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EFFECT OF MAGNETIC FIELD ON THE FRICTION AND WEAR DISPLAYED BY THE SCRATCH OF OIL LUBRICATED STEEL

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ABSTRACT
The present work discusses the effect of magnetic field on the friction and wear of steel scratched by TiC insert. The steel was lubricated by oil and dispersed by iron, copper and aluminium powders as well as polymeric powders such as high density polyethylene (PE), polymethyl methacrylate (PMMA) and polyamide (PA6). Molybdenum disulphide (MoS_2) and graphite (C) were added to the oil as dispersant. Paraffin oil was used as lubricant. Friction coefficient and wear of the tested composites were investigated using a tribometer designed and manufactured for that purpose.

It was found that application of induction magnetic field decreased friction coefficient. The decrease was significant for oil lubricated steel and oil dispersed by aluminium, copper, PMMA and PA6 + 10 wt. % C, while addition of iron, PE and MoS_2 particles showed slight friction decrease. At no magnetic field friction coefficient for oil dispersed by aluminium and copper particles showed values lower than that observed for oil dispersed by iron particles. The lowest values of friction coefficient were displayed by oil dispersed by PE particles. Magnetic field caused significant wear increase for oil lubricated steel, where aluminium, copper and PA + C particles displayed relatively higher wear, while addition of iron, PE, PMMA and Mo S_2 particles showed slight wear increase. At no magnetic field wear decreased due to the action of aluminium particles which formed a continuous layer on the steel surface and consequently decreased wear. Wear of oil lubricated steel dispersed by PE particles displayed relatively low values. Magnetic field showed no significant change on wear of the steel surface.

KEYWORDS
Induction, magnetic field, scratch, friction coefficient, wear, iron, copper, aluminium polyethylene, polymethyl methacrylate, polyamide, molybdenum disulphide, paraffin oil.

INTRODUCTION
Ferromagnetic materials have attracted much attention in both scientific and technical area, when they are under the influence of external magnetic field. There is an increasing demand to investigate the friction and wear of the mechanical drives that

performed under the effect of magnetic field. It was observed that sliding between two steel cylinders under external magnetic field showed that the attractive force induced by external magnetic field increased normal force on the contact area. The friction coefficient decreased in the presence of magnetic field, [1]. External magnetic field could change the properties of ferromagnetic materials to improve the performance of cutting tool during metal manufacturing, [2]. It was found that the rate of the ferromagnetic materials and the friction coefficient can be changed by external magnetic field [3, 4]. Oil dispersed by suspensions of magnetic particles is used in many application such as automotive brakes and vibration dampers, where their rheological properties can be dramatically altered by applying a magnetic field, [5 – 9]. When the magnetic field is applied magnetic particles orient themselves towards the magnetic flux line. This orientation of magnetic particles causes additional resistance to the flow and results in an increase in viscosity.

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, [10]. Tests were carried out at oil lubricated surfaces. Paraffin, fenugreek, camphor, cress, olive, almonds, sesame, aniseed and habet el-baraka 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 (CMOC), graphite, polytetrafluroethylene and polymethyl methacrylate, detergent additive (calcium sulphonate), was investigated, [11, 12]. 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, [13]. 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, [14 - 15], 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.

The presence of a magnetic field around the ferromagnetic steel couple in sliding contact modifies considerably its tribological behaviour with an important decrease in the wear rate [16 - 22]. Applied magnetic field around the rotating sliding ferromagnetic steel/steel modifies the friction and the wear behaviour of the contact, [23]. When a

magnetic field is applied, the contact in ambient air progressively became black, covered by a brittle thick black layer of oxides which leads to a low friction and a low wear mode. The application of a magnetic field can induce many effects on mechanical, physical and chemical phenomena of ferromagnetic materials, such as the magnetostriction (interaction between the stress field and the magnetic field), the chemical catalysis of the surface oxidation by applied magnetic field. The friction and wear behaviour of a nickel/steel couple was studied and analyzed in the presence and absence of a direct current magnetic field, [24]. A magnetic field was applied to the nickel pin and remained constant during each test. It was found that the application of a magnetic field increased the friction coefficient and microhardness of the sliding surface and decreased the wear rate. The sliding surface was filled with thin, black particles.

Biodegradable oils can replace mineral oils to solve the problem of pollution of the natural surroundings caused by mechanical systems. Natural biodegradable oils possess good anti-wear properties and low friction, [25]. The conventional lubrication mechanisms based on physical and chemical adsorption, where the polar molecules play a key role in interactions with the sliding surfaces, the best tribological performance is expected for vegetable oils, which consists of a considerable amount of fatty acids with unsaturated bonds, [26]. Moreover, when using oils with additives the wear was significantly lower and the adhesion was eliminated. This was true for all types of oil, which clearly indicates that additives were predominantly responsible for the wear protection. Efficiency of the lubricant depends on the strength of the fluid film and consequently on the adsorption on the sliding surfaces. Increasing the polar functionality in vegetable oil structure has a positive impact on wear protection resulting from stronger adsorption potential on metal surface as well as greater lateral interaction between the ester chains.

In the present work, the effect of induced magnetic field on the friction coefficient and wear caused by the scratch of steel lubricated by oil and dispersed by metallic and polymeric powders is investigated.

