# MECHANICAL ENGINEERING

# 1. INTRODUCTION

Recently, great attention has been devoted to aluminium alloys, in particular aluminium-silicon alloy for the increasing demand to use it in all types of internal combustion engines. This alloy is widely used for the manufacture of pistons, cylinder blocks and cylinder heads as well as speed brakes and hydraulic components in aircrafts. As aluminium cylinder bores were more prone to scuff under conditions of poor or failure lubrication, thus aluminium cylinder blocks usually have cast iron liners or are electroplated. A major breakthrough in the use of Al-Si cylinder blocks was achieved by General Motors Corporation. They used a die-cast hypereutectic Al-Si alloy in which the surface of the cylinder bores was electrochemically treated to remove aluminium and leave primary silicon particles proud. The resulting surface offers excellent scuff resistance. On the other hand, Rolls-Royce, in 1900, introduced the aluminium plain bearings that were used later in aero-engine applications. Today, steel-backed aluminium 20wt% tin is the most common plain bearing material used in most internal combustion engines in UK

Studying the tribological characteristics of Al-Si alloys have been a matter of interest for tribologists as it represents a polyphase material in which bard particles of silicon are contained within a softer matrix of aluminium [1-5]. Many of these polyphase alloys are in use as wear resistant materials. If improvements in their performance are to be made, more needs to be known about the basic nature of their friction and wear mechanisms. Thus, the current study investigates the dry sliding friction and the wear rate of Al-Si-Cu alloy, which is currently being used as an engine block material in several types of internal combustion engines [6]. Al-Si-Cu alloy is tested against alumina ceramic material which recently has been used as piston ring material.

Sarkar [7-9] has investigated the wear mechanisms of Al-Si alloys and the effect of silicon composition, counterface material, heat treatment and sliding distance upon the wear. He found that the load bearing capacity was highest for a near-eutectic alloy (about 11wt%Si). He proposed a model in which "micro-micro-asperities" (tiny asperities on deformed larger asperities) are reoriented and redistributed during sliding and that wear debris are produced by fatigue-induced spalling from the near-surface work-hardened layers. Eyre [10] has also investigated microstructure effects on the wear of Al-Si alloys and found that the amount of Cu and Fe in the alloy changes the load at which a transition between mild wear and severe wear occurred. Shivanath [11] concluded that the Si content in Al-Si alloy linearly increased the transition load and that the wear mode is affected by the counterface material. In general, different opinions exist regarding the optimum silicon content which relates to the maximum wear resistance. Some investigators reported it to be around the eutectic composition while others declared that silicon content bas no effect on wear of aluminium alloys until it exceeds 20 wt%. Pramila and Biswas [12] found that in the range 4-24 wt%Si, wear of binary unmodified Al-Si alloys did not differ significantly and that the coefficient of friction was insensitive to variations in Si%. On the other hand, Brun et al [13] reported that the wear rate of Al-40vol%SiC was independent of the structure of the alloy but affected by the Si content. Other investigators have incorporated some elements as alumina fibers [14], graphite [15] and modifiers [16] in aluminium alloy to improve its mechanical and tribological characteristics and performance.

It is known that for materials containing two or more phases, the casting and aging procedures have significant influences upon the grain size and the stress and strains enconntered in the phases and at the interfaces between the phases [17-19] which greatly affect their mechanical properties [20-21] and conseqnently their tribological behaviour. Therefore, the present study aims to study the influence of casting and aging procedures upon the tribological behaviour of Al-Si alloy produced by five different die-casting procedures.

## 2. TEST-RIG, MATERIALS AND PROCEDURE

### a) Description of Test-rig

Tests were carried out on a conventional lathe machine by incorporating some modifications for the tests. The ceramic pin was hold in a mandrel connected to a two-force dynamometer fixed to the lathe tool-post. Normal forces and friction forces were simultaneously detected by a two-channel dynamometer during sliding. Aluminium alloy disc of 25 mm in diameter, forming the counterface, was fixed by another mandrel clamped to the rotating lathe-chuck. Fig. 1 demonstrates a photographic view for the test arrangement. The signals from the dynamometer, representing the normal force and the friction force acting at the sliding surfaces, were converted to two transducers that were connected to a two-channel tracing oscillograph where traces of measuring forces were displayed on sensitive paper.

