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Wear Behavior of Aluminum Alloys under Low Stress Three Body Dry Sliding Abrasion Conditions

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ABSTRACT

Wrought Aluminum alloy 6063-O fingers of size 8 mm dia and 50 mm length were machined from 12 mm dia rods and cast Aluminum alloy A 356.0 rods of 12 mm dia were melted and cast in permanent cast iron moulds and later machined to 8 mm dia and 50 mm length fingers. Two types of cast samples were prepared namely the as-cast and T6 tempered conditions. Dry sliding 3 body abrasive wear behavior of these materials under low stress conditions with applied load from 1N to 3 N has been investigated using a specially designed pin on disc wear tester at a fixed sliding speed of 1.3 m/s. SiC emery paper of grit 220 was pasted on the steel counter face and made to run against the fixed pin made of the Aluminum alloy. The wear mass loss was measured for various test conditions and wear factor calculated and plotted. The wear mechanisms were identified and the wear scars viewed through the optical microscope and inferences drawn. The wear rate was found to decrease when the sliding distance and the applied load was increased. The results revealed that severe wear occurred, the wear factor being in the range 10^{-3} to 10^{-5} mg/Nm, in spite of the low stress applied. The wear behavior was correlated to the test conditions and the properties of the materials used. The study pertains to IC engines, valves, brakes, material handling equipment, bearings, electromechanical and MEMS devices to name a few.

Keywords: Low stress abrasion, three body abrasion, wears mechanisms; wear scar microstructures, wear factor, MML (Mechanically mixed layer).

I. INTRODUCTION

Wear may be defined (Budinski and Budinski, 2005) as the surface damage or removal of material from one or both of two solid surfaces in a sliding, rolling or impact motion to one another as a result of mechanical action. The wear phenomenon can occur due to adhesion, abrasion, surface fatigue or tribochemical reaction. In addition, many studies reveal that the wear situation comprising of the materials under consideration, its shape, weight, applied load, test duration and environment conditions, affect the wear rate and the wear mechanisms. Wear is a serious problem in many engineering applications, especially moving parts like bearings and engine parts. There is also an increasing demand for light weight materials with good wear resistance in the automotive and aerospace sectors (Gui et al. 2000).

Aluminum alloys exhibit mild to severe wear. A transition from mild to severe wear depends on the applied load and the sliding speed during dry sliding wear (Zhang and Alpas, 1997). When the wear is severe, ductile materials such as Aluminum alloys experience substantial surface plastic deformation at the surface (Dautzenberg and Zaat, 1973, Perrin and Rainforth, 1997, Singh and Alpas, 1996).

The investigation of Horn & Zeigler (1983) showed that pure Aluminum, non-heat treatable alloys and cast Al-Si alloys have poor dry abrasive wear resistance and that cold work does not cause a significant improvement. Heat treatable wrought alloys and cast alloys aged to optimum hardness showed improved performance. The work of Rao & Sekhar (1986) concluded that the wear rate of a range of Aluminum alloys did not decrease with the increase of their Vicker's Hardness. It has also been stated that friction is inversely proportional to hardness (Drozdov and Archegov ,1981). It is still not clear despite many studies which Al alloy would offer the best wear performance and whether a precipitation hardened matrix would be optimum, or whether a work hardened characteristic would be important (Ghazali et al., 2007).This applies to Al MMC's (Metal matrix composites) also. Therefore this paper attempts to study the wear behavior of cast Al A 356.0 in the as-cast and T6 tempered condition and compared to the wear performance of wrought Al alloy 6063-O, in the annealed stage. Both the alloys are Magnesium Silicon alloys, with the 6063 alloy, being a popular aerospace material and the cast alloy A 356.0 used for applications like machine tool parts, aircraft wheels, pump parts, valve bodies, cylinder heads and engine blocks.

