

Frictional Properties of Cast Al-Si-Cu-Zn Alloy in DOT4 Fluid

Ajibola, O. O., Adebayo, A. O., Falodun, O. E., Olubambi. P. A.

Abstract Frictional properties of cast aluminium based silicon-copper-zinc (Al-Si-Cu-Zn) alloy were studied in and without DOT4 brake fluid environment using a standard ball on disk tribometer. Substrates were prepared by grinding and polishing to 0.2 μm mirror-like, smooth and uniform surface. The examinations of the polished and worn surface morphologies and microstructural analysis were carried out using high resolution metallurgical microscope. Standard size 6 mm diameter alumina ball was rubbed on the cast Al-Si-Cu-Zn alloy specimens surface using different loads (1~10 N) at room temperature (25.00 $^{\circ}\text{C}$) and atmospheric humidity of 50%. Increased normal force F_n loading initially gave a considerable decline in coefficient of friction (CoF) values for the dry and wet sliding conditions but latter, the CoF stabilized over wide time range for both contact situations. The CoF values reduced from average of $\mu = 0.415$ to 0.174 at 1 N; $\mu = 0.4997$ to 0.1689 at 5 N; and $\mu = 0.82$ to 0.193 at 10 N respectively during the dry and wet sliding contacts. The results showed that the alloy was resistant to wear under the two experimental conditions.

Keywords: Frictional coefficient; wear; cast aluminium-silicon alloy; DOT4 brake fluid; tribometer

I. Introduction

The automotive and automobile industries have witnessed the highest consumption of aluminium alloys facilitated by the advantages of some notable engineering properties such as their high strength-weight ratio, heat-treatability, castability and combination of both cold and hot working characteristics. However, the alloys suffer creep at high temperatures, corrosion under some aggressive chemical atmosphere and wear in diverse hostile environments especially when there is friction at contact surfaces.

Despite the vast volume of reports by various researchers on the development of cast irons, steels, aluminium alloys and the composites; literature on the tribology and corrosion of these alloys and composites are sparingly available in this area of “brake fluids” subject matter.

However, some other relevant reports on wear and lubrication of similar alloys in some other types of lubricating oils are compared [1-4] from the limited chronicle of publications available in public domain within the last decades. Specific qualities of materials such as resistance to corrosion and wear, specific strength, ability to withstand high temperatures are of a great advantage in the automotive industry [5,6]. As it may apply to certain operations, tribology of wrought and cast aluminium alloys have been widely investigated under dry and wet sliding conditions [7,8]. Aluminium-silicon (Al-Si) alloys are regarded as exceptional class of alloys in engineering applications where high strength, wear and corrosion resistance are important. They have found vast usage in automotive, automobile and some structural applications [9]. Hypereutectic Al-Si alloys have better wear resistance [10], high strength to weight ratio, low thermal expansion, outstanding castability, admirable corrosion resistance, which makes Al-Si alloys suitable for vast tribological purposes in automobiles, pistons, cylinder liners, compressor scrolls and engine blocks [11] and in diverse

Ajibola, O. O., Adebayo, A. O.

(Department of Materials and Metallurgical Engineering,
Federal University Oye Ekiti, Nigeria)

Falodun, O. E.

(School of Chemical and Metallurgical Engineering,
University of the Witwatersrand, Johannesburg, South
Africa)

Ajibola, O. O., Olubambi. P. A.

(Centre of NanoEngineering and Tribocorrosion,
University of Johannesburg, Johannesburg, South Africa)

Corresponding Author: olawale.ajibola@fuoye.edu.ng

engineering applications [12,13]. Different means such as alloy/composite design (with Cu, Mg, Mn, Ti, Cr etc), heat treatment and coating have been established to enhance the wear, corrosion and high temperature stability in order to tackle application challenges in diverse aluminium alloys [14,15]. In a work, [16] had earlier developed a procedure to evaluate wear of aluminium-silicon alloy (Al-Si7) prepared by casting, strengthened with titanium carbide (TiC) micro-particles, and subjected to friction under counter-body with fixed abrasive prior and after being heat treated. The effects on mass wear, wear intensity, wear rate and wear-resistance were determined for alloys with diverse weight percent (wt.%) of micro-particles.

