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# WEAR BEHAVIOUR FOR STEEL\STEEL AND BRASS\STEEL SLIDING UNDER DRY AND LUBRICATED CONDITIONS IN THE PRESENCE OF MAGNETIC FIELD

# السلوك التآكلى لانزلاق صلب/صلب و نحاس/صلب تحت ظروف جافة و مزلقة فى وجود مجال مغناطيس

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**خلاصة** : يقدم هذا البحث المعملى دراسة عن تأثير المجـال المغناطيسـى على سلوك التآكل و معدلاته وتغير خشونة السطح لمجموعات من الصلب/صلب و نحاس/صلب و ذلك فى حالتى الانزلاق الجاف و الانزلاق فى وجود زيت تزليق و قد أجريت التجارب على ماكينة تآكل ذات أصبع مترددة على سطح ثابت و ذلك تحت تأثير أحمال ثابتة مقدارها ٥ و ١٠ نيوتن و عند سرعة انزلاقية قصوى ٠,٣ متر/ث فى وجود و عدم وجود مجال مغناطيسى ثابت ذو كثافة مغناطيسية ١,٦ مللى تسلا بين السطوح المنزلقة. و قد اوضحت التجارب ان للمجال المغناطيسى تأثير واضح فى خفض معدلات التآكل للمجموعات المختبرة فى حالتى الانزلاق الجاف و المزلق . كذلك حدث تحسن فى درجة الخشونة السطحية فى وجود المجال المغناطيسى مقارنة بدرجة الخشونة فى عدم وجوده و ذلك تحت ظروف التشغيل المختبرة.

**ABSTRACT:** An experimental investigation was carried out to elucidate the role of magnetic field on the wear behavior and surface roughness variations of steel/steel and brass/steel combinations under dry and oil lubricated sliding conditions. A reciprocating pin-on-plate wear testing machine was used with normal loads of either 5 or 10 N and with maximum sliding speed of 0.3 m/s. A constant magnetic field of 1.6 mT flux density was applied to the rubbing surfaces during tests conducted in the presence of magnetic field. The results of the experiments show that the presence of magnetic field has a significant effect upon reducing wear rates of tested combinations of materials under dry and lubricated sliding conditions. Furthermore improvements in surface roughness resulted in the presence of magnetic field between rubbing surfaces

## 1. INTRODUCTION

During rubbing of metals, continuous changes in the energy of atomic and molecular interactions of surfaces take place. A whole complex of interconnected mechanical, physicochemical and electrical phenomena are encountered [1]. These phenomena can influence both the force of interaction between atoms and atomic collections and the character of bonds. In addition, these phenomena continually disturb the conditions of the system, either in dry or lubricated sliding. This sort of disturbance results in changes in the macroscopic mechanical and physical parameters: friction force, wear rate, surface roughness, surface hardness ..etc. Therefore, it is evident that great applied value is attached to the study of specific features of the electrical and magnetic influences upon friction and wear of metals. The study should aim to decrease friction, wear resistance to plastic strains and work to overcome molecular forces in the formation of new surfaces

It is important to mention that in devising a new friction and wear theory, the resent emphasis is not on the mechanical models of interaction of solids but on the little studied category of electric and electromagnetic processes taking place between sliding surfaces, which influences the friction and wear [2-3]. For tribological systems, the principles of magnetism can be used for the separation of the surfaces in relative motion in two ways: The first is to utilize the effect of a load-carrying force generated by the flow of conducting fluid within a magnetic field causing magnetohydrodynamic (MHD) lubrication [4]. The second in case of no lubricant, the systems derive their load-carrying ability from the attraction and repulsion associated with the magnetic fields, as in magnetic suspension bearings [5]. It is known from the laws of electromagnetic that an electric charge (q) moving with a velocity (v) within a magnetic field (B) will experience a force (F) called Lorentz force, acting perpendicular to the direction of motion according to the equation :

$$F = q\,(v \times B)$$

It follows that for MHD lubrication, the conducting fluid will develop a pressure which can exceed the ordinary hydrodynamically generated pressure [8], capable of reducing friction and wear of sliding metal surfaces. Some investigators [6] have found that it is possible to control wear in ionically conducting fluid through the application of appropriate electrochemical potentials. They concluded that the wear of Ni(200) reduced by a factor of 10 over the wear at the open-circuit potential. Hiratsuka et al [7] found that a strong magnetic field of 3.5 x $10^3$ A/m resulted in a considerable decrease in wear. On the other hand, Kumagai et al. [8,9] found that very weak magnetic field also decreases wear. They postulated that the decrease in wear was caused by magnetic-field-promoted oxidation of wear particles. Muju et al. [10,11] concluded that the wear rate of materials having low magnetic permeability was reduced on application of a dc external magnetic field but the reason for this had not been clarified. Furthermore, Hiratsuka [12] also reported a reduction in wear of metals under boundary lubrication when a magnetic field was applied between sliding surfaces.

In the present work, an experimental study was conducted to elucidate the role played by a magnetic field, applied between rubbing surfaces, upon the wear rate and variations in counterface surface roughness. A constant magnetic field was applied during sliding of steel on steel and brass on steel. The tests were performed in both dry and oil lubricated sliding conditions. Comparisons between the wear rates and counterface surface roughnesses are presented with and without the presence of magnetic field.

