Influence of Contact Area on Tribo Response of Al 6061 in Ambient and Vacuum Environment

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Abstract. Aluminium alloys are used in spacecraft and aerospace industries because of their unique properties which are lightweight and high strength. The components of aluminium alloys used in aerospace and space environment are subjected to relative motion which results in the tribo-phenomenon. The designer needs tribo response data for designing components geometrical dimensions. The literature reports inadequate tribo response data, more particularly in a vacuum environment (adverse environment). In the present investigation, experiments were conducted using Al 6061 aluminium alloy pins with different diameters. The cylindrical pin diameters were 2mm, 4mm and 6 mm. The cylindrical pins were slid against a hardened En-8 steel disc. The normal pressure was maintained at 0.625 MPa and the sliding speed was 0.5 ms-1. The estimated friction coefficient from monitored frictional force and normal force and the dependency of estimated friction coefficient on sliding distance for cylindrical pins of different diameters were analysed.

Keywords— vacuum, apparent Contact area, Coefficient of friction, Al 6061, pin-on-disc

1. Introduction

In any tribo-system, friction and material removal called wear phenomenon, occur. The frictional force found in tribo-system is a passive force and results in reducing the efficiency of a system which is built with building blocks like kinematic pair which constitute a tribo-pair. The wear results in downtime of equipment for maintenance and in extreme condition leads to complete replacement of equipment demanding capital investment. There are situations where replacement of parts or equipment was found not practicable; the case is one of equipment used in space industries where the environment is adverse. The environment in space is different wherein vacuum and high temperatures are prevailing. Researchers have made attempts to understand the tribo response of a system in an adverse environment.

[1] Kumar and Kumar studied the tribo response of laser textured 6061 and 7071 Aluminium alloys. The experiments were conducted using a Pin on Disc (POD) test rig according to ASTM G95 standards. The laser textured aluminium alloy pins were slid against the hardened En-31 steel disc. The aluminium pin was of dimensions 20 mm diameter and 30 mm height. The aluminium pins
surface before laser texturing was prepared by lapping. The laser textures were set of circles, squares and triangles. The depth of the groove of laser texture was 0.1 mm. The normal load was 20 N and the sliding speed was 200 rpm with a wear track diameter of 60 mm. The sliding distance was 3000 meter. The result showed that triangularly laser textured aluminium pin surface improved the tribo response.

[2] Raj and Kailash studied the morphology of wear debris which was produced when Ti-6Al-4V, in both ambient and vacuum conditions, was slid against SS316L. The experiments were conducted using a specially designed vacuum-based high-temperature POD test rig. The experiments were conducted in ambient and vacuum environment. The normal load was 137.3 N which resulted in a contact pressure of 2.8 MPa. The sliding speeds were 0.01 ms\(^{-1}\), 0.1 ms\(^{-1}\), 0.5 ms\(^{-1}\), 1 ms\(^{-1}\) and 1.5 ms\(^{-1}\). The wear debris and worn pin surface were studied in Scanning Electron Microscope (SEM). The phase analysis of wear debris was studied by X-ray diffraction (XRD). The result indicated that the tribo response was found sensitive to the level of stress, the magnitude of sliding speed and the environment. The wear phenomenon, irrespective of environment, high load and low speed, was dominated by the adiabatic shear band mechanism. At high speed and ambient condition, the wear was dominated by tribo oxidation and a mechanically mixed layer. At high speed and vacuum conditions, the phase transfer controlled wear mechanism.

[3] Lepper et al. studied the wear response of aluminium alloys used in bearing materials. The experiments were conducted using a POD test rig configured vertically and housed in a bell jar which facilitated to conduct tests in a vacuum. The disc was aluminium alloy material with 25.4 mm diameter and the surface was metallographically polished using 0.05 µm sized alumina powder. The pin samples were balls of 52100 steel with a diameter of 6.4 mm. The normal load ranged from 0.88 kg-f to 1.13 kg-f. The sliding speeds were 15 mms\(^{-1}\) to 30 mms\(^{-1}\). Surface and subsurface studies were carried out using energy-dispersive X-ray spectroscopy (EDS) for identifying the elements on wear scar. The results indicated that the environment influenced the tribo response to a larger extent than alloy composition and its microstructure. The tribo response of tested aluminium alloys was found to be comparable with conventional bearing materials like Pb-Sn and Babbitt materials [3].

