EGTRIB Journal

JOURNAL OF
THE EGYPTIAN SOCIETY OF TRIBOLOGY
VOLUME 8, NO. 3, JULY 2011, 27 - 39

EFFECT OF MAGNETIC FIELD ON FRICTION COEFFICIENT DISPLAYED BY ROLLING BEARINGS

Abdel-Sattar S., Alahmady A. and Ali W. Y.

Faculty of Engineering, Taif University, Al-Taif, SAUDI ARABIA.

ABSTRACT

The effect of magnetic field and electric current on the friction coefficient displayed by rolling bearing greased by lithium grease dispersed by solid lubricants such as graphite, molybdenum disulphide, talc and polymeric particles is investigated.

It was shown that the magnetic field had no effect on friction coefficient observed for lithium grease without additives. Addition of talc showed significant increase in friction coefficient. This increase was influenced by magnetic field. No significant effect on friction coefficient was observed for grease dispersed by molybdenum disulphide. Generally molybdenum disulphide displayed relatively lower friction coefficient than graphite and talc. Copper particles dispersed in grease displayed the lowest friction values. Friction coefficient displayed by grease significantly decreased with increasing electric voltage due to decrease of grease viscosity as the voltage increased. In the presence of graphite and talc, friction coefficient increased up to maximum then decreased with increasing voltage. Slight friction increase was observed for grease dispersed by copper. The lowest friction coefficient was displayed by molybdenum disulphide dispersing grease. The highest friction coefficient was displayed by grease dispersed by graphite and talc, while the lowest friction was shown for molybdenum disulphide dispersing grease.

Grease dispersed by high density polyethylene showed friction decrease. The lowest friction reduction was observed for polymethyl methacrylate. The strong adhesion of polytetrafluroethylene particles into the sliding surfaces significantly increased friction coefficient. It seems that polytetrafluroethylene particles were adhered to surfaces of inner and outer races as well as the balls. Changing the terminal of the voltage applied to the rotating shaft cased significant friction decrease for polymethyl methacrylate. Viscosity of the grease decreased with increasing the voltage. Friction coefficient decreased for high density polyethylene and polytetrafluroethylene. The lowest friction values were observed at 6 volts which indicated that increasing voltage across the sliding surface could significantly decrease friction coefficient.

KEYWORDS

Magnetic field, electric voltage, friction coefficient, rolling bearing, grease, graphite, molybdenum disulphide, talc, copper and polymers.

INTRODUCTION

In electronic appliances the mechanical drives perform under the effect of magnetic field. It is necessary to investigate the tribological performance of sliding bearings which are probably made of high density polyethylene considering that effect, [1]. The friction and wear of polyethylene sliding against steel in the presence of magnetic field was investigated. It was found that, application of magnetic field decreases friction coefficient at dry sliding due to its influence to decrease the adherence of polyethylene worn particles into the steel counterface. Besides, the magnetic field favors the formation of oxide film on the contact surface, where it plays a protective role in dry friction, modifies the friction and changes wear from severe wear to mild. Lubricating the steel surface by oils caused significant reduction in friction coefficient, where the maximum reduction was displayed by paraffin followed by glycerine, almond, jasmine, corn, castor, olive and sun flower oils. Besides, wear of polyethylene test specimens shows relative decrease in the presence of magnetic field. Castor, sun flower, corn and olive oils shows the highest wear resistance, while glycerine, jasmine, almond and paraffin oils shows the lowest wear resistance.

The effect of the magnetic field on the friction and wear of steel and brass sheets scratched by a steel insert at dry, lubricated by vegetable oils and dispersed by polymeric particles such as polyethylene (PE), polyamide (PA6) and polymethyl methacrylate (PMMA) was investigated, [2, 3]. Based on the experimental observations, it was found that Olive oil displayed the lowest values of friction coefficient followed by castor oil, almonds, corn, chamomile and jasmine oils, where their polar molecules could 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 due to the enhanced ability of the oil molecules to orient themselves in relatively long chain adhered to the sliding surface and thus decreased the friction and wear.

The effect of applying external voltage on the sliding of copper, aluminium and polyethylene against steel surface lubricated by paraffin oil dispersed by polymeric particles such as polyethylene, polyamide and polymethyl methacrylate was tested, [4]. It was noticed that the friction coefficient and wear were significantly influenced by the generation of electric static charge on the contact surfaces which caused an attractive force imposed to the normal load. It was found that wear was more influenced by the electric static charge than friction coefficient.

In the presence of magnetic field around the tribocontact and in ambient air, the contact track was covered with very fine ferromagnetic particles, [5]. Friction and wear are influenced by the presence of oxide. The increase of oxide layer on the surface, the retention of passivated particles in the contact and their refinement by grinding modify the contact rheology which transits from metal/metal contact to oxide/oxide contact. It was noticed that magnetic field acts on the ferromagnetic contact surface by modifying their electrical and electronic behaviour. It increases the electronic speed in their orbits, [6], and creates the electrical fields and the electrical currents. Those electrical currents enhance the oxidation. Moreover, dislocations in subsurface of the materials in contact are influenced by contact shear stress field [7]. The stress field presents a decreasing gradient from the Hertzian point. The dislocations displace from the region of strong

stress gradient to the region of weak gradient. The existence of magnetic field around the contact facilitates the movement of dislocations due to mechanical stress, decreasing the obstacles through the rearrangement of magnetic domains. This accumulation of dislocations leads to the increase of surface hardness.

