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INFLUENCE OF MAGNETIC FIELD ON FRICTION COEFFICIENT DISPLAYED BY THE OIL LUBRICATED SLIDING OF STEEL

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ABSTRACT

The present work investigates the influence of magnetic field on the friction coefficient displayed by sliding of steel pin on aluminium, steel and polyamide discs lubricated by paraffin oil and dispersed by different lubricant additives such as zinc dialkyldithiophosphates (ZDDP), molybdenum disulphide (MoS_2), heteropolar organic based additive (CMOC), graphite (C), detergent additive (calcium sulphonate) (DA), polytetrafluroethylene (PTFE) and polymethyl methacrylate (PMMA).

The experiments showed that, aluminium as a paramagnetic material recorded higher values of friction coefficient than steel and polyamide. That observation confirms that in spite of the increase of the attractive force generated from the magnetic field for steel/steel and the electrostatic charge for polyamide/steel, oil molecules were more adhered into the surfaces of steel and polyamide than aluminium and consequently friction coefficient significantly decreased. When the oil was dispersed by additives, it was found that, friction coefficient slightly increased with increasing magnetic field for oil dispersed by ZDDP additive. For oil dispersed by MoS_2 friction coefficient displayed by aluminium disc showed relatively lower values in the presence of the magnetic field than that displayed by polyamide and steel discs. Magnetic field drastically decreased friction coefficient displayed by aluminium and steel disc. As for polyamide disc friction coefficient slightly increased with increasing the magnetic field.

Aluminium disc displayed the lowest friction coefficient in the presence of C, which decreased with increasing magnetic field. For steel disc friction coefficient displayed the highest values. Polyamide disc showed no change in friction values as the intensity of the magnetic field increased. For oil dispersed by DA, steel disc showed significant friction decrease. Aluminium disc showed slight friction increase with increasing magnetic field, while polyamide disc showed slight friction decrease. PTFE particles dispersed in the oil were much influenced by the magnetic field, where the friction coefficient displayed by steel drastically decreased with increasing magnetic field. Aluminium and polyamide discs showed an increasing trend as the magnetic field increased. As for PMMA particles dispersed in oil aluminium disc showed slight friction increase, while steel and polyamide discs gave decreasing trend of friction as the magnetic field increased.

KEYWORDS
Magnetic field, friction coefficient, steel, aluminium, polyamide, oil additives, polytetrafluroethylene, polymethyl methacrylate, molybdenum disulphide, zinc dialkyldithiophosphates and graphite.

INTRODUCTION

There is an increasing demand to save the frictional losses in various mechanical and electronic devices, where magnetic fields are applied. It is important to consider the friction and wear of their components and to understand the influence of magnetic field on their performance in order to prevent premature failure and to achieve higher energy efficiency. The effect of magnetic field on friction and wear processes has been studied by a number of researchers. The influence of magnetic field on the friction coefficient displayed by sliding of steel pin on polyamide disc lubricated by paraffin oil and dispersed by different lubricant additives such as zinc dialkyldithiophosphates (ZDDP), molybdenum disulphide (MoS_2), heteropolar organic based additive (CMOC), graphite (C), detergent additive (calcium sulphonate) (DA), polytetrafluroethylene (PTFE) and polymethyl methacrylate (PMMA) was discussed, [1]. When the polyamide disc was replaced by aluminium it was observed that, surfaces lubricated by paraffin oils free of additives friction coefficient increased with increasing applied load. As the magnetic field increased friction coefficient increased. In condition of application of magnetic field it was found that when the paraffin oil was dispersed by ZDDP, MoS_2, DA and PTFE friction coefficient increased, while COMC, C and PMMA showed significant decrease in friction coefficient. Besides, the lowest values of friction coefficient were observed for PTFE particles dispersed in the oil, [2].

It was observed a significant transformation in tool wear tests with the magnetic field, [3 - 8]. Abrasive wear without magnetic fields was transformed, in the presence of magnetic field, to fracture due to the shift of shear stress to the subsurface region. Also, a decrease in wear, a lower friction coefficient, increase in hardness of magnetized steel surface and a rise in temperature of rubbing surfaces were observed. In magnetic fields, strongly oxidised wear particles will pose a serious problem for the contact due to the paramagnetism of oxygen. Accelerated oxidation does affect not only wear particles but also contacting surfaces. More specifically, highly oxidized wear particles, affected by magnetic force operating between contacting surfaces, act both as abrasive and as lubricating agents depending on their conditions.

