Effect of Soft Material Hardness and Hard Material Surface Morphology on Friction and Transfer Layer Formation; Lubricated Condition

M Basavaraju, S Ranganatha

Abstract - Hot and cold forming of metals is carried out in industry for manufacturing engineering components. Such manufacturing processes employ dies, whose surface condition is one of the factors which characterize the surface finish of engineering components. The surface finish of engineering components is largely influenced by the tribological phenomenon at die and components interface. Lubrication, morphology and hardness of die surface are found to control surface finish of the products. In the present investigation a pin-on-plate sliding tester was used to identify the effect of surface morphology, lubrication and hardness on co-efficient of friction and transfer layer which characterizes the tribological behaviour. The morphology of mild steel (EN8) plate surfaces were modified by employing three different surface modification methods like grinding (silicon carbide wheel polishing), shot blasting and electric discharge machining methods. Surface roughness parameters which characterize the morphology of the steel plates were measured using a three dimensional optical profilometer. Role of hardness is studied by employing lead, copper and Aluminum (Al6082) pins which were slid against steel plates. Experiments were conducted for plate inclination angles of 1, 1.5,2 and 2.5 degrees. Normal load was varied from 1 to 150N during the tests. Experiments were conducted under lubricated condition in ambient environment. Scanning electron microscope was used to study the formation of transfer layer on plate and pin surfaces. It was observed that the co-efficient of friction and transfer layer formation were found to depend on the surface morphology of the harder surface under lubricated condition. The quantum of transfer layer formation on the surfaces is found to increase with increase in surface roughness.

Key words- friction, lubrication, hardness, surface morphology and transfer layer formation.

I. INTRODUCTION

In engineering applications where transfer of force, heat and electricity from one component to another component takes place through contacting interface, the extent of transfer of the above parameters requires detailed study of phenomenon which occurs at the interfacing contacting surfaces. Attempts have been made by different researches to scientifically understand the phenomenon at the interface. They have identified that the contact is established over a fraction of area called real area of contact instead of apparent area of contact [1-4]. They also identified that the contacting surface on microscopic scale is not smooth but consisting of asperities.

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The real area of contact, being fraction of apparent area of contact, leads to large magnitude of stresses at the real area of contact. Though the estimated engineering stresses based on apparent area of contact were smaller in magnitude than the design stresses; the actual stresses were large in magnitude than yield stresses of material and which brings about elastic, plastic deformation and fracture at the interface [2]. The surfaces are consisting of asperities which lead to a case of non-confirming contact. Hertzian contact theory which is applicable to non-conforming surfaces is one way or other way is made use by all researches to estimate the stresses at the contact interfaces [3]. Mindlin[5] gave a solution for sliding contact where in he assumed that the shear stress at contact surfaces is proportional to normal stress and proportionality constant is same as the co-efficient of friction between two interacting faces. Archard [6] tried to verify the Amontons's law considering the elastic deformation of surface asperities. Though elastic deformation of a single asperity does not explain the Amontons's law, in case of confirming surfaces the elastic deformation of many asperities do explain the Amontons's law. Similar observations are found for lubricated surface. Greenwood [7] and others used Hertzian contact theory to estimate stresses and deformation at contact surface where it is a case of multiple contacts. These attempts could not satisfactorily explain actual contact phenomenon i.e. these approach could not explain the in-elastic contact phenomenon at the interfaces. Bowden and Tabor [8] used these concepts in electrical contact and frictional problems. Staph [9] studied the effect of surface texture and surface roughness on scuffing using caterpillar disc tester. Attempts made to understand the surface finish and tolerance of the extrudate in extrusion process were also basically contact problems. Studies on the number of extrusion trials confirmed that the finish was improved after a minimum of three trials [10]. Providing a smaller amount of choking angle improved the surface finish of the product. It was reported that there was periodic variation in surface finish and this was found to be due to periodic variation in the thickness of transfer layer. It was reported that the best surface was obtained when the surfaces of polished and parallel ground dye were nitrated and sintered. [11]. Archard and Hirst [12] studied wear of wide range of material combination under loads ranging from 50gm to 10kg and speeds of 2 to 60cm per second were studied. It was suggested that the wear rate was proportional to load; in practice this simple relation is modified because the surface conditions depends on load. Azushima, and Sakuramoto[13] conducted a tension bending type of test to understand the tribilogical behaviour between die and work piece showed that in the presence of lubricant,

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the surface roughening was predominant with constant coefficient of friction at lower average contact pressure, whereas at higher average contact pressure the asperities were found to be flattening with decrease in co efficient of friction.

Koura [14], taking surface texture into consideration, developed a theoretical model for estimating adhesion and abrasion friction co- efficient. The results showed that frictional values depend on degree of surface roughness. Whitehead [15] conducted experiments on different materials for validating Amontons's law. It was found that when experiments were conducted on electrolytically polished copper surface; for small loads, the sliding did not obey Amontons's law. The deviation of Amontons's law was attributed to formation of oxide layer. Experiments were also conducted on lubricated conditions. Thus in these experiments the Amontons's law was not justified in general where as the results of dry sliding confirmed the Amontons's law.