EXPERIMENTAL

The test rig, used in the experiments, was top scratching tester equipped with a stylus to produce a scratch on a flat surface with a single pass. The details of the test rig is shown in Fig. 1. The stylus, used in experiments, was a square insert (12×12 mm^2) 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 the load cell. The ratio of the scratch force to the normal load was considered as friction coefficient. Wear was considered as the wear scar width of the scratch. The width was measured by optical microscope with an accuracy of ± 1.0 µm. The steel surface was ground by an emery paper (500 grade) before testing.

The steel was lubricated by paraffin oil dispersed by metallic powder such as iron, copper and aluminium. The concentration was 10 wt. % and their particle size was ranging between 30 - 50 µm. Polymeric particles such as PMMA, PE and PA6 (50 – 70 µm) as well as MoS_2 and C (3 – 10 µm) were used as dispersions in 10 wt. % concentration.

The load was applied by weights. The test speed was nearly controlled by turning the power screw feeding the stylus in the scratch direction. The scratch velocity was 2 mm/s. The normal load was 2, 4, 6, 8 and 10 N. All measurements were performed at 28 ± 2 º C and 50 ± 10 % humidity. Experiments were carried under the effect of constant magnetic flux intensity (0.1 T). It will be referred in the text as 0.1 T. The condition of no magnetic field will be referred as 0 T. The value of induction magnetic field nearby the contact point was measured by a teslameter in the static condition before the beginning of tribological test. At the end of experiment the wear scar width was measured using room tool microscope.

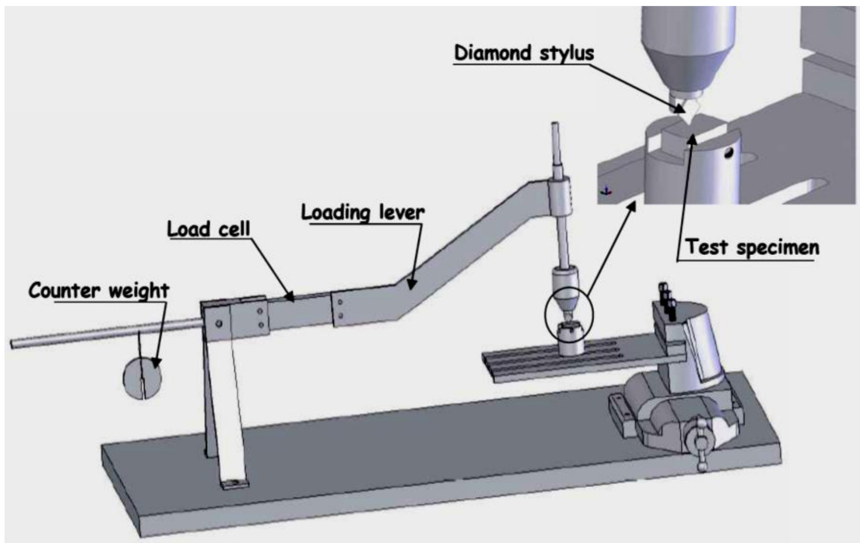

Fig. 1 Arrangement of the test rig.

RESULTS AND DISCUSSION

Friction coefficient displayed by the scratch of oil lubricated steel is shown in Fig. 2. Generally, friction coefficient increased with increasing applied load. Under the application of magnetic field friction coefficient showed relatively lower values. The behaviour could be explained on the basis that in oil lubricated contact, the oil molecules at the contact area rearrange to form multilayer of the oil polar molecules on the steel surface. The mixed lubrication provided by the oil is primarily governed by the formation of a stable oil film on the sliding surfaces, [27, 28]. This effect enhanced the adhesion of oil into the contacting surfaces. Consequently, severity of abrasion action of the insert into the steel surface could be reduced.

Application of magnetic field of 0.1 T flux intensity on the sliding surface caused significant friction decrease, Figs. 3, for oil dispersed by iron particles. The friction decrease might be attributed to the effect of the magnetic field which increased the viscous effect of the oil under the magnetic field. When the field is on, magnetorheological fluid behaves as a semi-solid with very high apparent viscosity. It is evident that the higher viscosities of magnetorheological fluid could decrease the friction accompanied to the abrasion process. It seems that The iron particles might form a

protective layer due to the shearing effect under the magnetic field. Therefore, friction coefficient decreased.

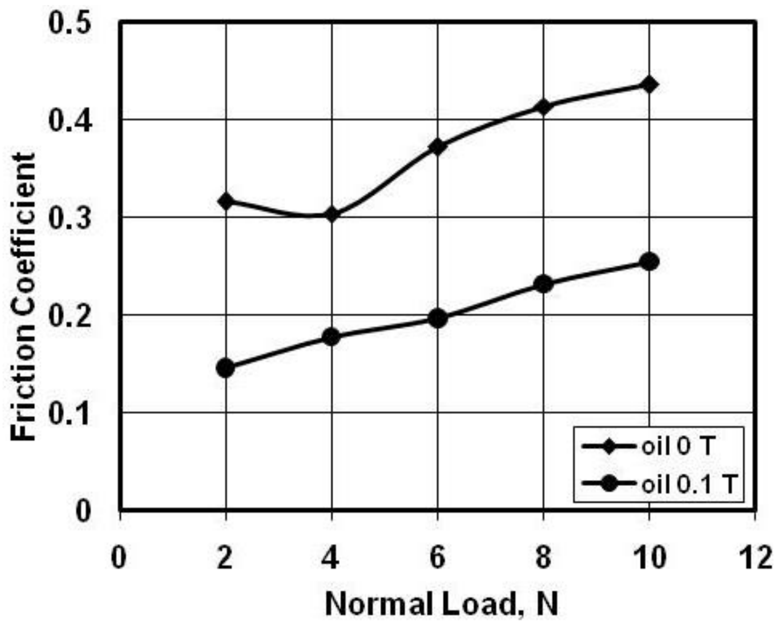

Fig. 2 Friction coefficient displayed by the scratch of oil lubricated steel.