[4] Rehaman & Jayahari studied the tribo response of Al-6061 alloy composite which was reinforced with machined steel chips. The tribo response was studied using a POD test rig. The aluminium composite matrix was processed by stir casting method. The reinforcement was AISI-1060 steel machined chip. The two composite with 5% and 10% by weight of steel chip were manufactured. The aluminium composite was used as a pin and slid against a hardened En-31 steel disc. The Load was 2.5 kg and the track diameter was 100 mm. The speed was 382 rpm and the test time was 100 s. The result indicated that the aluminium composite performed tribologically better compared to aluminium alloy.

[5] Proda et al. studied the tool wear in friction stir welding of Al-6061 composite reinforced with alumina. The result indicated that the tool wear rate was considerable for Al-6061 composite reinforced with alumina when compared to plain Al-6061 alloy.

[6] Wu et al. evaluated the wear response of micro-alloyed Al-10Sn-4Si 1Cu. The micro-alloy elements were Erbium (Er) and Zirconium (Zr). The wear tests were conducted using a reciprocating wear test rig. The ball was GCr15 bearing steel with a diameter of 5 mm. The plate was micro-alloyed aluminium alloy. The tests were conducted with a sliding frequency of 300 cycles per minute (5 Hz) with a stroke length of 5 mm. The normal loads were 30 N, 50 N and 70 N and the testing time was 900 seconds. The wear scar was studied in scanning electron microscope (SEM). The element analysis of wear scar and morphologies of wear debris were studied. The result indicated that micro-alloyed aluminium alloys showed improved wear performance. Abrasive, adhesive and delamination wear mechanisms were observed. The energy dispersive X-ray (EDx) analysis showed the oxidation of material.
[7] Elhefnawey et al. studied the wear response of samples of AA 707 alloy subjected to equal channel angular pressing (ECAP). The wear testing was conducted using a POD test rig according to ASTM G99-05 standards. The pins were made out of Aluminium alloy and the disc was hardened En-31 steel. The tests were conducted with a normal load of 5 N. The sliding speed was 0.15 ms$^{-1}$ and the sliding distance was 180 m. The worn-out surfaces were studied in scanning electron microscope (SEM). The result indicated that the number of passes in ECAP improved wear response. The scanning electron microscopic study revealed that the mechanism of wear, in the samples before ECAP was delamination and after ECAP, the wear mechanism was found to be ploughing bands.

[8] An et al. studied the influence of test temperature, normal load and wear transition of magnesium alloy. The alloy studied was magnesium alloy with Zinc and Yttrium. The wear tests were conducted using a high-speed high-temperature POD test rig. The testing temperatures were varied over a range of 293 K to 493 K, the sliding speed was 0.5 ms$^{-1}$ and the sliding distance was 565 m. The normal load was in the range of 20 N to 360 N. The magnesium alloy was machined and used as a pin with a diameter of 16 mm and a height of 13 mm. The disc was hardened En-31 steel. The worn surface of the pin was studied in SEM. The result indicated that the wear rate was found to be dependent on the extent of normal load. Mild wear and severe wear were observed. The transition from mild wear to severe wear occurred with the decreased load as test temperature increased. The reason for severe wear was attributed to the dynamic recrystallization phenomenon.

[9] The friction and wear of a metal forming tool were simulated during tailored surface finish obtained in micro-milling by Schewe et al. The numerical method was made used in studying wear and friction for different surface texture like sinusoidal and bionic which resulted in a different extent of friction. The sinusoidal surface texture resulted in anisotropic structural resistance during sliding. The bionic surface texture showed quasi-isotropic structural resistance.

