils. The variation of friction coefficient might be attributed to the ability of the tested oils to form multilayers of the oil polar molecules on the steel surface. The mixed lubrication provided by the vegetables oil is primarily governed by the formation of a stable oil film on the sliding surfaces. Polar molecules of the tested vegetable oils can significantly improve the wear resistance resulting from their adsorption on the sliding surfaces. The long fatty acid chain and presence of polar groups in the vegetable oil structure recommend them to be used as boundary lubricants, Fig. 5. The polar molecules orient themselves with the polar end directed towards the metal surface making a close packed monomolecular or multimolecular layered structure resulting in a surface film believed to inhibit metal-to-metal contact and progression of pits and asperities on the sliding surfaces.

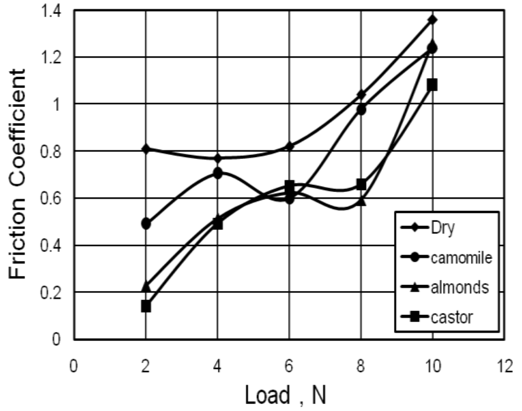	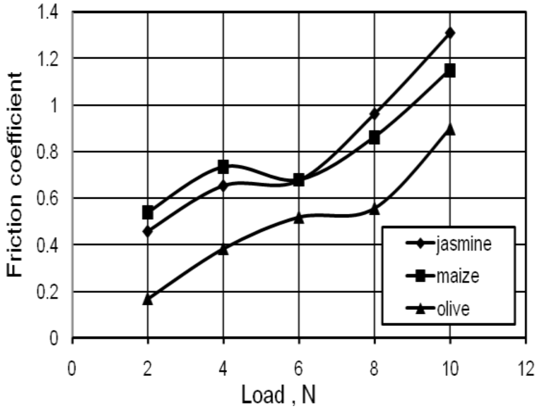
Fig. 3 Friction coefficient at dry and oil lubricated steel surface.	**Fig. 4 Friction coefficient at oil lubricated steel surface.**

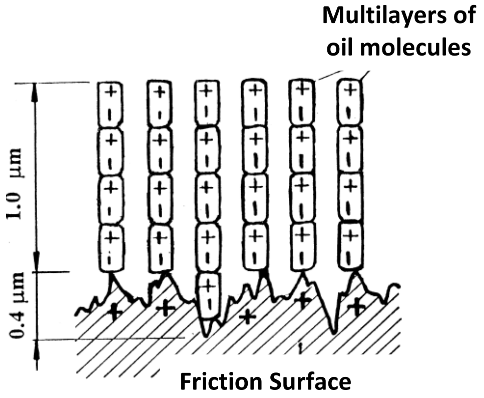

Fig. 5 The adherence of the molecules of the tested vegetable oils into the friction surface.

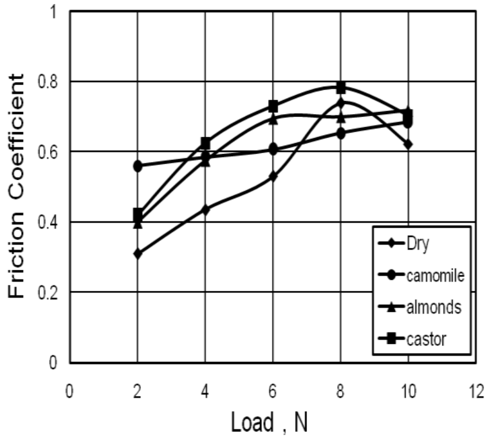	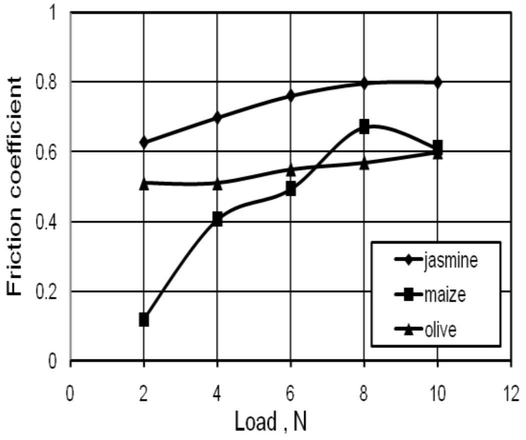
Fig. 6 Friction coefficient at dry and oil lubricated steel surface under application of magnetic field.	**Fig. 7 Friction coefficient at oil lubricated steel surface under application of magnetic field.**

Application of magnetic field on the sliding surface caused significant friction reduction at dry sliding, Fig. 6. This behaviour may be from the magnetization of the steel which is known to be accompanied by reduction of plasticity and increasing the brittleness. Lubricated steel surface displayed, too, remarkable friction reduction, where olive and maize oils showed the lowest friction followed by camomile, almond, castor and jasmine oils, Figs. 6 and 7. It seems that magnetic field enhanced the ability of the oil molecules to orient themselves in relatively long chain adhered to the steel surface.