It was observed that, for sliding of steel pin against oil lubricated brass discs, magnetic field decreased friction coefficient for all the tested oils, [9]. Dispersing oil by polyethylene (PE) particles significantly increased friction coefficient. A drastic reduction of friction coefficient was observed for olive, castor and almonds oils, when dispersing the tested oils by polyamide (PA) particles. Sliding of steel pin on oil lubricated aluminium disc caused significant friction increase for all the tested oils. Drastic friction reduction was observed for castor, almonds, jasmine and camomile oils when dispersed by PE particles. Dispersing vegetables oils by PA particles showed

relatively lower friction coefficient for olive and castor oils, while corn, almonds, camomile and jasmine oils showed relatively higher friction values. Sliding of steel pin on oil lubricated steel disc showed the highest values of friction coefficient. Dispersing the tested oils by PE particles did not decrease friction coefficient. Jasmine oil displayed relatively lower friction than the other tested oils.

The effect of magnetic field on the friction coefficient displayed by sliding of steel pin against steel disc lubricated by paraffin oil and dispersed by different lubricants additives was investigated, [10]. The experiments showed that, friction coefficient increased as the magnetic field increased due to the increase of the normal load caused by the magnetic force. The performance of ZDDP and Mo S_2 additives was not affected by the application of magnetic field. Besides, it was observed that magnetic field much affected the performance of oil dispersed by additives of electrical properties such as CMOC, DA and PTFE particles. The same trend of friction decrease was observed for PMMA particles dispersed in oil.

The friction and wear of polyethylene sliding against steel in the presence of magnetic field was investigated, [11]. 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.

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 high density polyethylene (HDPE), polyamide (PA6) and polymethyl methacrylate (PMMA) was investigated, [12, 13]. 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 PMMA was tested, [14]. 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.

It was shown that the magnetic field had no effect on friction coefficient observed for lithium grease without additives, [15]. Grease dispersed by high density polyethylene showed friction decrease. The lowest friction reduction was observed for polymethyl methacrylate. The strong adhesion of PTFE particles into the sliding surfaces significantly increased friction coefficient. 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. Viscosity of the grease decreased with increasing the voltage. Friction coefficient decreased for HDPE and PTFE. The lowest friction values were observed at 6 volts which indicated that increasing voltage across the sliding surface could significantly decrease 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, [16]. 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, [17], 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 [18]. 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.

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 embrittlement 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. 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.

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, [20]. 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, [21]. Experiments show that a magnetic field applied through the sliding contact leads to decrease the wear rate.

In the present work, the effect of magnetic field on the friction coefficient displayed by sliding of steel pin against aluminium disc lubricated by paraffin oil and dispersed by different lubricants additives is investigated.

EXPERIMENTAL

Experiments were carried out using pin on disc wear tester. It consisted of a rotary horizontal steel disc driven by variable speed motor. The details of the wear tester are shown in Fig. 1. The bearing steel pin (AISI 52100) is held in the specimen holder that fastened to the loading lever. It was in form of cylindrical pin of 6 mm diameter and 12 mm length. Friction force could be measured by means of the load cell, where the pin holder and magnetic field were assembled. The tested materials were in form of discs of carbon steel (St. 42.11, 0.25 % carbon content, 3.2 µm, Ra surface roughness), aluminium disc, made of aluminium base alloy (SAE 770, Sn 6.25 %, Cu 1.0 %, Ni 1.0 %, 0.67 µm, R_a, surface roughness) and polyamide 6 (6.4 µm, R_a, surface roughness). The discs were fastened to the rotating disc. Friction and wear tests were carried out under constant sliding velocity of 2.0 m/s and 20 N applied load. Every experiment lasted 30 minutes. All measurements were performed at 25 ± 5 ºC and 30 ± 10 % humidity.

