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FRICTIONAL BEHAVIOUR OF STEEL SURFACES LUBRICATED BY OIL DISPERSED BY POLYMERIC PARTICLES UNDER APPLICATION OF ELECTRIC VOLTAGE

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ABSTRACT
In the present work, polymeric particles such as polymethyl methacrylate (PMMA), polyethelene (PE) and polystyrene (PS) were used as solid lubricants dispersed in paraffin oil in concentration of 5, 10, 15 and 20 wt. %. Tests were carried out using cross pin wear tester. Friction coefficient was investigated under application of an electric voltage of 1.5, 3, 4.5 and 6 volts. Test specimens were in the form of cylinders of 18 mm diameter and 150 mm length.

The experimental observations showed that for oil free of polymer friction coefficient displayed a value of 0.08 at no voltage. For both positive and negative voltage friction coefficient decreased with voltage increasing. Adding polymeric particles into the oil displayed slight friction increase at no voltage. Friction coefficient increased with increasing voltage regardless the charge. Adding polymeric particles into oil caused significant friction increase in the presence of applied voltage. This is because the polymeric particles strongly adhered to the steel surfaces and the contact will be between polymeric particles and steel. The highest friction values were displayed by PS followed by PE and PMMA.

Applying electric current on the lubricated contact of the tested steel specimens showed that wear significantly decreased. Adding polymeric particles into the oil caused significant wear decrease when the electric voltage was applied. In condition of no voltage, wear slightly decreased due to the direct adherence of polymeric particles into steel. The enhancement in wear was observed for positive and negative voltages. Further increase in polymer content dispersing oil showed significant wear decrease. At no voltage, wear displayed the highest values. When the rotating pin was anode or cathode, wear significantly decreased.

KEYWORDS
Friction coefficient, wear, oil, polymeric particles, electric voltage.

INTRODUCTION

The mechanical drives in electric appliances are working under application of electric and magnetic fields. Influence of magnetic field on the friction and wear of polyethylene as bearing materials scratched by steel insert in the presence of different oil was discussed, [1]. Tests were carried out at oil lubricated surfaces. Paraffin, fenugreek, camphor, cress, olive, almonds, sesame, aniseed and El-Baraka Seed oils were used as lubricants. The friction coefficient and wear of the tested composites were investigated using a tribometer designed and manufactured for that purpose. Besides, the influence of magnetic field on the friction coefficient displayed by the sliding of steel pin on aluminium, polyamide and steel discs lubricated by paraffin oil and dispersed by different lubricant additives such as zinc dialkyldithiophosphates, molybdenum disulphide, heteropolar organic based additive, graphite, polytetrafluroethylene and polymethyl methacrylate, detergent additive (calcium sulphonate), was investigated, [2, 3]. Aluminium was used as friction counterface to reduce the magnetic force acting on the contact surfaces when the magnetic field was applying. The tribological performance of polyethylene, as bearing materials sliding against steel considering that effect, was discussed, [4]. 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 counter face. 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. Based on the experimental observations, [5, 6], it can be noticed that for abrasion of steel 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 oil. It seems that polar molecules of tested vegetable oils can significantly improve the wear resistance resulting from stronger adsorption on sliding surfaces. The long fatty acid chain and presence of polar groups in the vegetable oil structure recommends them to be used as boundary lubricants.

It was shown that when an electric current is passed between two sliding surfaces in the presence of engine oils, the wear characteristics of the two surfaces could be altered significantly, but not friction. The wear on the cathode surface decreased while the wear on the anode surface increased. The difference in wear rate of surfaces with and without current is attributed to the modification of the elemental composition of surface films. It was observed that in the presence of a metalworking fluid, the wear of the anode surface decreased significantly while the wear of the cathode surface increased slightly, [7]. Similar observations were made in face milling tests where the wear of milling insert was reduced when it was the anode and increased when the insert was the cathode.

It has been observed that friction and wear behaviour of two components sliding against each other can be greatly influenced by an externally applied electrostatic field or electric current. It was observed that under boundary lubrication conditions in a ball-on-disc machine, [8] 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 disc 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 because of the formation of a thin passivation layer on the disc surface. With continued sliding, damage to the

passivation layer led to increased friction coefficient. However, when the ball was at higher potential than the disc, no decrease in friction coefficient was observed, and the ball wear was lower than that obtained when no current passed through the contact.