Figure 1. Photographic View of Test-rig Arrangements

## B) Investigated Materials

The tested materials were Aluminium-Silicon alloy (Al-Si) and Alumina Ceramic ($Al_2$ $O_3$ with purity 99.5%). Table 1 demonstrates the chemical composition of the investigated aluminium alloy virgin material before casting in dies.

Table 1. Chemical Composition of Virgin Al-Si Tested Alloy

| Material | Chemical Composition (Wt. %) |
|---|---|
| Al-Si-Cu Alloy | 3.44% Si, 3.44% Cu, 0.41% Fe, 0.11% Ni, 1.2% Mg and 0.17% Mn. |

For the alumina ceramic, the 100% aluminium oxide is extremely brittle but has excellent resistance to wear and chemical diffusion. Thus the manufacturer add small amount of zirconia to increase the bulk toughness of alumina material.

Five different casting processes for the aluminium alloy were performed. These were: gravity die cast, aged gravity die cast, chill die cast, aged chill die cast and pressure die cast. It is known that solidification process, die conditions and aging of the aluminium alloy have a great influence upon the surface properties and grain size. Therefore, hardness tests were carried out on the different casting alloys and the measured average values of ten readings were as noted in Table 2.

Table 2. Brinell Hardness Average Values for Tested Al-Si-Cu Alloys

| Casting | Gravity | Aged Gravity | Chill | Aged Chill | Pressure |
|---|---|---|---|---|---|
| BHN | 69.3 | 75.5 | 88.4 | 92.3 | 80.3 |

The produced surface quality will eventually depend on the shape, distribution and volume fraction of silicon rich secondary phase. Thus, prior to testing, all aluminium specimens were machined and ground to attain almost similar values of initial surface roughness. The shape and dimensions of ceramic and aluminium specimens were as shown in Fig. 2.

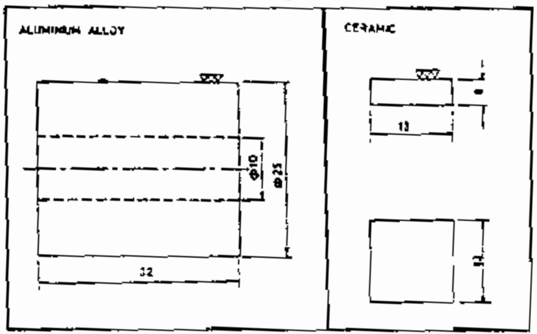

Fig. 2 Shape and Dimensions of Test-specimens

## C) Test Procedure

Before testing, both the aluminium and the ceramic surfaces were thoroughly cleaned from any traces of dust , contaminants or grease. The specimens were mounted in their mandrel and mounted in their places on the lathe machine. To allow for continuous contact between the rubbing surfaces during sliding while a changing in diameter, due to wear, took place for the aluminium specimen, a dead load was suspended vertically to the handle of the cross-slide wheel of the lathe. This also permitted to exert a radial force on the aluminium surface. This force, representing the normal force between the sliding surfaces, together with the frictional generated force, were detected separately by the dynamometer and then converted to two channel-tracing oscillograph. The normal force was recorded every two minutes. It was found that the recorded normal force was not constant but decreased with progressive sliding. Therefore, average values were calculated between successive interrupted times for specimen weighing and these averages were used to evaluate the wear rates. It is suggested that the decrease in normal force with increasing sliding was due to the decrease in Al-Si specimen diameter due to wear, the decrease in aluminium surface hardness due to frictional heating and the increase in surface roughness with sliding. Such decrease in normal force was found to be from about 120 N at the beginning of sliding to about 26 N at the termination of test. The rotating speed of the aluminium specimen was constant throughout the test at 33 revolutions per minute.