Kerridge and Lancaster [16] conducted a severe type of wear to understand basics of wear. The system was brass against a harder material component and conditions gave metallic debris. Two distinct steps in wear were recognized. They were transfer of material and formation of debris from transfer layer. Nellemann and Bay [17] initially developed a model to incorporate the influence of normal load, asperities slope, friction factor and lubricant bulk modulus on friction and real area of contact. Results showed that only normal pressure and bulk modulus have influence. Theng-ShengYang [18] developed a new model to predict the surface roughness of product under lubricated condition. This model predicted the surface more accurately in case of lubricated sheet metal forming.

Rigney and Hirth [19] developed a model to identify the source of friction in case of steady sliding. This model is based on plastic deformation at near surface. The model predicted well on the dependence of friction on load, sliding distance, surface temperature and micro structure. Suh and Sin [20] made attempt to explain friction with new theory; this theory was taken into account of sliding distance and environment. The theory suggested that the compatibility of sliding surface is dictated by mechanical properties like hardness than relative solubility.

II. EXPERIMENTAL PROCEDURE

Lead, Copper and aluminium (Al 6082) which are soft compared to harder mild steel (EN8) are machined to the shape of pin whose dimensions are shown in figure1. The EN8 steel is machined in the form of plate and whose dimensions are shown in figure 2. All dimensions are in mm.

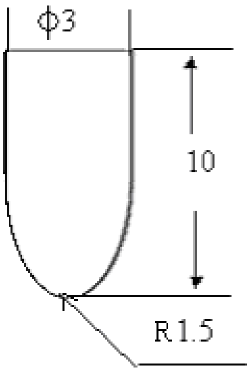

Fig.1. Dimensions of pin

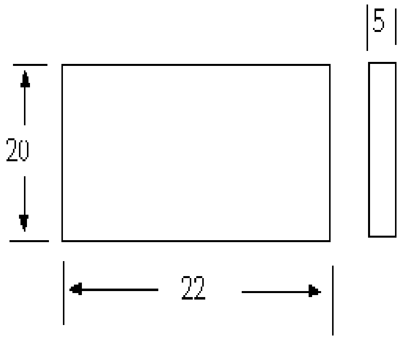

Fig. 2.Dimensions of Mild Steel (EN8) Plate

The EN8 flat surfaces were modified by three manufacturing processes, which are grinding (Silicon Carbide wheel polishing), sand blasting and electric discharge machining (EDM).The surface of such modified plates were studied using non contact type three dimensional optical profilometer. The average surface roughness parameter R_a was measured and recorded for each surface. Figure.3 shows the three dimensional surface profile of flat.

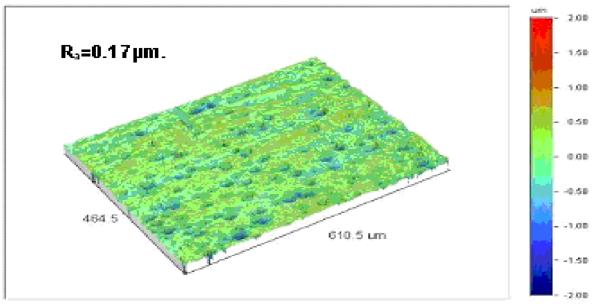

Fig.3 (a): The three dimensional view of ground (SiC wheel polished) plate surface.

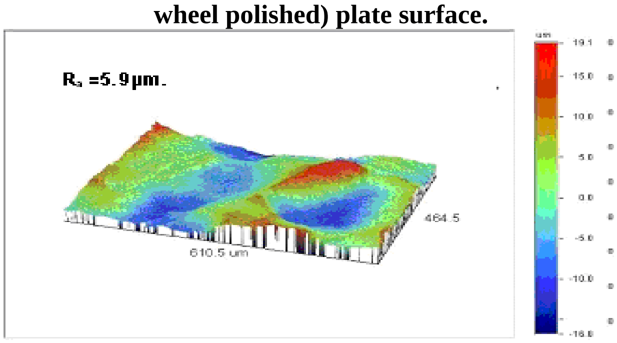

Fig.3 (b): The three dimensional view of shot blast plate surface

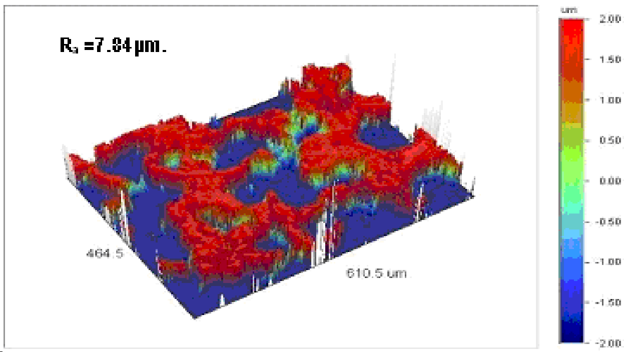

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Fig.3(c): The three dimensional view of EDM plate surface.

The average surface roughness value R_a of ground (Silicon Carbide wheel polished), sand blast and electric discharge machined (EDM) surfaces were respectively found to be 0.17µm, 5.90µm and 7.84µm. The R_a of ground (Silicon Carbide wheel polished) surface was minimum and R_a of Electric discharge machined surface was maximum. All the three surfaces were found to be peak dominated.

The pins were electro polished to remove any work-hardened layers that might have formed. Before each experiment the pins and steel plates were thoroughly rinsed with an aqueous soap solution. This was followed by cleaning the pins and plates with acetone in an ultrasonic cleaner.