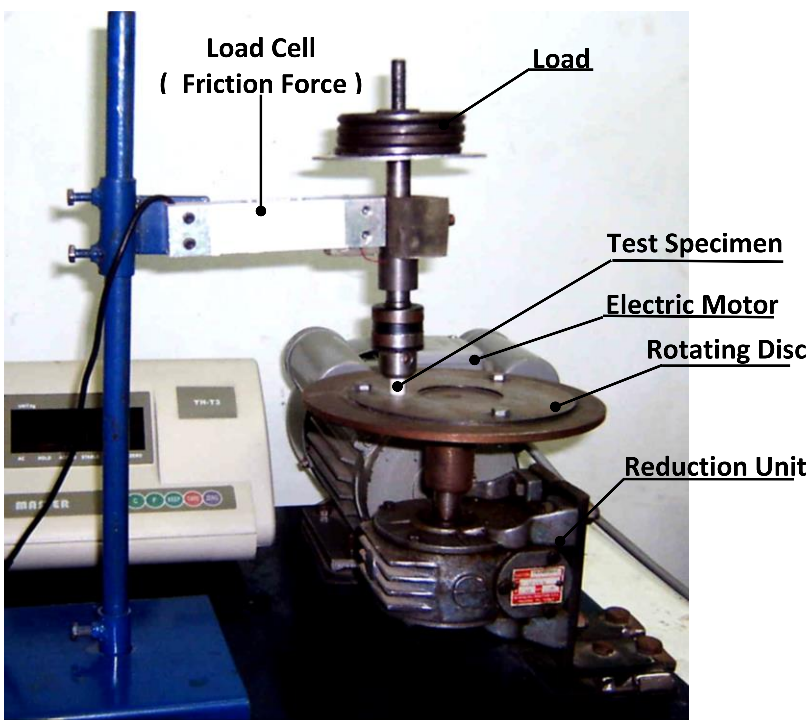

Fig. 1 Arrangement of the test rig.

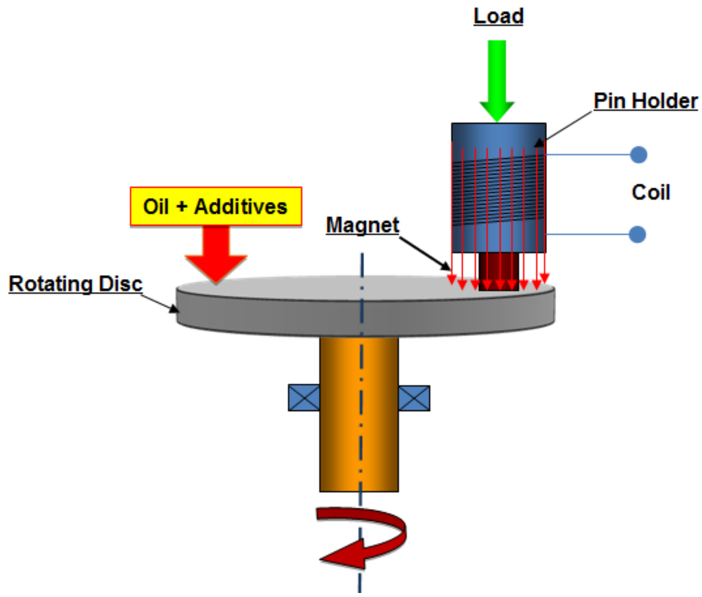

Fig. 2 Application of the magnetic field.

The lubricant used in the experiments was paraffin oil (SAE 30). Fine particles of C, MoS_2 and CMOC of particle size less than 1.0 µm were dispersed into the paraffin oil at 5.0 wt. % concentration. Besides, ZDDP and detergent additive (calcium sulphonate), (DA) were used. Polymeric powder such as PTFE and PMMA of (30 – 50 µm) particle size were used as dispersant in the oil. Magnetic field was applied by a coil assembled above the pin holder of 0.1, 0.2, 0.3 and 0.4 mG flux intensity, Fig. 2.

