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Dry/wet Sliding Activation Wear of Pure Al

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ABSTRACT

An experimental work to study the wear behavior of pure Aluminium (Al) block was conducted against steel counter surface in Pin-on-Disc (POD) and the aluminium ball using four ball testing (4BT) method on dry/wet sliding wear technique at room temperature. Wear test conditions of 10-50 N load with sliding speed of 20-100 rpm was used to assess the friction coefficient, wear rate and the severance of wear mechanism on the damage surface. Due to the friction from the third body abrasive and protruded Al surfaces showcased mild wear with a steady state coefficient friction ranging from 0.0019-0.0043 for dry sliding and on wet condition ranging from 0.12-0.23 in vegetable oil (with average scar area of 8.0752 mm^2) and from 0.058-0.085 for mineral oil used (with average scar area of 17.1549 mm^2). Stress generation of the uncoated sample allowed the abraded plastic deformation to be classified as severe wear.

Keywords: *Pure Al, Wear, Oxidation, Alumina, Dry/wet Sliding*

Introduction

Controlling frictional and wear in dry abrasion is critical for homogeneous finishing surfaces or in polishing processes. For industrial aluminum component, it is normal to encounter abrasion in contact with contaminants

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and dust during the process. High friction and catastrophic wear has been observed in machinery components upon rubbing on each other surfaces after long duration causing deteriorating, low quality products and the undesirable effect observed in the performance and lifetime of machinery components [1].

The objectives of this work mainly to investigate the tribological properties of pure aluminum sheet when subjected to dry/wet abrasion. Finally, the data was analysed and compared on the effect of dry and lubricated tests environment on pure aluminium sheet and pure aluminium spherical ball respectively. Advances in technology have enabled tribo-applications especially in the automotive and aerospace industries [2] to be studied. A schematic diagram of reciprocating motion using tribometer is shown in Figure 1 and the wear mechanism is shown in Figure 2.

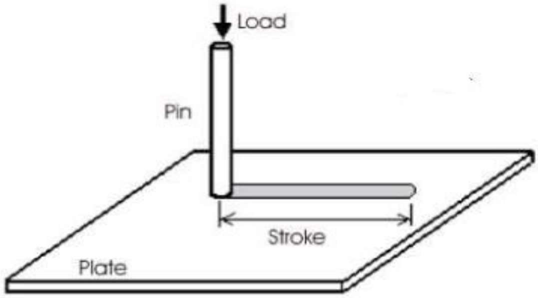


Figure 1: Schematic diagram of Pin on Disc Tribometer

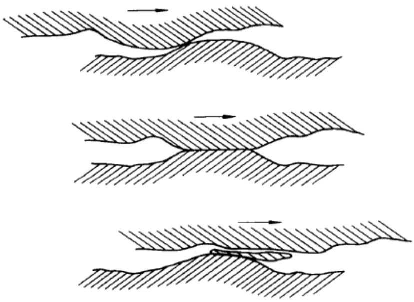


Figure 2: Wear Mechanism [3]

Normally, aluminum and its alloy are desirable materials due to high strength stiffness to weight ratio, good formability, good corrosion resistance, and recycling potential for use in automobile industries as components of internal combustion engines, e.g., cylinder blocks, cylinder heads and pistons. These alloys are susceptible to wear when matched to harder surfaces under high loads at elevated temperatures and tend to have poor wear resistance at atmospheric and high temperature conditions [4].

During testing operation, the disc material wears out and the volume of material loss is measured to determine the wear rate [1] [4] [5]. The schematic view of pin on disc testing machine is shown in Figure 3 and 4.

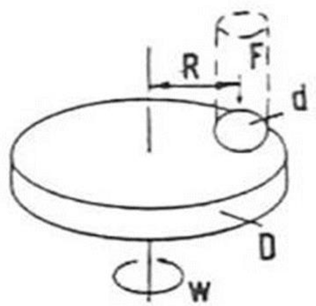


Figure 3: Schematic view of pin-on-disc testing machine

F : Applied normal load
R : Radius of the wear track that is produced
d : Diameter of the spherical top of the pin
D : Diameter of the disc
W : Rotational speed

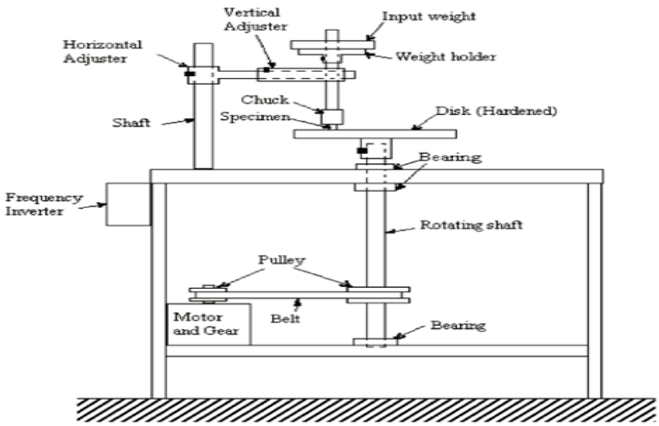


Figure 4: Pin-On Disc Type Wear Testing Machines [1].