In the mixed lubrication regime, removal of the electric field decreased the friction coefficient compared to 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, [9]. 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, [10]. The addition of a sulphur compound decreased wear on the cathodic surface and increased wear on the anodic surface. However, addition of a phosphate compound 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, [11, 12]. The friction and wear behaviour of a steel pair when an electric current was passed through the contact in the presence of fully formulated engine oils was discussed, [13]. The passage of electric current changed friction coefficient only to a small degree but the wear was impacted significantly. The wear changed by two to three orders of magnitude depending on the direction of current flow. The current level also played an important role in the magnitude of wear observed on surfaces. The difference in wear rate of surfaces with and without current was attributed to the modification of the elemental composition of surface films formed at the contact. High wear was observed on the anode surface and low wear on the cathode surface. This could have a significant practical implication.

There are applications where it is important to increase wear rate of one surface while minimizing wear rate on the other contacting surface. One example of such an application is machining (turning, drilling, milling, etc.) where one would like to increase metal removal rate (increase wear) while protecting cutting tools from wear. Tool wear is fully recognized as an important factor in materials cutting, [14]. The well established methods for its control are based on process optimization, application of lubricant, or use of tool coatings to provide wear resistance and low friction.

Experimental results showed that the presence of electric current and magnetic field around the tribocontact modifies the mechanical properties of the surface and subsurface, [15]. 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. The magnetic field and the

electric current modify the mechanical and chemical properties of this ferromagnetic material in the sliding contact by interaction with cyclic contact stresses and increasing the temperature on the contact surface. This interaction was characterized by an increase in the microhardness, the activation of oxidation on the surfaces, the difference of contact noise level, and the changes induced in subsurface structure.

Magnetostriction or deformation of material took place during the application of the magnetic field, [16]. An electric current crossing a sliding couple affects the surface temperature, the oxidation, and the contact behaviour. The magneto-tribological interaction of materials was investigated particularly for braking and cutting tools to increase their lifetime and to improve the surface quality after machining, [17]. It has been observed that the friction behaviour of ferromagnetic and non-ferromagnetic metals was modified in the presence of a direct current (DC) magnetic field. The effects induced by a simultaneous application of a DC electric current and an alternating current (AC) magnetic field on the surface and subsurface modifications of the ferromagnetic contact couple steel/steel were presented. The application of the electric field induces an interfacial polarization on the particle owing to a mismatch of the dielectric constant between the particle and the liquid, and the polarization thus induced on the particle plays a role to form a chain-like structure along the electric field, leading to the increase in the viscosity of the suspension.

The effects of external electric fields on frictional behaviour of Al_2O_3/brass, Al_2O_3/stainless steel, and Al_2O_3/carbon steel couples under boundary lubricating conditions were studied on a self-made plate/plate-type tribotester, [18]. Emulsion of 1 wt% zinc stearate dispersed into deionized water was used as lubricant in the experiments. The experimental results showed that external electric fields affect the friction coefficient and its fluctuation of each rubbing couple substantially.

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, [19]. The apparent friction coefficient was changed by reversing the polarity of the external electric field because of the change in real normal pressure. The results showed that the change in friction coefficient can reach up to ±25 per cent. An extraordinary change in friction coefficient of graphite/graphite rubbing couples was discovered, [20] 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 per cent by applying an external DC electric field [21]. 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, [22, 23]. It was reported that an AC

voltage has effects on lubricating ability of synovia constituents, [24]. It was observed that for Al2O3/brass couple lubricated with emulsion of zinc stearate, the change in friction coefficient because of an external DC voltage is not only remarkable, reaching 200 per cent, but also quick and reversible, [25, 26]. Besides, friction coefficient of Al2O3/brass couple increased with increasing external electric field intensity. The effect of applying external voltage on the sliding of copper, aluminium, and polyethylene (PE) against steel surface lubricated by paraffin oil dispersed by polymeric particles such as PE, polyamide (PA), and polymethyl methacrylate (PMMA) was investigated, [27]. It was found that wear was more influenced by the electric static charge than friction coefficient. Besides, the effect of the external voltage on generating electric static charge was higher than friction. Among the polymeric particles, crystalline polymers such as PE and PA performed more effectively than glassy polymers such as PMMA. PE as cathode showed minimum wear when the oil was dispersed by polymeric particles.

In the present work, the effect of applying electric voltage on the friction of carbon steel sliding against oil-lubricated hardened steel in the presence of polymeric particles is investigated.

KEYWORDS
Friction coefficient, oil, polymer particles, electric current.

EXPERIMENTAL

Experiments were carried out using a cross pin tester, Fig. 1. It consists, mainly, of rotating and stationary pins of 18 mm diameter and 150 mm long. The rotating pin (Hardened steel, H_v = 3100 N/mm^2) was attached to a chuck mounted on the main shaft of the test rig. The stationary pin (Carbon steel, H_v = 1100 N/mm^2) 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 gear reduction unit. Moreover, the motor speed is adjustable and can be controlled by varying the input voltage using an autotransformer.