## 2. TEST-RIG, MATERIALS AND TEST PROCEDURE

### 1- Test-rig

The experimental work in this paper was conducted on a reciprocating wear testing machine. The machine is driven by a constant A.C. motor of 1 horsepower and 1725 rpm. A voltage regulator is connected to the motor to reduce the input speed of the test-rig to any desired speed value. Output speed due to voltage regulator reduction was 82 rpm resulting in sliding speed of 0.3 m/s at the middle of the sliding track. The drive motor is connected to a crank-shaft through a flexible coupling to compensate for any misalignment. The crankshaft is supported on two sealed deep-groove ball bearings, mounted in two casted split pedestal bearings. On the crankshaft, two connecting-rods are mounted on the crankpins with needle bearings at the big-ends of the connecting-rods. The ratio of the crank radius to the connecting-rod length is 1:3.5. The small ends of the connecting-rods are connected to reciprocating pin-holder blocks by means of pins supported on sealed ball-bearings. Two pin-holders are vertically freely connected in the pin-holder blocks and these support the applied dead loads at one end while at the other end, the pin tested materials are fixed.

The counterfaces to the pins were two flat metal plates fixed in rectangular grooves formed in two metal blocks which are fastened to the test-rig base. The rectangular grooves allowed tests to be conducted either dry or lubricated by oil poured in the recesses. A mechanical counter is fixed to the base near the reciprocating block to count the number of strokes performed in each test. For tests conducted in the presence of magnetic field, magnets were attached to the tested reciprocating pins. Fig. 1 demonstrates a view for the test-rig.

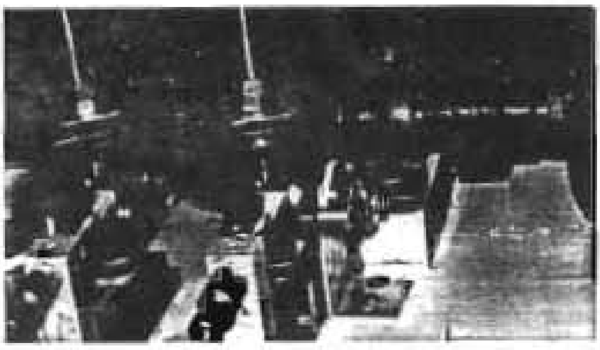
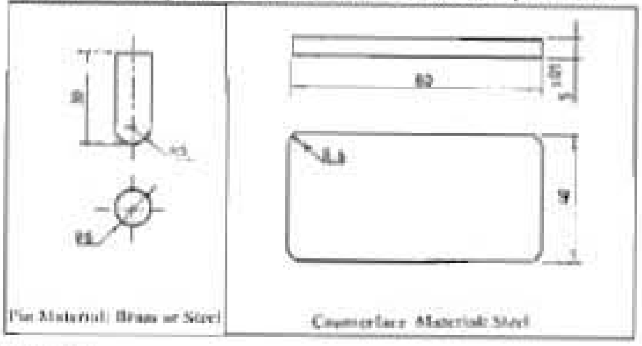


*Fig. 1. View of Test-rig*

**II- Materials**

The materials tested were commercial steel 302 (110 BHN) and 70/30 brass (48 BHN). The shape and dimensions of the tested specimens were as shown in Table 1. The chemical composition and mechanical properties of the tested materials were as illustrated in Table 2. Lubricated wear tests were performed using Petromin gearbox oil (85W90, SAE grade).

**Table 1. Shape and Dimensions of Tested Specimens**



**III- Test Procedure**

The operating conditions which were employed for testing program were as given in Table 3. The test surfaces of the steel plates were machined and ground to surface roughness in the range 0.05-0.13 $\mu m$ Ra. The surface roughnesses were measured before and after testing using a Taylor-Hobson Talysurf profilometer. Measurements were taken parallel and normal to sliding direction within the wear tracks and at the ends of the stroke. The roughness values quoted in this work are mean values of five traversals in each direction arbitrarily chosen. Before performing tests surfaces were chemically and mechanically cleaned using acetone and ultrasonic cleaning devise to remove any traces of grease, dust or contaminants. Wear rates were calculated from weight losses recorded after predetermined sliding distances. The tests were interrupted periodically to allow the pins to be weighed using sensitive digital balance of accuracy $10^{-4}$ g. Weight losses were converted to equivalent volumes by dividing them by the density of the material. The wear rate was then calculated from the formula:

**Wear rate = Volume loss / (Normal load x Sliding distance)** [ $mm^3/N.m$ ]

The field strength of the applied magnetic field was 796 A/m which is equivalent to a magnetic flux density of 1.6 mT. It is worth noting that many previous investigators used the magnetic field strength as a parameter in their investigations for the effects of magnetic field upon wear as it was found hard to exactly measure the magnetic flux density [7,8 and 9].