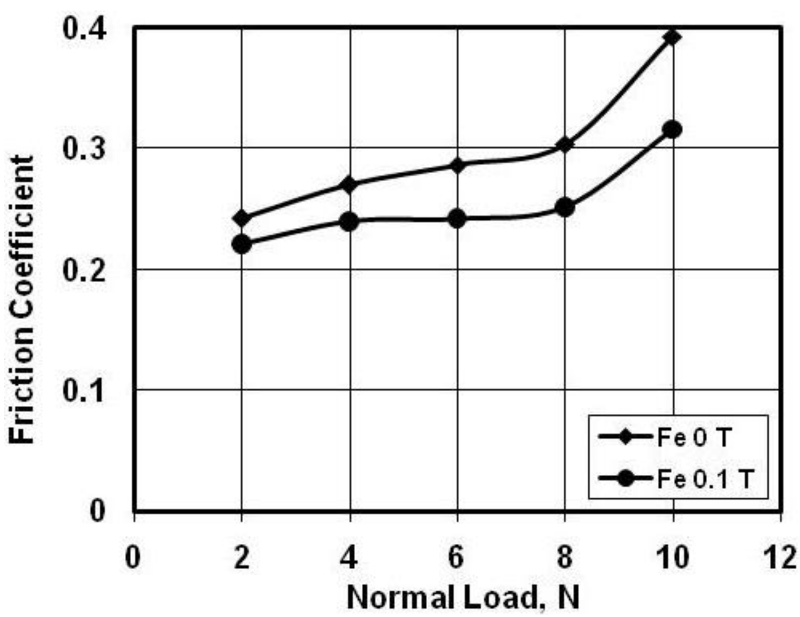

Fig. 3 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by iron particles.

Although aluminium is paramagnetic material significant friction decrease was observed when oil was dispersed by aluminium particles, Fig. 4. At no magnetic field friction coefficient showed values lower than that observed for oil dispersed by iron particles. Aluminium is relatively softer than iron and easily deformed at the contact

area to give more protection against abrasive action. When magnetic field was applied friction coefficient drastically decreased.

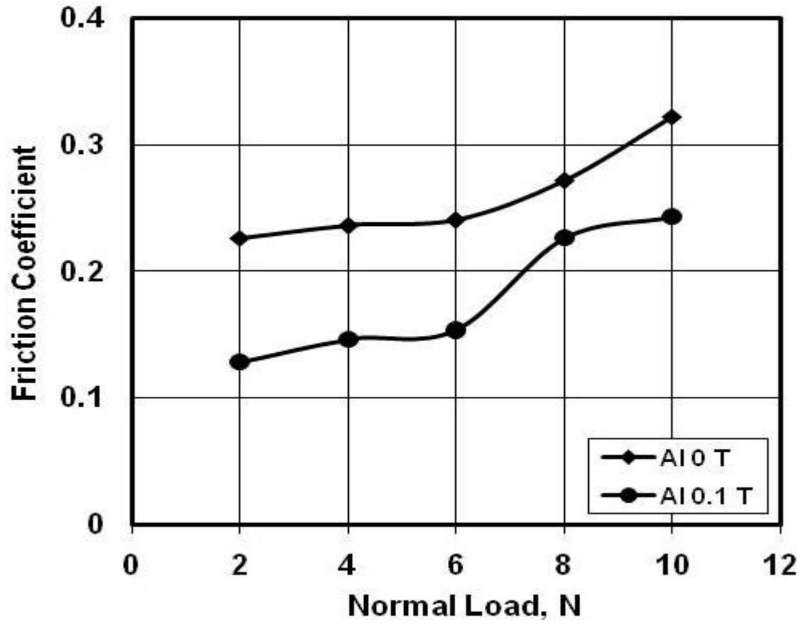

Fig. 4 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by aluminium particles.

Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by copper particles showed further decrease, Fig. 5. During scratch the contact area was covered by oil and copper particles. Polar molecules of the oil could significantly improve friction due to their adsorption on the sliding surfaces. The long fatty acid chain and presence of polar groups in the oil structure decreased the abrasion. 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. Copper particles could cover the rest of the contact area leading to further friction decrease.

It is clearly seen that the magnetic field accelerated the reorientation of the oil molecules to be strongly adhered to the surfaces of insert and steel test specimen, Fig. 6. It is well known that PE particles strongly adhere into the steel surface due to the electric static charge generated from friction against steel. Presence of magnetic field caused slight friction decrease. Oil dispersed by PE particles displayed the lowest values of friction coefficient among the tested dispersing materials.

Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by PMMA particles is shown in Fig. 7. Application of magnetic field caused significant friction decrease. It can be concluded that without magnetic field PMMA particles were dispersed freely into the base oil. When the magnetic field was applied, they formed columnar structures, parallel to the applied field near the contact area. The probability

of PMMA particles getting into the contact zone was accelerated due to the action of magnetic field which forced PMMA particles to decrease the ability of the insert to abrade the steel surface.