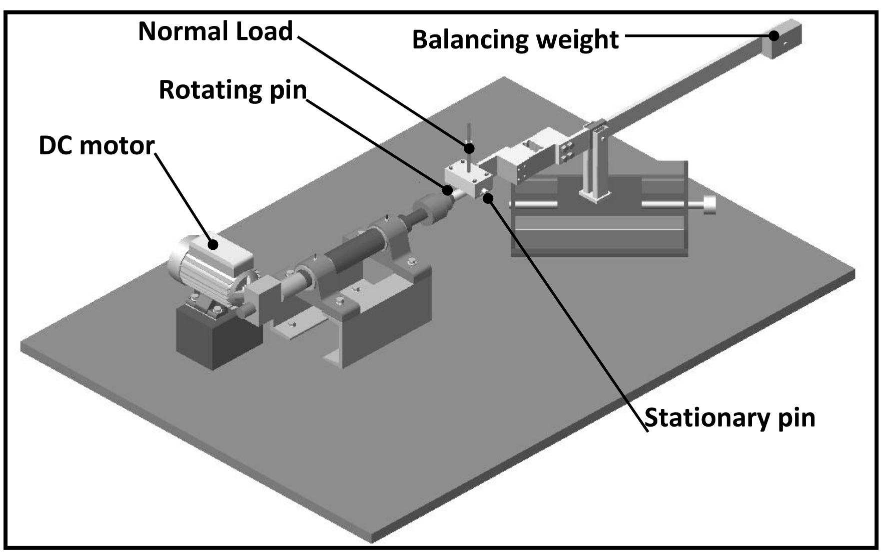

Fig. 1 Arrangement of the test rig.

RESULTS AND DISCUSSION

In the present experiments, friction and wear tests were carried out under the application of electric voltage. The experimental observations are illustrated in Figs. 2 to 9. Friction coefficient displayed by the sliding of hardened steel against lubricated carbon steel by oil and polymers is shown in Fig. 2. For oil free of polymer friction coefficient displayed a value of 0.08 at no voltage. For both positive and negative voltage friction coefficient decreased with increasing voltage. This behaviour may be attributed to polarity of the molecules of paraffin oil. Polar molecules of the tested oil can significantly decrease the friction coefficient resulting from stronger adsorption on sliding surfaces. 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. Application of direct current strengthens the adherence of the oil molecules into the sliding surfaces.

Addition of polymeric particles into the oil displayed slight friction increase, where the friction coefficient increased with increasing voltage regardless the charge. The highest friction values were displayed by PS followed by PE and PMMA. The friction increase might be attributed to the adherence of polymeric particles into the steel surfaces as a result of the triboelectrification. It is supposed that an electric static charge will be formed on the contact surfaces from the friction provided by the rubbing of dissimilar materials together, where equal and opposite charges are always produced. PE has a negative charge as a result of its friction against steel. Some of the PE particles will adhere to one of the steel surfaces. In this condition, a partial contact will be between PE and steel. When negative voltage is applied, PE particles will adhere to the other steel surface.

Addition of PMMA particles into the oil caused slight increase in friction coefficient when no voltage was applied onto the contact surfaces. PMMA particles have positive charge when they rubbed steel. They adhered to the steel surface, so that the friction will be between steel and PMMA causing relative increase in friction coefficient. Changing the polarity of the charge to negative on the rotating steel pin, PMMA particles would adhere to the surface of stationary steel pin, where the contact will be between PMMA and steel. PMMA particles in oil showed the lowest values of friction coefficient although the positive charge gained by those polymeric particles during friction was relatively high. It seems that PMMA particles tend to roll more than to adhere to the sliding surfaces because of the nature of the glassy polymers.

As the polymer content increased up to 10 wt. % friction coefficient slightly increased in the presence of the applied voltage, Fig. 3. Presence of polymeric particles in oil caused significant friction increase when the voltage was applied. This is because the polymeric particles strongly adhered to the steel surfaces and the contact will be between polymeric particles and steel.