Exploring effects of electric field on the frictional behavior of materials has become an attractive subject in recent years to many researchers in the world. It was found that friction and wear were attributed to the migration of electrons across the interfaces of metals with different work functions. Indeed reduction in friction coefficient has been verified by canceling out the self-generated electric potential across a dry metallic contact with an external voltage. It was found that the difference in the orientations of function groups of polymers under different electric fields influences the intensity and the direction of interfacial forces between polymer and metal surfaces, [8]. The apparent friction coefficient was changed by reversing the polarity of the external electric field due to the change in real normal pressure. The results showed that the change in friction coefficient can reach into 25%. An extraordinary change in friction coefficient of graphite/graphite rubbing couples was discovered, [9], under a large DC current at a critical sliding speed, jumping from a high value (about 0.7) to a low value (about 0.07) as rubbing slows down or from the low value to the high value as rubbing speeds up. It was found that for intentionally insulated metallic contacts lubricated with liquid crystals the relative friction coefficient under boundary lubrication conditions can be reduced by up to 35% by applying an external DC electric field, [10]. DC voltages were found to be able to promote the generation of chemisorbed and chemical reaction films of ZDTP additives in mineral lubricating oils on metal surfaces, leading to a reduction in friction, [11, 12]. It was reported that an AC voltage has effects on lubricating ability of synovia constituents, [13]. It was observed that for Al_2O_3/brass couple lubricated with emulsion of zinc stearate the change in friction coefficient due to an external DC voltage is not only remarkable, reaching 200%, but also quick and reversible, [14]. Besides, friction coefficient of Al_2O_3/brass couple increased monotonously with increasing external electric field intensity in the range of 0 - 30 DCV, [15], and that the fastest increase of friction coefficient occurs within the range of 0 - 20 DCV.

From the analyses of experimental data, it is shown that in presence of active gases, the oxide layer growth and the transferred graphite films on the steel track are enhanced by a magnetic field. The graphite layer possesses good adhesion to the steel surface and leads to the best reduction of wear and friction coefficient, [16, 17]. However, when the friction test is operated in inert environment and in presence of a magnetic field, the opposed phenomenon is observed. The transfer of a harder steel to a softer graphite surface is responsible for the increase of friction and wear. This abnormal process is due to a magnetization of a ferromagnetic steel which is known to be accompanied by reduction of plasticity and increasing the brittleness. It is known that, during friction on metals or dielectric couples, part of the energy consumed turns into electrical energy. In the second part of the study, electrical phenomena induced by friction will be examined in situ. Hence, the appearance of the potential difference generated by lubricated friction will be studied. This electrical effect leads to an embrittlment of friction surfaces and also involves a greater reactivity of surfaces with the lubricant. Indeed, stress corrosion cracking, and hydrogen embrittlement have been described in similar terms. Hence, an externally applied voltage may modify the wear behaviour of the

lubricant and also, without friction, its decomposition and its reactivity on the surface; we shall try to analysis these effects in this paper, [18]. Because of triboelectrification, the charged surfaces can interact with each other due to the direct electrostatic forces, [19]. 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, [20]. 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.

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. The oxide film formed on the anode surface being harder than the bulk steel, the rubbing surface at the anode side was little worn, but it at cathode side was abrasively worn considerably. The application of an electric field, however, is considered to promote the breakdown of EHL film formed. Therefore, the effect of the application of an electric condition tested, [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 show that a magnetic field applied through the sliding contact leads to decrease the wear rate.

Tribo-emission is a term describing the emission of electrons, ions and photons as a response to friction and wear processes. The mechanisms involved in tribo-emission are complex and not known in detail [23]. However, it is speculated that triboemission precedes and is even necessary for tribochemical reactions to occur in the tribocontact. During wear surface cracks are generated as a result of severe deformation of the worn surface. In general, when a crack forms there is an imbalance of electrons on opposite faces of the crack [24 - 26]. This imbalance is particularly evident in ionic solids which are composed of alternating layers of anions and cations. For example, when a crack develops in aluminium oxide, one side of the crack will contain oxide anions while the opposite side will contain aluminium cations. The narrow gap between opposing faces of a crack causes formation of a large electric field gradient (electric field gradient is controlled by the distance between opposite electric charges). This electric field is sufficient to cause electron escape from the anions [26]. It is believed that not all the electrons which escape from the anions are collected by the cations on the opposing crack face. This results in tribo-emission or the release of electrons into the wider environment under the action of sliding.

In the present work, the effect of magnetic field and electric voltage on the friction coefficient displayed by rolling bearing greased by lithium grease dispersed by solid lubricants such as graphite, molybdenum disulphide, talc and polymeric particles is investigated.