The experiments were conducted using an inclined pin- on-plate sliding tester also called an inclined Scratch tester. It was also used to find the effect of load on the co-efficient of friction. A schematic diagram of pin and inclined plate is shown in figure 4.

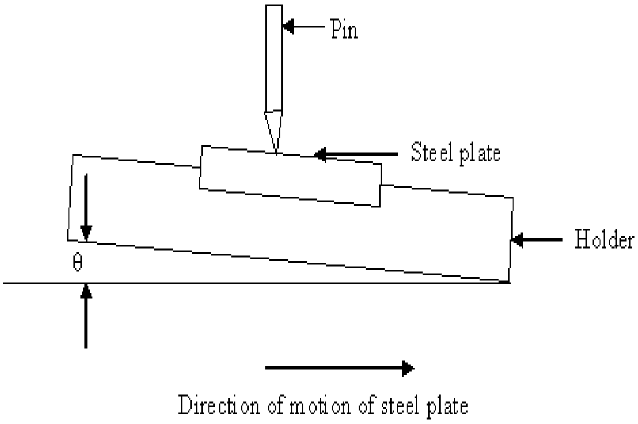

Fig .4: Schematic diagram of Pin on Plate with Inclined steel plate.

The cleaned pins were slid at a velocity against the cleaned lubricated EN8 steel plates from lower end to the higher end of the inclined surface for a sliding length of approximately 10 mm. The normal force and shear forces were continuously monitored using a computerized data acquisition system. The normal load was varied from 1-150N during the test. The co-efficient of friction µ, which is the ratio of the shear force (T) to the normal force (N), was calculated from the recorded forces using the formula

$$\mu = \frac{T}{N} = \frac{F_T \cos\theta - F_N \sin\theta}{F_T \sin\theta + F_N \cos\theta}$$

Experiments were conducted for different parameters under lubricated condition.. The parameters were surface roughness (R_a), hardness of pin and plate inclination angle (θ). Pins used were lead, copper and aluminium. The surface roughness was characterized by R_a. The plate inclination angle was 1, 1.5,2 and 2.5 degrees.

For each parameter the sliding tests were conducted under lubricated conditions on each plate in ambient environment. Engine oil lubricant (SAE 40, API rating SJ class)of 0.05ml was applied to the steel surface and tests were performed. The lubricant oil viscosity was found to be 40 cSt at 40 degree Celsius. For each inclination angle the test were conducted for different surface roughness values in lubricated condition. Tests were performed to obtain five parallel lubricated wear tracks on the same plate for each inclination angles. After experiment the pins and EN8 flat surface were studied in scanning electron microscope (SEM) to understand the origin of transfer layer and its relation with estimated friction co-efficient.

III. RESULTS AND DISCUSSIONS

The typical dependency of co-efficient of friction on sliding distance for ground (SiC polished), sand blast and EDM surfaces are respectively shown in figures 5, 6 and 7. The Y axis indicates co-efficient of friction values and X axis indicates the sliding distance in mm.

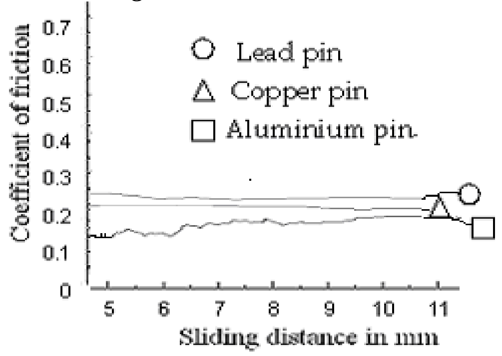

Fig. 5: Dependency of co-efficient of friction with sliding distance for ground (SiC polished) steel surface.

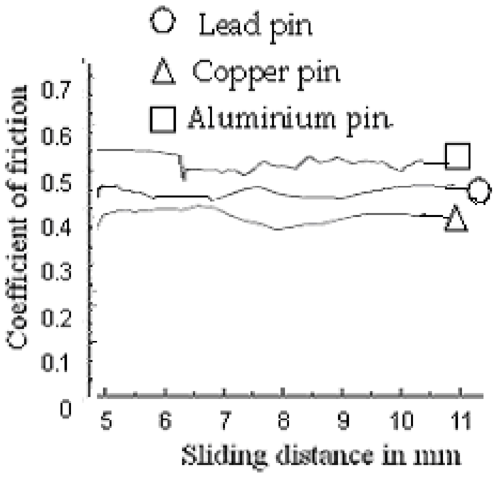

Fig. 6: Dependency of co-efficient of friction with sliding distance for shot blast steel surface.