The addition of polyethylene particles into the dry sliding against steel surface caused slight friction decrease as a result of the adhesion of polyethylene particles in both of the stylus and counterface, Fig. 8. It is supposed that an electric static charge would be formed on the contact surfaces as well as polyethylene particles from the friction produced from rubbing the contact surfaces, where equal and opposite charges are always produced. Lubricated steel surfaces by the tested oils and dispersed by polyethylene, show slight decrease in friction coefficient, Figs. 8 and 9, due to the adherence of polyethylene particles into the steel surface.

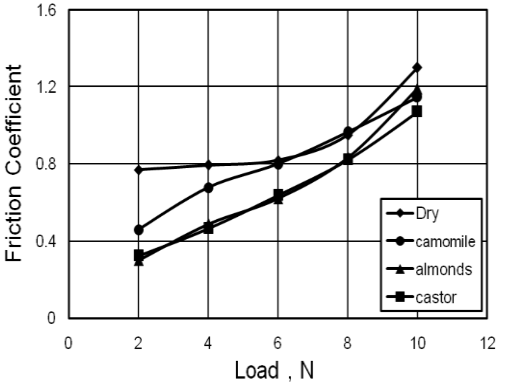

Fig. 8 Friction coefficient at dry, oil lubricated and PE contaminated steel surface.

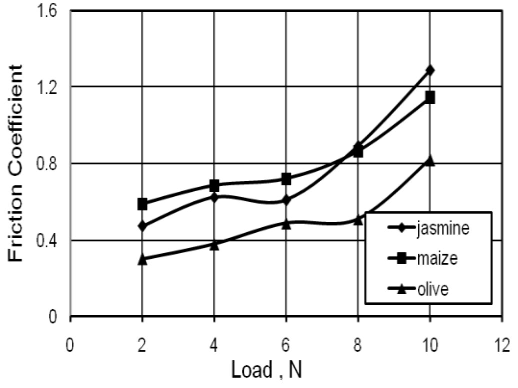

Fig. 9 Friction coefficient at oil lubricated and PE contaminated steel surface.

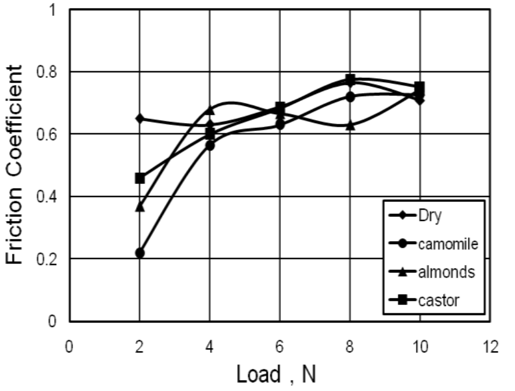

Fig. 10 Friction coefficient at dry, oil lubricated and PE contaminated steel surface under application of magnetic field.

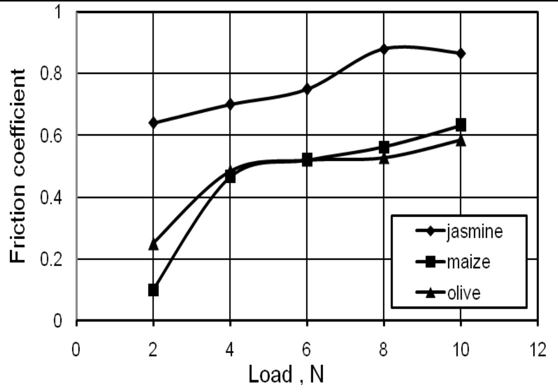

Fig. 11 Friction coefficient at oil lubricated and PE contaminated steel surface under application of magnetic field.

Application of magnetic field significantly decreased friction coefficient, Figs. 10 and 11. The maximum decrease was observed for the dry sliding, where friction coefficient decreased from 1.3 to 0.7 at 10 N normal load. As the load increased friction reduction increased. The minimum values of friction coefficient were observed for olive and maize oils, while castor, almonds, chamomile and jasmine oil caused low friction in less degree.