RESULTS AND DISCUSSION

The friction coefficient displayed by the steel pin sliding against the rotating disc under application of magnetic field is discussed, Figs. 3 - 10. Friction coefficient slightly increased with increasing the intensity of the magnetic field. It can be noticed that aluminium as a paramagnetic material recorded higher values of friction coefficient than steel and polyamide. It means that in spite of the increase of the attractive force generated from the magnetic field for steel/steel and the electrostatic charge for polyamide/steel oil molecules were more adhered into the surfaces of steel and polyamide than aluminium and consequently significantly decreased friction coefficient.

Based on the sliding velocity and load the sliding was considered as mixed lubrication (partially metal to metal and partially hydrodynamic film). Therefore, friction increase might be attributed to the interaction of the asperities of the two contact surfaces, where increasing the intensity of magnetic field caused an increase in the magnetic force which was superimposed on the normal load. The effect of magnetic field on the performance of paraffin oil depends on the paraffinic molecules which are approximately linear and consequently they are more effective than other hydrocarbons in preventing solid contact. This allows for the formation and persistence of a relatively thicker film. Since the molecules are polar the opposite ends are attracted to form pairs of molecules which are subsequently incorporated into the viscous surface layer. At the interface with the substrate the attractive force of the free end of the molecules to the substrate is sufficient to firmly bond the entire layer. The presence of polar groups in oil structure enhanced the orientation of oil molecules to form a surface film able to inhibit metal to metal

contact. This behaviour leads to the friction decrease. Although polyamide is not a magnetic material, friction coefficient slightly increased as the magnetic field increased. Sliding of steel against polyamide charged the contact surfaces so that they could interact with each other due to the direct electrostatic forces. Since these forces are strong and effective, they contribute a major part of the adhesion force.

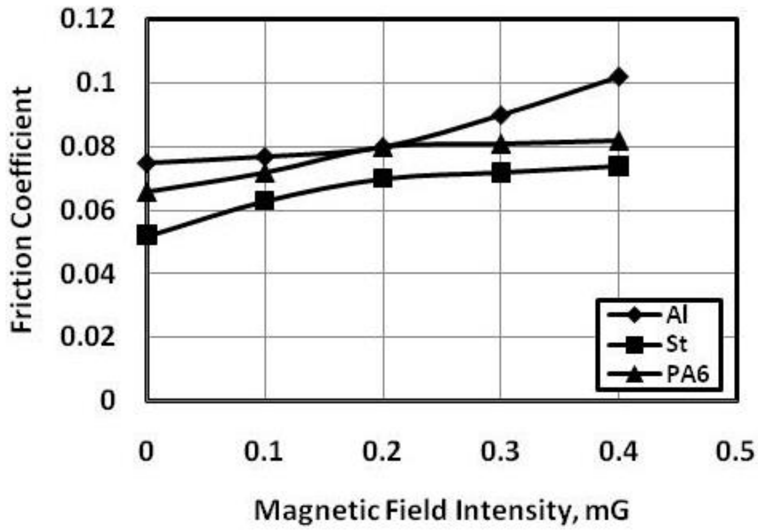

Fig. 3 Friction coefficient displayed by the sliding of steel pin against oil lubricated tested materials.

Significant friction decrease was observed when the oil was dispersing by ZDDP additive due to its decomposition to zinc polyphosphate and a mixture of alkyl sulphides which are the precursors of the antiwear action of ZDDP, Fig. 4. Zinc phosphate reacts with the surface oxide layer by physical absorption and FeS on the steel surface is formed via the oxide layer and elemental sulphur generated from alkyl sulphides with Fe_2O_3. It is hypothesized that their presence there as fusible glassy compounds, phosphorus as polyphosphate and iron sulphide as a ternary eutectic, provides the antiwear action of ZDDP. The formation of the glassy layer on the steel surface was responsible for the friction decrease, where oil film covered most of the contact area. The performance of ZDDP additive was not affected by application of the magnetic field. Aluminium disc displayed higher friction than polyamide and steel discs. This behaviour confirmed that the influence of magnetic field can not be reduced in only increasing the applied load by the extra magnetic force superimposed on it. It seems that magnetic field also strengthened the adhesion of the oil film into the sliding surface so that the area of hydrodynamic lubrication increased leading to the decrease of friction coefficient. For optimum lubrication, the oil must thoroughly wet out the contact surfaces. Wetting out means the oil flows and covers the contacting surfaces to maximize the oil film between the sliding surfaces. This phenomenon was realized for steel and polyamide more than aluminium.