In the present study, to give an insight on the dominant wear mechanism, magnified examination of the tracks was performed by optical microscope of magnifications 100 and 400

**Table 2. Composition and Mechanical Properties of Tested Materials**

| Type of Material | Chemical Composition | Mechanical Properties | | | | |
|---|---|---|---|---|---|---|
| | | $\sigma_y$ (MPa) | $\nu$ | E (GPa) | BHN | $\rho$ ($kg/m^3$) |
| **Brass 70/30** | 70% Cu, 0.75% Sn, 1.5% Pb, Zn(rest). | 400 | 0.35 | 105 | 48 | 8450 |
| Steel 302 | 0.2%C, 0.9%Mn, 0.04%P, 0.05%S, 0.15%Si, 0.4%Mo | 300 | 0.35 | 207 | 110 | 8000 |

**Table 3. Experimental Test Conditions**

| Parameter | Conditions |
|---|---|
| Type of motion | Reciprocating |
| Type of contact | Pin-on-flat |
| Pin stroke | 7 cm |
| Crank speed | 82 rpm |
| Range of sliding speed | 0 - 0.3 m/s |
| Test conditions | Dry and oil lubricated |
| Type of lubricant | Petromin Gearbox oil (85W90) |
| Oil viscosity | 174 cSt at 40 °C |
| Oil specific gravity | 0.902 at 15 °C |
| Normal load | 5 and 10 N |
| Max. (Hertz) pressure | (Steel/Steel, 10 N) 9.2 GPa<br>(Steel/Steel, 5 N) 7.3 GPa<br>(Brass/Steel.10 N) 7.2 GPa<br>(Brass/Steel, 5 N) 5.7 GPa |
| Ambient conditions | 30 °C and 60% Humidity |
| Initial plate roughness | 0.05 - 0.13 $\mu m$ Ra |
| Test intervals | 4300 cycles for dry tests<br>7100 cycles for lubricated tests |
| Total sliding distance | 4.8 km for dry tests<br>8 km for lubricated tests |

## 3. TEST RESULTS

### I- Wear of Steel Against Steel

**A) Under Dry Sliding Conditions**

Fig. 2 displays the variations of wear rate with sliding distance of steel pins reciprocating against steel counterfaces under applied loads of 5 and 10 N in dry sliding conditions. As can be seen, in the absence of magnetic field, the wear rates at both 5 and 10 N loads increase linearly with increasing sliding distance, being higher in values for the 10 N load. On the other hand, when the magnetic field was applied, the wear rates exhibit a linear decrease with the increase in sliding distance, either at 5 N or 10 N load. The tested lighter load (5 N) displays a significant reduction in wear rates with progressive sliding distances. In dry sliding tests, the wear rates are of $10^{-3}$ order of magnitude.

**B) Under Oil Lubricated Sliding Conditions**

Fig. 3 demonstrates the relationships between the wear rates and sliding distances for steel on steel in lubricated sliding under loads of 5 N and 10 N. In the absence of magnetic field, the presence of lubricant plays the major role in reducing the wear rates with progressive sliding distance, as shown for the 5 and 10 N loads. The later load obviously exhibits higher wear rate values compared with the 5 N load. Although the application of magnetic field between the rubbing surfaces results in lower wear rates at both investigated loads, compared with those obtained in the absence of magnetic field, but, as can be seen, the wear rates, for 10 N load, with the presence of magnetic field, increase with continuous sliding. On the contrary, the applied magnetic field resulted in large progressive reduction in wear rates with increasing sliding distance for the lower tested load (5 N). The wear rates in lubricated sliding are of $10^{-4}$ order of magnitude which demonstrates the high beneficial effect of the lubricant upon reducing wear when compared with dry sliding conditions.

### II- Wear of Brass Against Steel

**A) Under Dry Sliding Conditions**

The variations of wear rates with sliding distances, for brass pins sliding against steel counterfaces, under dry sliding conditions, are shown in Fig. 4. The results indicate that progressive reduction in the wear rates occurs with increasing sliding distances for the 5 N load while the 10 N load exhibit slight increase in wear rates with continuous sliding in the absence of the magnetic field. As in previous results, for steel on steel, the application of the magnetic field results in lower wear rates compared with those obtained in the absence of magnetic field at both tested loads. It is worth noting that in the presence of magnetic field, the 10 N load results in a linear increase in the wear rates with increasing sliding distance. However, the 5 N load exhibits a continuous linear decrease in the wear rate values with increasing sliding distance.

**B) Under Oil Lubricated Sliding Conditions**

Fig. 5 illustrates the resulted relationships between the wear rate and sliding distance for brass against steel under oil lubricated sliding conditions. As can be seen, all wear rate plots, either at 5 N or 10 N load and with the absence or presence of the magnetic field, decrease exponentially with increasing sliding distance. Similar to previous results, the presence of the magnetic field results in lower wear rate values then those obtained at

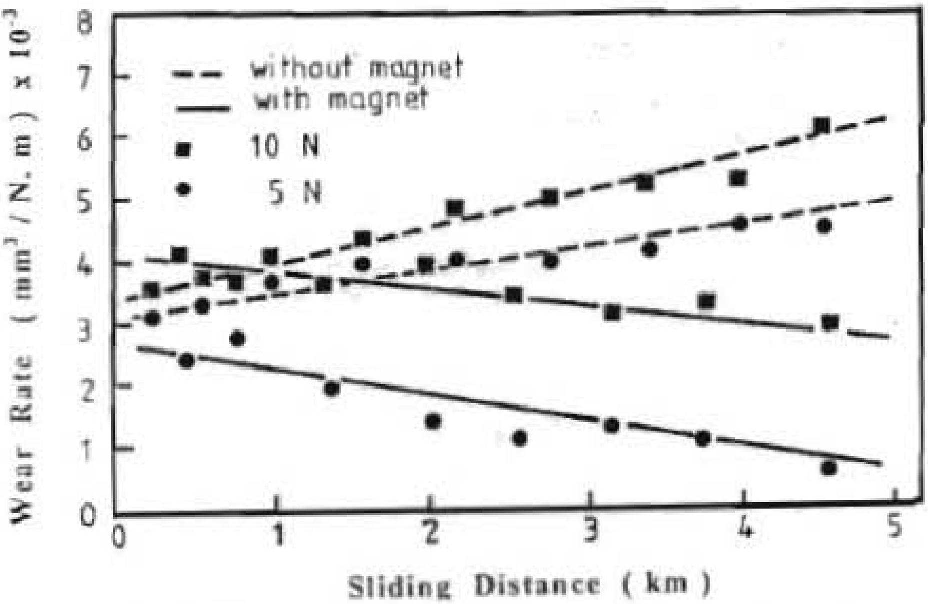


*Fig. 2 Variation of Wear Rate with Sliding Distance for Steel/Steel Combination under Dry Sliding Conditions.*