Friction coefficient at dry, oil lubricated and PA 6 contaminated steel surface is shown in Figs. 12 and 13. At dry sliding, friction coefficient decreased due to the adhesion of polyamide particles into the surface of steel. For oil lubricated sliding, no enhancement was observed. It seems that the polar molecules of oil disabled the positive charge polyamide particles to be adhered into the sliding surface.

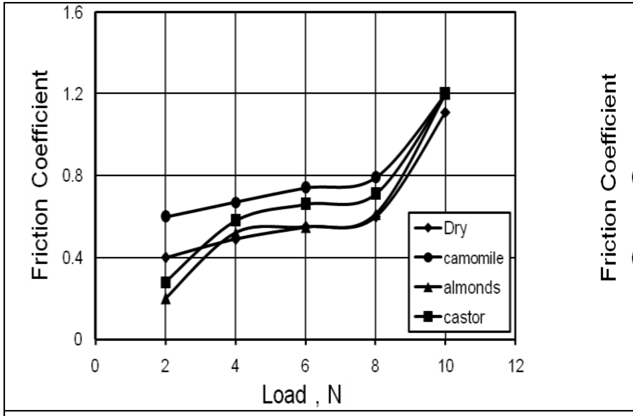

Fig. 12 Friction coefficient at dry, oil lubricated and PA 6 contaminated steel surface.

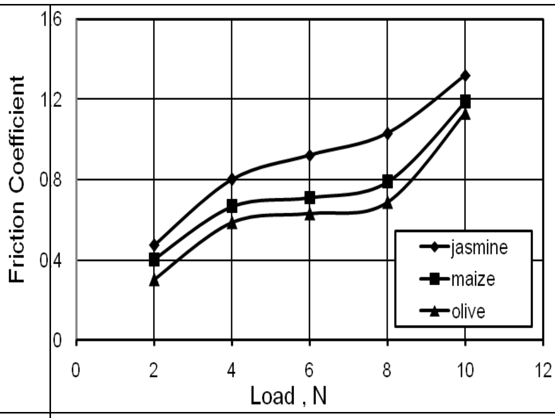

Fig. 13 Friction coefficient at dry, oil lubricated and PA 6 contaminated steel surface.

Application of magnetic field on the sliding surface caused significant friction decrease, Figs. 14 and 15. It seems that magnetic field accelerated the reorientation of the polyamide particles to adhere into the surfaces of insert and test specimens and consequently increased the adhesion force.

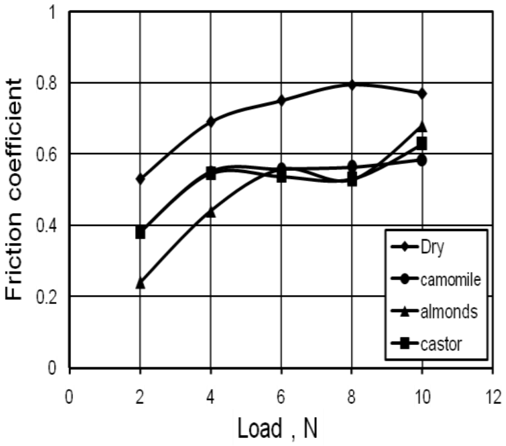

Fig. 14 Friction coefficient at dry, oil lubricated and PA 6 contaminated steel surface under application of magnetic field.

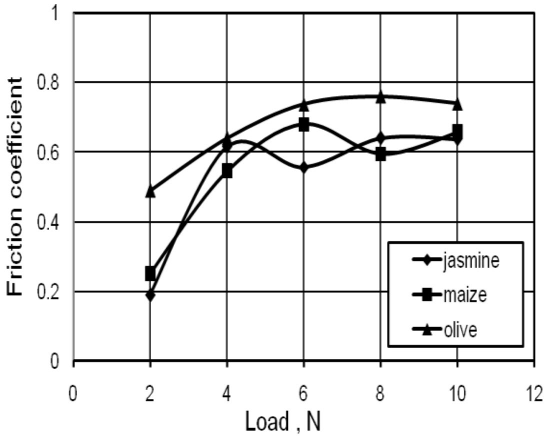

Fig. 15 Friction coefficient at oil lubricated and PA 6 contaminated steel surface under application of magnetic field.

Addition of PMMA into the oil made no change in friction coefficient at dry, oil lubricated steel surface, Figs, 16 and 17. Although the static electric charge generated from the friction of PMMA particles rubbing steel was much higher than that generated for PA 6, the adherence of PMMA into the steel surface was relatively weak. This behavior may be from the ability o PMMA particles to roll than to adhere into the sliding surface.