Wear rates of aluminium alloys were evaluated from weight losses recorded after predetermined sliding distances. The tests were interrupted periodically to allow for the weigh of the specimens, using sensitive balance of accuracy 0.0001 gr., to take place. The weight losses were converted to equivalent volume losses by dividing them by the density of aluminium. It is worth noting that the density of the tested aluminium alloys varied slightly according to the casting procedure. Wear rates were calculated by dividing the volume loss per meter of sliding by the normal load measured by the dynamometer. On the other hand, the coefficients of friction were calculated as the ratio of the friction force to the normal load. Surface roughnesses of the wear tracks were measured at the beginning of tests and at the test-interrupted intervals using Talysurf. Five roughness readings were taken arbitrary within the aluminium wear track and an average value in µm $R_a$ was evaluated. To give insight on the wear mechanism dominating at the aluminium surface and possible material transfer between rubbing surfaces, scanning electron microscopy was used to examine the wear tracks for both the ceramic and aluminium alloy specimens.

To prepare the tested chill die casting aluminium alloy, the melt was poured inside a preheated die of 600 °C. The die was allowed to cool by pressurized air to 200 °C and the ingot was then ejected from the die cavity and left in room conditions to cool. For the aged chill die cast, ingot produced by the chill die cast was treated by heating to 520 °C for 2 hours followed by oil quenching. The ingot was artificially aged at 175 °C for 8 hours. On the other hand, a pressure of 40 MPa was applied just after arresting die heating to produce the pressure die cast aluminium alloy. The molten alloy was allowed to cool while keeping the applied pressure until complete solidification occurred. By applying the pressure the melt fills the casting mold, producing higher quality of mold surface print and closer contact between the melt and the mold at the first stage of casting solidification, compared to the gravity casting procedure.

## 3. TEST RESULTS

### A) Variations of Wear with Sliding Distance

Fig. 3 demonstrates the variations in volume loss in ($mm^3$) versus the sliding distance in (m) for the different casting aluminium alloys. It also illustrates the variation in average normal force acting between the sliding surfaces. As can be seen, the lowest values for volume losses were encountered for the aged chill die cast aluminium alloy. On the other hand, the highest volume losses resulted from the sliding of the gravity die cast aluminium alloy against the ceramic counterface. The pressure die cast aluminium produced volume losses between the two extreme cases and at the same time slightly higher than the chill die cast alloy and slightly lower than the aged gravity aluminium.

The wear rates of the tested aluminium alloys are displayed in Fig. 4. Within the investigated sliding distance, all tested alloys exhibited linear trend between the wear rate and the sliding distance. All wear rates were in the order of $10^{-4}$ $mm^3/N.m$. The wear rates of tested alloys increased with the increase in sliding distances showing a higher percentage increase for the gravity and aged gravity die cast alloys compared to the other tested aluminium alloys. The maximum wear rate values characterized the behaviour of the gravity die cast alloy while minimum wear rate values were obtained for the aged chill die cast aluminium alloy. Similar to the trend observed in the volume losses against the sliding distances, the pressure die cast aluminium displayed wear rate values in-between the two extreme alloys with values lower than the aged gravity alloy and higher than the chill die cast alloy. It is worth noting that the surface hardness of the tested alloys greatly influenced the wear rates. The greater is the surface hardness the lower is the wear rate.

### B) Variation of Coefficient of Friction with Sliding Distance

The coefficients of friction of the sliding aluminium alloys against the ceramic counterfaces increased with progressing sliding as shown in Fig. 5. All tested alloys, at the beginning of sliding, exhibited coefficients of friction in the range 0.20-0.35, but their values rapidly increased at a rate depending on the casted aluminium alloy tested. The high increase in coefficients of friction with increasing sliding distance is presumably due to the aluminium material itself which exhibits high friction coefficient values against most other metals and due to the exposing of silicon particles at the surface which deteriorate the surface roughness and conseqnently increase friction. Furthermore the increase in temperature at the rubbing surfaces, due to the dry sliding, also contributed to the rapid increase in friction coefficients. The coefficients of friction reached a maximum value of abont 0.95 for the gravity die cast aluminium after a sliding