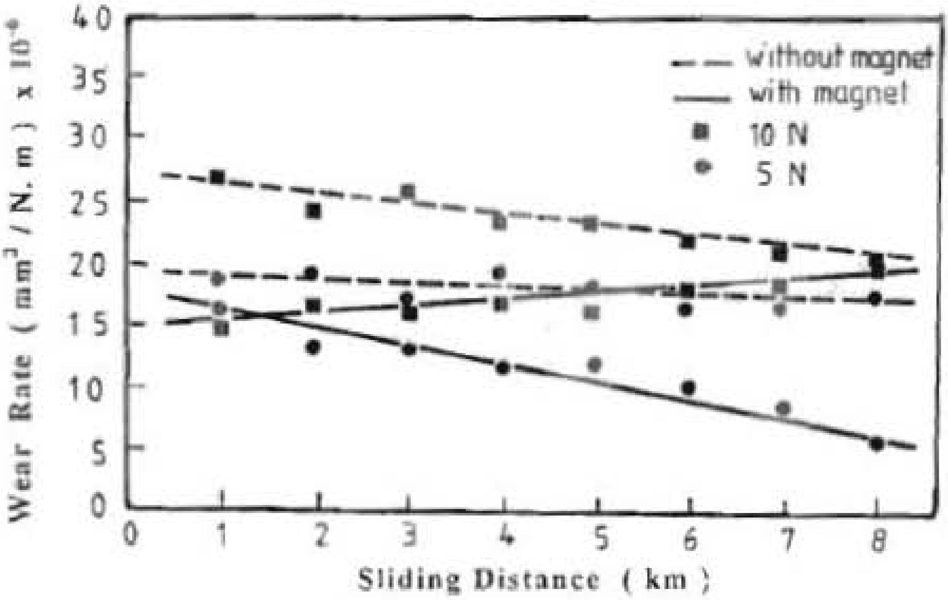


*Fig. 3 Variation of Wear Rate with Sliding Distance for Steel/Steel Combination under Oil Lubricated Sliding Conditions.*

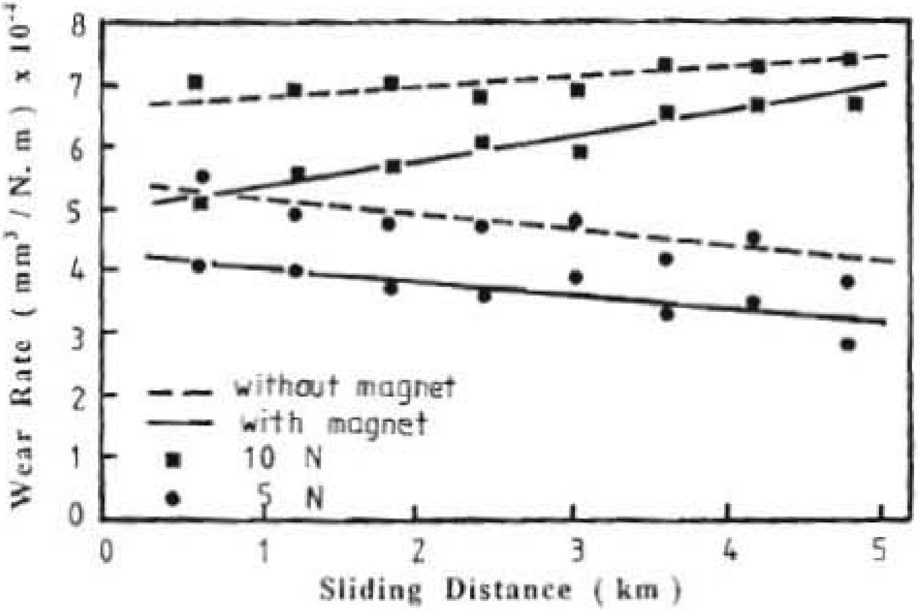


*Fig. 4 Variation of Wear Rate with Sliding Distance for Brass/Steel Combination under Dry Sliding Conditions.*