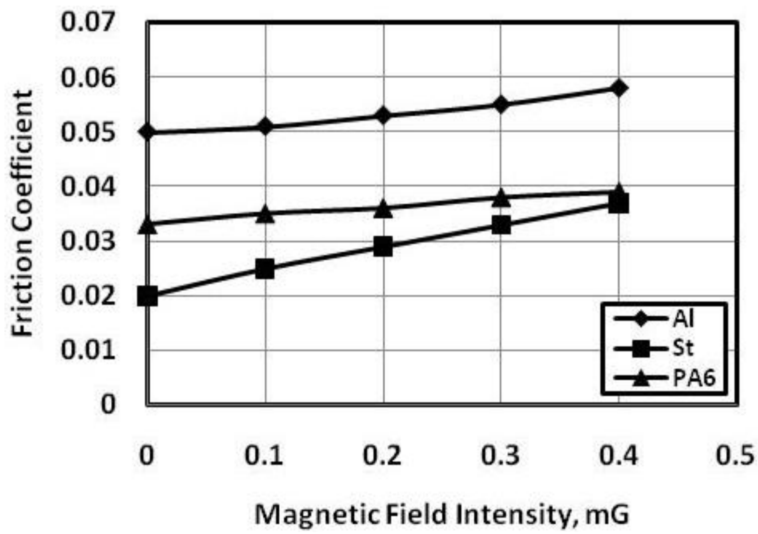

Fig. 4 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by ZDDP.

Friction coefficient displayed by the sliding of steel pin against the tested disc materials lubricated by oil and dispersed by MoS_2 is shown in Fig. 5. Friction coefficient displayed by aluminium disc showed relatively lower values in the presence of the magnetic field than that displayed by polyamide and steel discs. Both aluminium and polyamide discs showed slight friction increase with increasing magnetic field. Steel disc displayed significant friction decrease with increasing magnetic field of values higher than that displayed by aluminium and polyamide. The friction decrease might be from the influence of magnetic field on the adsorption of MoS_2 particles on the steel surface. Generally, friction values observed for oil dispersed by MoS_2 showed higher values than that observed for oil and oil dispersed by ZDDP. This performance will be enhanced if the particles are strongly adhered to the contact area and the shear strength of the solid lubricant is less than the adhesion to the substrate. In addition, a film of solid lubricant should be built up of sufficient thickness to cover the contact area completely, and sliding takes place between two smooth oriented layers of lamellar solid lubricant.

The magnetic field drastically decreased friction coefficient displayed by aluminium and steel disc, Fig. 6. It seems that the polarity of CMOC particles strengthened their adherence into the contact area. Under the action of the magnetic field the force of adhesion significantly increased causing proper surface coating which caused the friction decrease. As for polyamide disc, friction coefficient slightly increased with increasing the magnetic field. It should be mentioned that, adhesion force was affected by the electrostatic force generated by friction between steel and polyamide surfaces as well as the magnetic force generated from the magnetic field. The mechanism of action of the CMOC additive is to keep the two contacting surfaces away from each other by forming a protecting layer on the sliding surfaces. The adherence of CMOC particles, which are smaller than 1.0 µm size, into the sliding surfaces is enough strong due their electronic properties. The degree of adherence of solid lubricant into the sliding surfaces is responsible for the friction and wear decrease.