EXPERIMENTAL

Experiments were carried out using cross pin wear tester, Fig. 1. The rotating pin was attached to a chuck mounted on the main shaft of the test rig. In the rotating pin the tested deep groove ball bearing was fastened and greased. The stationary pin was fixed to the loading block where the load is applied. The main shaft of the test machine is driven by DC motor (300 watt, 250 volt) through a V-belt drive unit. Moreover, the motor speed is adjustable and can be controlled by varying the input voltage using an autotransformer. The test rig is fitted by a load cell to measure the frictional torque generated in the contact zone between the rotating and stationary pins. Normal load was applied by means of weights attached to a loading lever. A counter weight is used to balance the weights of the loading lever, the loading block and the stationary specimen. The tests were carried out at sliding velocity of 0.5 m/s and load of 50 N. The rotating specimens were greased before the test and further greasing was carried out every minute during the test. The test time was 30 minutes. The magnetic field was applied by three magnets of 0.1, 0.2 and 0.3 mG (flux intensity) assembled to the loading block. The details of the critical part of the tested bearing is shown in Fig. 2. Besides, Direct current of voltage difference of 0, 1.5, 3.0, 4.5 and 6.0 volts was applied between the inner and outer races of the tested bearing (Deep groove ball bearing No. 6302). The sign of the voltage is referred to the polarity of the inner race.

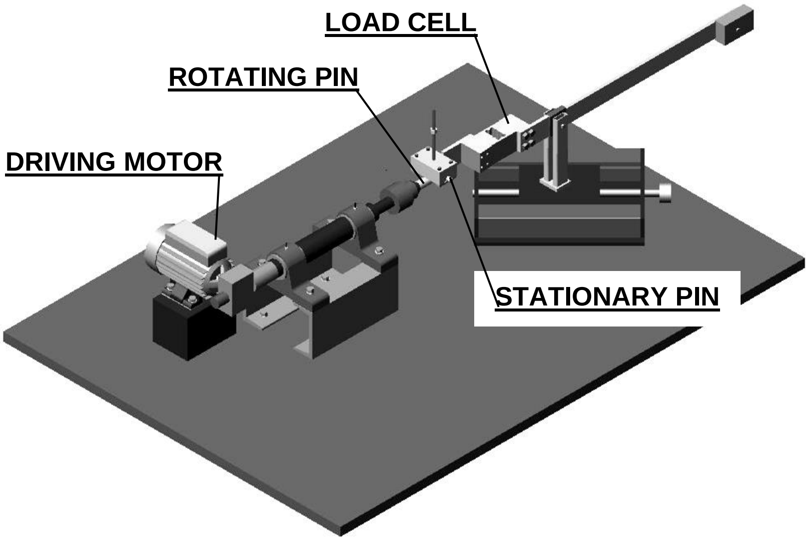

Fig. 1 Arrangement of the test rig.

Experiments were carried out at 25 °C using lithium based grease, the solid lubricant additives were graphite (C), molybdenum disulphide (MoS_2), copper (Cu) of (0 - 80 µm) particle size and talc. Polymeric materials such as high density polyethylene (HDPE), polytetrfluroethylene (PTFE), and polymethyl methacrylate (PMMA) of (0 - 50 µm) particle size were used as thickener for lithium based grease at concentration of 10 wt.%.

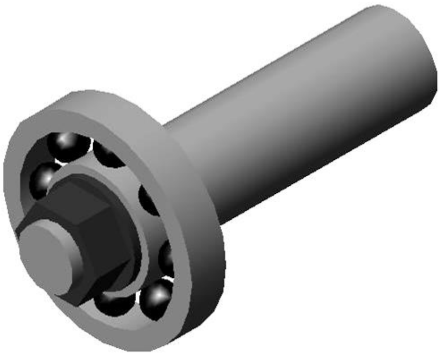

Fig. 2 Details of the tested bearing.

RESULTS AND DISCUSSION

The effect of magnetic field on the friction coefficient displayed by the deep groove ball bearings when the lithium grease was dispersed by graphite (C), talc, molybdenum disulphide (MoS_2) and copper (Cu) is illustrated in Fig. 3. Insignificant effect of the magnetic field on the friction coefficient was observed for lithium grease without additives. Addition of talc showed significant increase in friction coefficient. This increase was influenced by magnetic field, where it decreased with increasing magnetic field. It seems that the rolling motion of talc particles was accelerated by the magnetic field. No significant effect on friction coefficient was observed for grease dispersed by MoS_2. Generally MoS_2 displayed relatively lower friction coefficient than C and talc. Cu particles dispersed in grease displayed the lowest friction values. The mechanism of action of copper particles depends on the relatively lower shear strength of copper particles when compressed between the two sliding surfaces.