As already stated the wear situation plays a major role in the wear behaviour of any material and in this study the counterface of steel is pasted with SiC 220 grit emery paper with 75 micron size irregular shaped abrasives. The pin being Al alloy, the wear rate would be severe in nature and hence lower applied loads 1N to 3 N have been applied. The wear situation is expected to be more aggressive than the adhesive wear situation, studied by many authors. Wear studies have been conducted earlier at the Meso, Micro and Nano scales for MEM'S devices, with applied loads ranging from a few nN to 100 mN (Le, et al., 2008). Adhesive wear studies involved higher applied loads up to 50 N.Very little work has been conducted on low stress abrasion and sliding and fretting wear, and this pertains to coatings. Little or no work has been carried out in the load range 1N to 3 N for bulk materials or coatings, with the wear situation described.

II. EXPERIMENTAL WORK

2.1 Apparatus

The experimental test fixture is shown in Figure 1, which is a pin on disc tribometer.Here the flat pin of size 8 mm x 50 mm length is loaded precisely with weights of 1N, 2 N and 3 N. The wear loss of the test material is calculated from the mass loss during the test. The test conditions like load applied, sliding speed and distance simulate the real life situations of many practical wear applications. The set-up has been specially designed and fabricated to test with low load applications.

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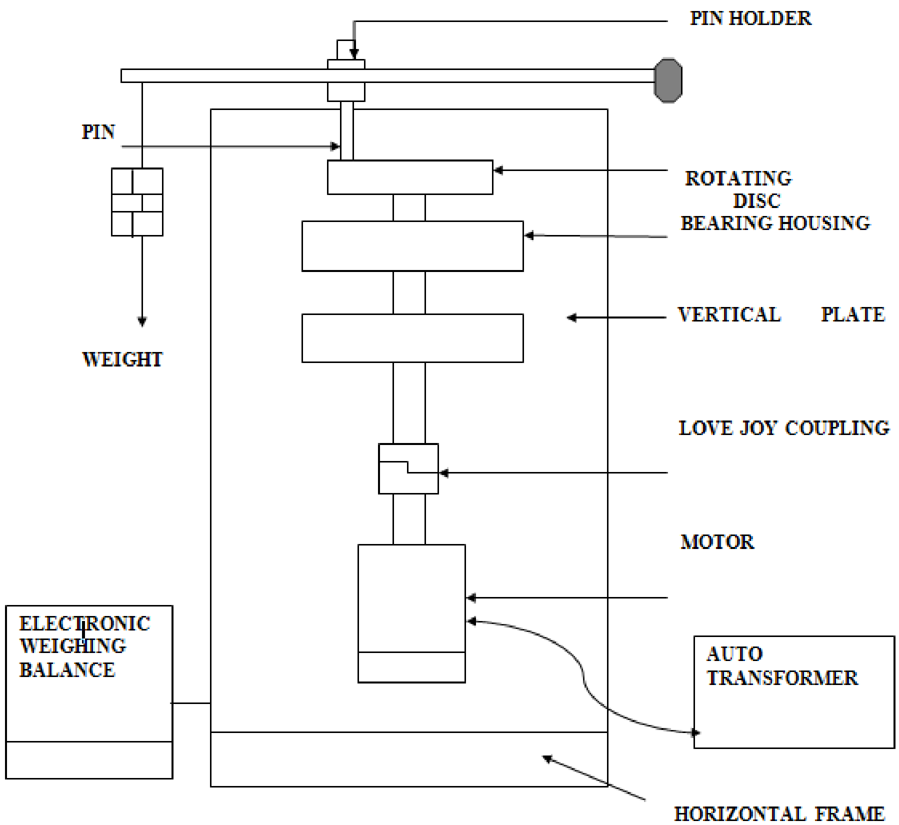