Different parameters such as load, sliding velocity, contact geometry, hardness, flow stress, critical strain, friction coefficient, and fracture mode are taken into consideration [6]. Sliding velocity can be varied by two ways (i) by changing the rotation of the shaft and (ii) by changing the radius of the point of contact of the sliding pin [7]. The variation of friction and wear rate depends on interfacial conditions such as normal load, geometry, relative surface motion, sliding speed, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, stick slip, relative humidity, lubrication and vibration. Among these factors sliding speed and normal load are the two major factors whose play significant role for the variation of friction and wear rate [7] [8].

As a result of sliding contact between pin and disc, material from the disc is worn out. The difference of mass of the disc before the test and that of after test gives the mass loss in the disc specimen as a result of wear [9]. The wear volume was calculated using the profiles obtained from the wear track cross-section, and thus the wear rate was attained using Eq. 1[10]

$$\mathbf{K=V/\,(w\cdot s)} \qquad (1)$$

Where, K is the value of the wear rate,
V is the worn volume,
w is the normal load, and
s is the distance moved [4]

Hardness and weight measurement

The average hardness value was measured using Vickers hardness under standard ASTM E92 to eliminate the possible of segregation effect [10] [11]. The samples were dried properly after ultrasonic cleaning to enhance the accuracy of weight measurement [1, 5].

During sliding, the entire surface of the pin has contact with the surface of the steel disc and machine marks on the steel disc can also be observed [12] [13] [14]. Worn surfaces and cross-section of worn subsurface were also examined using SEM. The samples were polishing and etching before sputtered with gold prior to microstructure examination [15]. The energy dispersive X-ray (EDX) attached with the SEM was used for micro-analysis of the investigated material [16] [17]. The machine brand and model use in SEM is Hitachi S-3400N Scanning Electron Microscope (SEM).

Hypothetically, the effect of applied load is directly proportional to wear rate, i.e., as applied load increases, wear rate also increases and the positive coefficient of load indicates that dry sliding wear rate of the composite increases by increasing load[18] [19].

Amongst these alloys, the wear loss of pure Al was considerably higher than those of other materials. Pure Al also has the highest friction coefficient when compare with its alloys. The micro cracks formed on Al surface could be attributed to its lowest mechanical strength and corrosion resistance [20] [21]. Application of lubricant can significantly reduce the wear rate of the alloys and friction force gradually decreased with the lubricant thickness [22]. An unlubricated surface of materials will caused adhesive wear to take place on it [23]. In the case of lubricated sliding wear, a thin film of lubricant is always maintained .This film causes more slipping action of the mating surfaces and leads to significantly less coefficient of friction as well as change in temperature [24]. The coefficient of friction will be influenced by the external vibration as well. The presence of external horizontal vibration indeed affects the friction force of aluminum considerably. Therefore, the coefficient of friction of aluminum increases with the increase of frequency of vibration.

Experiment

The pure aluminum balls were purchased from supplier (Multi Products Supply Enterprise) with diameter of 12.7mm (half inch). The pure aluminum ball is then clean with acetone to remove the contaminants or dust on the ball surface before conduct the four ball test. The lubricants used in this experiment are mineral oil (Shell 4T) and vegetable oil (Pure palm oil) as shown in Figure6 and typical properties of the lubricant is shown in Table 1.

Table 1: Typical physical characteristics of 4T mineral oil and Palm vegetable oil

SAE viscosity grade	-	15W-40	Palm oil
Kinematic viscosity@40^{o}C mm^2/s	ASTM D4 45	106.2	39.6
Kinematic viscosity@100^{o}C mm^2/s	ASTM D4 45	14.3	
Viscosity Index	ISO 2909	150	
Density @15^{o}C kg/m^3	ASTM D4052	870	0.9180
Flash Point (COC) ^{o}C	ISO 2592	235	267
Pour Point ^{o}C	ISO 3016	-30	-
Cloud Point ^{o}C	-	-	31.0

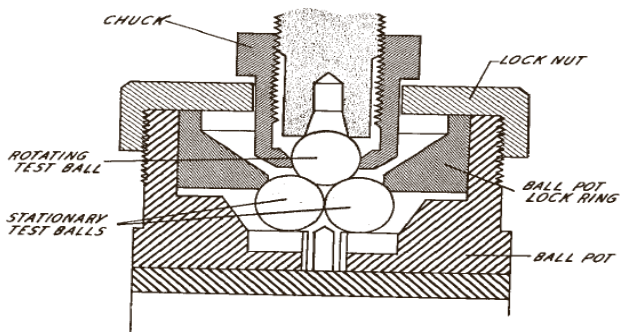


Figure 5: Schematic diagram of Four Ball tester arrangement.

A four ball tester is use in the wet abrasion test of pure aluminum ball over different type of lubricant as shown in Figure5 and as specified the parameters as shown in Table 2.