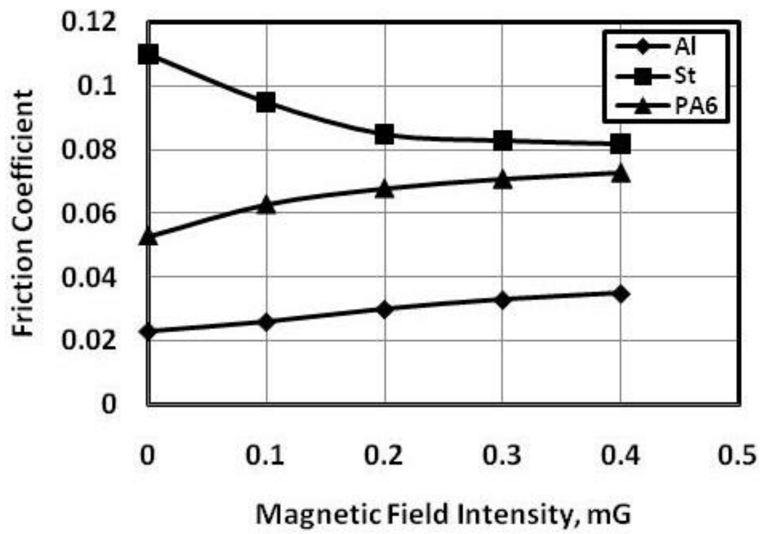

Fig. 5 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by MoS_2.

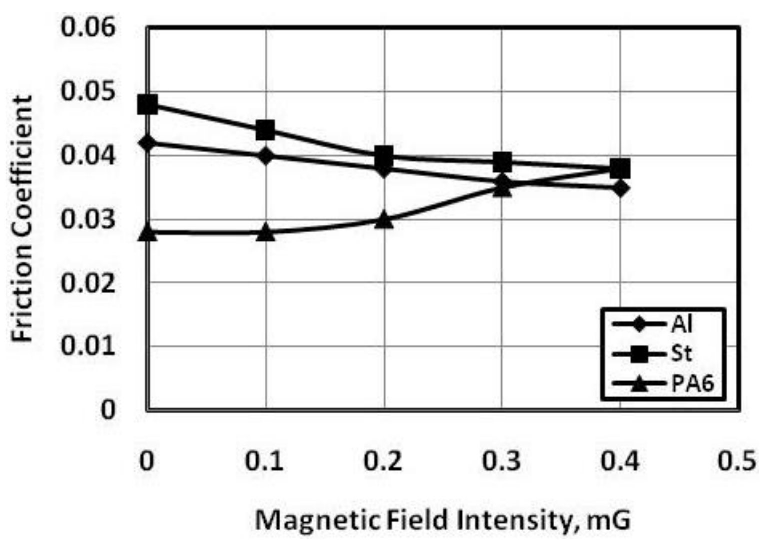

Fig. 6 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by CMOC.

Friction coefficient displayed by the sliding of steel pin against the tested materials lubricated by oil dispersed by C is shown in Fig. 7. Aluminium disc displayed the lowest friction coefficient, which decreased with increasing magnetic field. For steel disc friction coefficient displayed the highest values due to the increase of the magnetic force that superimposed on the normal load applied to the steel pin. Polyamide disc showed no change in friction values as the intensity of the magnetic field increased. This behaviour is attributed to the electronic properties of C, where dispersion of C particles into the oil distributed the electric static charge on the sliding surfaces and consequently adhesion

among C particles, polyamide and steel surfaces increased. As already mentioned, not all lamellar solids are capable of interlamellar sliding at low shear stresses. The nature of bonding between the C lamellae is a weak Van der Waals bonding acting between lamellae. The friction increase might be from the relatively high adhesion between lamellae. The lubrication mechanism of C is believed to be a result of the relatively free movement of adjacent layers in these substances.

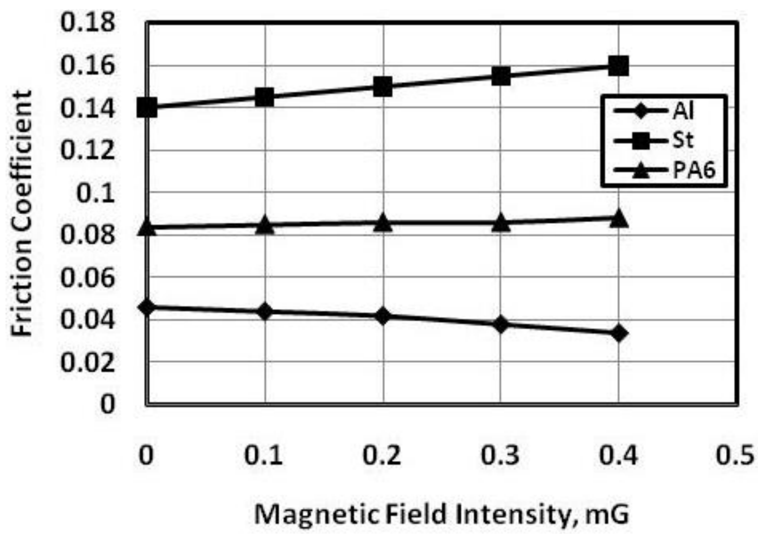

Fig. 7 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by graphite.