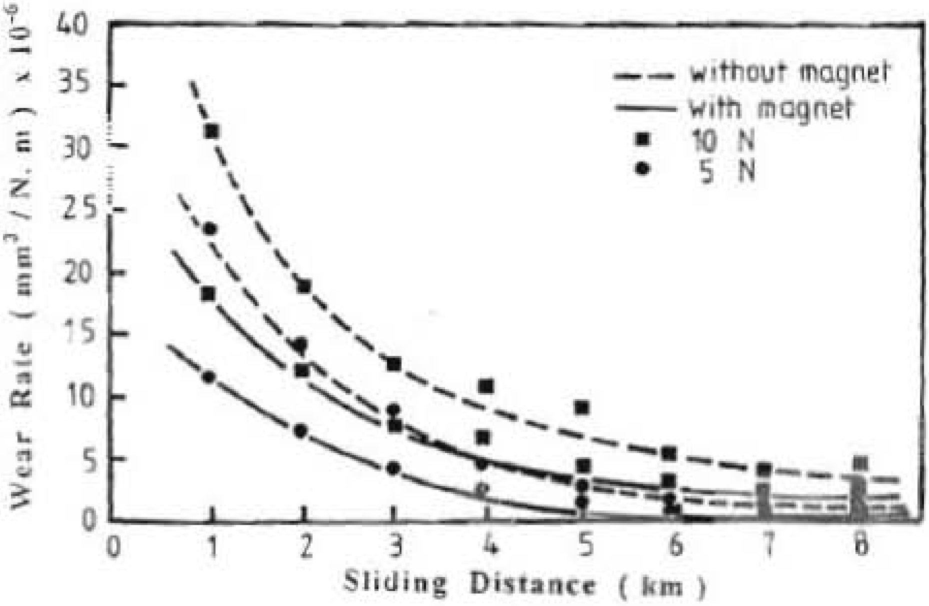


*Fig. 5 Variation of Wear Rate with Sliding Distance for Brass/Steel Combination under Oil Lubricated Sliding Conditions.*

similar sliding conditions without the magnetic field. The 5 N load, with the presence o magnetic field, exhibits the lowest values of wear rates against sliding distances.

### III- Counterface Surface Roughness Variations

Fig. 6 represents bar graphs for the variations of steel counterface surface roughness values for steel on steel and brass on steel under the different testing conditions. As expected, the deterioration in surface roughness is always higher with the utilization of the higher load tested (10 N) compared to that of (5 N). Furthermore, the presence of lubricant reduces to large extend the variation of surface roughness relative to the initial surface roughness. It is interesting to observe that the presence of the magnetic field has a highly beneficial effect upon reducing the increase in surface roughness to about 50% of the values obtained at similar testing conditions in the absence of the magnetic field. The reduction of roughness, in the presence of magnetic field, was noticed at the middle of the wear track where the sliding speed is maximum, therefore, Lorentz force is also maximum. On the other hand, measurements of roughness at the end of sliding tracks, where the sliding speed is zero and Lorentz force diminishes, reveal that relatively higher surface roughnesses are obtained. The reversal of sliding, at the ends of the wear tracks, also contributed to the increase in roughness, either in the absence or present of the magnetic field. Such reduction in surface roughness due to the magnetic field presence is more enhanced for steel on steel than for brass on steel. The main reason for that reduction is the attraction of wear debris to the magnet attached to the pin due to the magnetization of the debris. This phenomena is shown in Fig. 7. This eventually reduces the possibility of three body abrasion during sliding and results in decreasing wear rates and limited increase in surface roughness. In addition, the magnetic field results in generation of Lorentz force which tends to separate the contacting sliding surfaces thus decreasing the real area of contact and reducing wear.

It is worth noting that in the presence of both lubricant and magnetic field, the surface roughness values at the termination of tests were even lower than the initial surface roughness in particular with the lower tested load (5 N). The variations of surface roughness within the middle of sliding tracks, in the parallel and normal measuring directions to sliding, exhibit similar trends.

### IV- Optical Examination of Wear Tracks

#### A) Wear tracks for steel against steel

Optical examination of the wear tracks, resulting from tests of dry sliding of steel on steel, has revealed that there is a large deterioration in surface roughness. Transfer of steel to the counterface takes the form of loose and adhering particles which soften due to the large friction heating resulted. These softened dispatched and dispersed particles quickly cooled when subjected to air, forming rough surfaces. Some of these particles were pushed away to the edge of the wear track, as shown in Fig. 8. However, in the middle of the wear track, where maximum speed occurring, there is lack of heat dissipation which results in a completely molten layer shown in Fig. 9. Meanwhile, due to repeated sliding on the same track, some of the hardened molten transfer was subject to fatigue as cracks were formed within the matrix of these particles. Such fatigue manifested as crack initiation and propagation is shown in Fig. 10.

In the presence of the magnetic field in dry sliding, the metal transfer to the counterface was less due to the attraction of loose particles to the magnet, in particular at the middle of the