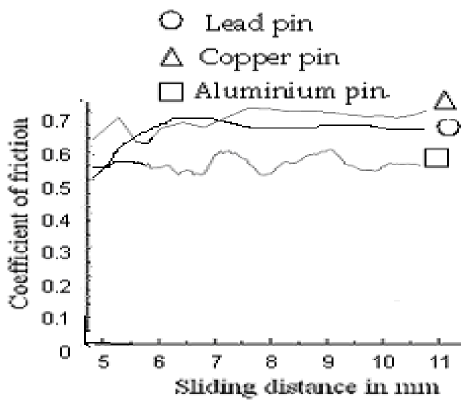

Fig.7: Dependency of co-efficient of friction with sliding distance for EDM surface

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The graphs shown in fig.5, Fig.6 and Fig.7 show the dependency of co-efficient of friction on sliding distance. The co-efficient of friction was found to be steady with sliding distance. The co-efficient of friction for lead is found to be more when compared to copper and aluminium pins for ground (SiC wheel polished) surface. In case of shot blast surface the aluminium pin was found to have maximum co-efficient of friction instead of lead and copper pin. In case of EDM surface the co-efficient of friction for copper pin is maximum. Further the co-efficient of friction is found to increase with R_a of the surfaces. The steady state of sliding is found for all the sliding experiments and average frictional co-efficient is found from these experiments. These average co-efficient of friction are made use to understand the effect of plate inclination angle, hardness of pin and surface roughness of the flat surfaces in presence of lubrication. The average co-efficient of friction was estimated and its dependency on plate inclination angle are shown in figures 8(a)(b)and (c), when lead, copper and aluminium pins were slid against ground (silicon carbide polished), shot blast and electric discharge machined steel surfaces. The curves with open symbols represent the lubricated sliding.

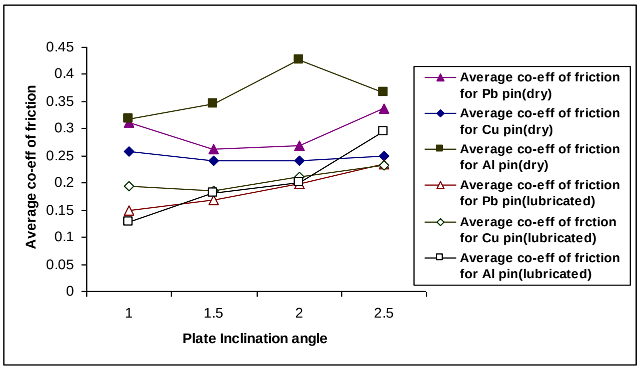

Fig. 8(a): The dependence of Average co-efficient of friction with plate inclination angle when Pb, Cu and Al pins slid on ground (SiC) steel surfaces.

The average co-efficient of friction for aluminium pins slid on ground (SiC) steel surfaces under lubricated condition was found to be independent of plate inclination angle. Whereas in case of copper and lead pins the co-efficient of friction under identical condition was found always smaller for lubricated surface compared to dry surface. Under lubricated condition, in general, the co- efficient of friction was found to be independent of plate inclination angle.

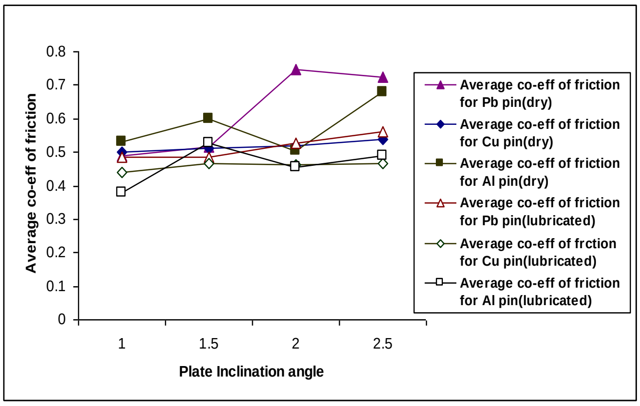

Fig. 8(b): The dependence of Average co-efficient of friction with plate inclination angle when Pb, Cu and Al pins slid on shot blast steel surfaces

The average co-efficient of friction in case of shot blast surfaces which is shown in figure 8(b),similar to ground (SiC) steel surfaces, was also found not to vary much with plate inclination angle, except a small fluctuation in average co-efficient of friction value for aluminium pin at an inclination angle of one degree. The co-efficient of friction value under identical condition was found to be less for lubricated sliding compared to dry sliding.

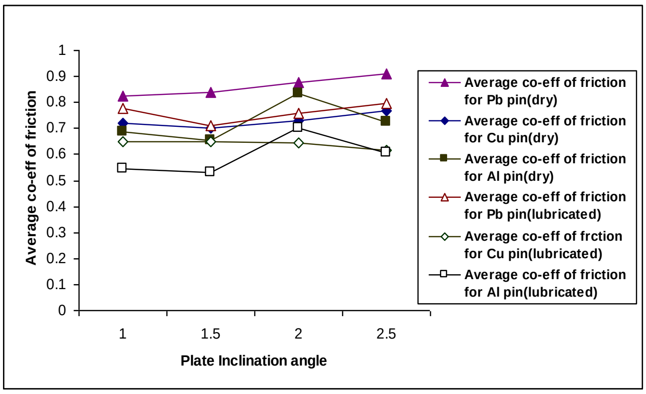

Fig. 8(c): The dependence of Average co-efficient of friction with plate inclination angle when Pb, Cu and Al pins slid on electric discharge machined steel surfaces.

Figure8(c) shows that co-efficient of friction values for lead and copper was found to be independent of plate inclination angle, whereas there was marginal increase in friction value for aluminium pin. The friction value for lubrication condition like in other two surfaces was found to be less compared to dry sliding. The average co-efficient of friction for lead, copper and Aluminium pins were plotted against the roughness parameter of the harder steel surface at various plate inclination angles. These plots are shown in figures 9(a), 9(b), 9(c) and 9(d).