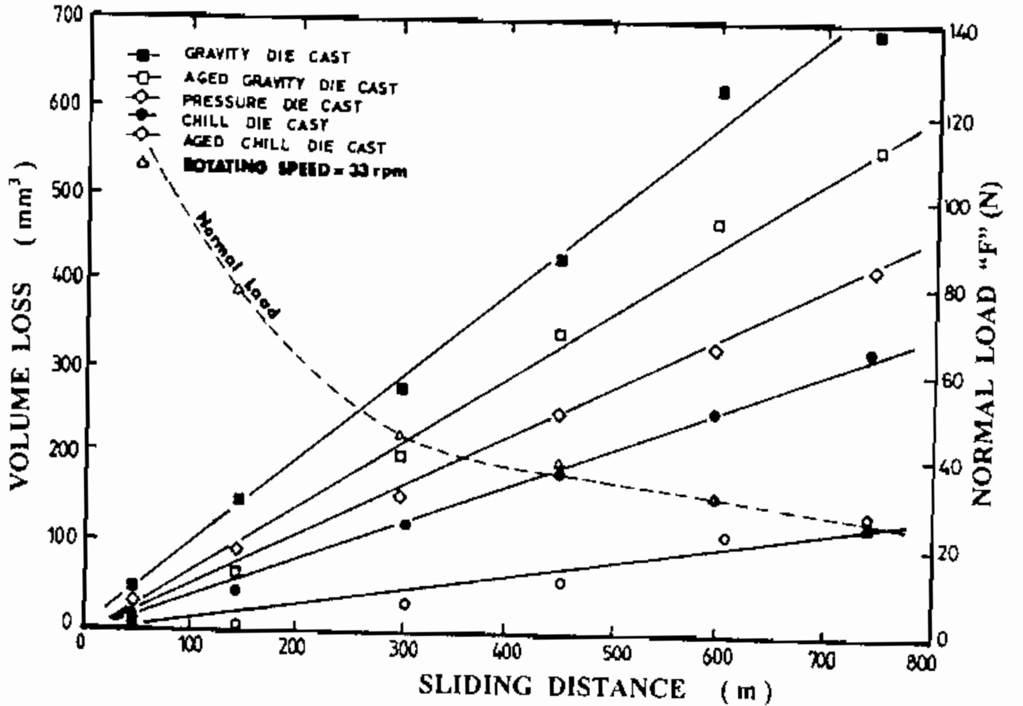

Fig. 3 Variations of Volume loss and Normal Load with Sliding Distance for Al-Si Alloys.