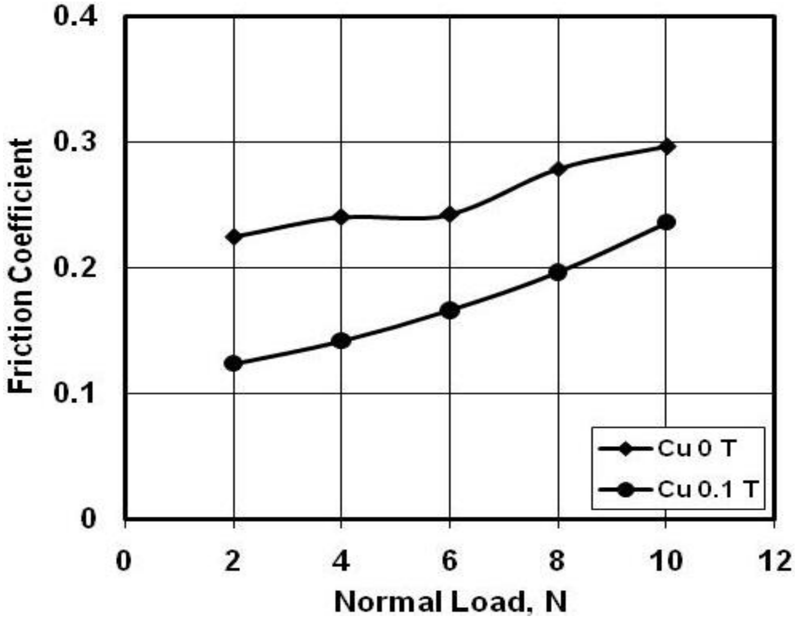

Fig. 5 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by copper particles.

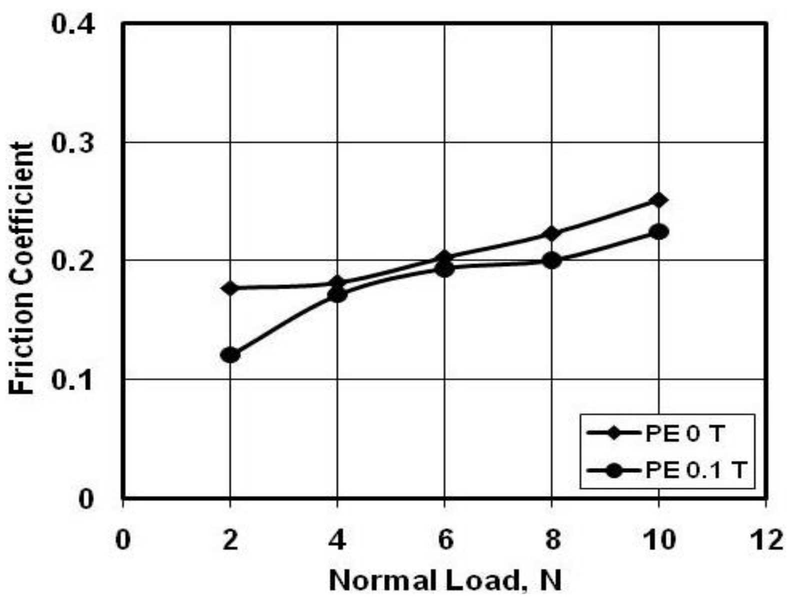

Fig. 6 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by PE particles.

When the oil was dispersed by PA6 + C magnetic field showed significant friction decrease, Fig. 8. At no magnetic field friction coefficient increased to values higher than that calculated for PE and PMMA. It seems that PA6 + C particles were adhered into the cutting edge of the insert and steel surface so that the cutting process became more difficult.

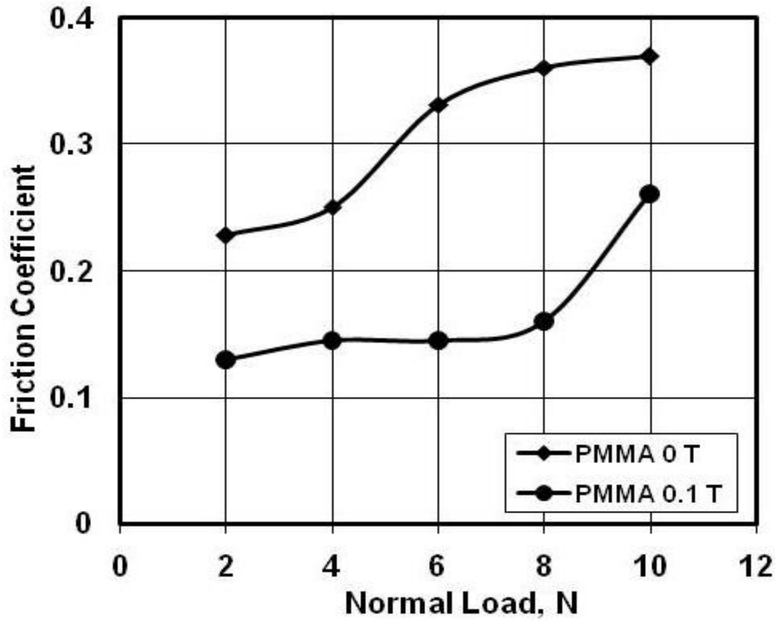

Fig. 7 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by PMMA particles.