Friction coefficient displayed by the sliding of steel pin against the tested materials lubricated by oil and dispersed by DA showed significant friction decrease displayed by the steel disc, Fig. 8. Aluminium disc showed slight friction increase with increasing magnetic field, while polyamide disc showed slight friction decrease. It seems that the polarity of calcium sulphonate molecules is responsible for the decrease of friction coefficient observed for steel and polyamide. Application of the magnetic field might modify the orientation and adherence of the additive particles on the sliding surfaces. Significant reduction in friction coefficient was caused by the magnetic field. The lowest values of friction coefficient were displayed at the highest value of the magnetic field. The lowest friction coefficient value was 0.02 at 0.4 mG magnetic field intensity.

The lowest values of friction coefficient were displayed in the presence of PTFE dispersing oil. The good lubricating properties observed for PTFE additive can be from its ability to form a layer on the sliding surfaces. The very low intermolecular forces of PTFE allow the layer to slide over the friction surface with a minimum of interaction and hence a minimum of friction. PTFE particles dispersed in the oil were much influenced by the magnetic field, Fig. 9, where the friction coefficient displayed by steel drastically decreased with increasing magnetic field. Aluminium and polyamide discs showed an increasing trend as the magnetic field increased. As for PMMA particles dispersed in oil, Fig. 10, aluminium disc showed slight friction increase, while steel and polyamide discs gave decreasing trends of friction as the magnetic field increased. The values of friction coefficient were relatively higher than that observed for PTFE. Adherence of PTFE into PA surface might be attributed to the relatively high amount of electric static charge generated from PTFE when rubbed both PA and steel, where PTFE gained negative charge and steel as well as polyamide surfaces gained positive charge. Besides PA surface gained extra positive charge when slid on steel.

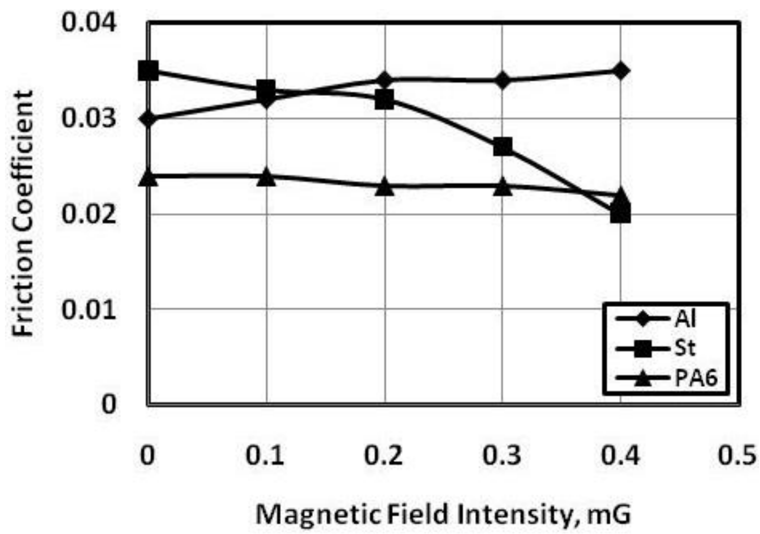

Fig. 8 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by DA.