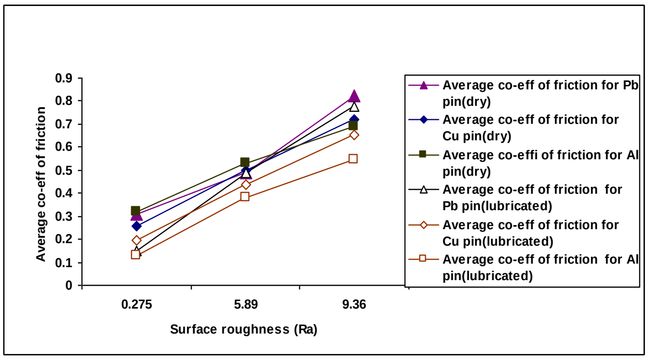

Fig. 9 (a): The variation of average co-efficient of friction with surface roughness (R_a) for Pb, Cu and Al pins slid on steel surfaces when θ=1 degree.

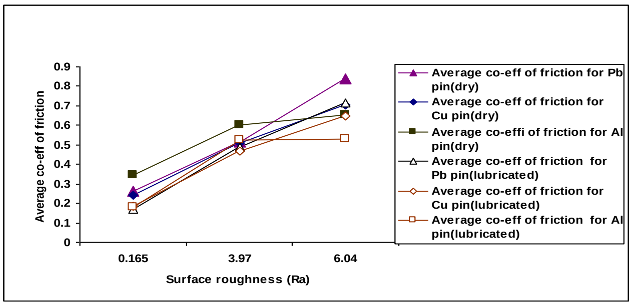

Fig. 9 (b): The variation of average co-efficient of friction with surface roughness (R_a) for Pb, Cu and Al pins slid on steel surfaces when θ= 1.5 degree

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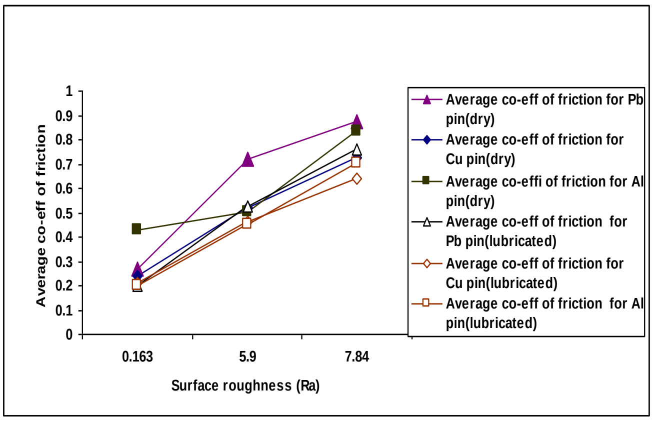


Fig. 9 (c): The variation of average co-efficient of friction with surface roughness (R_a) for Pb, Cu and Al pins slid on steel surfaces when θ= 2 degree

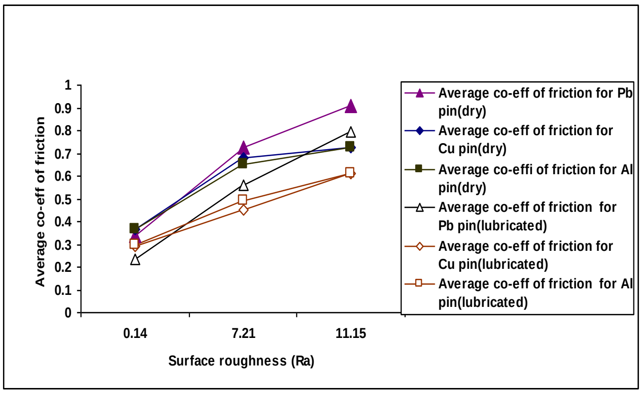
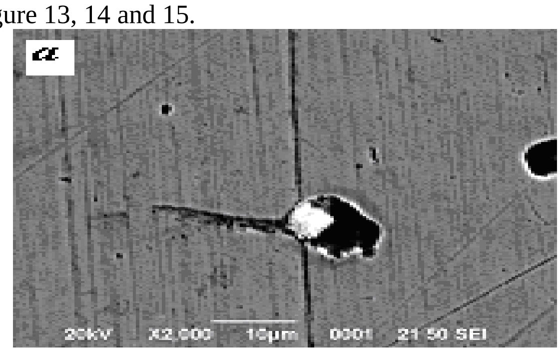


Fig. 9 (d): The variation of average co-efficient of friction with surface roughness (R_a) for Pb, Cu and Al pins slid on steel surfaces when θ= 2.5 degree

The average co-efficient of friction as shown in figure 9(a), 9(b), 9(c) and 9(d) for all pins in general is found to increase with increase in surface roughness of the harder steel surface . The co-efficient of friction for lead was found to monotonically increase with surface roughness R_a irrespective of plate inclination angle. Similar trend was not obtained for copper and aluminium pins. The experiments showed larger extension of dependency of co-efficient of friction with respect to morphology of surfaces. In general the co efficient of friction is found to be less for lubricated sliding than dry sliding.

The transfer layer on EN8 steel plates and pin surfaces when lead, copper and aluminium slid were studied using scanning electron microscope (SEM) for understanding the dependency of co-efficient of friction on morphology of surfaces.