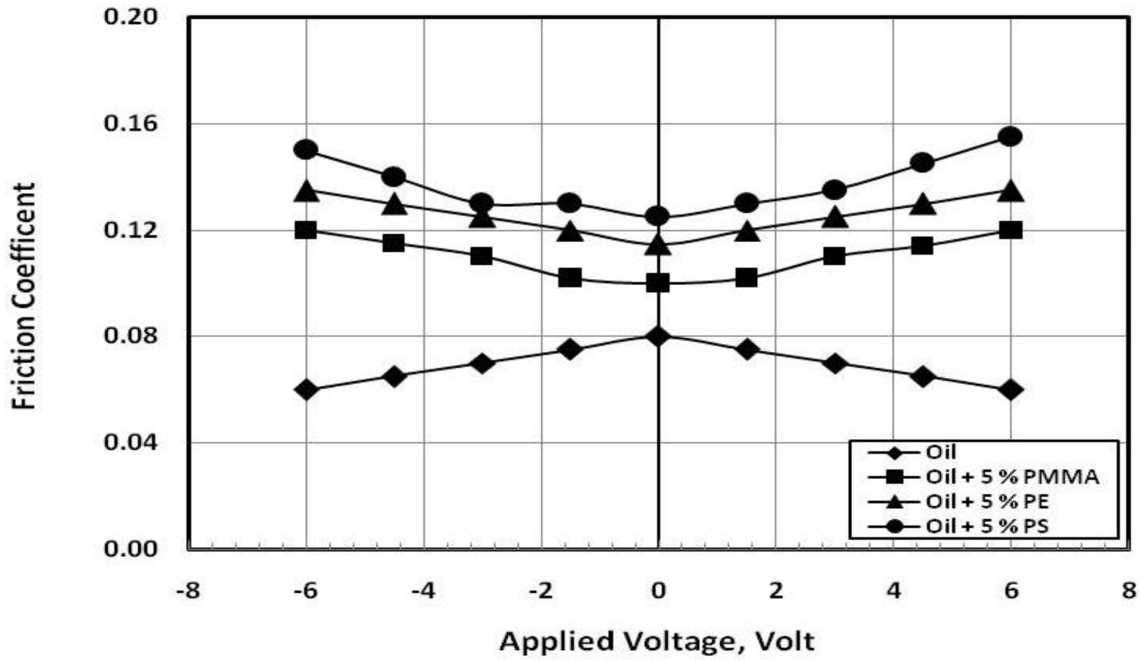

Fig. 2 Friction coefficient displayed by steel surfaces under application of applied voltage.

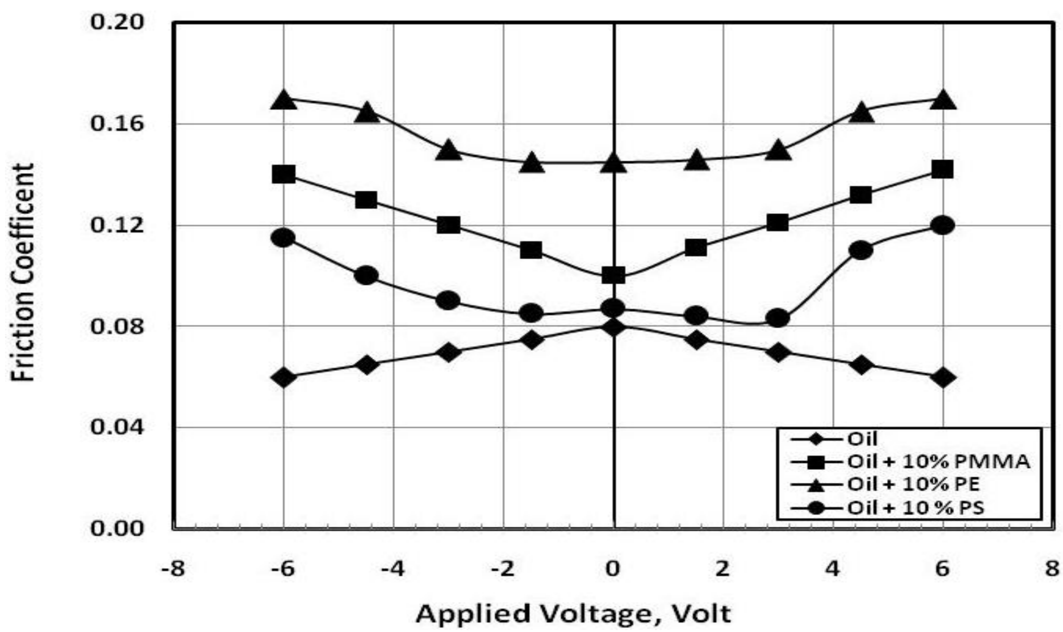

Fig. 3 Friction coefficient displayed by steel surfaces under application of applied voltage.

When the rotating pin was the cathode, it gained a negative charge. Therefore, the ability of the particles of PE and PS to adhere to the stationary steel surface caused

slight decrease in friction coefficient. When the rotating steel pin was the anode, PMMA particles adhered to the stationary steel pin surface and slightly increased friction.