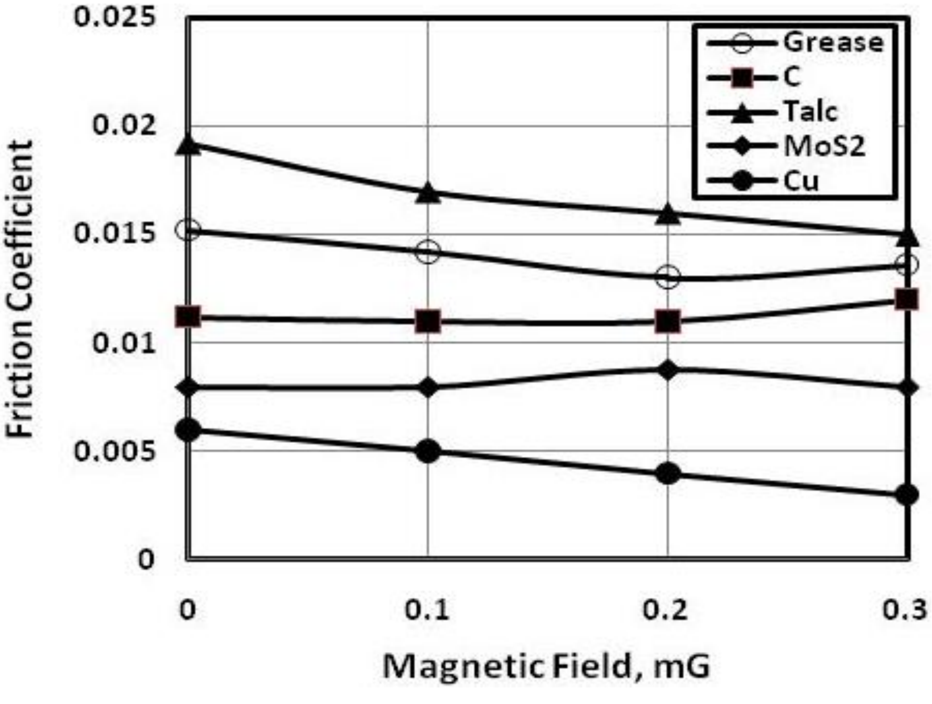

Fig. 3 Effect of magnetic field on friction coefficient.

The effect of positive voltage applied to the shaft on the friction coefficient is shown in Fig. 4. Friction coefficient displayed by grease free of additives significantly decreased with increasing electric voltage. It seems that viscosity of the grease decreased as the voltage increased. In the presence of C, friction coefficient increased up to maximum then decreased with increasing voltage. The same trend was observed for grease dispersed by talc. Slight friction increase was observed for grease dispersed by copper. It seems that the good conductivity of copper affected the viscosity of the grease. The lowest friction coefficient was displayed by MoS_2 dispersing grease.

The change of the voltage terminal applying on the rotating shaft into negative did not cause significant change on the friction coefficient, Fig. 5. The highest friction coefficient was displayed by grease dispersed by C and talc, while the lowest friction was shown by MoS_2 dispersing grease. As already mentioned, not all lamellar solids are capable of interlamellar sliding at low shear stresses. The nature of bonding between the talc lamellae is a weak van der Waals bonding acting between lamellae, [27]. Good solid lubricants therefore exhibit only weak bonding between lamellae. Although adhesion between lamellae is highly undesirable, adhesion of lamellae to the worn surface is essential. In general, material that does not adhere to a worn surface is quickly removed by the sweeping action of sliding surfaces.

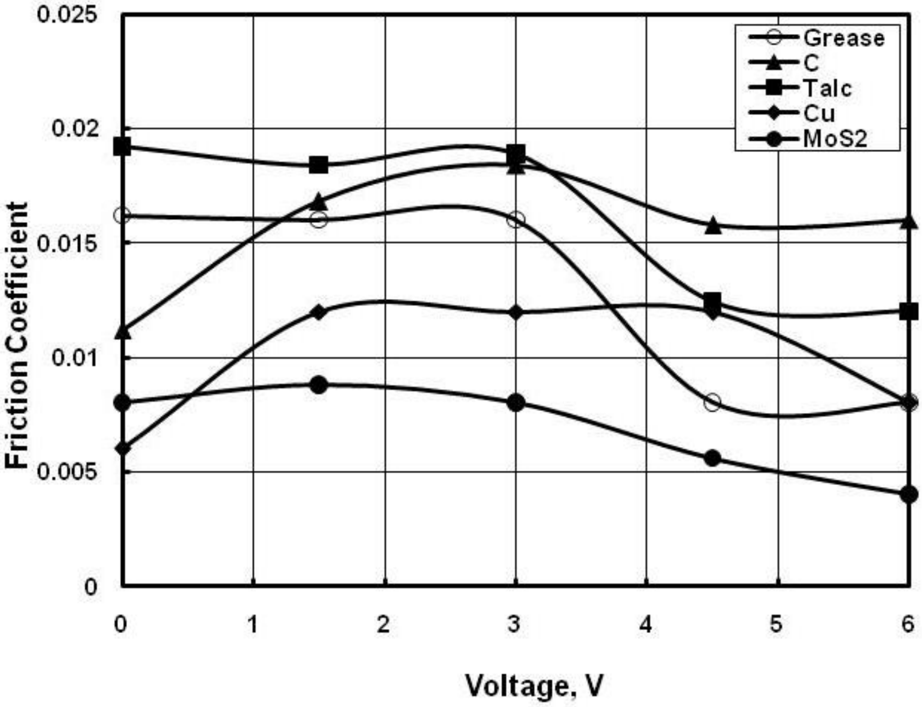

Fig. 4 Effect of positive voltage applied to the shaft on the friction coefficient.

The frictional properties of C, MoS_2 and talc applied as powders to sliding steel surfaces are found to be quite different although all three substances have the required lamellar crystal structure. After sliding, transferred layers of C and MoS_2 were found on the worn surfaces. The crystal structure of these transferred layers showed orientation of the lamellae parallel to the worn surface. It was found that talc was transferred in much

smaller quantities than C, MoS_2, with negligible orientation of lamellae parallel to the worn surface. To explain the poor performance of talc, it has been suggested that talc, unlike C, MoS_2, is too soft to be mechanically embedded in the surface. In the case of steel surfaces it is thought that the sulphur ions in the molybdenum disulphide bond with the iron in a steel surface.