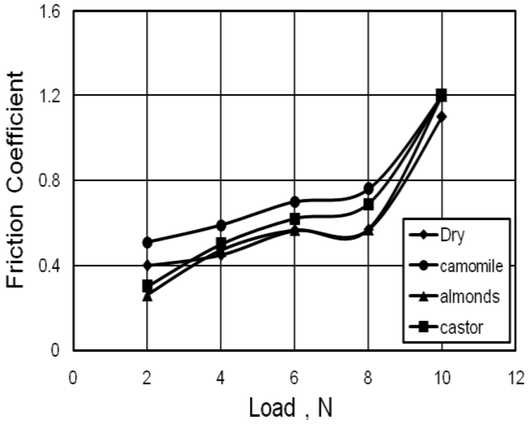

Fig. 16 Friction coefficient at dry, oil lubricated and PMMA contaminated steel surface.

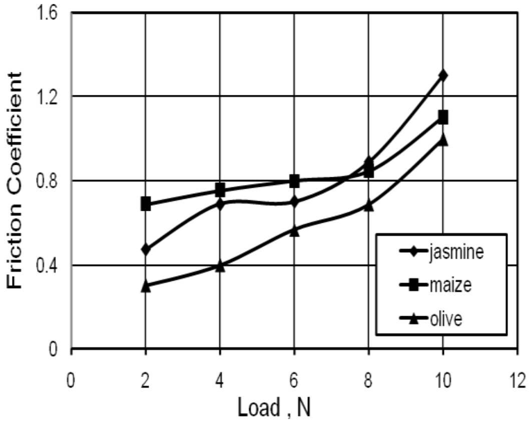

Fig. 17 Friction coefficient at oil lubricated and PMMA contaminated steel surface.

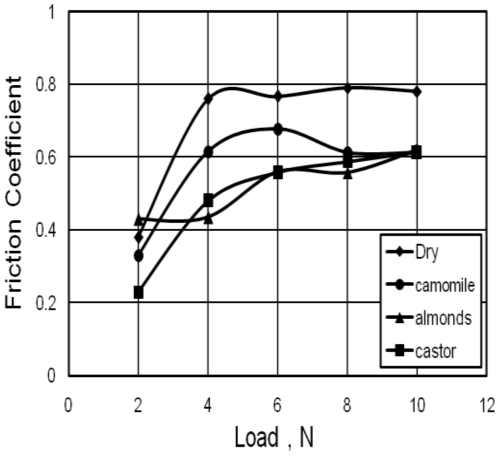

Fig. 18 Friction coefficient at dry, oil lubricated and PMMA contaminated steel surface under application of magnetic field.

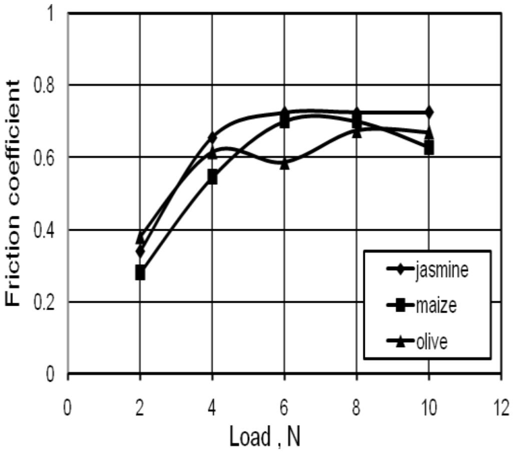

Fig. 19 Friction coefficient at oil lubricated and PMMA contaminated steel surface under application of magnetic field.

Application of magnetic field significantly decreased friction coefficient, Figs. 18 and 19, at dry, oil lubricated and PMMA contaminated steel surface. This behaviour may be attributed to the ability of the magnetic field to reorient the PMMA particles as well as oil molecules and adhere them into the sliding surfaces forming a protective layer. Based on the experimental observations, The formed layer was able to withstand the asperities interaction of the two sliding surfaces.

Wear of steel test specimens measured in scratch width displayed by the abrasion of the steel sheet test specimes by the steel insert at dry and oil lubricated working conditions, is shown in Figs. 20 and 21. Generally wear increased with increasing applied load. Dry sliding gave the highest wear. The best wear resistance was observed for olive, maize, jasmine, castor, camomile and almonds oils. The polarity of the oil molecules enhanced the oil to form a thick layer on the friction surface and consequencely reduced the interaction of the insert into the scratch.

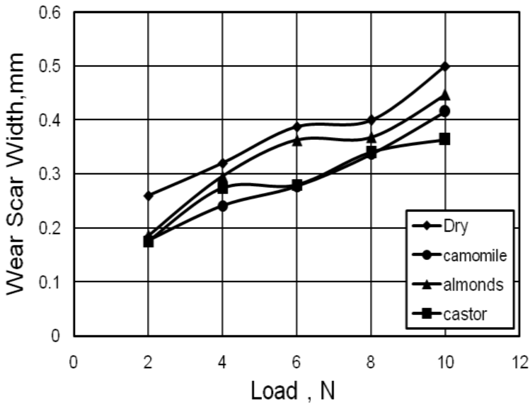

Fig. 20 Wear displayed by dry and oil lubricated steel surface.