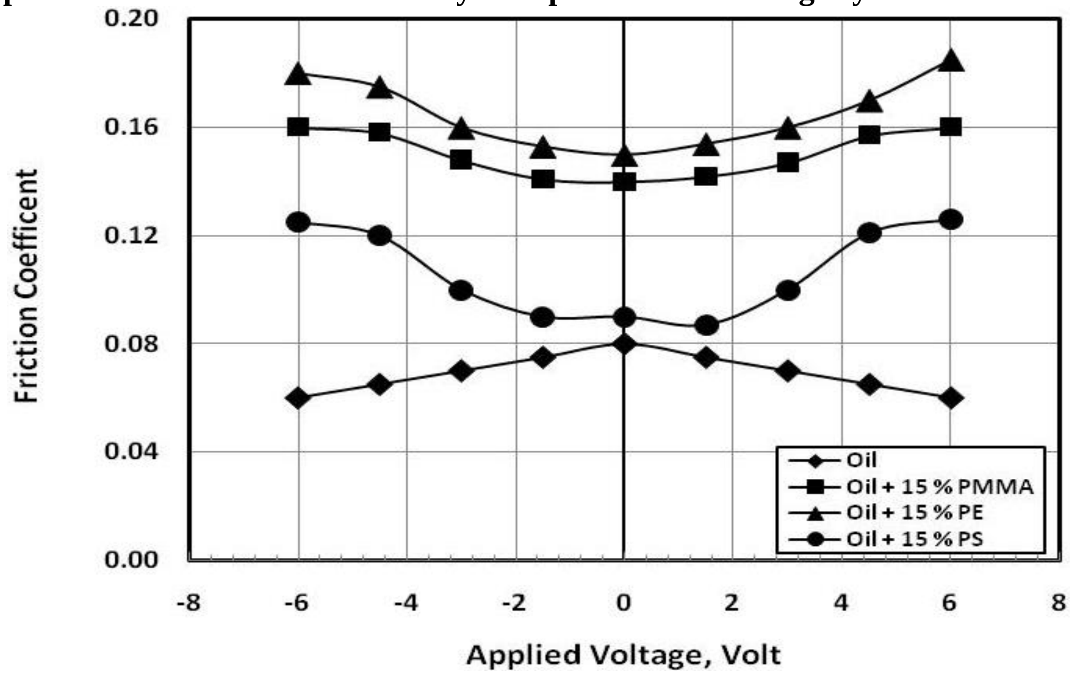

Fig. 4 Friction coefficient displayed by steel surfaces under application of applied voltage.

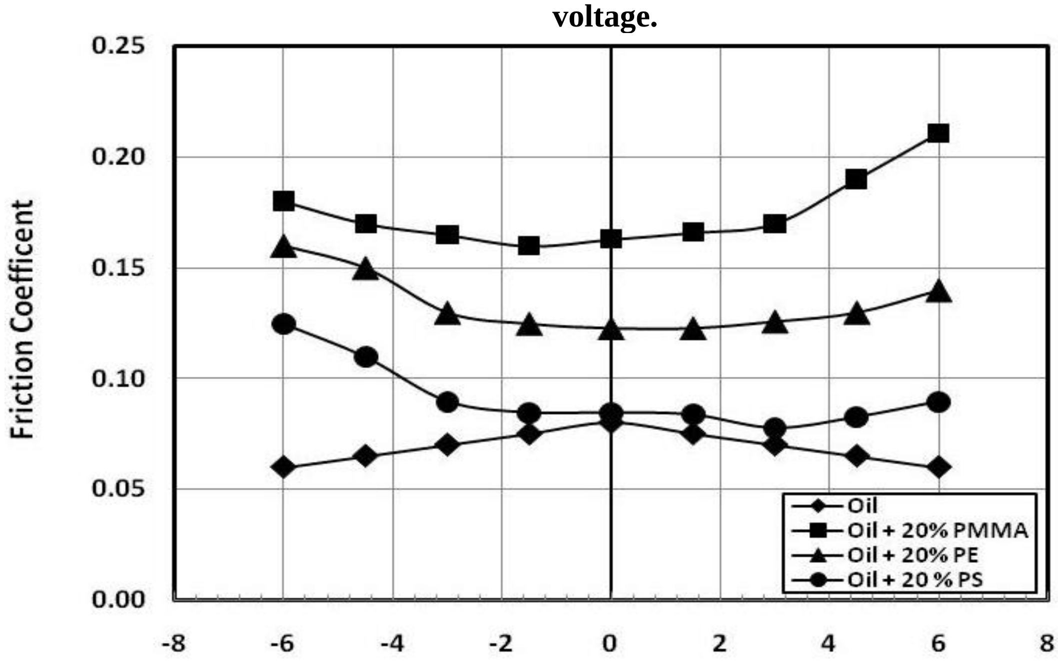

Fig. 5 Friction coefficient displayed by steel surfaces under application of applied voltage.

Changing the polarity to negative, PMMA particles adhered to the rotating steel surface, where partially the contact will be between PMMA and steel and consequently friction coefficient increased.