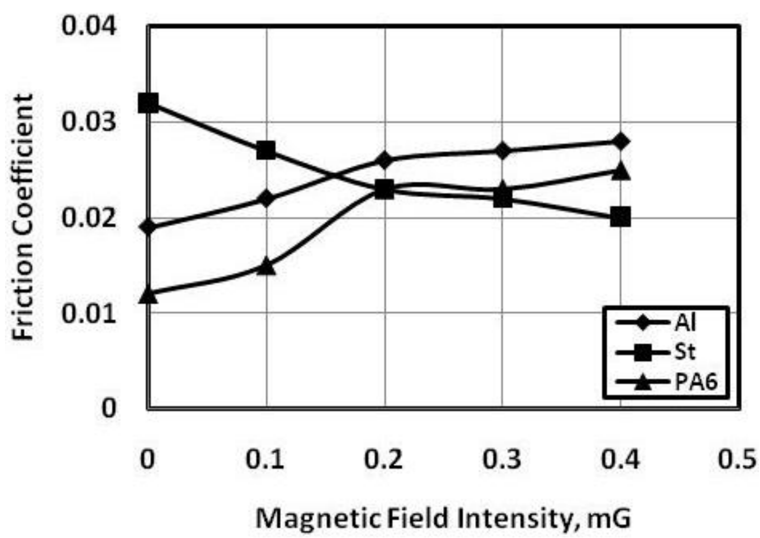

Fig. 9 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by PTFE.

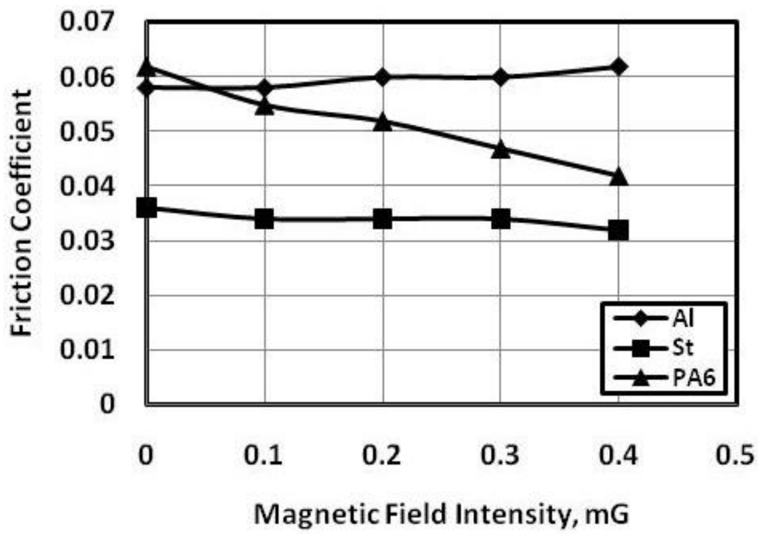

Fig. 10 Friction coefficient displayed by the sliding of steel pin against tested materials lubricated by oil dispersed by PMMA.

CONCLUSIONS

1. As the magnetic field increased friction coefficient slightly increased for surfaces lubricated by paraffin oils free of additives. Aluminium as a paramagnetic material recorded higher values of friction coefficient than steel and polyamide.

2. Friction coefficient slightly increased with increasing magnetic field for oil dispersed by ZDDP additive.

3. For oil dispersed by MoS_2, friction coefficient displayed by aluminium disc showed relatively lower values in the presence of the magnetic field than that displayed by polyamide and steel discs.

4. Magnetic field drastically decreased friction coefficient displayed by aluminium and steel disc. As for polyamide disc friction coefficient slightly increased with increasing the magnetic field.

5. For oil dispersed by C, aluminium disc displayed the lowest friction coefficient, which decreased with increasing magnetic field. For steel disc friction coefficient displayed the highest values. Polyamide disc showed no change in friction values as the intensity of the magnetic field increased.

6. For oil dispersed by DA, steel disc showed significant friction decrease. Aluminium disc showed slight friction increase with increasing magnetic field, while polyamide disc showed slight friction decrease.

7. PTFE particles dispersed in the oil were much influenced by the magnetic field, where the friction coefficient displayed by steel drastically decreased with increasing magnetic field. Aluminium and polyamide discs showed an increasing trend as the magnetic field increased.

8. As for PMMA particles dispersed in oil, aluminium disc showed slight friction increase, while steel and polyamide discs gave decreasing trends of friction as the magnetic field increased.

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