Apart from having a lamellar crystal structure, a layer structure is also present in both C, MoS_2, where layers about 1 µm thick were detected. The layers of MoS_2 are quite flexible and can slide over each other repeatedly without damage. It was found that under repeated sliding, films of MoS_2 can move significant distances over the worn surface. The lubrication mechanism of C, MoS_2 is believed to be a result of the relatively free movement of adjacent layers in these substances. There are some clear distinctions in performance between graphite and molybdenum disulphide films on steel under atmospheric conditions [28]. In general, however, C films fail at lower loads and exhibit shorter lifetimes than MoS_2 films. The limiting contact stresses for C are a little over half that of MoS_2.

Soft plastic metals such as copper have often been used as solid lubricants by applying them as a thin surface layer to a hard substrate, e.g. carbon steel, [29]. The application of these metallic layers can result in a significant reduction in the coefficient of friction. In general, thin metallic films do not offer equal or superior lubrication MoS_2 and for this reason interest has been limited, although there are some exceptions. The copper sheet is subjected to a shear stress which will cause plastic flow as soon as it reaches the shear yield strength, which is well known property of copper. The sliding resistance is less than the shear strength of the copper. So the coefficient of friction cannot exceed the ratio between the shear strength and yield compressive strength.

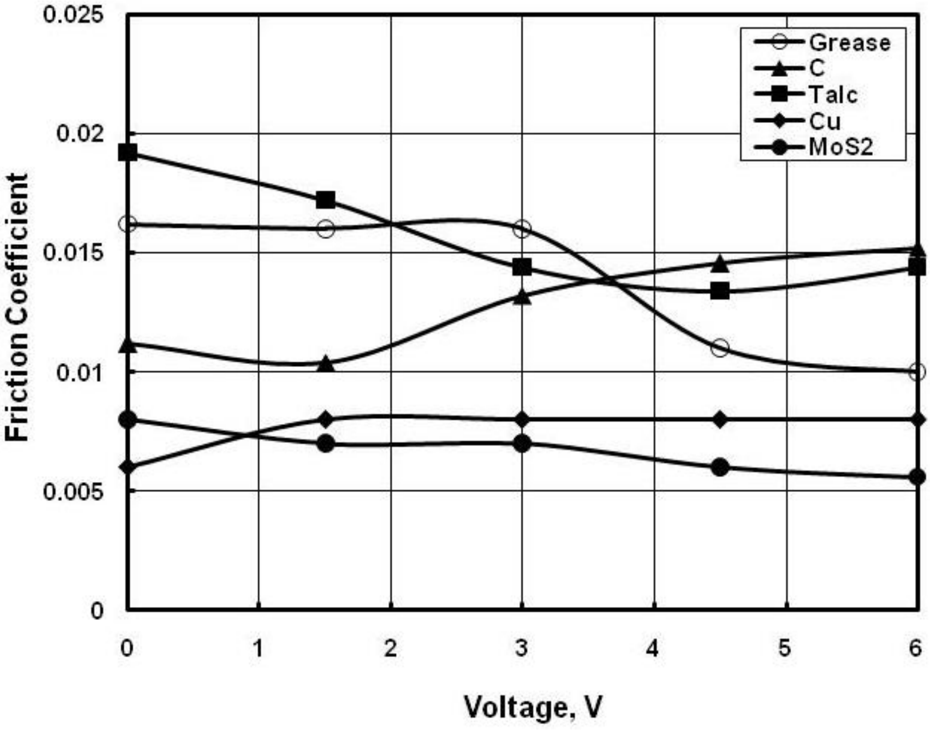

Fig. 5 Effect of negative voltage applied to the shaft on the friction coefficient.

Surface atoms of the polymer are believed to bond with surface atoms of the metal and this can occur irrespective of the inertness of the polymer in bulk. For a long time it was thought that most polymers adhere to other materials by van der Waals forces. In most wear situations, this form of adhesion is not strong enough as observed in experiments. Strong adhesion between a metal and polymer based on chemical interaction forms the basis for the mechanism of polymer on metal wear. Van der Waals forces, although they do not directly cause adhesive wear, provide a significant component of frictional resistance for elastomers such as rubber.