Table 2: Parameter used based on Standard ASTM D4172 B

Test Temperature, °C	75 ±1.7
Test Duration, min	60 ± 1
Spindle Speed, rpm	1200 ± 60
Load, kg	40 ± 0.2

Three ½ inch diameter pure aluminum balls are clamped together and covered with the test lubricant. A fourth ½ inch diameter pure aluminum ball is pressed into the cavity formed by the three clamped balls for three point contact, and rotated for a set duration as shown in Figure5. Lubricants are compared using the average size of the scar diameters worn on the three lower clamped balls. At the beginning of the experiment, the pure aluminum balls, cup and ball holder are cleaned and assembly by acetone and then dry in atmosphere. Then, lubricant sample is placed on the erected plate where three balls are held in position into a cup (at the end of the motor spindle) with the clamping ring and assembly secured by tightening the locknut. The fourth ball is then fitted on the upper balls chuck. Mounting discs are placed between the thrust bearing and the cup. The desired loads are then placed on the load lever to be tested. After the test end, the wear scar diameter can be observed and measured under optical image acquisition machine and the graph of coefficient of friction will show automatically on the software "winducom 2010".

In dry abrasion setting, the experiment specimen of pure aluminium sheet has a dimension of 4 ft x 8 ft x 1.5mm and was purchased from local supplier. The whole aluminum sheet was cut into 40 pieces by using shearing machine into smaller size with suitable dimension which is length 100mm x width 25mm x thickness 1.5mm. The surface is polished by using Autosol (polishing cream) with a smooth cloth and clean with acetone. All samples were polished and keep separately avoiding the scratch of surface.

The specimens were indented by the diamond indenter of the machine in the shape of right pyramid with square base subjected to a load applied by the machine. The load was allowed to apply for 5 to 10 seconds. The two diagonals of the indentation were measured using microscope and Vickers hardness were obtained. Next, one of the pure aluminum sheet was chosen randomly to conduct the hardness test by using Vicker's Hardness Tester with Time, t=15s, N= 1/256N.

Materials were tested in pairs (pin and disc) under nominally non-abrasive conditions. For the pin-on-disc wear test, two specimens are required—a cylindrical pin specimen and a flat disc specimen. During the experiment, the specimen was placed onto the specimen holder and fix horizontally. The pin specimen was pressed against the disc at a specific load by means of an arm level and attached weights subjected to reciprocating movement. It is because the rotary motion of specimen require an accurate plate holder to hold the specimen on the pin-on-disc tester to prevent it from slipping off the surface when move in circular motion. Different parameters such as load, sliding velocity, sliding distance and time were varied which included 5N-25N at the speed of 20rpm-100rpm respectively. A table of Design of Experiment was constructed to create the all the possible testing combination. Wear rate and coefficient of friction of each specimen are obtained after getting the data. When the materials were well prepared, it proceed to pin on disc test. 25 samples for dry abrasion test with different parameters.

Finally, the specimens were observed under SEM and EDAX to study the compositions of several materials that present using Hitachi S-3400N Scanning Electron Microscope (SEM).

Results and Discussion

The hardness results are shown in Table 3. Hardness ranging from 37-39 HV is within accepted range for the ball fabricated based on ASTM D4172 B specifications.

Table 3: Hardness value of pure aluminum sheet

Test Parameters	1	2	3	Average
Diameter, D1(mm)	686.2	688.6	698.9	691.23
Diameter, D2 (mm)	692.4	697.5	710.8	700.23
Hardness value, (HV)	39	38.6	37.3	38.3

Effect of speed and load on wear rate

Several experiments have been carried out to observe the effect of normal load and sliding speed on wear rate of aluminum. The variation of friction and wear rate depends on interfacial conditions such as normal load, geometry, relative surface motion, sliding speed, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, stick slip, relative humidity, lubrication and vibration. Amongst these factors sliding speed and normal load are the two major factors whose play significant role for the variation of friction and wear rate [7] [8]. In order to compare the effect of speed and load on the wear rate of pure aluminum, the wear rate for pure aluminum at 1200th sec. and at 40 rpm and 100 rpm at different load as shown in Figure 6.