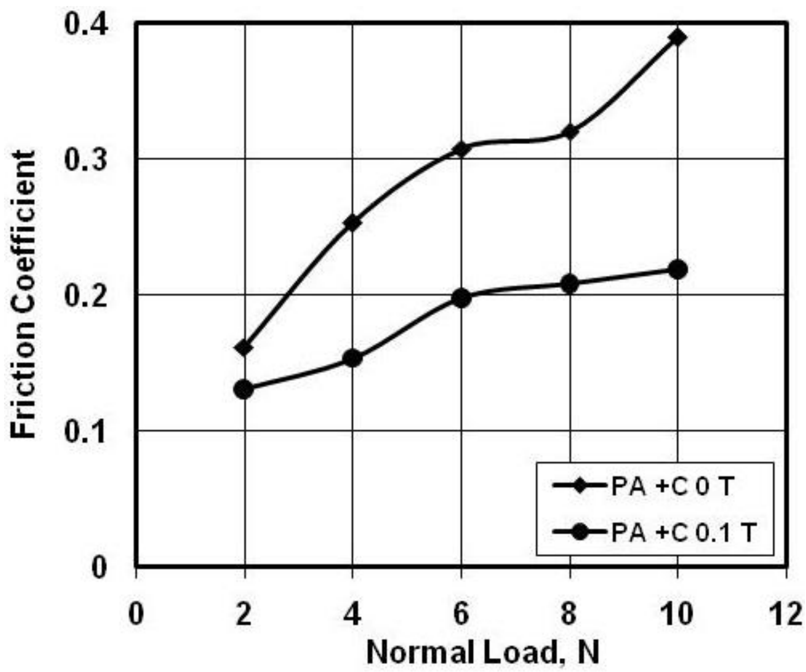

Fig. 8 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by PA6 + C particles.

Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by MoS_2 particles is shown in Fig. 9. Significant friction decrease was observed. At no magnetic field friction coefficient decreased due to the action of MoS_2. The good surface adherence of MoS_2 is attributed to the strong metal-sulfur bonds, where the compound shears easily to give low friction because of the weakness of the sulfur-to-sulfur bond.

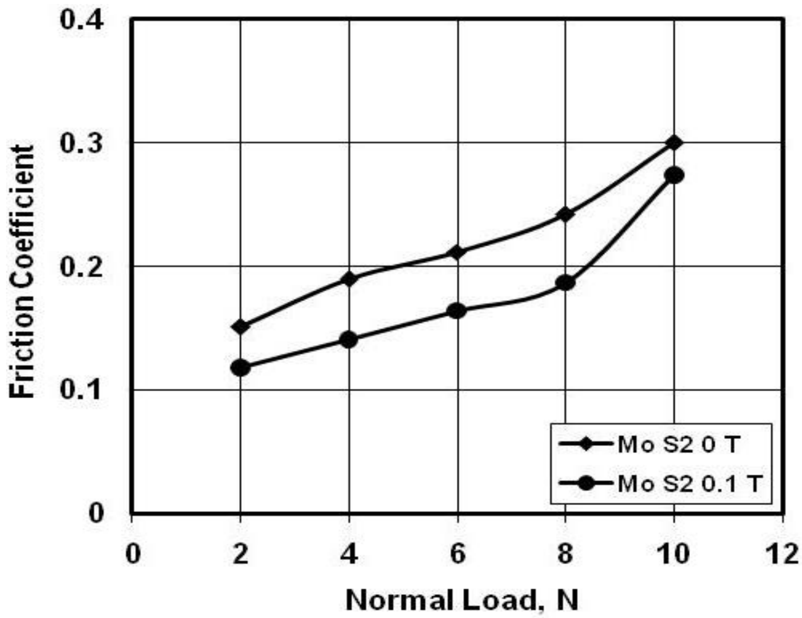

Fig. 9 Friction coefficient displayed by the scratch of oil lubricated steel and dispersed by MoS_2 particles.

Wear of oil lubricated steel measured in wear scar width is shown in Fig. 10. Generally, wear increased with increasing normal load. Magnetic field caused significant wear increase. As the external magnetic field was applied, the local magnetic flux was modulated. The debris generated from wear was constrained to the region near the contact point due to the larger local magnetic flux. Induction magnet behaves like a permanent magnet as long as there is power applied to it. It is a magnet that can be turned on and off 50 times a second (50 Hz), and its magnetic strength can be varied as the voltage to it is varied. The variation of the magnetic flux would decrease accumulation of the debris around contact asperities and make the steel surface clean for further abrasion. This could produce further wear of the surface and result in a higher wear of the surface under induction magnetic field. The fine debris generated during scratch process under induction magnetic field would be removed from the wear track.

When oil was dispersed by iron particles magnetic field had no effect on wear of the steel surface, Fig. 11. Because iron particles are magnetic they were attracted to the steel surface and orient themselves towards the magnetic flux lines. This orientation of magnetic particles caused additional resistance to wear. At no magnetic field wear value was lower than that observed for oil lubricated steel as shown in Fig. 10.

Wear of oil lubricated steel dispersed by aluminium particles is shown in Fig. 12. Magnetic field caused remarkable wear increase. At no magnetic field wear decreased due to the action of aluminium particles which formed a continuous layer on the steel surface and decreased wear.