At no voltage, further friction coefficient increase was observed as a result of the increase in polymer content up to 15 and 20 wt. %, Figs. 4 and 5 respectively. The same trend was observed when the voltage was applying, where friction coefficient increased. Based on the values of friction coefficient, it is clearly shown that PS particles showed the lowest friction coefficient compared to PMMA and PE.

The influence of applying electric current on the wear of lubricated contact of the tested steel specimens is shown in Fig. 6. At no voltage, steel test specimens represented the highest wear values. As the voltage was applied wear significantly decreased. Adding polymeric particles in 5 wt. % content into the oil caused significant wear decrease when the external voltage was applied. In condition of no current, wear slightly decreased due to the direct adherence of polymeric particles into steel. The enhancement in wear was observed for positive and negative voltages. In this case, the contact would be between polymers and steel. PMMA particles displayed the lowest wear values. The relatively strong positive charge of PMMA caused by friction facilitated its adherence into steel surfaces. As a result of that adherence, the steel surfaces could be protected from excessive wear. This behaviour can be attributed to the ability of PMMA particles of positive charge, gained by friction, to adhere to the steel surface of negative charge. Consequently, wear caused by the sliding of the steel surface coated by a layer of PMMA particles against steel surface decreased. The enhancement in wear resistance significantly increase when the voltage was applied between the sliding surfaces.

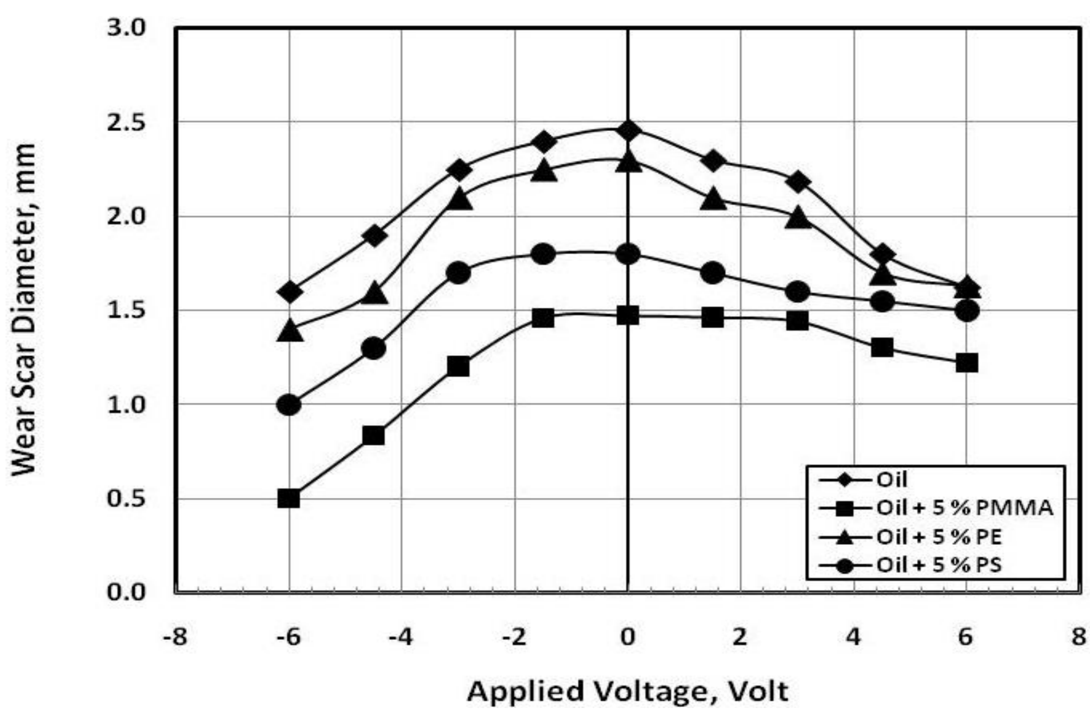

Fig. 6 Wear displayed by steel surfaces under application of applied voltage.