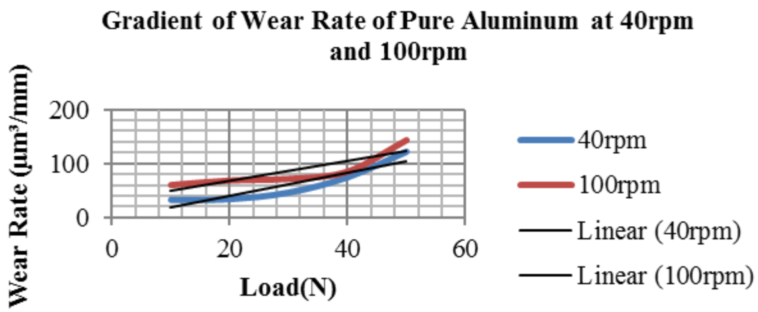


Figure 6: Wear Rate against load of Pure Aluminum at 40rpm and 100rpm

The value of wear rate shows forces needed to wear away the specimens and it depends on the microstructure of the specimens. The greater the value of wear rate, the lesser the force is needed to wear the specimen. The results of the specimens of pure aluminum at 40 rpm and 100 rpm are closer to the ideal results. In Figure 7 it shows that the wear rate is increasing from applied load of 10N to 50N. The wear rate is also showing increasing trend when we compare it at constant load but different sliding speed. The positive trend of load indicates that dry sliding wear rate of the pure aluminum increases by increasing load. This is because, the temperature at the interface between the disc and the pin increases with increase in the applied load [18]. Moreover, when the applied load increase, the frictional heat which generates at the contact surface will increase as well and hence decrease the strength of materials. Therefore, the wear rate will increase since there is more material being removed from the pure aluminum. Next, as we compare the wear rate of pure aluminum at 40rpm and 100 rpm, it shows that the wear rates increase as the speed of the wearing surface between the specimen and the reciprocating disc increase. This is due to the fact that duration of rubbing is the same for all sliding speed, while the length of rubbing is more in case of higher speed. Moreover, the greater sliding speed will creates greater force that will remove the specimen greater. Hence, the wear rate increases.

Effect of speed and load on average coefficient of friction

In order to compare the effect of speed and load on the average coefficient of friction of pure and recycled aluminum, the average value of coefficient of friction at 20 rpm and 100 rpm at different loads are calculated and shown in Figure 7.

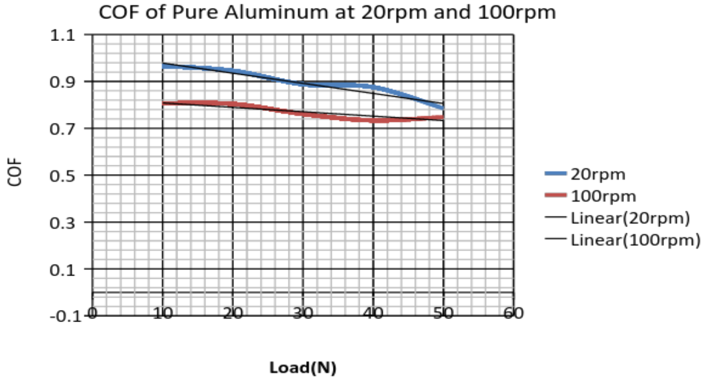


Figure 7: Gradient of COF of Pure Aluminum at 20rpm and 100rpm

The value of coefficient of friction (COF) depends on the contact surface between the specimens and the reciprocating pin. Therefore, greater frictional force needed to be overcome between the surfaces if the value of coefficient of friction is higher. The greater the value of coefficient of friction, the greater force needed to move the specimen against the surface of reciprocating pin. The results of coefficient of friction of pure aluminum at sliding speed of 20 rpm are close to ideal but not ideal at 100rpm. When the test parameter reach the maximum which is at 50N with 100rpm, the coefficient show the slightly increasing trends. This is because the coefficient of friction is influenced by the external vibration. The presence of external horizontal vibration indeed affects the friction force of aluminum considerably. Therefore, the coefficient of friction of aluminum increases with the increase of frequency of vibration [26]. The results show that the values of friction coefficient decrease with the increase of sliding speed. This is because the greater speed creates greater inertia that helps to overcome some of the frictional force between the surfaces. Hence, the value of coefficient of friction decreases as the speed increase. Next, the value of coefficient of friction decrease when the applied load increase. This is because when there is greater load applied, the contact surfaces become larger and there is greater force created. Hence, it is easier to overcome the friction between the surface and the value of coefficient of friction become smaller.

In optical tests, the worn out surface of some selected /typical specimens after the wear test are observed under scanning electron microscope and EDAX. Morphology of the worn surface of the unreinforced Al and composition of pure aluminum sheared at different sliding speed at 40 rpm and 100 rpm with applied load of 50N of a wearing time of 20min is shown in Figure 8(a)-(d).

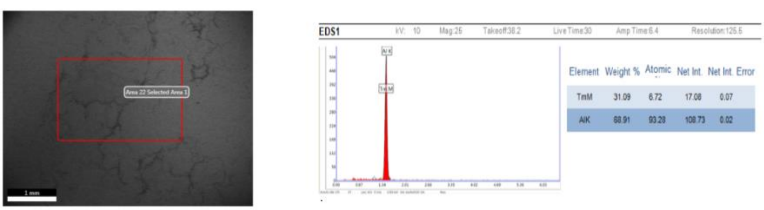


Figure 8: (a) Micrograph of pure aluminum at 40 rpm (50N) and EDAX analysis of Pure aluminum at 40 rpm (50N)

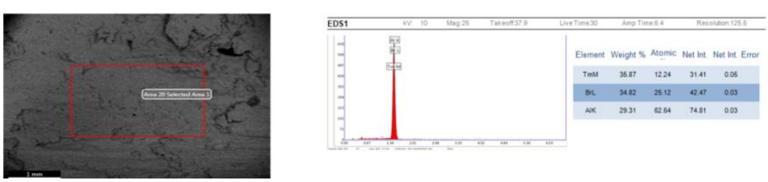
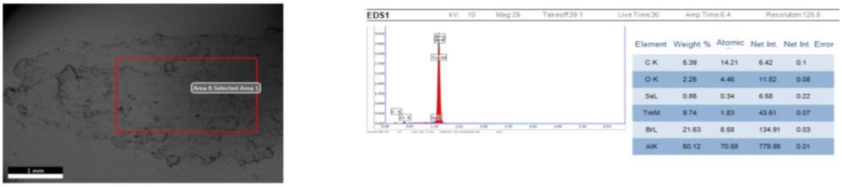