Figure 1. Pin on disc wear test apparatus

2.2 Test conditions

The test pins are made of Al 6063-O wrought alloy and cast Al A 356.0 in the as-cast and T6 treated conditions, of size machined to 8 mm dia x 50 mm length. The counter face is made of EN-8 steel with SiC 220 grit emery sheet pasted on it. The size of SiC particles is 75 microns with irregular particle shape. The emery sheets are replaced after the test duration of 7 minutes. The diameter of the disc is 60 mm and thickness 15 mm.The test conditions for testing were sliding speed of 1.3 m/s, applied loads 1N, 2N and 3N and the sliding distances of 82 m, to 574 m in steps of 82 m. Prior to testing, test samples were polished with emery paper and cleaned in acetone, dried and then weighed using an electronic balance having a resolution of 0.1 mg. After each test, the specimens were removed, cleaned in acetone and weighed in a similar fashion. At each load the mass loss from the surface of the specimens were determined as a function of the applied load and the sliding distance. Confirmation tests were also conducted to establish the values. Additional information pertaining to the wear situation is detailed below (Raymond) in Table-1.

Table 1. The wear situation

Parameter	Description
No. of bodies	3 body(the abrasive particles are constrained by a counter face and trapped between the two independent bodies)
Stress level	Low stress up to 0.019 MPa to 0.059 MPa
Presence of fluid	Dry abrasion
Relative hardness of particles to surface	Surface softer than particles
Motion	Sliding unidirectional high speed (1300 rpm)
Contact geometry	Circular area in surface contact
Test environment	25 C, 50% RH
Materials	Dissimilar

The wear factor (K) in mg/Nm is calculated as per the following formula:
K=$W \div LN$, where W is the wear mass loss in 'mg', L is the sliding distance in 'm', and N is the applied load in 'N'.

2.3 Materials

The composition and properties of Al 6063-O and Al cast A 356.0 are shown in Tables 2 to 4 and the counter face characteristics are detailed below (Elwin).
Counter face: SiC fine emery sheet of grit 220, particle size 75 microns, irregular shape. SiC has a hardness of 2800 kg/mm^2 and compressive strength of 3900 MPa.

Table 2. Composition of Al 6063 –O (annealed).

Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Others**	**Al**
.20 to .60	.35	.1	.10	.45 to .90	.1	.1	.10	.15	rest

Table 3. Composition of cast Al A 356.0

Si	**Fe**	**Cu**	**Mn**	**Mg**	**Ni**	**Zn**	**Ti**	**Others**	**Al**
6.5-7.5	.2	.2	.10	.25 to .45	Nil	.1	.20	.05	rest

Table 4. Properties of wrought Al 6063-O and cast Al A 356.0

Sl.no.	Property description	Al 6063-O	Al A 356.0
1	Melting point , °C	600	650
2	Density, g/cc	2.68	2.67
3	Thermal Expansion Coefficient ,10^{-6} °C	23.4	21.4
4	Thermal Conductivity at 20 °C, W/mK	200	167
5	Specific Heat KJ/kgK	0.91	0.963
6	Elastic modulus GPa	70	72.4
7	Hardness HB	25	42 (soft) 63 (T6)
8	UTS (Ultimate tensile strength) MPa @ R.T.	131	234
9	Poisson's ratio, 'υ'	0.33	0.33

2.4 Metallographic observation: Specimens for the metallographic observations were prepared by standard polishing techniques. The microstructure of the specimens were investigated by means of optical microscopy model Censico with a magnification of 200 X. Keller's reagent with composition, 194 ml distilled water, 5 ml Nitric acid, 3 ml HCl and 2 ml Hydrofluoric acid was used as the etching reagent. The wear scars of the worn surfaces were similarly prepared and observed. The specimens were run for duration of 3 minutes for the various applied loads before polishing.

III. RESULTS AND DISCUSSION

The results of the wear loss measured are plotted in the graphs shown in Figure 2.

Figure-3 shows the wear factor against sliding distance curves at the applied load range of 1 to 3 N.

Figure - 4 shows the microstructures of the materials.

Figure – 5 to 7 shows the wear scars of the material.