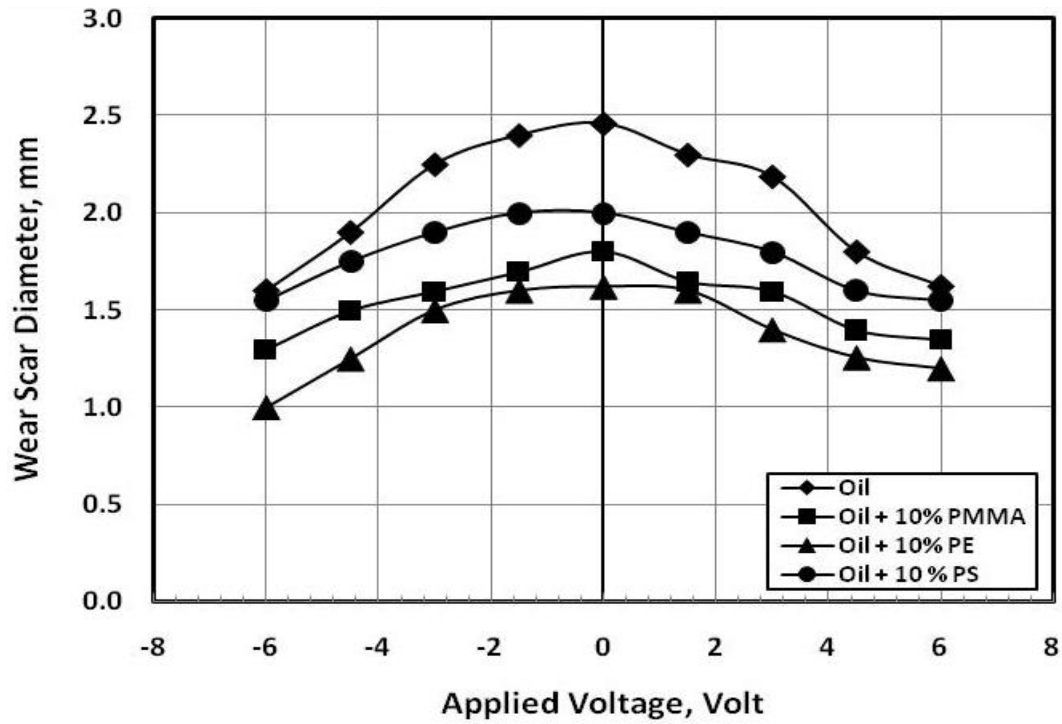

Fig. 7 Wear displayed by steel surfaces under application of applied voltage.

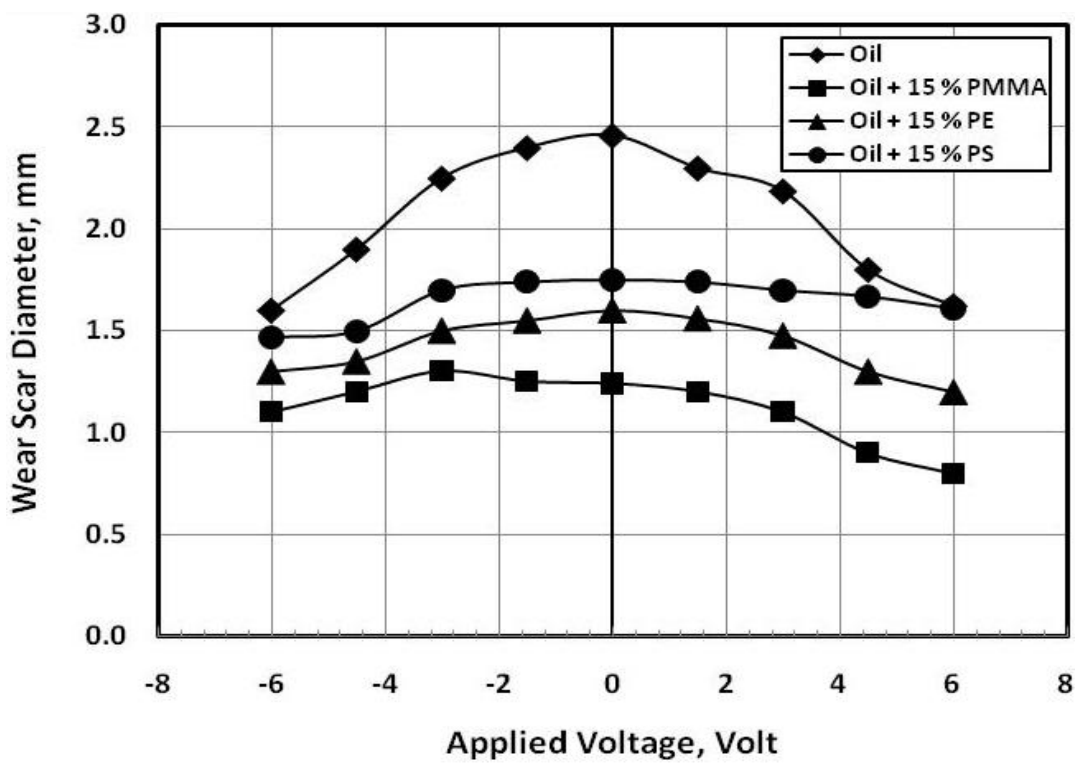

Fig. 8 Wear displayed by steel surfaces under application of applied voltage.