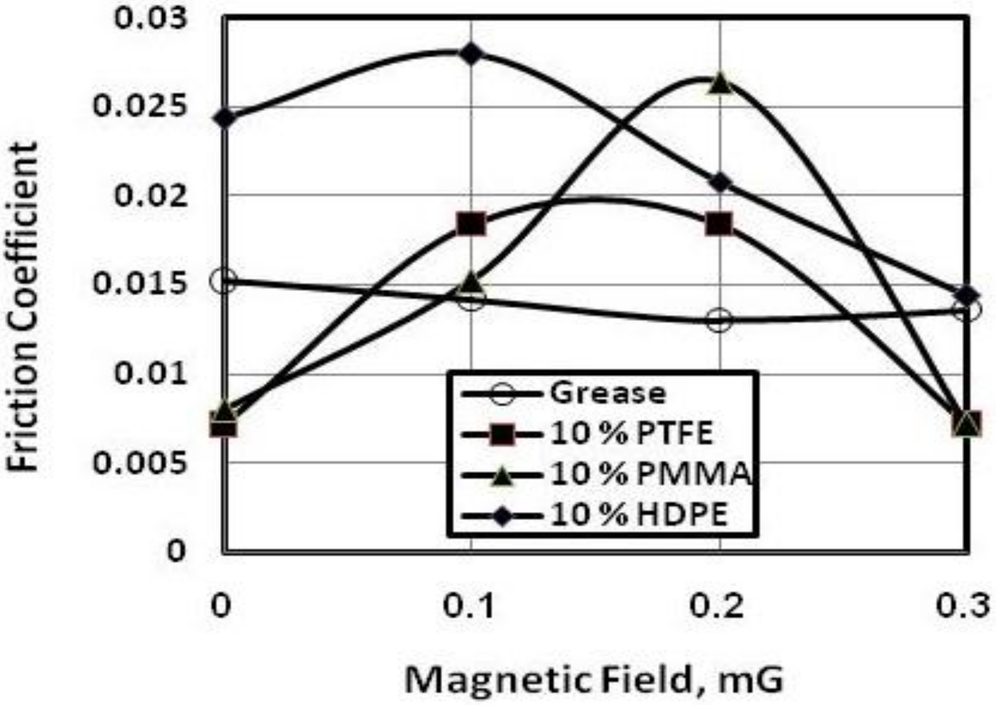

Fig. 6 Effect of magnetic field on friction coefficient.

The effect of the presence of polymeric particles in the grease on friction coefficient is shown in Fig. 6. Magnetic field showed no effect on grease free of polymeric particles on the friction coefficient. HDPE dispersing grease showed the highest friction coefficient followed by PMMA and PTFE. Generally, friction coefficient increased up to maximum then decreased with increasing magnetic field. The friction increase is attributed to the adhesion of the polymeric particles into the sliding surface. Polymeric powders such as HDPE, PMMA and PTFE of (0 - 50 µm) particle size were used as thickener for lithium based grease at concentration of 10 wt.%. Also, the results of the tested grease with and without magnetic field were described. It can be noticed that, a general improvement of the friction coefficient of the rubbing surfaces was achieved due to the dispersion of the polymeric powder. This can be attributed to the formation of a polymeric layer on the sliding surfaces. However, the lowest friction coefficient was obtained from the test specimens lubricated by grease containing the powder of PTFE. It seems that friction coefficient decreased as the adherence of the polymeric film increased. HDPE and PTFE have negative charges as a result of their friction with steel. Some of those particles

would strongly adhere to the steel surface. The friction of PMMA particles generates positive electric charge when they rub steel surface, while particles of HDPE and PTFE particles gain negative charge.

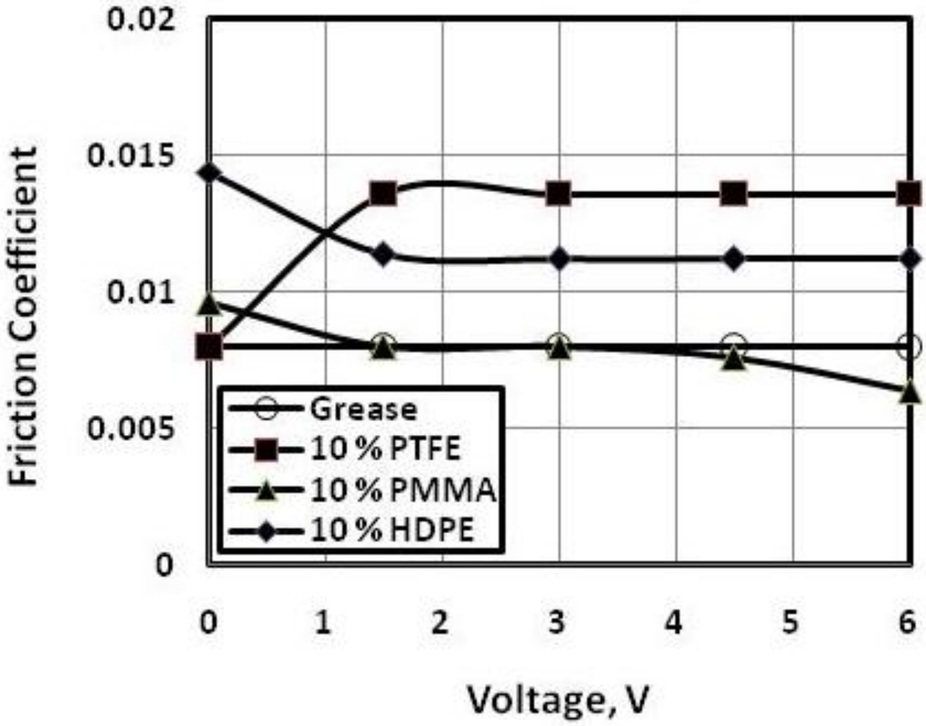

Fig. 7 Effect of positive voltage applied to the shaft on the friction coefficient.