[10] Reddy and Vadivuchezian studied the wear response of thermally treated Al-6061 and Al-6082 alloy using a POD test rig. The disc was of thickness 8 mm and 160 mm diameter. The pin was 6 mm in diameter. The normal load was 10 N and the sliding speed was 1.5 ms$^{-1}$. The hardness of Al-6061 was 105 BHN and that of Al-6082 was 95 BHN. The result showed that the oxide layer and contact surface introduced an abrasive wear mechanism. The formation of an oxide layer and its failure resulted in the observed dependency of coefficient of friction on sliding time.

[11] Sharma et al. studied the tribo response of Al-6061 composite reinforced with rarer earth particles (REP). The composite was manufactured by stir casting. Six composites were fabricated wherein SiC+Al$_2$O$_3$ particulates were varied from 5 wt. % to 15 wt. % and CeO$_2$ (REP) was varied from 0.5 wt. % to 2.5 wt.%. The test was conducted using a POD test rig. The pin dimensions were 10 mm diameter and 12 mm height. The disc was hardened En-31 steel. The normal loads were 10, 20 and 30 N. The sliding speeds were 0.5 ms$^{-1}$, 1 ms$^{-1}$ and 2.5 ms$^{-1}$. The sliding distances were 500, 1000, 1500 and 2000 m. The worn-out surface was studied in SEM. The result showed that the optimum quantity of CeO$_2$ with 2.5 wt. % resulted in a composite that exhibited improved tribological performance. The SEM study of the worn-out surface showed ploughing, adhesion, micro-cutting and plastic deformation wear mechanisms.

[12] Man et al. studied the tribo response of Al-6061 alloy whose surface was alloyed with NiTi using a laser beam technic. Experiments were conducted using a pin on disc (POD) test rig. The counter surface was a diamond ball of diameter 2mm. The normal load was 2.5 N and the sliding speed was 200 rpm. The Al-6061 alloy with T6 Heat treatment was cut into rectangular samples of 40 mm x 25 mm x 10 mm. The NiTi (Ni-54 wt. % and Ti-46 wt. %) with a grain size of 40 to 100 µm was used to prepare the aluminium alloy surface. The aluminium alloy surface was sandblasted. The NiTi powder with binder was coated on aluminium surface. The coating was processed by a laser beam to get a quality deposit. The result showed that the laser surface alloying with NiTi resulted in
better wear resistance. The hard inter-metallic dendrites filled with soft aluminium in the inter-dendritic region favoured in improving wear response.

[13] Kumar and Kumarswamydas studied the wear response of composite Al-6061 alloy reinforced with AlN and ZrB2. The composite was produced by the stir casting technique. The composite was prepared with 3 wt. %, 6 wt. %, 9 wt. % and 12 wt. % of reinforcements. The pin sample was of the dimension of 10 mm diameter and 20 mm length. The normal loads were 10, 20, 30, 40 and 50 N. The sliding speeds were 1, 2, 3, 4 and 5 ms⁻¹. The sliding distance was 2000 m. The worn surfaces of the pin were studied in SEM. The result showed that the tribo response was dependent on wt. % of particulates, sliding speed and normal load. The weight percent of particulate which resulted in improved wear resistant composite was found to be 12 wt. %.

[14] Maleki et al. studied the wear characteristic of SiC particulated Al-6061 composite. The reinforcement material was high content SiC, fabricated by pressure-assisted infiltration. The preform was processed using SiC powder of grain size 15 µm and polyethylene glycol with a particle size less than 1mm. The composite was produced by pouring Al-6061 alloy into a mould where the preform was placed. The POD test was carried out to understand the tribo response. The sliding speed was 0.6 ms⁻¹, and the normal load was 50 N, 100 N and 150 N. The wear scar was studied in SEM and elemental analysis was conducted by the energy dispersive X-ray analysis (EDAX) method. The result showed that the composite, Al-75 wt.% SiC, showed improved wear performance compared to aluminium 67 wt.% SiC composite. The SEM study revealed the formation of tribo layers.