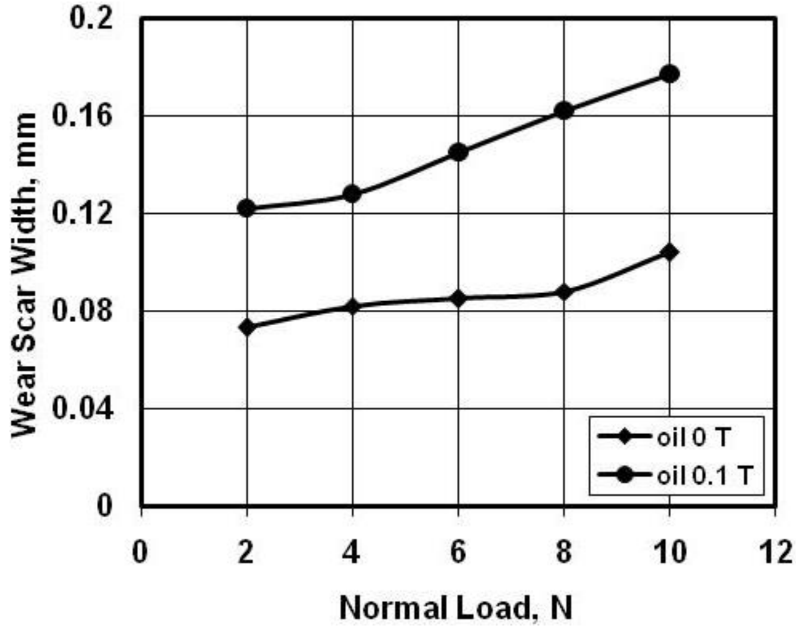

Fig. 10 Wear of oil lubricated steel.

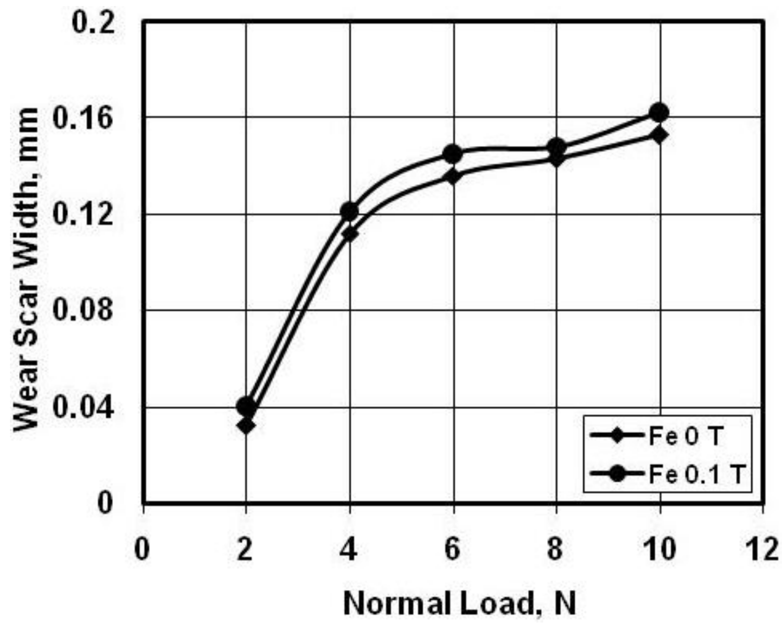

Fig. 11 Wear of oil lubricated steel dispersed by iron particles.

When copper was dispersing oil no enhancement was observed under the application of magnetic field, Fig. 13. Wear displayed values lower than observed for oil free of dispersants. The highest wear values were 0.15 and 0.155 mm for 0 and 0.1 T magnetic flux respectively. The low shear strength of copper particles enabled them to be deformed on the contact area to protect the steel surface from further wear.

Wear of oil lubricated steel dispersed by PE particles displayed relatively lower values, Fig. 14. It can noticed that a relative improvement of the wear resistance of the sliding surfaces was displayed by the dispersion of PE. This can be attributed to the relatively strong adhesion of polymeric particles into the contact surfaces.

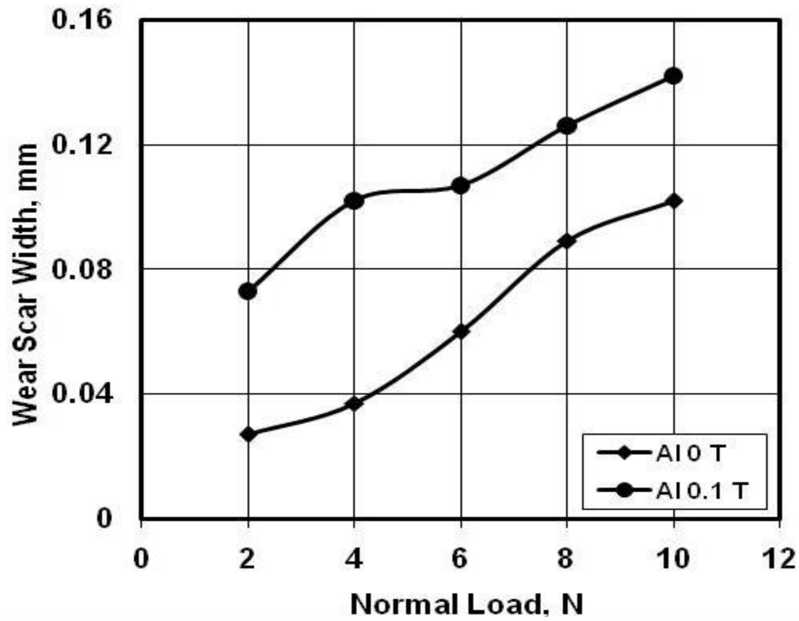

Fig. 12 Wear of oil lubricated steel dispersed by aluminium particles.