The scanning electron micro graphs (SEM) of transfer layer on EN8 surfaces are shown in figure 10, 11 and 12.The scanning electron micro graphs (SEM) of pins are shown in figure 13, 14 and 15.



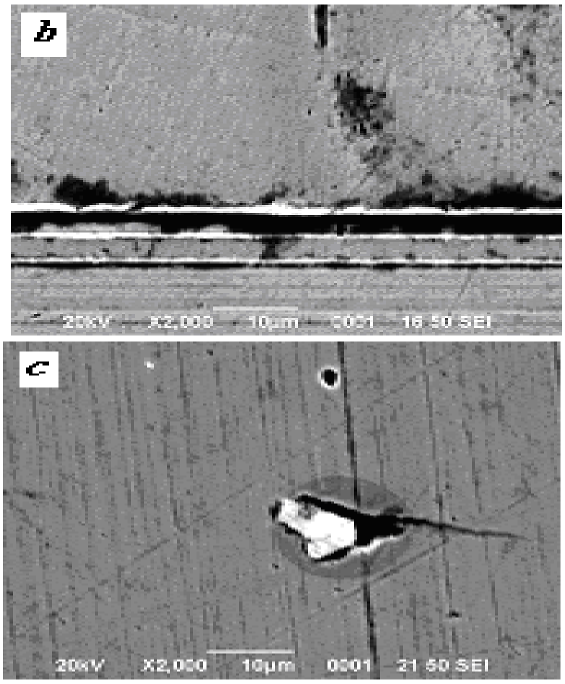


Fig.10 (a) (b) and (c): SEM micrographs showing lead, copper and aluminium transfer layer on ground EN8 steel surfaces (SiC wheel polished). (X2000)

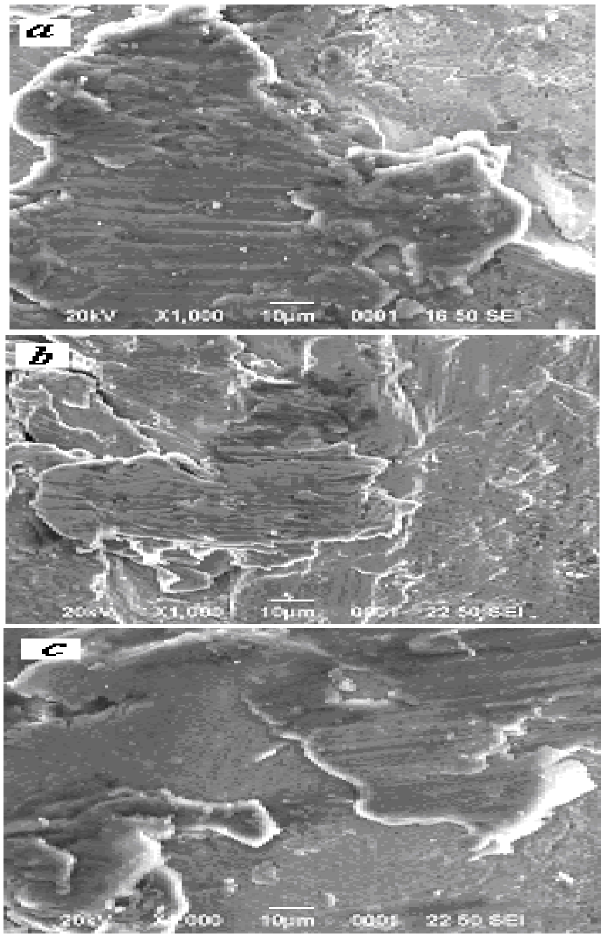


Fig.11 (a) (b) and (c): SEM micrographs showing lead, copper and aluminium transfer layer on shot blast EN8 steel surfaces. (X1000)