[15] Aruri et al. studied the wear response of 6061-T6 aluminium alloy whose surface was modified by (SiC + Gr) and (SiC + Al2O3) particulates using friction stir processing. The surface modifications were carried out by friction stir processing and process parameters were documented in the reference. The wear testing was carried out using a POD tribometer according to ASTM G99-05 standards. Pins of size 8mm diameter were cut from surface modified Al-6061–T6 aluminium alloy. The disc was hardened En-31 steel. The track diameter was 100 mm. The normal load was 40N and the sliding speed was 3.4 ms⁻¹. The worn-out surfaces of the pin were studied in SEM. The result showed that surface modification improved the wear performance. The SiC carried the load and Graphite acted as a lubricant.

[16] Qutub et al. studied the wear response of Al-6061 composite reinforced with submicron-sized Al2O3 particles. The composite was processed by the powder metallurgy method. The composite was processed with different Al2O3 concentrations and these concentrations of Al2O3 in volume/ volume were 10 %, 20 % and 30%. The wear testing was conducted using a POD test rig. The pin was made of an aluminium composite of diameter 6 mm and spherical tipped. The disc was hardened En-31 steel. The sliding speed was 1 ms⁻¹ and the sliding distance was 1000 m. The normal loads were in the range of 0.5 N to 40 N. The worn-out surfaces of the pins were studied in SEM. The results showed that wear resistance increased with the increased percentage of sub-micron sized Al2O3 particles. Abrasion, delamination and adhesion wear mechanism were revealed in the SEM study.

The literature reports the wear response of Al-6061 aluminium alloy in an ambient environment where normal loads, temperature and speeds were varied. The effect of varied apparent contact areas on tribo-response in an adverse environment (vacuum) was not carried out by researchers and reported in the literature. In the present investigation, the effect of varied apparent contact areas on tribo response, was studied by conducting a set of experiments where both ambient and vacuum conditions were maintained in a specially configured POD test rig. The different apparent contact area was achieved in using pin of different diameters.
2. Experimental Details

A set of experiments using a cylindrical pins machined out of Al 6061 aluminium alloy with different diameters were conducted. The different diameters of the cylindrical pins were 2 mm, 4 mm and 6 mm. The dimensions of these three cylindrical pins samples are shown in Fig 1.

![Fig. 1. The drawing showing dimensions in mm of all cylindrical pins.](image)

Fig 1.a is the drawing of a cylindrical pin of 2 mm diameter. Fig 1.b is the drawing of a cylindrical pin of 4 mm diameter. Figure: 1.c is the drawing of a cylindrical pin of 6 mm diameter.

The schematic view of the specially configured Pin-on-Disc (POD) test rig is shown in Fig. 2

![Fig. 2 Schematic view of specially configured pin-on-disc [17]](image)

The test rig is consisting of five subsystems and are;

A. Chamber to hold the sample, heating furnace and to hang normal load.
B. To accommodate the disc driving system.
C. The chamber to house instruments.
D. The vacuum system.
E. Stand to mount Pin-on-Disc (POD) test rig.

The disc was mounted in a vertical configuration and was driven with the help of a direct current (DC) servomotor. The normal load was transferred to the pin with a leverage of approximately 1.5. The frictional force was sensed by beam type load cell and the frictional force was recorded in PC. The sliding speed of the disc was 0.5 ms\(^{-1}\). The normal pressure was 0.625 MPa. Experiments were
conducted in ambient and vacuum conditions and the vacuum level was 4 x 10^{-4} Pa. The monitored frictional force was used for estimating the frictional coefficient. The dependency of the frictional coefficient on sliding distance for different apparent contact areas was studied.

3. Results and Discussions

Experiments were conducted using a Pin-On-Disc (POD) test rig in ambient and vacuum conditions. The Al 6061 aluminium alloy in the form of cylindrical pins of diameters 2 mm, 4 mm and 6 mm were slid against a hardened EN-8 steel disc. The speed was maintained at 0.5 ms^{-1} and pressure was 0.625 MPa.