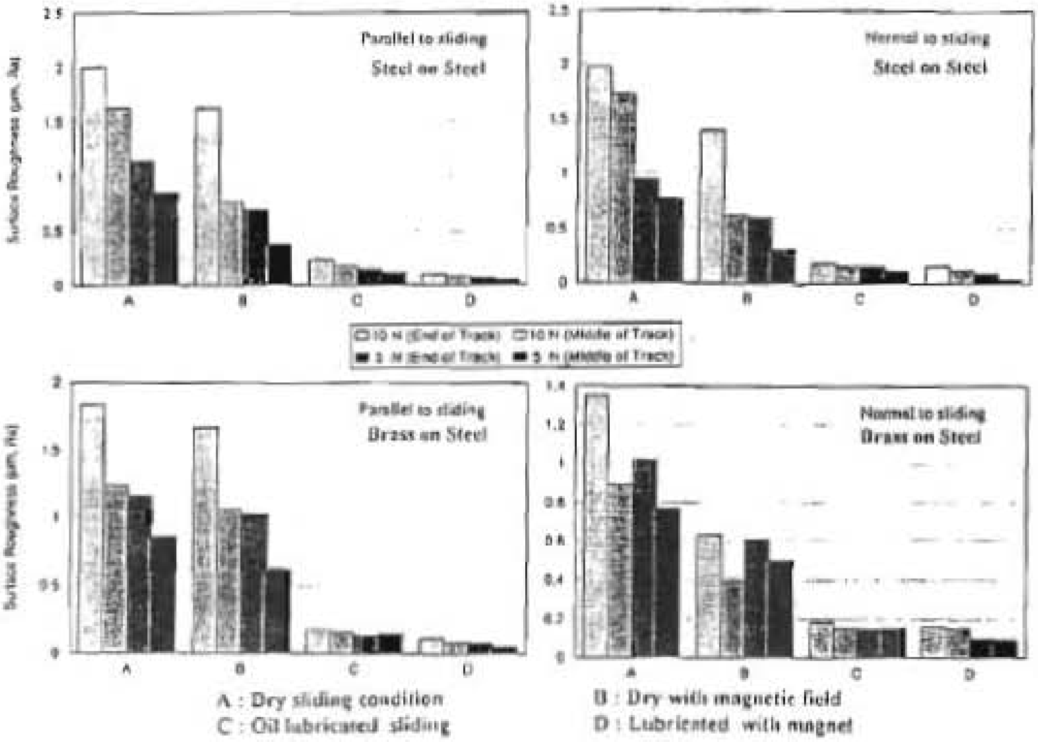


*Fig. 6 Surface Roughness Variations for Steel Counterfaces Relative to the Initial Surface Roughness.*

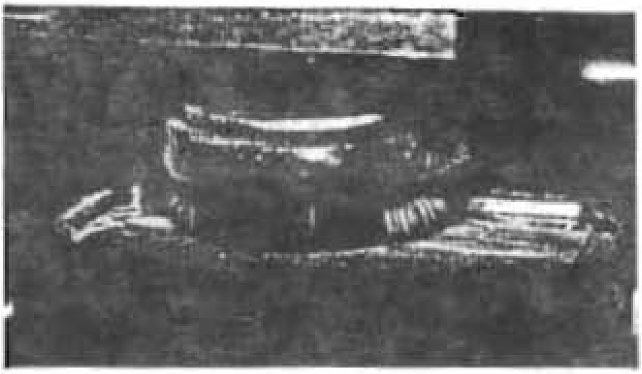


*Fig. 7 View for the Attracted Wear Particles to the Steel pin and the Magnet*

wear track. At the middle of track, magnetic force is maximum compared to the ends of the track where the roughness are higher in value due to the loose of the effect of the magnetic field. At these regions of the wear track, the impulsive character of friction forces at the point of reversal of velocity also contributes to the increase in roughness. Therefore, less tendency to high and large molten debris was encountered at the middle of the track. Generally, the metal transfer took the form of dispersed particles of small volumetric dimensions, adhering to the counterface, as shown in Fig. 11.

On the other hand, for lubricated tests, there was no significant changes in the surface roughness of the counterfaces prior and after testing. Occasionally, small detached minute particles adhered to the counterfaces, as shown in Fig. 12. Meanwhile, in the presence of the magnetic field, the resulting wear tracks were very smooth, approaching that of the initial roughness, with fine abrasion lines in the sliding direction, as shown in Fig. 13.


*Fig. 8. Steel fragment pushed out from the wear track ( x100).*


*Fig. 9. Optical micrograph showing a molten steel layer at the middle of track ( x100).*

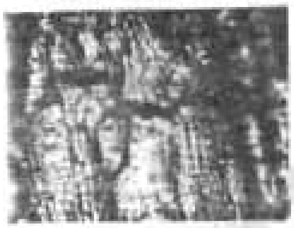


*Fig. 10. An optical view showing crack formation due to fatigue ( x400).*


*Fig. 11. Optical view showing a lumpy transfer in the presence of magnet. ( x100).*

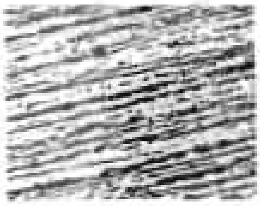


*Fig. 12. Optical view showing minimum transfer in steel oil lubricated tests ( x100).*

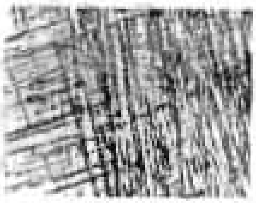


*Fig. 13. View showing the smooth wear track in lubricated tests with magnetic field ( x100)*

### B) Wear tracks for brass against steel

In the dry sliding of brass/steel combination, there was a transfer from the brass pins to the steel counterfaces. Adhesion plays the dominant role in the wear process. The brass transfer is facilitated by the softening process taking place at the interface. Examination of the wear tracks indicates that transfer occurred in the form of particles, which by repeated sliding, flattened on the steel surface while others jumped out the wear track as shown in Fig. 14. The molten brass transfer was also subjected to fatigue as cracks were detected. It is suggested that the cracks initiated beneath the surface, at weak points, then propagated to the surface resulting in surface area removal in these weak spots, as illustrated in Fig. 15.

In oil lubricated tests, transfer of brass to steel was minimized and took the appearance of descrete brass particles on the steel surface as shown in Fig. 16. However, in the presence of the magnetic field, the counterfaces remained smooth with slight improvement in surface roughness values relative to the initial surface roughness. Fig. 17 demonstrates the wear track in the presence of lubricant and magnetic field.