Figure 8: (b) Micrograph of pure aluminum at 100 rpm (50N) and EDX analysis of specimen Pure aluminum at 100



Element	Weight %	Atomic	Net Int.	Net Int. Error
C K	6.39	14.21	6.42	0.1
O K	2.25	4.46	11.82	0.08
SeL	0.86	0.34	6.58	0.22
TmM	9.74	1.83	43.51	0.07
BrL	21.63	8.58	134.91	0.03
AlK	60.12	70.58	779.86	0.01

Figure 8: **(c)** Micrograph of pure aluminum at 40 rpm (10N) and EDX analysis of specimen Pure aluminum at 40 rpm. (10N)

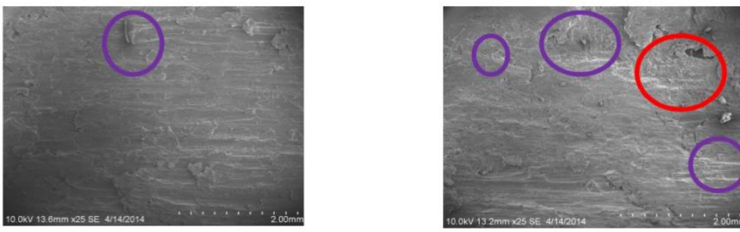


Figure 8: (d) Micrograph of Pure aluminum at 40 rpm and Micrograph of Pure aluminum at 100rpm

Refer to Figure 8 d, the area that is black in color is mainly consists of aluminum and the worn surface of pure aluminum sliding at 40 rpm is smoother than 100rpm at maximum applied load of 50N. With higher sliding velocity, the wear rate will be higher and the worn surface will become deeper and wider. Therefore, there are more ridges (purple circle) and crack area (red circle). As the sliding velocity increases to 100rpm the smooth patch region decreased and the size of the craters was increased. At a speed of 100rpm the smooth patch vanishes and the size of the crater is maximum indicating severe loss of the material. Referring to Figure 8 (a, b and c), in EDX analysis, it shows that the composition of aluminum at 40rpm (68.91%) is higher than 100rpm (29.31%) while there are still other composite such as Tm (Thulium) and Br (Bromine) in the pure aluminum sheet. The existence of higher amount of other composites in the composition of pure aluminum increases the wear resistance of the pure aluminum. The existence of thulium and bromine in the microstructure increases the resistance between the layers of grain boundaries. The grain boundaries need more force to overcome the frictional force or friction that created. However, when the applied load and sliding speed are high, it creates sufficient energy to break the layers of grain boundaries and weaken the strength of pure aluminum specimen. Hence, the pure aluminum which sliding at 100rpm has greater wear rate compared to the pure aluminum which sliding at 40rpm. Similar observation is done with different applied load (10N and 50N) with same sliding velocity (40rpm) as shown in Figure 8.

During the wet abrasion test, there are some observation have been made as shown in Fig 9(a-h). The comparison of wear scar diameter and coefficient of friction of pure aluminum ball over vegetable oil and mineral oil are shown in Figure 9(a)(e and f). The comparison of wear scar of upper and lower pure aluminum ball by SEM which tested under mineral oil and vegetable oil as lubricant are shown in Figure 9(e)-(k).

The wear scar diameter of three lower pure aluminum balls under vegetable oil is much larger than mineral oil as lubricant. Furthermore, the upper pure aluminum ball with mineral oil show the “ring” shape of scar on its surface while the upper pure aluminum ball with vegetable oil show a larger and deeper “ring” shape of scar not only on its surface but also get into certain depth of the aluminum ball. The Average wear scar diameter can be calculated using Eq. (2) and tabulated as shown in Table 5.

$$\frac{Horizontal\ Reading + Vertical\ Reading}{2} \quad (2)[25]$$

Table 5: Average scar diameter of pure aluminum ball

Lubricant Oil	**Average Wear Scar Diameter (µm)**	**Average Wear Scar Area (mm²)**	**Difference in Percentage of Wear Scar (%)**	
			Diameter	**Area**
Mineral Oil	3202.07	8.0752	0	0
Vegetable Oil	4435	17.1549	+38.48	+112.44

Then, in Figure 9(b) it shows that the comparison of frictional torque between mineral oil and vegetable oil during wet abrasion test. The frictional torque of mineral oil (red) as lubricant show a stable and steady trend which the range of value within 0.10Nm ~ 0.15Nm while the frictional force of vegetable oil (blue) as lubricant show a unstable and deviate trend which the range of values are much more larger and fall within 0.06Nm ~ 0.38Nm. The frictional force of vegetable oil will reach a peak after a short period of time flow (about 200s-400s) and it keep repeating until the end of experiment. The coefficient of friction of pure aluminum against mineral oil (0.078738) is higher than vegetable oil (0.055106).