**Ambient condition**

A typical graphs showing dependency of coefficient of friction on sliding time in an ambient condition for 2 mm, 4 mm and 6 mm diameters pins are shown in Fig 3

![Graph showing dependency of coefficient of friction on sliding time for pin of 2 mm diameter in ambient.](image)

Fig 3.a Dependency of coefficient of friction on sliding time for pin of 2 mm diameter in ambient.

Fig 3.a shows the dependency of coefficient of friction on sliding time for the aluminium pin of diameter 2 mm slid in ambient. The normal pressure was 0.625 MPa and the sliding speed was 0.5 ms^{-1}. The sliding attained the steady-state after an approximately 10 s of initial sliding time. The sliding, until the finish of testing, i.e., up to a sliding time of 1800 s, was found to be steady. The average coefficient of friction during the steady-state of sliding was found to be 3.30.
Fig. 3.b Dependency of coefficient of friction on sliding time for pin of 4 mm diameter in ambient.

Fig 3.b shows the dependency of coefficient of friction on sliding time for the cylindrical aluminium pin of 4 mm diameter slid in ambient. The pressure was 0.625 MPa and the sliding speed was 0.5 ms\(^{-1}\). The sliding was found to be unsteady with fluctuating coefficient of friction over a time of approximately 200 s before attaining the steady-state. The magnitude of the average coefficient of friction during the unsteady sliding time of the first 200 s, where the coefficient of friction fluctuated, was found to be 1.08. The sliding was found to be steady after 200 s and until the end of the experiment. The average coefficient of friction during the steady state of sliding was found to be 0.78 and lower than the average coefficient of friction 1.08 found during initial unsteady state of sliding.

Fig. 3.c Dependency of coefficient of friction on sliding time for pin of 6 mm diameter in ambient.

Fig 3.c shows the dependency of coefficient of friction on sliding time for the cylindrical aluminium pin of 6 mm diameter slid in ambient. The pressure was 0.625 MPa and the sliding speed was 0.5 ms\(^{-1}\). The sliding was found to be unsteady with coefficient of friction being fluctuated over a
time of approximately 75 s before attaining the steady-state. The magnitude of the average coefficient of friction during unsteady initial sliding time of 75 s, was found to be 0.33. The sliding was found to be steady after initial unsteady state of sliding which was lasted for a time of 0 s to 75 s. The average coefficient of friction during the steady state of sliding was found to be 0.40. The average coefficient of friction during the steady state of sliding being 0.40 is found to be larger than the average coefficient of friction which is 0.33 found in initial unsteady state of sliding.

**Vacuum condition**

A typical graphs showing dependency of coefficient of friction on sliding time in vacuum condition for 2 mm, 4 mm and 6 mm diameters pins are shown in Fig. 4

![Graph showing dependency of coefficient of friction on sliding time for pin of 2 mm diameter in vacuum.](image)

**Fig: 4.a** Dependency of coefficient of friction on sliding time for pin of 2 mm diameter in vacuum.

Fig 4.a shows the dependency of coefficient of friction on sliding time for a cylindrical aluminium pin of diameter 2 mm slid in vacuum. The normal pressure was 0.625 MPa and the sliding speed was 0.5 ms\(^{-1}\). The vacuum was maintained at \(4 \times 10^{-4}\) Pa. The steady-state of sliding was established within approximately time interval of 0 s to 5/10 s and during this time interval i.e., 0 s to 5/10 s, the coefficient of friction fluctuated and estimated average coefficient of friction was found to be 3.89. The steady-state of sliding was established after time interval of 0 s to 5/10 s and persisted until the completion of experiment. The average coefficient of friction during the steady-state of sliding was found to be 3.37 which was found to be smaller when compared to the average coefficient of friction 3.89 found during time interval of 0 s to 5/10 s.
Fig: 4.b Dependency of coefficient of friction on sliding time for pin of 4 mm diameter in vacuum.