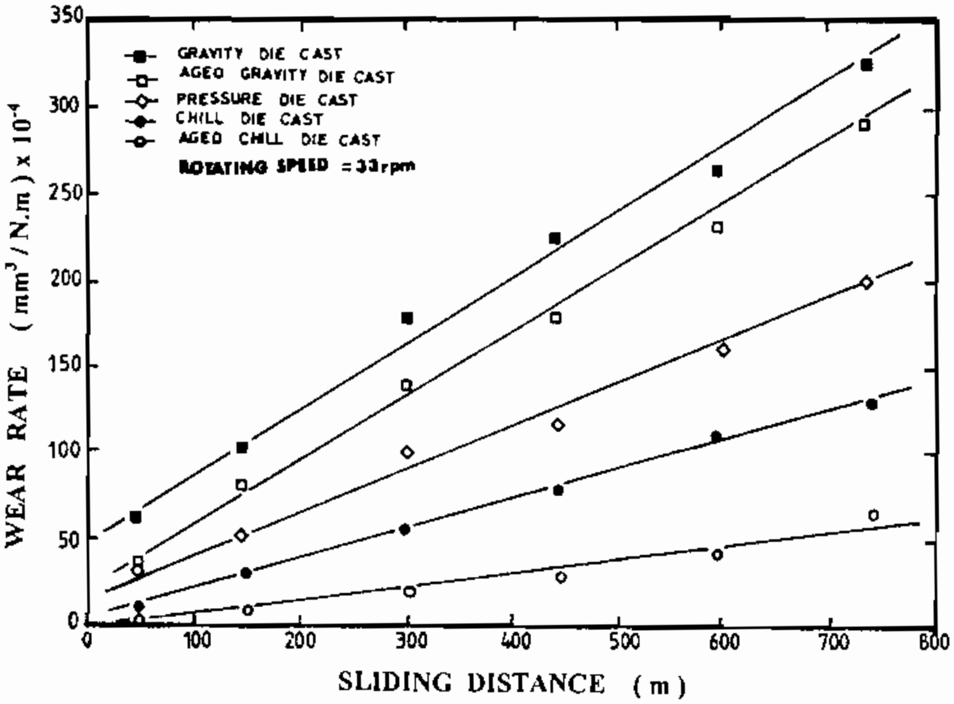

Fig. 4 Variations of Wear Rate with Sliding Distance.

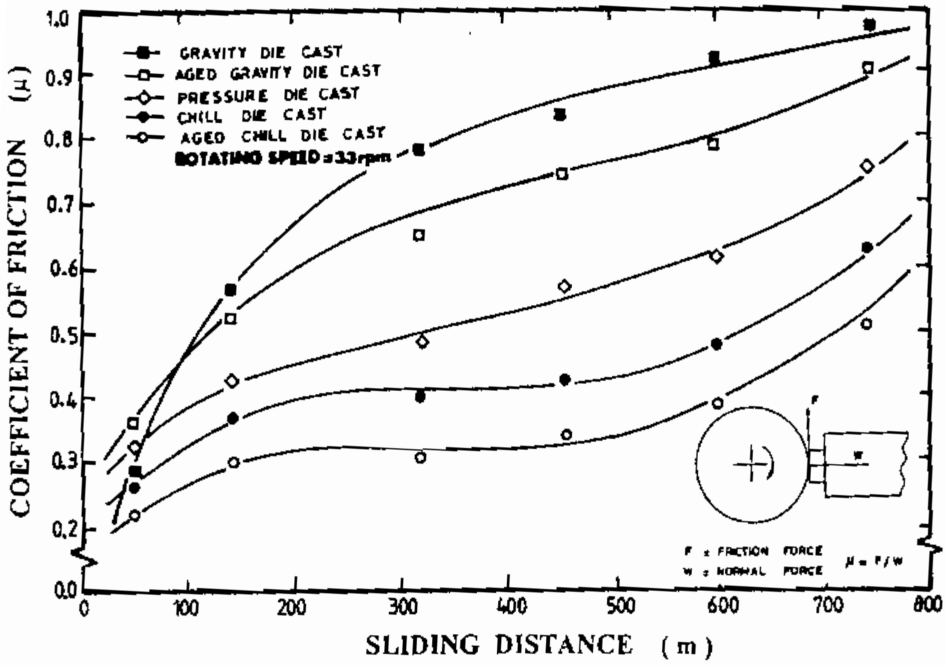

Fig. 5 Coefficient of Friction Variations with Sliding Distance for Al-Si Tested Alloys.