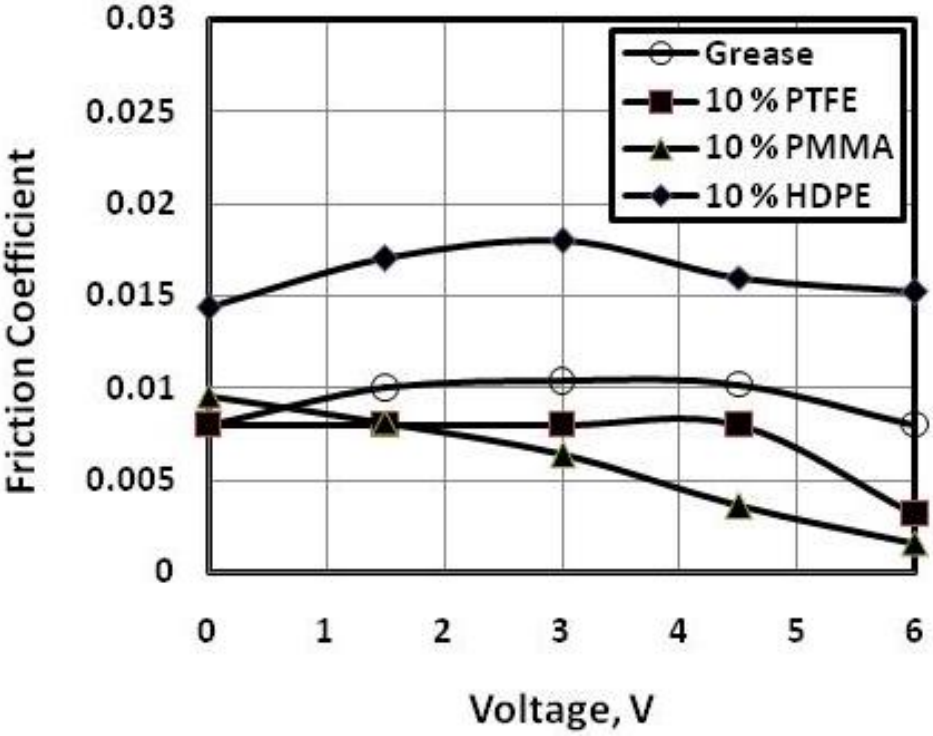

Fig. 8 Effect of negative voltage applied to the shaft on the friction coefficient.

The effect of positive voltage applied to the shaft on the friction coefficient displayed by ball bearing containing polymeric particles dispersed in grease is shown in Fig. 7. Grease free of polymers showed no change with magnetic voltage, while grease dispersed by HDPE showed friction decrease due to the adherence of its particles in the surface of the inner race and balls. The transfer of HDPE particles into the inner race might be to the fact HDPE gained negative charge from friction with steel. The lowest friction reduction was observed for PMMA, which gained positive charge during friction with steel and consequently was adhered into the surface of the bearing outer race. Besides the rolling motion of PMMA particles facilitated the sliding motion and decreased friction coefficient. The role of PTFE in lubricating the moving surfaces of the tested ball bearing was quite different. The strong adhesion of PTFE particles into the sliding surfaces significantly increased friction coefficient especially the inner race of the bearing. It seems that PTFE particles were adhered to surfaces of inner and outer races as well as the balls.

Changing the terminal of the voltage applied to the rotating shaft cased significant friction decrease for PMMA, where the rolling motion of the PMMA particles was accelerated by the application of the voltage, Fig. 8. In addition to that viscosity of the grease decreased with increasing the voltage. Friction coefficient decreased for HDPE and PTFE due to their adherence into the surface of the outer race. The lowest friction values were observed at 6 V which indicated that friction coefficient significantly decreased by increasing voltage across the sliding surfaces.

CONCLUSIONS

1. The magnetic field had no effect on friction coefficient observed for lithium grease free of additives. Addition of talc showed significant increase in friction coefficient. This increase was influenced by magnetic field. No significant effect on friction coefficient was observed for grease dispersed by MoS_2. Generally MoS_2 displayed relatively lower friction coefficient than C and talc. Cu dispersed in grease displayed the lowest friction values.

2. Friction coefficient displayed by grease significantly decreased with increasing electric voltage due to decrease of grease viscosity as the voltage increased. In the presence of C and talc, friction coefficient increased up to maximum then decreased with increasing voltage. Slight friction increase was observed for grease dispersed by copper. The lowest friction coefficient was displayed by MoS_2 dispersing grease.

3. The highest friction coefficient was displayed by grease dispersed by C and talc, while the lowest friction was shown by $Mo\ S_2$ dispersing grease.

4. Grease dispersed by HDPE showed friction decrease. The lowest friction reduction was observed for PMMA. The strong adhesion of PTFE particles into the sliding surfaces significantly increased friction coefficient especially the inner race of the bearing. It seems that PTFE particles were adhered to surfaces of inner and outer races as well as the balls.

5. Changing the terminal of the voltage applied to the rotating shaft cased significant friction decrease for PMMA. Friction coefficient decreased for HDPE and PTFE.

REFERENCES

1. Mohamed M. K., "Effect of Magnetic Field on the Friction and Wear of Polyethylene Sliding Against Steel", EGTRIB Journal, Journal of the Egyptian Society of Tribology, Vol. 5, No. 1, April 2009, pp. 13 – 24, (2009).

2. Abeer A. E., Abo El-Ainin H. M., Khashaba M. I., Ali W. Y., "Effect of Magnetic Field on Friction and Wear of Steel", Journal of the Egyptian Society of Tribology, Vol. 8, No. 2, April 2011, pp. 1 – 15, (2011).