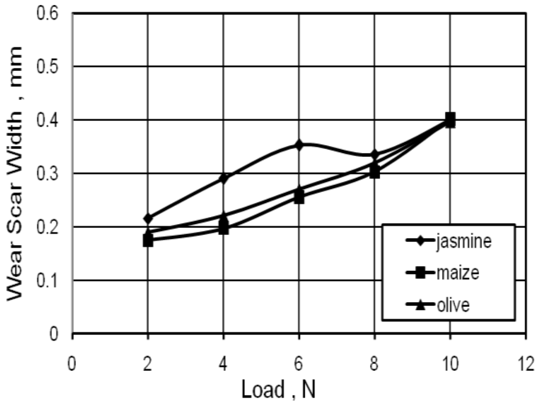

Fig. 21 Wear displayed by oil lubricated steel surface.

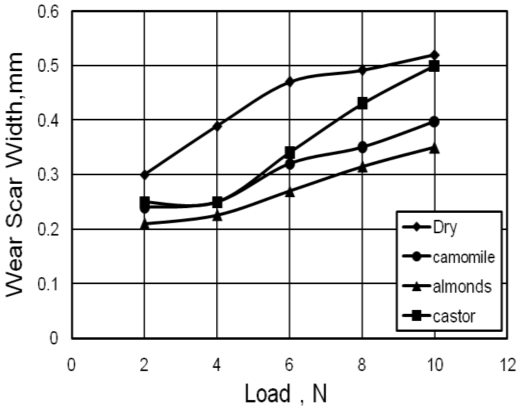

Fig. 1. 22 Wear displayed by dry and oil lubricated steel surface under application of magnetic field.

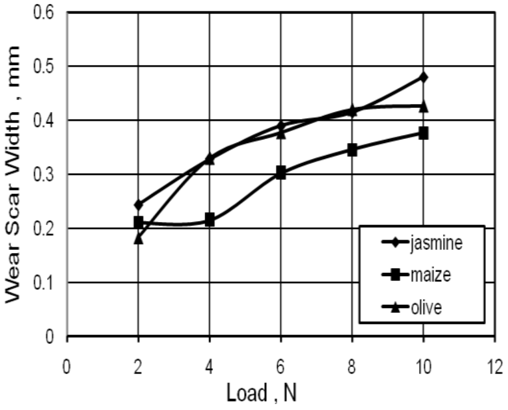

Fig. 1. 23 Wear displayed by oil lubricated steel surface under application of magnetic field.

Under the application of the magnetic field wear slightly increased, Figs. 22 and 23. The wear increase was observed for all the sliding conditions. It seems that the magnetization of the steel surface, accompanied to the application of magnetic field, caused the wear increase as a result of the reduction of plasticity and the increase of the brittleness. In this condition, the material removed from the groove scratched by the insert increased, while the material deformed in front and ridge ridges decreased. In the presence of PE on the sliding surface, wear significantly decreased due to the ability of PE particles to adhere into the scratch track forming protective layer from excessive wear, Figs. 24 and 25. The PE layer (negative electric charge) is probably adhered on the insert cutting edges (positive electric charge) as a result of the attractive electric force.

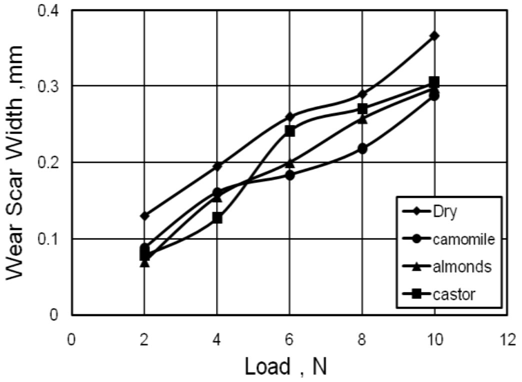

Fig. 24 Wear displayed by dry and oil lubricated and PE contaminated steel surface.

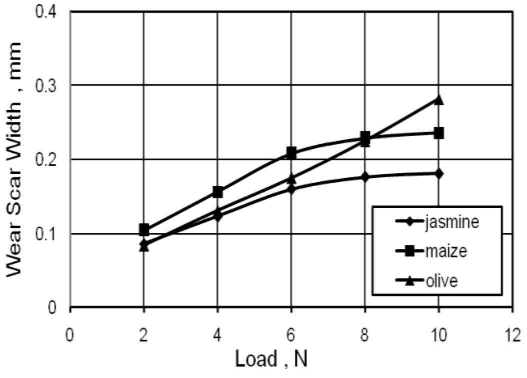

Fig. 25 Wear displayed by oil lubricated and PE contaminated steel surface.