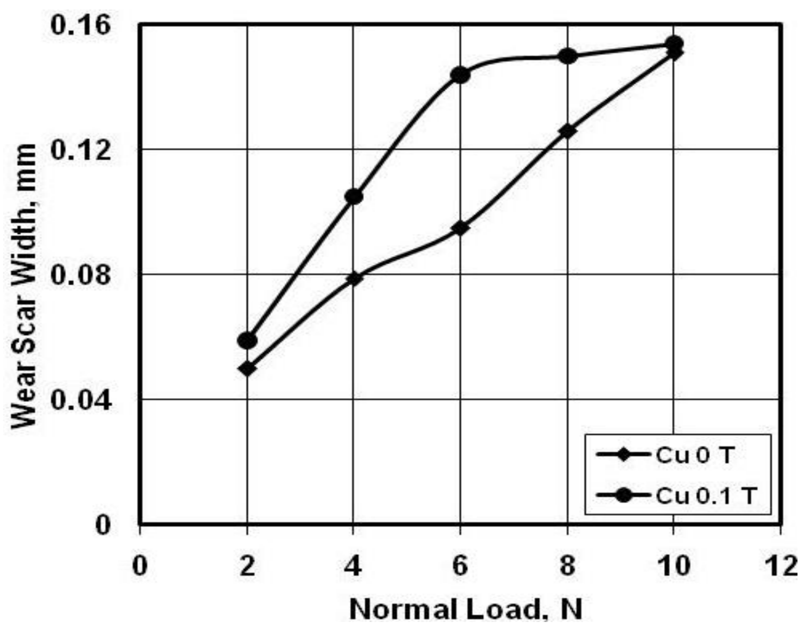

Fig. 13 Wear of oil lubricated steel dispersed by copper particles.

A mechanism of action of solid lubricant dispersion was proposed, [29]. It can be explained on the basis that the particles fill the pits and valleys in the roughness of the sliding surface, thereby increasing the contact area and providing a reservoir of solid lubricant. 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 is built up of sufficient thickness to cover the contact area completely, and sliding takes place between two smooth oriented layers of lamellar solid lubricant. Magnetic field showed no significant change on wear of the steel surface.

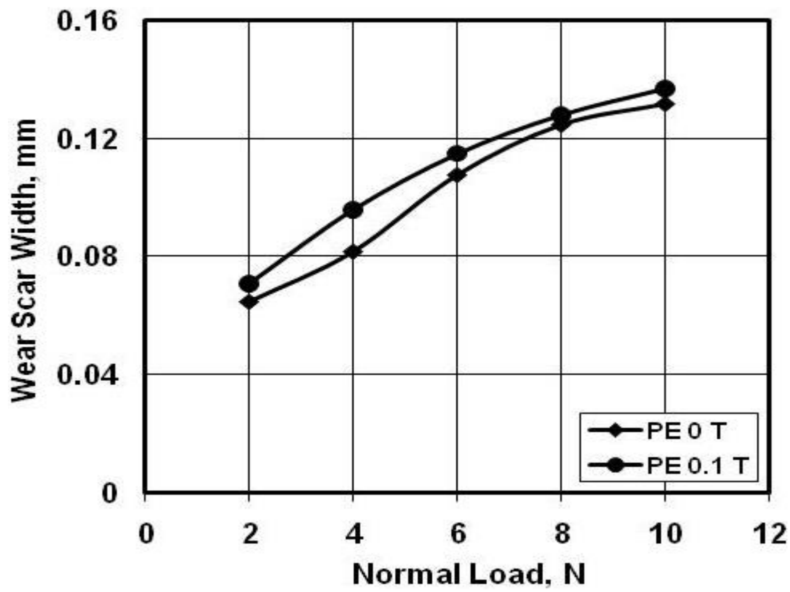

Fig. 14 Wear of oil lubricated steel dispersed by PE particles.

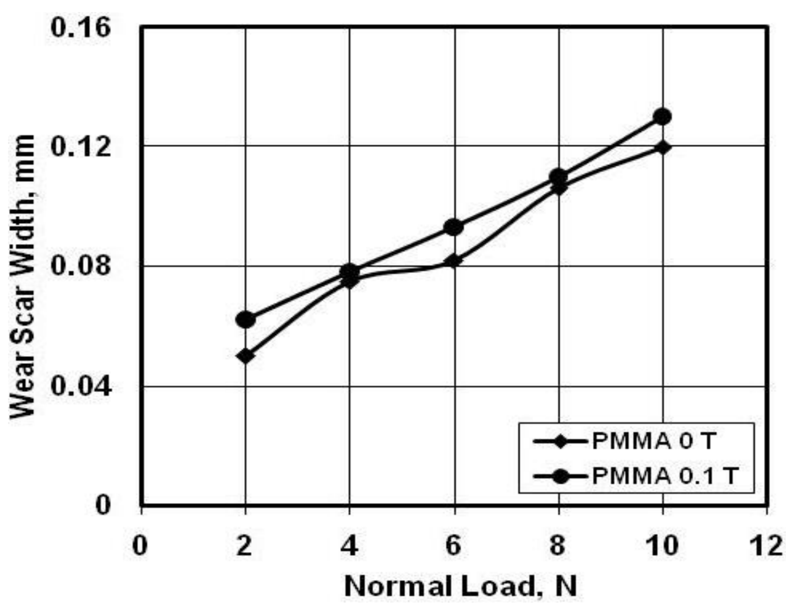

Fig. 15 Wear of oil lubricated steel dispersed by PMMA particles.