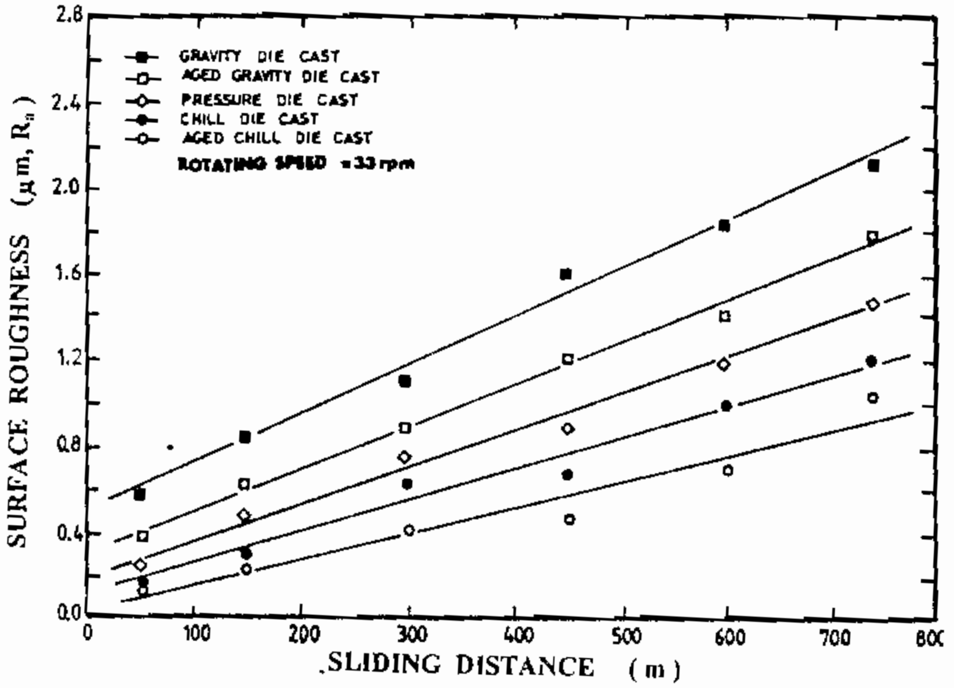

Fig. 6 Surface Roughness Variations with Sliding Distance

distance of 750 m. On the other hand, for the same sliding distance, the aged chill die cast aluminium resulted in a coefficient of friction of 0.5. It is clearly noticed that the casting procedure has a pronounced effect upon the friction coefficient values resulting from the sliding of aluminium alloys. Similar to the trend of volume loss and wear rate against the sliding distance, the gravity die cast alloy displayed the highest coefficient of friction values versus the sliding distance compared to other casted alloys. The aged gravity alloy produced lower coefficients of friction than the gravity die cast alloy. both the chill die cast and the aged chill die cast alloys, behaved similarly concerning the general trend but the aged chill aluminium displayed lower friction coefficients. The coefficients of friction resulting from the pressure die cast aluminium were lower than the gravity and aged gravity alloys and higher compared to the chill and aged chill alloys. It is worth noting that the coefficient of friction plots, for all tested alloys, showed rapid increases in the friction coefficients when exceeding a sliding distance of about 600 m.

## C) Variation of Surface Roughness with Sliding Distance

Fig. 6 illustrates the variation of aluminium alloy surface roughness with progressive sliding distance. It is seen that the surface roughness increases monotonically with the increase in sliding distance showing linear relationship for each tested alloy. The gravity die cast aluminium displays the highest surface roughness value, while the aged chill die cast alloy exhibits the lowest roughness values compared to other alloys. As in the case of wear rate and coefficient of friction, the surface roughness variations followed the same trend concerning the arrangement of alloys with respect to the resulted values of roughness. It seems that as the wear rate increases, both the friction coefficient and the surface roughness increase. However, these trends are inversely proportional to the hardness value.

## D) Surface Examination by Scanning Microscopy

Examinations of the aluminium-silicon wear surfaces were performed by scanning microscopy. Microstructure observations were essential to acquiring an accurate understanding of the physical sliding process. In the present work, sliding was taken place between a hard ceramic surface and soft aluminium alloys. Obviously there will be a transfer from the softer surface to the harder one during rubbing under dry conditions. Typical example of the aluminium transfer to the ceramic is shown in Fig. 7 which illustrates the original ceramic surface and after sliding against aluminium. The transfer of aluminium takes the form of discrete particles adhering to the smooth ceramic surface. Evidence of some wear scar for the ceramic surface is noticed in Fig. 8. It is interesting to observe that also some particles from the hard ceramic were transferred and embedded in the aluminium surface as shown in Fig. 9. With continuous sliding, the wear of aluminium surfaces has the appearance of layers sheared plastically showing severe deformed surfaces. For the gravity die cast aluminium, severe wear appeared as multigrooves on the surface as illustrated in Fig. 10. Such grooves may result from silicon particles exposed to the surface or trapped