Fig 4.b shows the dependency of coefficient of friction on sliding time for a cylindrical aluminium pin of diameter 4 mm in vacuum. The normal pressure was 0.625 MPa and the sliding speed was 0.5 m s\(^{-1}\). The vacuum was maintained at 4 \(\times 10^{-4}\) Pa. The steady-state of sliding was established within approximately about 50 s. The coefficient of friction during the time interval of 0 s to 50 s was found to fluctuate and estimated average coefficient of friction during the time interval 0 s to 50 s was 1.15. The steady-state of sliding was established after about 50 seconds of sliding and continued until the end of the experiment i.e., 1800 seconds. The average coefficient of friction during the steady-state of sliding was found to be 1.22 and smaller compared to average coefficient of friction 1.15 found during time interval of 0 s to 50 s.

Fig: 4.c Dependency of coefficient of friction on sliding time for pin of 6 mm diameter in vacuum.

Fig 4.c shows the dependency of coefficient of friction on sliding time for a cylindrical aluminium pin of diameter 6 mm in vacuum. The normal pressure was 0.625 MPa and the sliding speed was 0.5 m s\(^{-1}\). The vacuum was maintained at 4 \(\times 10^{-4}\) Pa. The coefficient of friction was found to be
fluctuating with an average value of 0.55 during the time interval of 0 s to approximately 700 s. The coefficient of friction was found to gradually increase from 0.55 to approximately 0.70 over a time interval of 700 s to 1000 s. The coefficient of friction during time interval of 1000 s to 1800 s was found to fluctuate to a larger extent compared to fluctuation observed during time interval of 0 s to 700 s. The sliding was found to be steady during time interval 1000 s to 1800 s and estimated average coefficient of friction during steady state of sliding was fond to be 0.72.

The average coefficient of friction for both ambient and vacuum conditions during steady state of sliding for pins of diameter 2 mm, 4 mm and 6 mm are tabulated in Table 1.

| Diameter of the pin in mm | Average coefficient of friction |
|---------------------------|---------------------------------|
|                           | Ambient | Vacuum |
| 2                         | 3.30    | 3.36   |
| 4                         | 0.78    | 1.22   |
| 6                         | 0.40    | 0.62   |

The magnitudes of the average coefficient of friction for 2 mm diameter pin in ambient and vacuum was found to be 3.30 and 3.36 respectively. The magnitudes of the average coefficient of friction for 4 mm diameter pin in ambient and vacuum was found to be 0.78 and 1.22 respectively. The magnitudes of the average coefficient of friction for 6 mm diameter pin in ambient and vacuum was found to be 0.40 and 0.62 respectively. The magnitudes of the average coefficient of friction in vacuum compared to ambient for a given condition was found to be larger.

The magnitudes of the average coefficient of friction tabulated in Table 1 is drawn in a bar chart and shown in Fig: 5.

![Bar chart showing average coefficient of friction for different pin diameters in ambient and vacuum](image)

**Fig. 5.** Average coefficient of friction for different pin diameters in ambient and vacuum.

The bar chart shows the average coefficient of friction values for different apparent contact areas of the pins which were slid both in atmosphere and vacuum environment. The coefficient of friction for the cylindrical pin of diameter 2 mm was 3.30 and 3.36 in ambient and vacuum respectively. The
average coefficient of friction for other diameters i.e. 4 mm and 6 mm, in both ambient and vacuum conditions, were found to be lesser in magnitude compared to the average coefficient of friction for the cylindrical pin of 2 mm diameter.

4. Conclusions

1. The coefficient of friction was found to be dependent on the environment, i.e. ambient and vacuum.
2. The coefficient of friction, in general, was found high in vacuum when compared to ambient condition for a given apparent contact area.
3. The coefficient of friction, in both ambient and vacuum, was found to be dependent on apparent contact area rather than pressure intensity.
4. The coefficient of friction was found to decrease with an increase in pin diameters for both ambient and vacuum conditions.
5. The coefficient of friction was found to be maximum for a pin with a contact diameter of 2 mm and the coefficient of friction decreased as the contact area changed to 4 and 6 mm from 2 mm.

5. References

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