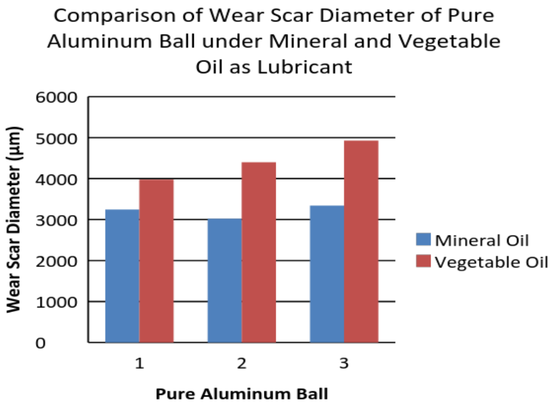
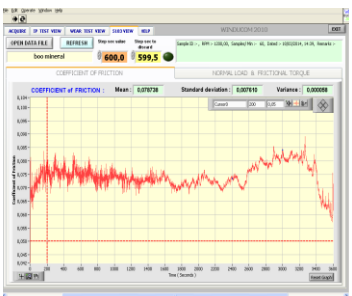
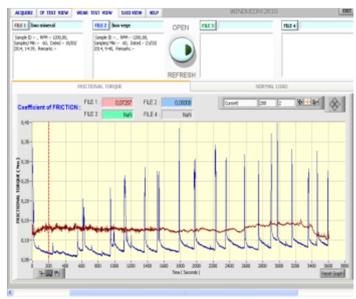


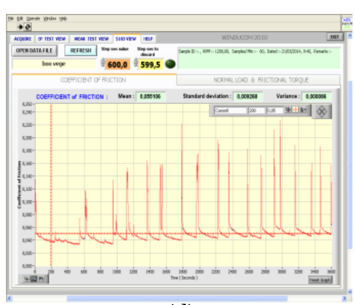
Figure 9: (a) Comparison of Wear Scar Diameter of Pure Aluminum Ball under Mineral and Vegetable Oil as Lubricant



(b)



(c)



(d)

Figure 9: Comparison between (b) Frictional Torque of mineral oil (red) and vegetable oil (blue) as lubricant in four ball test. (c): Coefficient of friction of pure aluminum ball over Mineral oil (d): Coefficient of friction of pure aluminum ball over vegetable oil

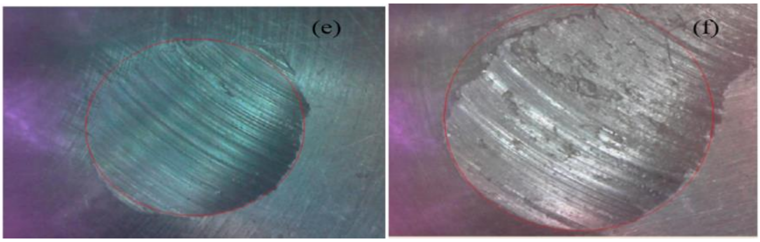


Figure: 9 (e) & (f): Comparison of wear scar of lower pure aluminum ball by SEM which tested under mineral oil (Left) and vegetable oil (Right) as lubricant.

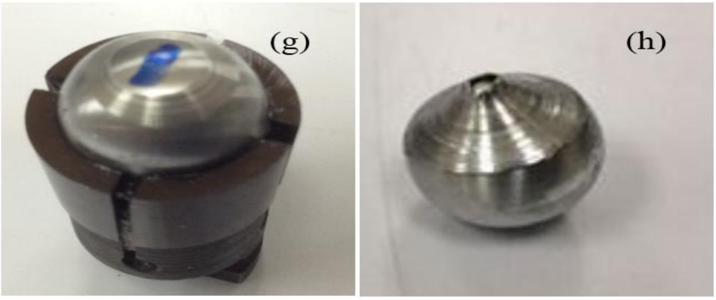


Figure 9: (g) & (h): Comparison of wear scar of upper pure aluminum ball which tested under mineral oil (Left) and vegetable oil (Right) as lubricant.

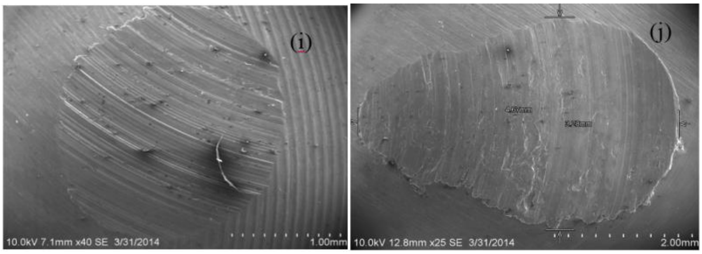


Figure 9: (i) and (j): Comparison of wear scar of lower pure aluminum ball by SEM which tested under mineral oil (Left) and vegetable oil (Right) as lubricant.