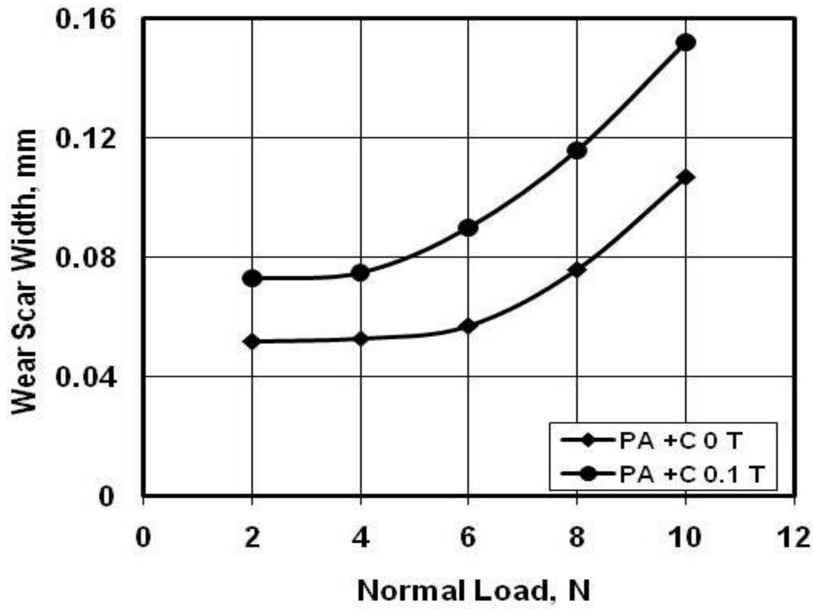

Fig. 16 Wear of oil lubricated steel dispersed by PA6 + C particles.

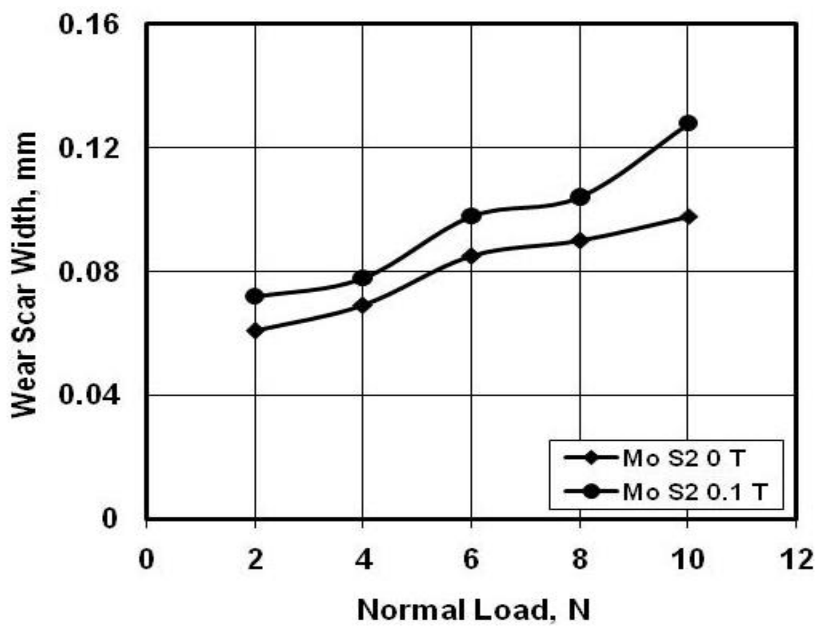

Fig. 17 Wear of oil lubricated steel dispersed by MoS_2 particles.

When oil was dispersed by PMMA particles further wear decrease was observed, Fig. 15. It is well known that, PMMA has positive charge as a result of their friction with steel. Those particles would strongly adhere to the steel surface protecting it from excessive wear. The lowest wear was observed for PMMA due to the rolling of its particles between the two sliding surfaces. Magnetic field showed insignificant increase

in wear. PA6 + C as dispersants in oil did not decrease wear of the steel, Fig. 16. Application of magnetic field significantly increased wear.

Wear of oil lubricated steel dispersed by MoS_2 particles displayed relatively low values, Fig. 17. This is because MoS_2 has a good surface adherence attributed to strong metal-sulfur bonds and shears easily to give low friction due to the weakness of the sulfur-to-sulfur bond. Application of magnetic field showed higher wear values due to removing steel debris out of the contact area.

CONCLUSIONS

Influence of induction magnetic field on the friction and wear of oil lubricated steel was investigated. The oil was dispersed by metallic powders, polymeric powders and MoS_2. Paraffin oil was used as lubricant. The experimental results showed that application of induction magnetic field decreased friction coefficient caused by the scratch of oil lubricated steel. The decrease was significant for oil lubricated steel. Dispersing oil by aluminium, copper, PMMA and PA + 10 wt. % C showed significant decrease. Magnetic field of 0.1 T flux intensity caused significant wear increase for oil lubricated steel. Aluminium, copper and PA + C displayed relatively higher wear. Addition of iron, PE, PMMA and MoS_2 showed slight wear increase.

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