*Fig. 14. View for a brass fragment outside the counterface wear track.( x100).*

*Fig. 15. Optical micrograph showing evidence of fatigue wear mechanism. ( x400).*

*Fig. 16. Optical view showing the brass transfer to the steel counterface in oil lubricated tests ( x100).*

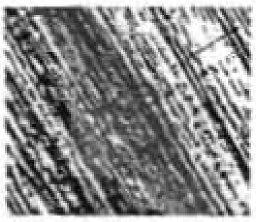


*Fig. 17. Appearance of smooth wear track for oil lubricated tests with magnetic field ( x 100).*

## V- Scanning Electron Microscopy of Wear Pin Surfaces

Most metals transfer from one surface to the other during unlubricated sliding. This transfer can be beneficial or detrimental to the wear properties, depending upon the topography generated. In the present study, scanning electron microscopy was conducted on the steel and brass pins to examine the transfer films from the counterface to the pin surface in the presence and absence of the magnetic field. Fig. 18(A) demonstrates the worn surface of the steel pin tested under a load of 10 N in the absence of magnetic field. Severe wear, manifested as deep sliding grooves, was noticed. This was accompanied by highly deformed build-up layers on the surface. On the contrary, in the presence of magnetic field, under similar testing conditions, the surface of the steel pin became smoother with build-up layers covering most of the parent material as shown in Fig. 18(B). This eventually contributed to the improvement in counterface surface roughness and the reduction in wear rate.

For brass pins sliding on steel counterfaces, under dry sliding conditions, scanning microscopy has revealed that, under a load of 10 N with no magnetic field applied, melting of the pin surface layer was encountered as shown in Fig. 18(C). In the presence of magnetic field, the melting layers were minimized and the surface became smoother, Fig. 18(D).

In lubricated tests, for brass on steel, minimum wear rates were reported and no significant variations in counterface surface roughness were observed. Fig 18(E) illustrates the brass pin surface for tests conducted under a load of 10 N in the absence of magnetic field. As can be seen, small embedded wear particles were noticed in the bulk material. These particles contributed to the slight increase in the surface roughness, relative to the initial roughness. On the other hand, with the application of magnetic field, at same sliding conditions, wear particles were minimized resulting in smoother surface roughness and minimum wear rates. Fig. 18(F).

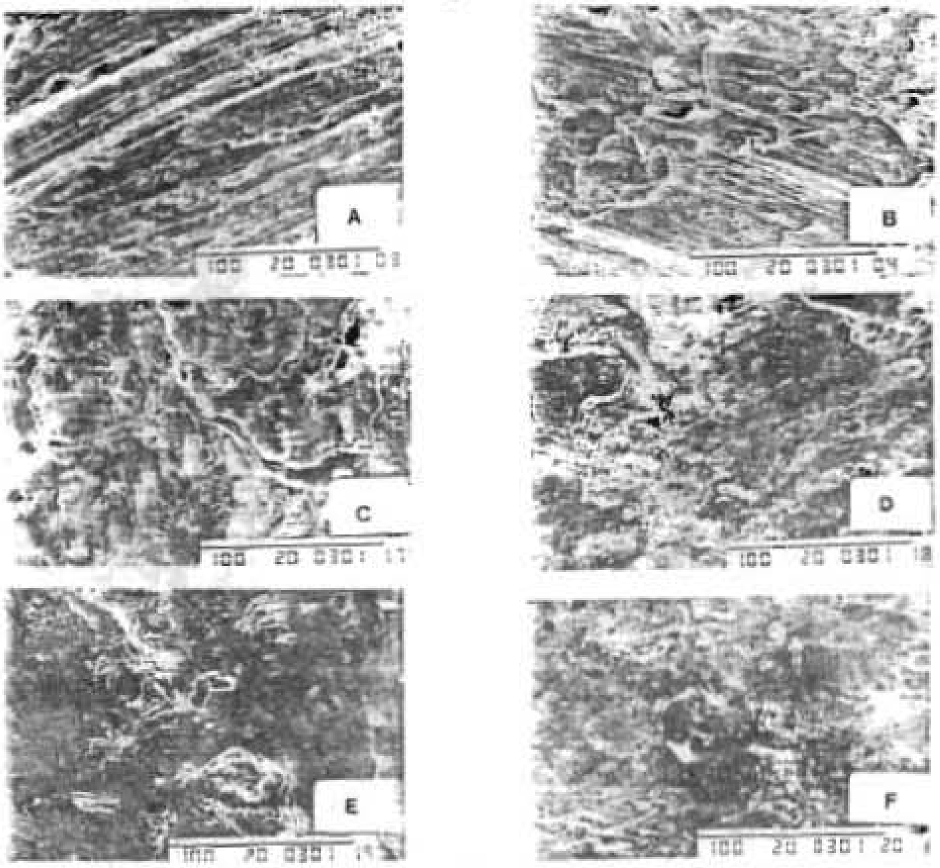


*Fig. 18. SEM pictures of the morphology of the wear pin surfaces*

(A) *Steel pin surface (Steel/Steel, Dry sliding, no magnetic field, 10 N, L= 4.8 km)*; (B) *Steel pin surface (Steel/Steel, Dry sliding, magnetic field, 10 N, L= 4.8 km)*; (C) *Brass pin surface (Brass/Steel, Dry sliding, no magnetic field, 10 N, L= 4.8 km)*; (D) *Brass pin surface (Brass/Steel, Dry sliding, magnetic field, 10 N, L = 4.8 km)*; (E) *Brass pin surface (Brass/steel, Lubricated sliding, no magnetic field, 10 N, L= 8 km)*; (F) *Brass pin surface (Brass/Steel, Lubricated sliding, magnetic field, 10 N, L = 8 km)*;