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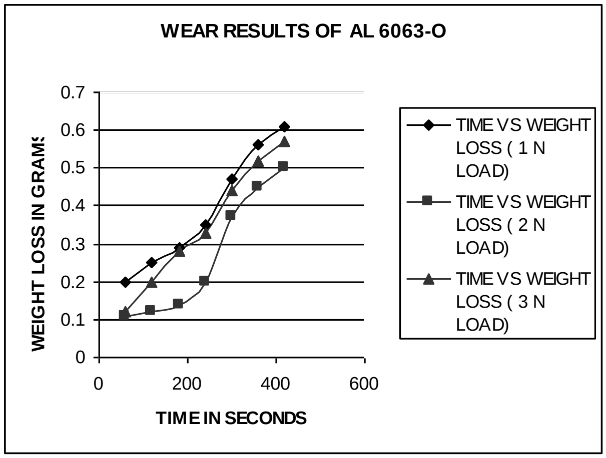

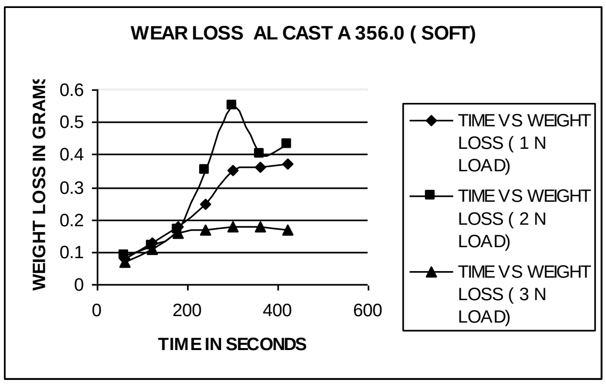

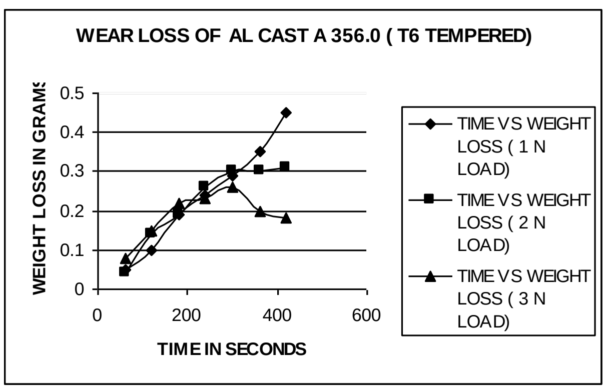

Figure 2. Wear loss in grams as a function of sliding distance and applied load

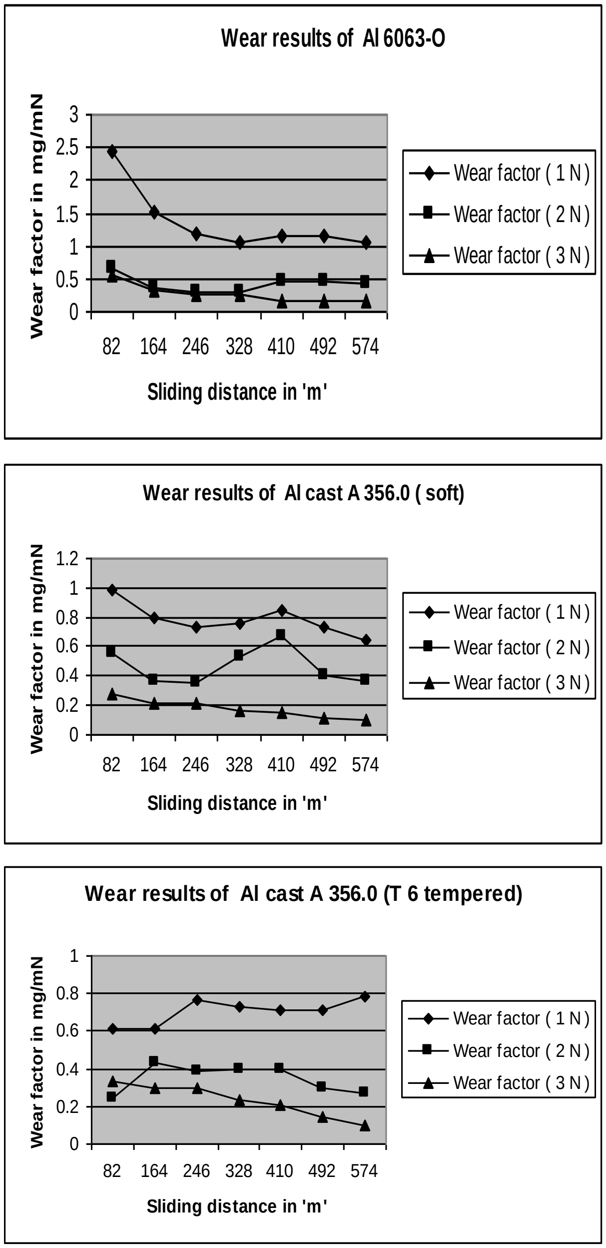

Figure 3. Wear factor in 10^{-3} mg/Nm as a function of sliding distance and applied load

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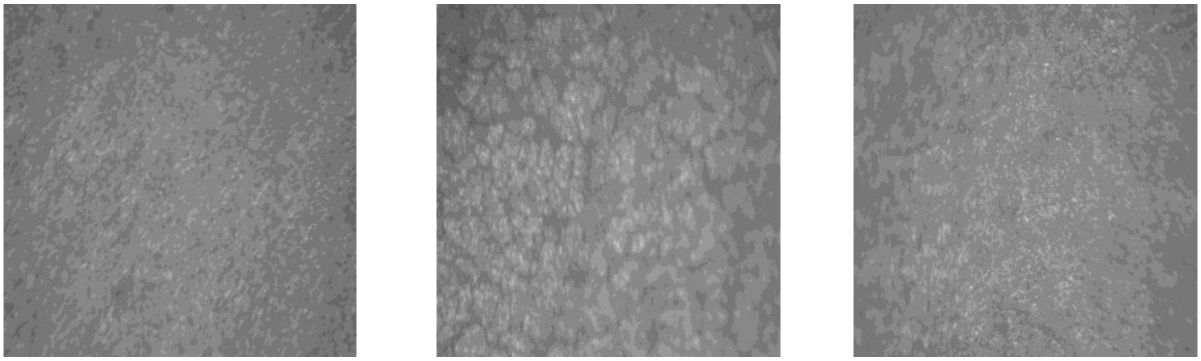

a) Al 6063-O **b) Al cast A 356.0 as-cast** **c) Al cast A 356.0 T6 treated**

Figure 4: Microstructures of the test specimens run for 246m sliding distance and 3 N applied load
The microstructure is typical of Aluminum alloy with small particles of Silicon and Magnesium in Aluminum solid solution.

a) Al 6063 (1N load) **b) Al 6063 (2N load)** **c) Al 6063 (3N load)**

Figure 5. Wear scars of Al 6063-O for various applied loads
The wear scars show a plowing and grooving action due to low hardness and flow stress of the material. The wear rate is high though the MML is present. The dark patches are that of SiC.