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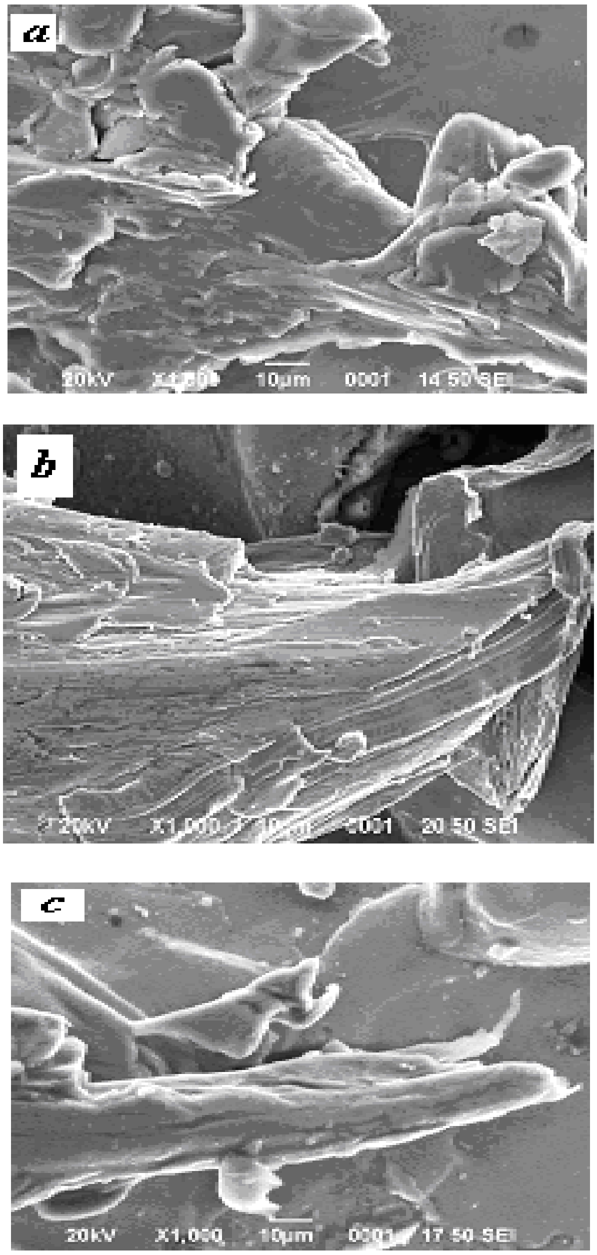
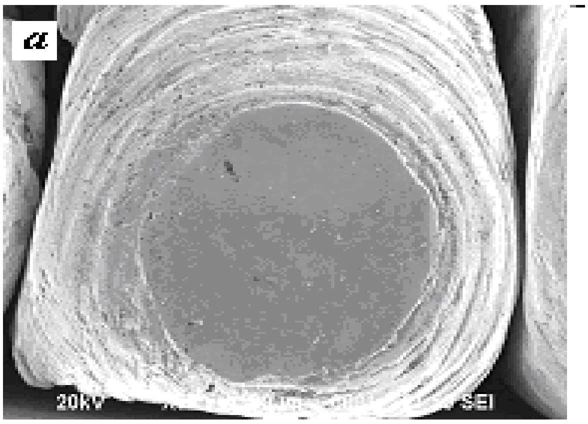


Fig.12 (a) (b) and (c): SEM micrographs showing lead, copper and aluminium transfer layer on electric discharge machined EN8 steel surfaces. (X1000)

The transfer layer in figure 10, 11 and 12 revealed that the quantity of transfer layer for lead is more compared to copper and aluminium. The energy spent in forming quantum of transfer layer explains the difference in friction for lead, copper and aluminium pins



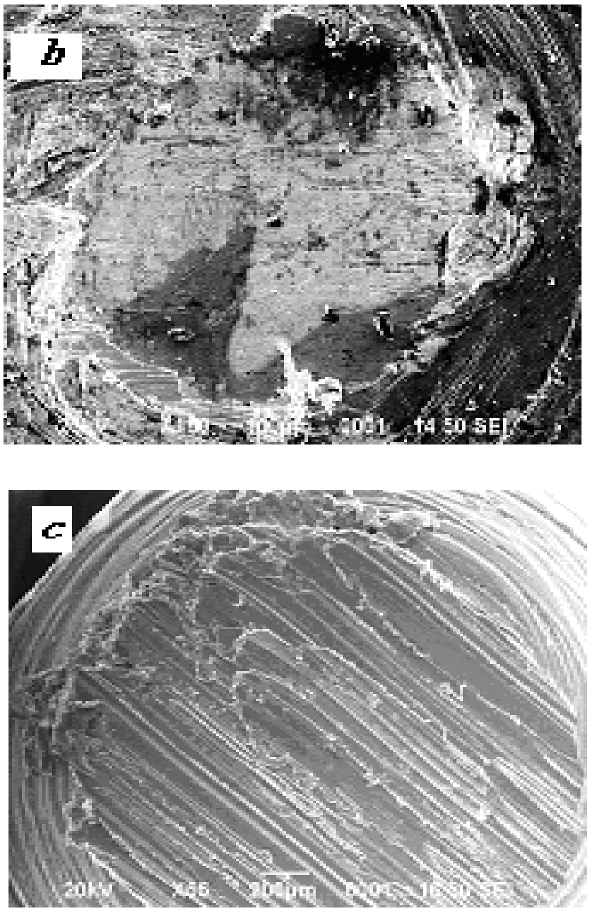
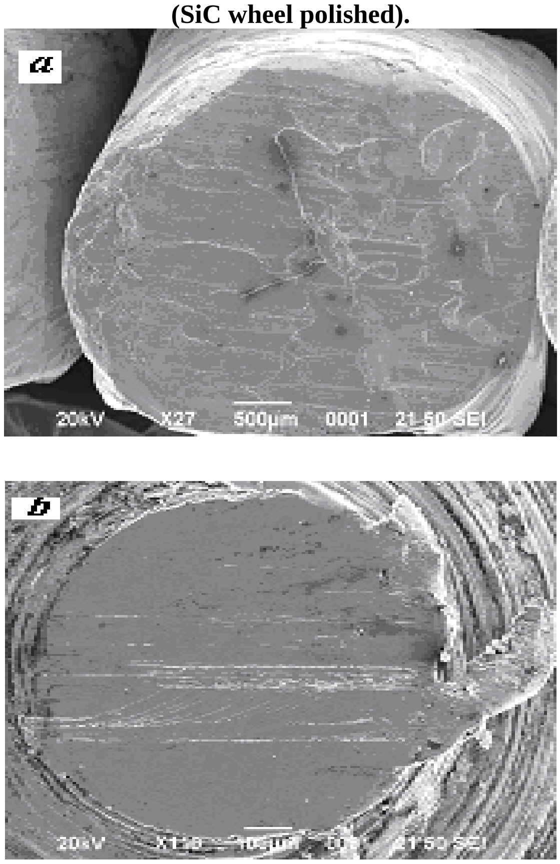


Fig.13 (a) (b) and (c): SEM micrographs of lead, copper and aluminium pins after sliding on EN8 steel surface (SiC wheel polished).