## 4. DISCUSSION OF RESULTS

The present experimental investigation has revealed that the presence of a magnetic field, between rubbing surfaces, has a remarkable effect upon the wear rate and surface roughness variations. For steel or brass pins, reciprocating against steel counterfaces, under 5 or 10 N load, the magnetic field results in lower wear rates and improving surface roughness compared to similar tests performed without magnetic field. Some investigators [7,9] speculated that the only dominant reason for wear rates reduction, under dry sliding of metals, is the oxidation promoting effect occurring to metals in the presence of magnetic fields. They noted that this accelerated oxidation disturbs the mutual transfer and growth and results in finer wear particles. Accordingly, the wear decreasing effect of the magnetic field is caused by the fine wear particles formed by promoted oxidation and then attached to the wear surfaces due to magnetization forces. The present results are in agreement with previous works in that the presence of magnetic field reduces the wear rates of metals. However, our reasons for such wear rate reduction contradict with those proposed by previous mentioned investigators. The present work has clarified that, in dry sliding of steel on steel, the metal transfer in the presence of magnetic field, was much reduced. It is proposed that two main reasons are responsible for wear rate reduction and improvement in counterface surface roughness under magnetic field. The first is the change of contact mechanism from three-body abrasion (metal/transfer/metal) to mainly two-body abrasion (metal/metal) due to the attraction of loose wear particles to the magnet during sliding. The second reason is the mutual repulsion created by Lorentz force between the sliding surfaces as the pin and counterface acquire the same sign of charge in the presence of the magnetic field. Evidence of such repulsion is manifested at the middle of the wear track where Lorentz force reaches its maximum value due to the maximization of sliding speed. Moreover, this repulsive force is more enhanced under the lighter normal load tested. Evidence of such repulsion is observed in Fig. 2, where the reduction of wear rates, under the lighter load, is much higher then that under the heavier tested load. It is worth noting that there was no sign of wear particles oxidation, which was proposed by other investigators, as the wear particles did not grow darker in color which would suggest that oxidation is promoted by the magnetic field.

Similar behaviors for the wear rates and counterface surface roughnesses in the presence of magnetic field are manifested in lubricated tests. The wear rates obtained in the presence of magnetic field were lower in values than those for tests performed under similar conditions without magnetic field. The proposed oxidation effect, put forward by previous workers, is not also valid for the lubricated sliding reduction in wear due to the presence of oil which contains anti-oxidant additives, thus preventing the oxidation of contact surfaces and wear particles. For lubricated tests, it is suggested that magnetohydrodynamic lubrication will be in action in the presence of magnetic field. This type of lubrication will generate lifting pressure capable of decreasing the real area of contact between the sliding surfaces, thus reducing wear rates to minimum values in particular under light load. The results obtained in lubricated sliding support such suggestion as the wear rates under 5N load decreased linearly to about 75% of their initial wear rate value within the duration of test. The counterface roughness at the end of lubricated tests were almost similar in values to the initial roughness.

For brass sliding on steel, either dry or lubricated, the influence of magnetic field upon wear rates has a similar trend to that of steel on steel. The wear rates in magnetic field were lower in values than those obtained for similar tests with no magnetic field. However, the lubricant plays a major role in reducing wear rates when comparing dry and lubricated wear values. For steel on steel, the dominant wear mechanisms during sliding were abrasive and fatigue, while for brass on steel adhesive and fatigue were more enhanced. In lubricated sliding for brass on steel there was no significant changes in the counterface surface roughnesses compared to the initial roughness. Therefore, the mutual repulsive forces in dry sliding and the magnetohydrodynamic lubrication in lubricated sliding were the two main mechanisms responsible for the reduction in wear rates and the limited increase in surface roughnesses.

## 5. CONCLUSIONS

From the obtained results, the following conclusions can be deduced:

1. The presence of magnetic field between rubbing surfaces, in the early stages of sliding, decreases the wear rates of steel/steel and brass/steel combinations either under dry or lubricated sliding conditions. The influence of magnetic field is more enhanced under light load and relatively high sliding speed. However, severe wear rates may be expected at longer sliding distance due to premature fatigue effects.
2. The wear decreasing effect of the magnetic field, in dry sliding of steel against steel, is caused by the change of contact from three-body to two-body abrasion mechanism and the reduction of real contact area due to repulsive forces (Lorentz force).
3. The main dominant wear mechanisms for dry sliding of steel on steel, under the tested conditions, are abrasive and fatigue, as noted by optical microscopy and SEM.
4. Magnetohydrodynamic lubrication, gained in the presence of lubricant and magnetic field, reduces wear rates and improves surface roughness of tested combinations, in particular at the middle of the wear track where the magnetic field is maximized.
5. For brass sliding against steel, adhesive and fatigue wear mechanisms are dominant under reciprocating dry sliding conditions.
6. The influence of magnetic field in reducing wear and improving surface roughness is more noticeable for steel/steel than for brass/steel combinations.
7. At the middle of the wear track the surface roughness was lower in Ra value than at the ends of the track due to the effectiveness of magnetic force at the middle of track.
8. SME of the steel and brass pin surfaces has revealed that build-up layers were adhered to the parent material in dry sliding conditions and were less in the magnetic field.

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