In the presence of the magnetic field and PE particles, wear increased for dry and lubricated sliding, Fig. 26 and 27, for two reasons. The first is the magnetization of the scratched steel surface and the second is for the effect of the magnetic field to reduce the electric force attracting PE particles and steel insert.

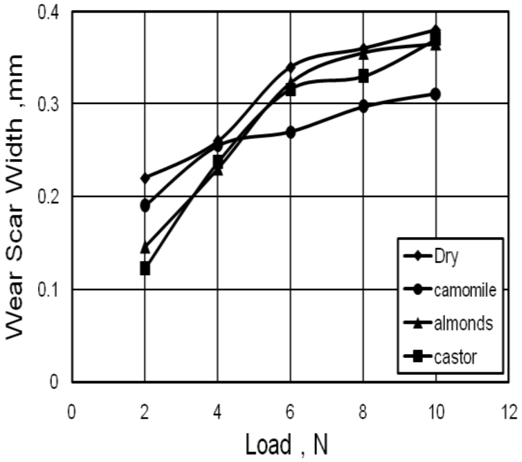

Fig. 26 Wear displayed by dry and oil lubricated and PE contaminated steel surface under application of magnetic field.

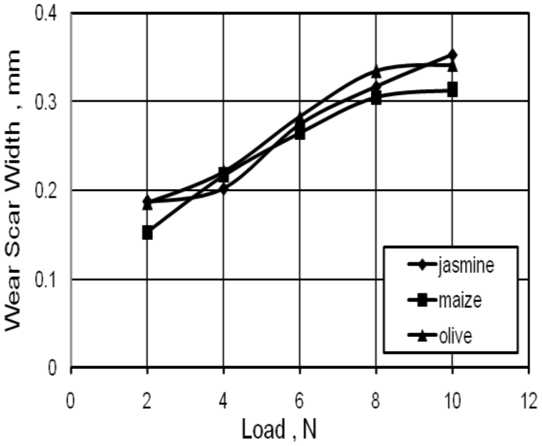

Fig. 27 Wear displayed by oil lubricated and PE contaminated steel surface under application of magnetic field.

In the presence of PA 6 as loose particles (positive charge) adhered into the surface of the steel insert (negative charge), Figs. 28 and 29, wear displayed slight decrease. In condition of applying magnetic field on the scratched track, wear increased. This behavior might be attributed to the magnetization of the steel test specimens as well as the reduction of the attractive electric force.

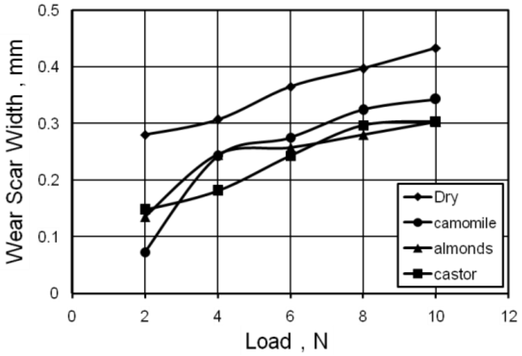

Fig. 28 Wear displayed by dry and oil lubricated and PA 6 contaminated steel surface.

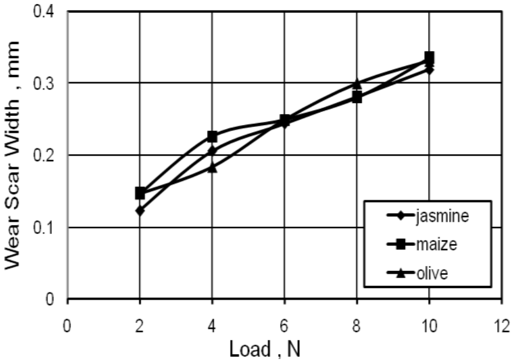

Fig. 29 Wear displayed by oil lubricated and PA 6 contaminated steel surface.

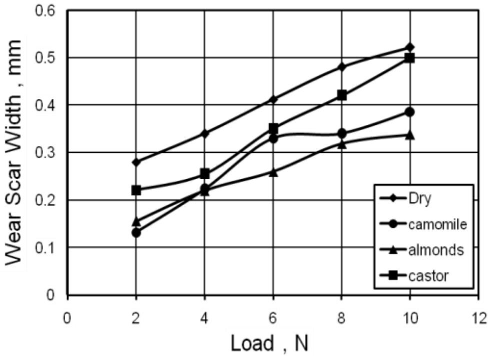

Fig. 30 Wear displayed by dry and oil lubricated and PA 6 contaminated steel surface under application of magnetic field.