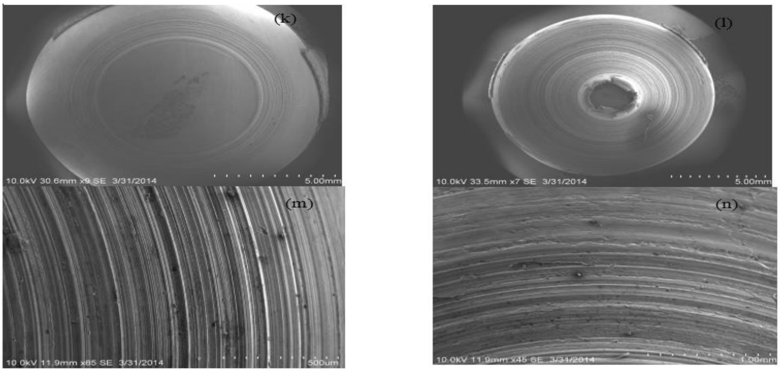


Figure 9: (k-n): Comparison of wear scar of upper pure aluminum ball by SEM which tested under mineral oil (k &m) and vegetable oil (l &n) as lubricant

In Figure 9 (i) and (j), comparison was made by observing the wear scar of the lower pure Al in mineral and vegetable oil respectively. There are some possible causes which affect the result of wet abrasion test of pure aluminum ball between mineral oil and vegetable oil. First, the viscosity of mineral oil is higher than vegetable oil. Viscosity refers to internal friction of a fluid. It is the property used for identification of individual grades of lube oil and for monitoring the changes occurring in the lube oil while in service. This is observed in Figure9 (k and m) for mineral oil and Figure 9 (l and n) for vegetable oil respectively. It created by molecular attraction or cohesion, which make fluid resistance to flow. A viscous fluid has a cohesive and sticky fluid consistency. For example, engine oils have to be viscous to be able to adhere better to moving engine parts. Higher viscosity indicates thicker lubricant oil between two contact areas of metal. It has higher film strength and more stable viscosity base. As we can see from the graph of coefficient of friction (in Figure 9 d) whereby vegetable oil act as a lubricant, the value will maintain at low coefficient of friction (0.03-0.06) for a few minutes and will rise dramatically to a very high coefficient of friction (0.12-0.23). This phenomenon is due to the thickness of vegetable oil as lubricant is thin and when two metal moves in continuous motion, the surface of two metals will contact and collide with each other and cause the coefficient of friction come to a sudden increase. However, as shown in Figure 9 (b), the mineral oil can perform in a more stable way (0.058-0.085) as lubricating agent than vegetable oil because it has thicker lubricant and hence has better prevention of contact by two surfaces as proposed by [25].

Next, viscosity index of mineral oil is higher than vegetable oil. Therefore, mineral oil offer better high temperature oxidation resistance, high film strength, very low tendency to form deposits, stable viscosity base and low temperature flow characteristics [26]. Last but not least, the performance of mineral oil as lubricating medium is better than vegetable oil is because mineral oil can withstand greater load and temperature range than vegetable based lubricant [27]. Hence, there are vast potential and modification needed before vegetable oil could comprehend as high performance automobile lubricant [28].

Conclusion

The study of tribological properties of pure aluminum at dry abrasion is depending significantly on the normal load applied and the sliding velocity of the contact surfaces. The average coefficient of friction reduced linearly as the normal load applied increase. For average coefficient of friction at 20 rpm (0.0043), the gradient is decreasing steeper than at 100rpm (0.0019). For wet abrasion test, the wear scar diameter of pure aluminum balls under vegetable oil is much larger than mineral oil as lubricant (>38.48%). The coefficient of friction of vegetable oil as lubricant will maintain at low coefficient of friction (0.03-0.06) for a few minutes and will rise dramatically to a very high coefficient of friction (0.12-0.23) while the mineral oil can perform in a more stable way (0.058-0.085) as lubricating agent. This is mainly due to the viscosity of mineral oil is higher than vegetable oil. Higher viscosity indicates thicker lubricant oil between two contact areas of metal. It has higher film strength and more stable viscosity base. Therefore, mineral oil can perform better than vegetable oil as lubricating medium.

References

[1] Yasmin T., Khalid A. A., and Haque M. M., "Tribological (wear) properties of aluminum–silicon eutectic base alloy under dry sliding condition." *Journal of Materials Processing Technology* 153 (2004): 833-838.

[2] A. Rac, K.-D.B., A. Vencl, A. Tsouknidas, *Tribological properties of thixoforming al-alloy a356 and influence of heat treatment.* Journal of tribological and mechanical engineering, 2005

[3] Mehta, D. S., S. H. Masood, and W. Q. Song. "Investigation of wear properties of magnesium and aluminum alloys for automotive applications."*Journal of Materials Processing Technology* 155 (2004): 1526-1531.

[4] Arslan, E., Totik, Y., Demirci, E. E., Vangolu, Y., Alsaran, A., & Efeoglu, I. "High temperature wear behavior of aluminum oxide layers produced by AC micro arc oxidation." *Surface and Coatings*

Technology 204.6 (2009): 829-833.

[5] Ugur Ozsarac, S.A., Wear behaviour investigation of wheel/rail interface in water lubrication and dry friction. Journal of Industrial Lubrication and Tribology, 2008: p. 101-107

[6] Kato, K., *Abrasive Wear of Metal.* 1997. 30(No.5): p. 333-338

[7] Chowdhury, M. A., Khalil, M. K., Nuruzzaman, D. M., & Rahaman, M. L. "The effect of sliding speed and normal load on friction and wear property of aluminum." *Int. J. Mech. Mechatron. Eng* 11.01 (2011): 53-57.