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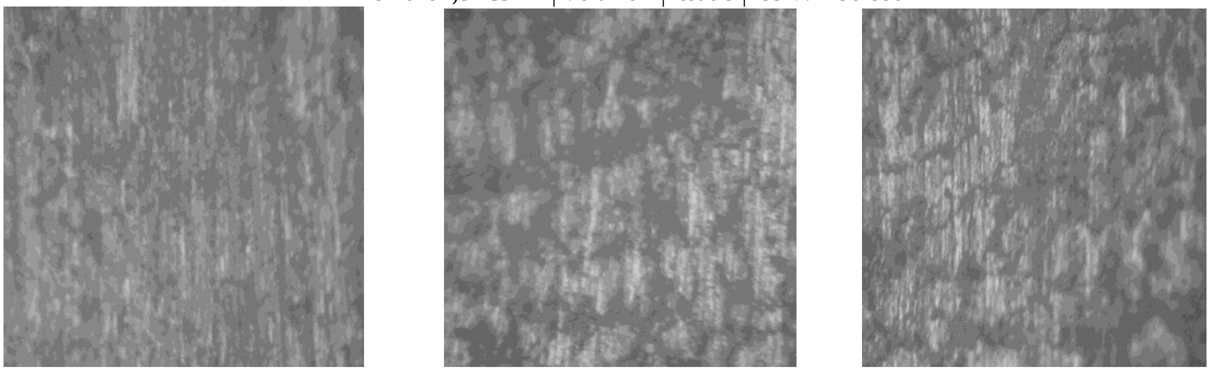
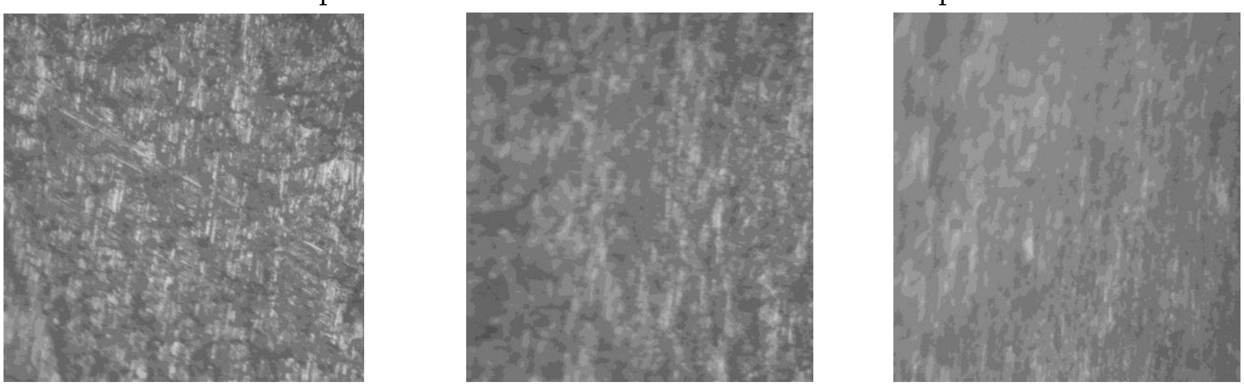


a) Al A 356/0 As-cast (1N load) **b) Al A 356/0 As-cast (2N load)** **c) Al A 356/0 As-cast (3N load)**

Figure 6. wear scars of cast Al A 356.0 for various applied loads

The higher hardness and higher flow stress values lead to cutting and fragmentation and lower ploughing and also due the presence of the MML the wear rate is lower. Dark patches of SiC are seen.



a) **Al A 356.0 T 6 treated (1 N load)** **b) Al A 356.0 T 6 treated (2 N load)** **c) Al A 356.0 T 6 treated (3 N load)**

Figure 7. Wear scars of cast Al A 356.0 T 6 treated, for various applied loads

The wear scars are polished and wear mechanism is mainly due to fragmentation and less ploughing due to the MML Wear rate is lower. Dark patches of SiC are seen.

3.1Properties of materials and wear conditions correlated to wear behavior (Raymond):

1. The wear rate depends on the hardness of the specimens, as the depth of indentation for a given load by the abrasive particle is a function of the hardness of the material. The results show ploughing wear mechanism in the case of Al 6063-O with deeper grooves when compared to cast Al A 356.0 in the tempered condition. Higher the hardness, lower the ductility resulting in a change in the abrasion mechanism from predominantly plowing/cutting to fragmentation.

2. Wrought Al being more ductile than cast Al, plowing takes place and the probability of wear debris formation is high which get embedded in the grooves and also the proportion of ploughing will be more than cracking or fragmentation.

3. As the Contact pressure increases, the wear rate increases.

4. The contact conditions of velocity and impingement angle of the abrasive plays a major role in the wear rate. Higher the sliding velocity, higher will be the wear rate. In this study the sliding velocity has been kept constant. The impingement angle is 0° in this study and hence a lower wear rate.

5. The abrasive particle characteristics like size and hardness ratio of wear material and the abrasive are important parameters. Higher the abrasive size, the greater will be the wear rate. Lower the H/Ha, as in the case of 6063 Al, plastic deformation takes place as in this study.