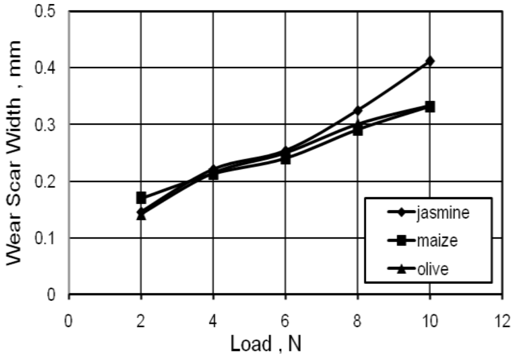

Fig. 31 Wear displayed by oil lubricated and PA 6 contaminated steel surface under application of magnetic field.

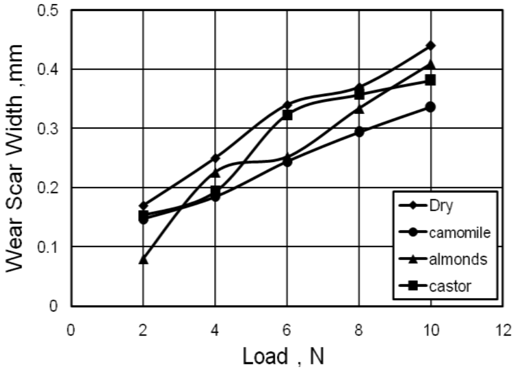

Fig. 32 Wear displayed by dry and oil lubricated and PMMA contaminated steel surface.

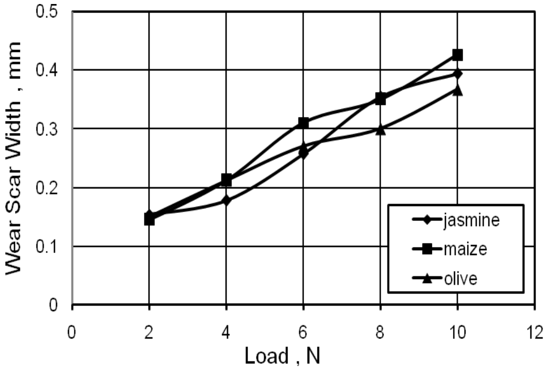

Fig. 33 Wear displayed by oil lubricated and PMMA contaminated steel surface.

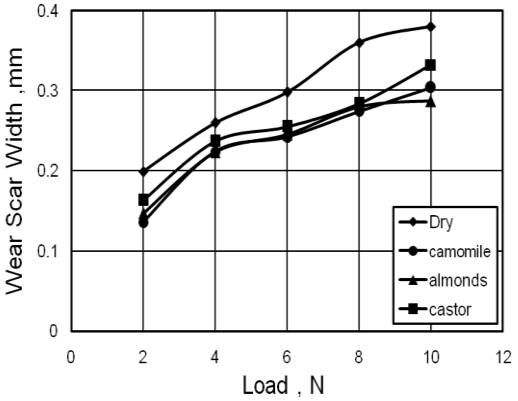

Fig. 34 Wear displayed by dry and oil lubricated and PMMA contaminated steel surface under application of magnetic field.

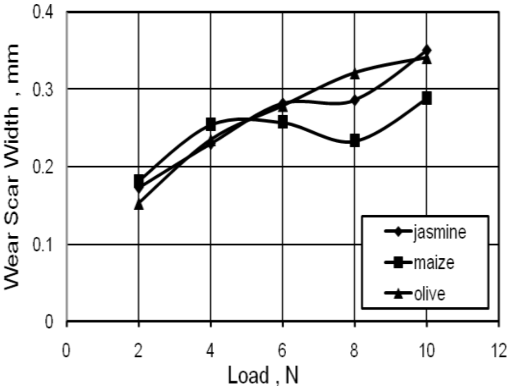

Fig. 35 Wear displayed by oil lubricated and PMMA contaminated steel surface under application of magnetic field.

In the presence of PMMA particles on the scratched surface, wear decreased for dry sliding and chamomile, almonds and castor oils, Fig. 32, while for olive, maize and jasmine oils no change was observed, Fig. 33. It is well known that electric charge generated from triboelectrification on the PMMA particles is relatively higher than that generated on PE and PA 6. On the other hand, PMMA particles are spherical and therefore their tendency to roll is higher than to adhere into the sliding surfaces. Based on these facts, their wear protection is relatively lower than PE and PMMA particles.

Wear displayed by dry and oil lubricated and PMMA contaminated steel surface under application of magnetic field is shown in Figs. 34 and 35. It is clearly illustrated that wear significantly decreased compared to the condition of no magnetic field applied. The enhancement in wear resistance may be from the action of the magnetic field which increased the adherence of PMMA particles into the cutting edges of the steel insert.