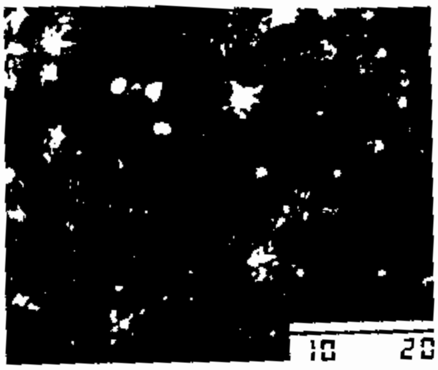

Fig. 7 Electron Scanning Photomicrograph of Aluminium Particles Transfered to the Ceramic Counterface.

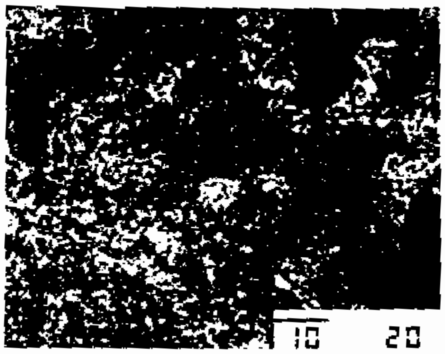

Fig. 8 Electron Scanning Photomicrograph for the Ceramic Surface After Rubbing showing Evidence of Wear Scars Formation.

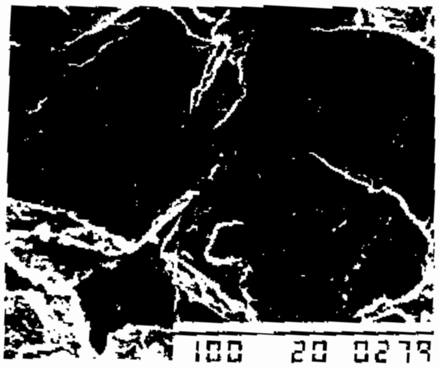

Fig. 9 Seen of the Embedded Hard Ceramic Worn Particles in the Softer Al-Si Alloy Surface.

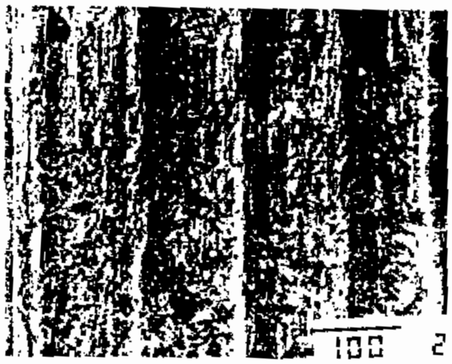

Fig. 10 Appearance of Multi-Grooves due to Severe Wear of the Aluminium-Silicon Gravity Die-Cast Alloy.

Fig. 11 View for the Formation of Aluminium Lips on the worn Track.

Fig. 12 Severe Wear Appearance in a Close View for the Gravity Die-Cast Al-Si Alloy Surface.

between the sliding surfaces. Relatively large debris of aluminium were observed both clinging to the side of the wear tracks and remote from them as if the particles had been thrown off during sliding. The periodic raised lips of aluminium observed on the tracks, as shown in Fig. 11, presumably were delamination platelets [22] or merely the edges of some deformed layers subjected to subsequent slider passes. As wear rate increases, more grooves and lips were formed as seen in Fig. 12. On the contrary, for low wear rate tested alloy, i.e. the aged chill die-cast Al-Si, the plastically deformed layers of aluminium tended to spread homogeneously on the worn surface forming a smooth layer which relatively reduced the coefficient of friction, the wear rate and limit the surface roughness variation.

## 4. DISCUSSION OF RESULTS

Although aluminium-silicon alloys are presently widely used in automotive engineering applications, limited work on their tribological performance is available. Aluminium, in general, exhibits poor wear resistance and high friction against steel due to its solid solubility with iron. The face-centered cubie structure of aluminium with eight {111} planes of densely packed atoms will promote slip and plastic deformation. However, the presence of silicon in the Al-Si alloy reduces the wear rate as it forms a non-metallic hard substance that limits the wear to the aluminium fraction in the composite.