6. The microstructure plays a major role in the wear rate of the materials. In the T 6 treated condition the microstructure is more homogenous and hence the wear rates are lower.

7. For materials of equivalent hardness, the plastic flow behavior depends on the E/σ_y ratio. Higher the ratio more will be the plowing action. Flow stress σ_y for Al 6063-O is lower and E/σ_y is higher and hence a ploughing action results. E/σ_y is lower for the case of Cast Al.Cutting and microchips formed in this case.

3.2 Discussion of the wear loss and the wear factor results.

1. The wear loss increases as the sliding distance is increased for all the load conditions and materials.

2. The wear loss of Al 6063 is more than the cast alloy 356.0 for all load conditions and sliding distances.

3. In the case of Al 6063, the wear loss for the applied load of 2 N is lower for all the sliding distances, which is due to the mechanically mixed layer of SiC and Aluminum formed with a higher load bearing capacity. Refer the wear scar microstructure. The dark areas are that of SiC in white patches of Al.

4. In the case of Al cast 356.0, both in as cast and T6 tempered conditions, for the applied load of 1N the wear loss is more than for other loads. Al specimens in T 6 condition fared better than the soft specimens.

5. The experiments were not conducted for higher loads as the trend was similar.

6. The tests were discontinued after a sliding distance of 574 m as the wear loss stabilized.

7. The wear loss is lower for higher applied loads, due to the MML formation.

8. The wear factor decreases for all the applied loads and increasing sliding distances for the materials considered.

9. The wear factor for the 2N and 3 N applied loads is lower than the wear factor for 1 N load, which shows the better wear performance of the materials at higher applied loads.

10. The wear factor is the highest for the Al 6063 alloy and the lowest for the Cast Al 356.0 T6 tempered condition revealing the better performance of the cast alloy in the heat treated condition.

11. The morphology of the wear scars of 6063 –O Al and cast A 356.0 Al, for the applied loads of 1N to 3N, sliding speed of 1.3 m/s and sliding distance of 246 m are shown in the figures.

For 1 N load, 6063 Al exhibited a rough wear surface with deeper grooves, with the major wear mechanism being ploughing (plastic deformation due to higher ductility).Similarly for the cast specimens, the scars are rough due to cutting/fragmentation. The microstructure is less rough and seen as polished due to the mechanically mixed layer formation comprising of Al and SiC phases in the case of 2N and 3 N loads for Al 6063 and Al 356.0 cast specimens. The mechanism is a combination of micro cutting and ploughing.The mechanically mixed layer has a higher load bearing capacity and hence the lower wear rates. Li and Tandon, (2000) state that the MML played a vital role in dry sliding wear in the range of loads.

12. In general, the wear loss of the materials increases linearly with increasing sliding distance and applied load, but the wear rate decreased with increasing sliding distance since wear rate is the ratio of wear mass to sliding distance in a certain wear condition.

IV. CONCLUSIONS

1. Wear rate of any material depends on the hardness of the material and its ductility. Cast Al A 356.0 T6 treated showed a better wear performance than Al A 356.0 in the as cast condition and Wrought Al alloy 6063-O in the annealed condition.

2. The wear performance of the materials selected showed a better result for higher loads applied due to the formation of a mechanically mixed layer with a higher load carrying capacity. This is applicable for the low stress range and the sliding distances selected and also for the wear situation described.

3. The wear loss increases as a function of sliding distance and applied load initially and then flattens for the materials tested.

4. In this study, the wear is found to be severe in all cases; though it is better in the case of heat treated cast alloys. The wear rate being in the range 10^{-2} to 10^{-5} mg/Nm falls in the regime of severe wear. Critical load is the applied load when the transition from mild to severe wear takes place. In this study, for the wear situation considered 1 N may be considered well above the critical load.

5. Though applied stresses are lower, the wear situation, especially the abrasive grain size of 75 microns of SiC, has contributed for the severe wear.

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VI. ACKNOWLEDGEMENT

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