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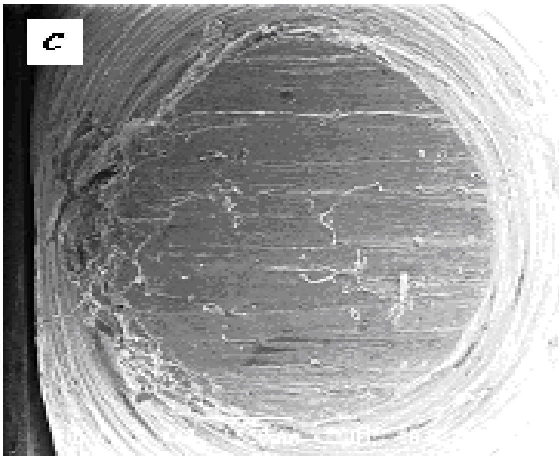

Fig.14 (a) (b) and (c): SEM micrographs of lead, copper and aluminium pins after sliding on shot blast surface.

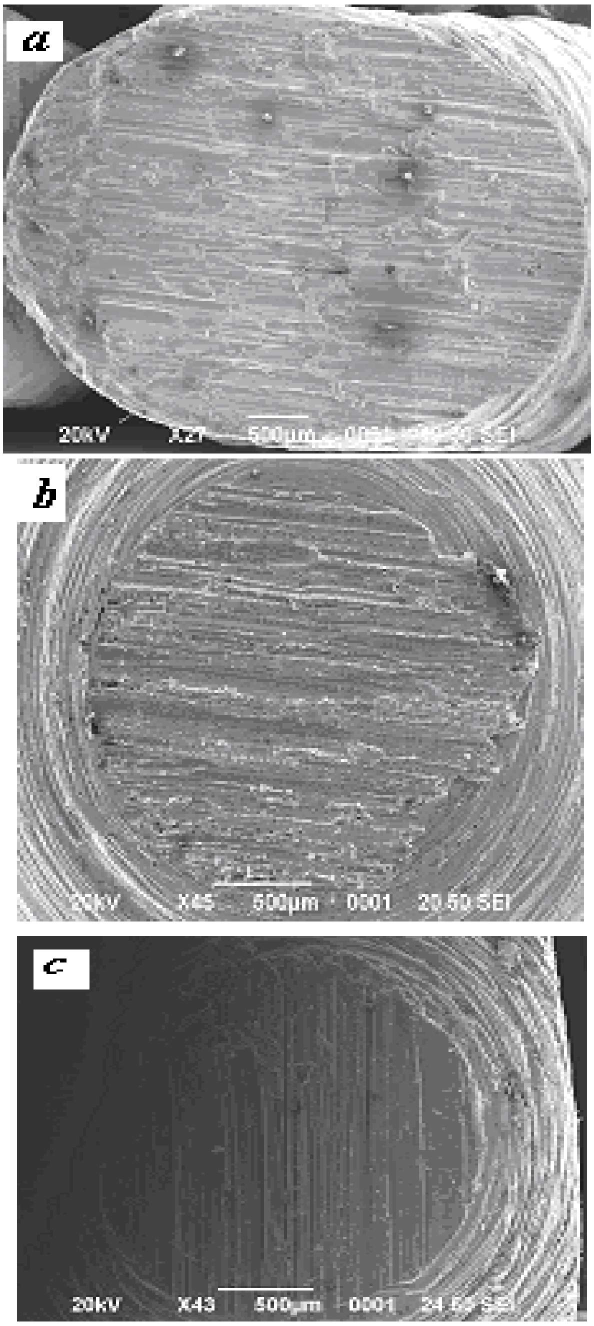

Fig.15 (a) (b) and (c): SEM micrographs of lead, copper and aluminium pins after sliding on electric discharge machined surface.

The lead pin surface is smoother for all steel surfaces compared to copper and aluminium pins. The smoothness of the lead pin surface is due to softness of the material.

IV. CONCLUSIONS

In the present investigation a pin-on-plate sliding tester was used to identify the effect of surface morphology and hardness on co-efficient of friction and transfer layer which characterizes the tribological behavior when lead, copper and Aluminum (Al6082) pins were slid against steel (EN8) plates for different plate inclination angles under lubricated condition in ambient environment.

The conclusions of the experiments are as follows;

- The dependence of co-efficient of friction against sliding distance under lubricated condition showed the steadiness of sliding.
- The average co-efficient of friction under lubricated condition was found not to vary much with plate inclination angle.
- The average co-efficient of friction under lubricated condition was found to increase with surface roughness (R_a).The increase in co-efficient of friction was found to be related to transfer layer formation.
- The quantum of transfer layer under lubricated condition was more as the co-efficient of friction increases
- The average co-efficient of friction under dry condition was found to be more compared to lubricated condition.

V. ACKNOWLEDGEMENTS

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