[8] Danijel Pavković, M., IEEE, Nenad Kranjčević, Milan Kostelac, Zvonko Herold, and Joško Deur. "Normal force control for a pin-on-disc tribometer including active or passive suppression of vertical vibrations." *Control Applications (CCA), 2012 IEEE International Conference on*. IEEE, 2012.

[9] Feyzullahoğlu, Erol, and Nehir Şakiroğlu. "The wear of aluminium-based journal bearing materials under lubrication." *Materials & Design* 31.5 (2010): 2532-2539.

[10] Radhika, N., and R. Subramaniam. "Wear behaviour of aluminium/alumina/graphite hybrid metal matrix composites using Taguchi's techniques." *Industrial lubrication and tribology* 65.3 (2013): 166-174.

[11] Angus, H.T., *The significance of hardness.* Journal of wear, 1979. 54: p. 33-78.

[12] Radhika, N., Subramanian, R., Venkat Prasat, S., & Anandavel, B. "Dry sliding wear behaviour of aluminium/alumina/graphite hybrid metal matrix composites." *Industrial Lubrication and Tribology* 64.6 (2012): 359-366.

[13] Zhong, Zhaowei, and Nguyen Phu Hung. "Grinding of alumina/aluminum composites." *Journal of materials processing technology* 123.1 (2002): 13-17.

[14] Pydi, H. P., Prasad Saripalli, H. K. R., Abburi, M. R., Murthy, B. S. N., & Sivaprasad, D. "Scanning Electron Microscope Studies on Dry Sliding Wear Behaviour of Metal Matrix Composites With Aluminium and Rice Husk Ash." *International Journal of Integrative sciences, Innovation and Technology* 1.2 (2012): 1-5.

[15] Jha, N., Badkul, A., Mondal, D. P., Das, S., & Singh, M. "Sliding wear behaviour of aluminum syntactic foam: A comparison with Al–10wt% SiC composites." *Tribology International* 44.3 (2011): 220-231.

[16] Zhang, L., Zhu, D., Wu, R., Liu, E., & Zhang, D. "Tool wear investigation using SEM 3D reconstruction technique." *Digital Manufacturing and Automation (ICDMA), 2011 Second International Conference on*. IEEE, 2011.

[17] Chen, J. H., Tichelaar, F. D., Terryn, H., & Katgerman, L. "Optical

and transmission electron microscopical study of the evolution of surface layer on recycled aluminium along the rolling mills."*Surface and Coatings Technology* 201.8 (2007): 4561-4570.

[18] Radhika, N., R. Subramanian, and S. Venkat Prasat. "Tribological behaviour of aluminium/alumina/graphite hybrid metal matrix composite using Taguchi's techniques." *Journal of Minerals and Materials Characterization and Engineering* 10.05 (2011): 427.

[19] Abbasi, M., Kheirandish, S., Kharrazi, Y., & Hejazi, J. "On the comparison of the abrasive wear behavior of aluminum alloyed and standard Hadfield steels." *Wear* 268.1 (2010): 202-207.

[20] Zhang, Tiancheng, and D. Y. Li. "Improvement in the resistance of aluminum with yttria particles to sliding wear in air and in a corrosive medium." *Wear* 251.1 (2001): 1250-1256.

[21] Kumar, G. Hemath, and H. Mohit. "Wear testing of nano Alumina-Zirconia ceramic matrix composites." *Nanoscience, Engineering and Technology (ICONSET), 2011 International Conference on*. IEEE, 2011.

[22] Tani, H., Mitsutome, T., Kamei, D., & Tagawa, N. "Relationship of Adhesion/Friction Forces and Slider Vibration in Surfing-Recording HDI System." *IEEE Transactions on Magnetics* 49.7 (2013): 3752-3755.

[23] Shi, Z., Sun, Y., Bloyce, A., & Bell, T. "Unlubricated rolling-sliding wear mechanisms of complex aluminium bronze against steel." *Wear* 193.2 (1996): 235-241.

[24] Ishii, Mieko, Youichi Kawakubo, and Naoya Sasaki. "Lubricant behavior and pin wear on thin-film magnetic disks." *IEEE transactions on magnetics* 35.5 (1999): 2341-2345.

[25] Osward, M.M., Standard Test Method for Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method). 2007.

[26] Kothavale, B. S. "Evaluation of Extreme Pressure Properties Lubricating Oils Using Four Ball Friction Testing Machine."*Wear* 150: 0-463.

[27] Kalam, M. A., Masjuki, H. H., Varman, M., & Liaquat, A. M. "Friction and wear characteristics of waste vegetable oil contaminated lubricants." *Proceedings of Regional Tribology Conference 2011: RTC2011*. Malaysian Tribology Society, 2011.

[28] N. Nuraliza*, S. Syahrullail, M.H. Faizal , Tribological properties of aluminum lubricated with palm olein at different load using pin-on-disk machine. *Jurnal Tribologi* 9, pp.45-59.