Clearly, many mechanisms contribute to the dry sliding of the Al-Si complex polyphase alloy, influencing its friction and wear. Among these mechanisms are the load, the counterface material, the aluminium oxide, the surface finish, the hardness, the transferred material, the percentage of silicon and the chemical composition.

The results of the present study revealed that the die-cast procedure for the Al-Si alloy has a profound effect upon the wear rate, the coefficient of friction and the surface roughness variation during sliding under dry conditions. The die-casting procedure will eventually influence the surface structure of the alloy in terms of particle size, hardness and percentage of silicon to aluminium at the surface. The study has revealed that the surface hardness varied from 69.3 BHN for the gravity die-cast alloy to 92.3 BHN for the aged-chill alloy. Davies and Eyre [23] using energy-dispersive spectrometry for the dry wear of Al-Si pins against steel, found a commixed oxides of aluminium and iron, built up to a thickness between 25 and 75 μm. However, an increased level of complexity exists in interpreting sliding characteristics based on oxide effects for the Al-Si alloys used in the present study due to the presence of silicon particles which are presumably protected by their own oxide films. For many years, the importance of surface roughness and its effect on friction and wear has been recognized but the manner by which the microstructures of various elements in a composite like Al-Si alloy contribute to and are affected by the friction and wear is not an easy task to reveal.

In the present work, the wear rates and the coefficients of friction of tested alloys increased with progressive sliding distance. These increases were pronounced for the low surface hardness alloys such as gravity and aged gravity die-cast Al-Si alloys. On the contrary, the chill and the aged-chill die-cast alloys, that exhibited relatively higher hardness, relative to the other tested alloys, resulted in lower friction and wear. The pressure die-cast alloy displayed intermediate friction and wear values between the gravity and chill alloys. In addition to the role played by the surface hardness in dictating the dry friction and wear behaviours, the particle size at the exposing surface also contributed to the friction and wear characteristics. Gravity die-cast alloy is known to have finer particles on its surface. Therefore, the wear rate and the coefficient of friction can be considered structure-sensitive, such that the finer the surface particles the lower are the dry friction and wear.

The variations in surface roughness, in the present study, also followed similar trend to the friction and wear. Increasing the sliding distance resulted in a continnous increase in the surface roughness values. Moreover, the harder the Al-Si alloy surface, the lower was the variation in the surface roughness values.

SEM micrographs of the worn surfaces have revealed two main features for the Al-Si surfaces. The first was the long and continuous grooves formed on the softer material surface while the second was the entrapped of hard ceramic wear particles in the aluminium matrix. Furthermore, aluminium particles were found adhered to the ceramic counterface. This mutual transfer of particles during dry sliding enhanced the formation of severely damaged regions on the softer Al-Si alloy snrfaces.

## 5. CONCLUSIONS

Under the present experimental conditions, the following conclusions can be made:

(1) Wear rate, coefficient of friction and surface roughness of Al-Si alloys exhibit a monotonous increase with the increase in sliding distance.

(2) The strong dependence of wear rate, coefficient of friction and surface roughness variation on the snrface hardness of tested Al-Si alloys proves that the dominant wear mechanism in the dry sliding is an abrasive process.

(3) Mutual transfer of material particles takes place between the relatively soft Al-Si alloy and the harder ceramic counterface under the testing conditions.

(4) The die-casting procedure of Al-Si alloy plays a major role in dictating the characteristics of the surface in terms of hardness, grain size and percentage fraction of silicon to aluminium which in turn influences both wear rate, coefficient of friction and surface roughness variations.

(5) Gravity and aged gravity die-cast Al-Si alloys exhibit higher wear rates, coefficients of friction and variations in surface roughness compared with the chill and aged chill die-cast alloys. The pressure die-cast alloy displays intermediate friction, wear and roughness values.

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