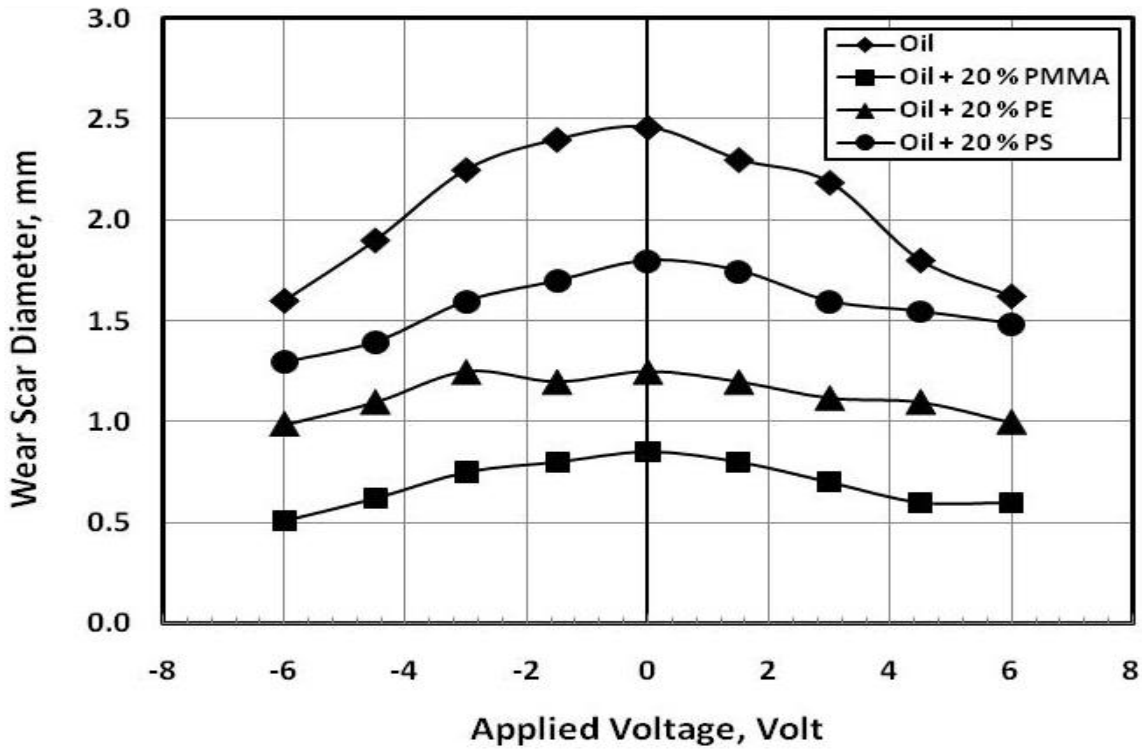

Fig. 9 Wear displayed by steel surfaces under application of applied voltage.

Further increase in polymer content dispersing oil showed significant wear decreased after sliding against steel as shown in Figs. 6 - 9. At no current, wear displayed the highest values. When the rotating pin was anode or cathode, wear significantly decreased. The wear decrease might be from the formation of adhered polymeric layer protecting the steel surfaces from excessive wear. PS particles showed the lowest wear at no voltage. Then wear increased when voltage was applied. In the presence of electric voltage, regardless of the polarity, wear significantly decreased because of the adherence of polymer particles onto the surfaces of steel.

Polymeric particles in oil decreased wear of steel pins at no current because of their adherence to the steel surfaces. Applying positive or negative voltage on steel surface decreased wear because of the adherence of polymeric particles onto the steel surface. The minimum wear was observed for PE and PMMA particles dispersed in oil. The best wear resistance was observed for oil dispersed by PMMA particles, Figs. 8 and 9, at polymer content of 15 and 20 wt. % respectively. It seems that the rolling motion of PMMA particles was responsible for the wear decrease.

CONCLUSIONS

1. Friction coefficient decreased with increasing voltage when positive and negative voltage were applied on the steel surfaces for oil free of polymeric particles. Addition of polymeric particles into the oil displayed slight friction increase, where the friction

coefficient increased with increasing voltage regardless the charge. The highest friction values were displayed by PS followed by PE and PMMA.

2. As the polymer content increased friction coefficient slightly increased at no voltage and in the presence of the applied voltage.

3. At no voltage, steel test specimens represented the highest values. As the voltage was applied wear significantly decreased. Polymeric particles caused significant wear decrease when the external voltage was applied.

4. Wear slightly decreased due to the direct adherence of polymeric particles into steel at no voltage. The enhancement in wear was observed for positive and negative voltages.

5. Further increase in polymer content dispersing oil showed significant wear decrease. The best wear resistance was observed for oil dispersed by PMMA particles at polymer content of 15 and 20 wt. %.

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