CONCLUSIONS

1. At dry sliding, friction coefficient displayed the highest values. Olive oil lubricated steel surface displayed the lowest values of friction coefficient followed by castor, almonds, maize, chamomile and jasmine oils.
2. Polar molecules of tested vegetable oils can significantly improve wear resistance resulting from their strong adsorption on sliding surfaces. The long fatty acid chain and presence of polar groups in the vegetable oil structure recommend them to be used as boundary lubricants.
3. Application of magnetic field on the sliding surface caused significant friction reduction at dry sliding. This behaviour may be from the magnetization of the steel which is known to be accompanied by reduction of plasticity and increasing the brittleness. Besides, magnetic field enhanced the ability of the oil molecules to orient themselves in relatively long chain adhered to the steel surface.
4. The addition of polymeric particles such as PE, PA 6 and PMMA particles caused slight friction decrease as a result of the adhesion of those particles into the insert/test specimens.
5. Further friction decrease was observed in condition of application the magnetic field.
6. Dry sliding gave the highest wear. The best wear resistance was observed for olive, maize, jasmine, castor, camomile and almonds oils. The polarity of the oil molecules enhanced the

oil to form a thick layer on the friction surface and consequencely reduced the interaction of the insert into the scratch.

7. Under the application of the magnetic field, wear slightly increased. The wear increase was observed due to the reduction of plasticity and the increase of the brittleness, where the material removed from the groove scratched by the insert increased, while the material deformed in front and ridge ridges decreased.

8. Presence of polymeric particles significantly decreased wear due to the ability of those particles to adhere into the insert/scratch track forming protective layer from excessive wear. In the presence of the magnetic field wear increased for polyethylene and polyamide. Magnetic field strengthened the adherence of PMMA particles into the cutting edges of the steel insert.

REFERENCES

1. Gangopadhyay A., Barber G., Zhao H., “Tool wear reduction through an externally applied electric current”, Wear 260, pp. 549 - 553, (2006).
2. Yamamoto Y., Ono B., Ura A., “Effect of applied voltage on friction and wear characteristics in mixed lubrication”, Lubr. Sci. 8 pp. 199 - 207, (1996).
3. Takeuchi A., “Various tribological phenomena in current flow (Part 3): control of running-in by application of electric field”, Jpn. J. Tribol. 41 pp. 735 - 744, (1996).
4. Katafuchi T., “Effects of electric current on wear under lubricated conditions”, JSLE 30 pp. 887 - 893, (1985).
5. Wistuba H., “The effect of an external electric field on the operation of an aluminum oxide-cast iron sliding contact joint”, Wear 208, pp. 113 - 117, (1997).
6. Endo K., Fukuda Y., Takamiya O., “Wear behaviors of metals under lubricated condition and the effect of small electric potential”, Bull. JSME 14, pp. 1281 - 1288, (1971).
7. Gangopadhyay A. K., Peck M., Simko S., “Wear control in a lubricated contact through externally applied electric current”, Tribol. Trans. 45, pp. 302 - 309, (2002).
8. El Mansori M., Pierron F., Paulmier D., “Reduction of tool wear in metal cutting using external electromotive sources”, Surface and Coatings Technology 163 –164, pp. 472 - 477, (2003).
9. Zaidi H., Chin K. J., Frene J., “Electrical contact steel/steel in magnetic field: Analysis of surface and subsurface of sliding”, Surface and Coatings Technology 148, pp. 241 - 250, (2001).
10. Hongjun J., Yonggang M., Shizhu W., Hong J., “Effects of external electric fields on frictional behaviors of three kinds of ceramic/metal rubbing couples”, Tribology International 32, pp. 161 - 166, (1999).
11. 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).
12. 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, pp. 145 – 162, (1995).
13. 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).

14. Ali W. Y., “Influence of Applied Voltage on Friction and wear of Polymeric Coatings Sliding Against Steel”, Tribologie und Schmierungstechnik, 43. Jahrgang, March/April 1996, pp. 83 - 87, (1996).
15. 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).
16. 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).
17. Youssef, M. M., “Triboelectrification of Metallic and Polymeric Materials” Bulletin of the Faculty of Engineering, El-Minia University, Vol. 20, No. 1., July 2001, pp. 31 – 41, (2001).
18. 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 2004 in Göttingen, pp. 9/1 – 9/14, (2004).
19. Mohamed M. K., “Effect of Magnetic Field on the Friction and Wear of Polyethylene Sliding Against Steel” Journal of the Egyptian Society of Tribology, Vol. 5, No. 1, April 2009, pp. 13 – 24, (2009).