3. Abeer A. E., Abo El-Ainin H. M., Khashaba M. I., Ali W. Y., "Effect of Magnetic Field on Friction and Wear of Brass", Journal of the Egyptian Society of Tribology, Vol. 8, No. 2, April 2011, pp. 16 – 30, (2011).

4. Mahmoud M. M., Mohamed M. K. and Ali W. Y., "Tribological Behaviour of the Contact Surface in the Presence of Electric Current", IME, Journal of Engineering Tribology, Vol. 224 No J1 2010, pp. 73 – 79, (2010).

5. Zaidi H., Amirat M., Frene J., Mathia T., Paulmier D., "Magnetotribology of ferromagnetic/ferromagnetic sliding couple", Wear 263, pp. 1518 - 1526, (2007).

6. Zaidi H., Senouci A., "Influence of magnetic field on surface modification and friction behaviour od sliding couple aluminium/XC48 steel", Surf. Coat. Technol. 120 - 121, pp. 653 - 658, (1999).

7. Chin K.J., Zaidi H., Mathia T., "Oxide film in magnetized sliding steel/steel contact analysis of the contact stress field and film failure mode", Wear 259, pp. 477 - 481, (2005).

8. Lavielle L. "Electric field effect on the friction of a polythyleneterpolymer film on a steel substrate", Wear 176, pp. 89–93, (1994).

9. Csapo E, Zaidi H, Paulmier D. "Friction behavior of a graphite– graphite dynamic electric contact in the present of argon", Wear 192, pp. 151–6, (1996).

10. Kimura Y, Nakano K, Kato T, Morishita S. "Control of friction coefficient by applying electric fields across liquid crystal boundary films", Wear 175, pp. 143 – 9, (1994).

11. Tung SC, Wang SS. "In-situ electro-charging for friction reduction and wear resistant film formation", Tribology Transaction 34(4), pp.479–88, (1991).

12. Tung SC, Wang SS. "Friction reduction from electrochemically deposited films", Tribology Transaction 34(1), pp. 23–34. (1991).

13. Nakanishi Y, Murakami T, Higaki H. "Effects of electric field on lubricating ability of sodium hyaluronate solution", Nippon Kikai Gakai Ronbunshu (C Hen),62(598), pp. 2359–66, (1996).

14. Hongjun J, Yonggang M, Shizhu W, "Effects of External DC. Electric fields on friction and wear behavior of alumina/brass sliding pairs", Science in China (series E),41(6), pp. 617–25, (1998).

15. Hongjun J, Yonggang M, Shizhu W, Wong PL, "Active control of friction by applying electric fields across boundary films of stearate", Proceedings of ASIATRIB'98, Beijing, China, pp. 755–60, (1998).

16. El Mansori M., Schmitt M., Paulmier D., "Role of transferred layers in friction and wear for magnetized dry frictional applications", Surface and Coatings Technology 108–109, pp. 479–483,(1998).

17. M. El Mansori, E. Csapo, H. Zaidi, D. Paulmier, "Study of magnetized steel XC48/ graphite couple in the sliding contact", Nordtrib 96, 7th Nordic symposium on tribology, Bergen, Norway,Vol. III, (1996).

18. Morizur, M. F. and Briant, J., "Modifications of Electron Properties of Friction Surfaces in Boundary Lubrication", C2/4/87, IMechE, (1987).
19. Taylor, C. M., "Engine Tribology", Tribology Series, 26, Elsevier, Amsterdam, pp. 76, (1993).
20. 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, 1989, Espo, Finland, pp. 276 - 281, (1989).
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. Dickinson J. T., Scudiero L., Yasuda K., Kim M. W. and Langford S. C., "Dynamic Tribological Probes: Particle Emission and Transient Electrical Measurements", Tribology Letters, Vol. 3, , pp. 53 - 67, (1997).
24 Rosenblum B., Braunlich P. and Himmel L., "Spontaneous Emission of Charged Particles and Photons During Tensile Deformation of Oxide-Covered Metals Under Ultrahigh Vacuum Conditions", *Journal of Applied Physics*, Vol. 48, 1997, pp. 5263-5273, (1997).
25. Nakayama K. and Hashimoto H., "Triboemission, Tribochemical Reaction and Friction and Wear in Ceramics Under Various N-Butane Gas Pressures", Tribology International, Vol. 29, 1996, pp. 385-393, (1996).
26. Kajdas C., "Physics and Chemistry of Tribological Wear", Proceedings of the 10th International Tribology Colloquium, Technische Akademie Esslingen, Ostfildern, Germany, 9-11 January, 1996, Volume I, (editor: Wilfried J. Bartz), publ. Technische Akademie Esslingen, 1996, pp. 37 - 62, (1996).
27. Gardos M.N., "The Synergistic Effects of Graphite on the Friction and Wear of Molybdenum Disulphide Films in Air", *Tribology Transactions*, Vol. 31, 1988, pp. 214 - 227, (1988).
28. Bartz W. J. and Xu J., "Wear Behaviour and Failure Mechanism of Bonded Solid Lubricants", *Lubrication Engineering*, Vol. 43, 1987, pp. 514 - 521, (1987).
29. Kondo H., Maeda K. and Tsushima N., "Performance of Bearings With Various Solid Lubricants in High Vacuum and High Speed Conditions", Proc. JSLE, International Tribology Conf., 8-10 July 1985, Tokyo, Japan, Elsevier, pp. 787 - 792, (1985).