Engine oil serves different purposes in an automotive engine as lubricant and friction reducing fluid [17], corrosion inhibitor [18] and coolant or heat absorbent [6]. When the vaporized motor oils work poorly, it decreases fuel potency and contributes to extra emissions and engine wear [19]. Usual mono-grade motor oils have a tendency to “boil off” at high temperatures, losing up to a quarter of the original weight [20]. The multigrade engine oil SAE20W50 has high performance and resists vaporization [19,21].

Whereas most brake fluids are glycol-ether based, silicone based fluids and mineral oils that require high boiling point to avoid its vaporisation in the lines. Glycol-ether (DOT 3 or DOT 4) brake fluids are hygroscopic while more contemporary fluids (silicone/DOT 5) are hydrophobic. The brake fluids must not corrode the metal components such as pistons used inside the master cylinders and must maintain low level of compressibility even with varying temperatures. In the case of glycol and silicone, fluid mixture may cause corrosion due to trapped moisture [22]. Corrosion inhibitors are added to the base fluid as formulation additives to protect against corrosion in case moisture enters the system. The report [4] investigated the dry and lubricated sliding tribological tests on hypereutectic Al-25Si alloy fabricated by

rapid solidification technique at T6 condition using a ball-on-disk configuration and small amount (0.1-0.12 ml of lubricant) of commercial engine grade synthetic oil SAE20W50 at room temperature. The primary Si phases acts as solid lubricant which plays important role in the friction behaviour of the fabricated hypereutectic Al-25Si alloy in SAE20W50.

The present work is a subset of large research on diverse aluminium alloys. Reports are scarce on investigations involving wear and corrosion of materials in hydraulic brake fluids. Therefore, results obtained in the present study could only be compared with the previous results on brake fluids (DOT3 and DOT4) and few related subjects available in literature. The prominent among such research results on the tribological behaviours of aluminium alloys with and without brake oil are being circulated. The paper [23] discovered that experimented eutectic structured sand cast aluminium alloy pistons have relatively better abrasive wear resistance than the as-received cast aluminium alloy piston specimen in DOT3 oil; it was concluded that the cast alloy deteriorations was aggravated from the chemical adulteration of the oil.

Some other findings showed that the addition of MgFeSi from 1 to 3% improved the wear resistance of the cast 6061 aluminium alloy piston under lubricating condition using DOT3 brake oil [24].

Research findings on diverse control methods such as surface coating by electroless-nickel plating and heat treatment have been investigated as remedies to issues of wear and corrosion of the aluminium alloys have also been reported [25]. Thus, this study serves as the bases for the comparison of tribological behaviours of Al-Si-Cu-Zn with the Al-Si, A6061, steels and aluminium-alloyed ductile iron with and without DOT4 and DOT3 brake fluids as regarding their applications in automobile engine block and cylinders, brake piston and cylinders.

In order to illustrate the theoretical background of frictional wear study, Figure 1 shows typical

ball-on-disk setup with the standard parameters required to study the friction properties of contacting surfaces from which wear can be calculated.

where, r = ball radius, F_n = normal force exerted on the ball, R = wear track radius and; s = disk rotational speed.

Force F_t is tangential forces needed to be overcome on the plane surface for the solid bodies to slide over each other. It is proportional to the force normal to the surfaces (F_n) according to Amonton's law as in Equation (1);

$$F_t = \mu F_n \quad (1)$$

where μ is constant (the friction coefficient).

A solid body on a plane surface will be in motion by reason of gravity in case the surface is elevated at angle, θ to the friction as shown in Equation (2); where

$$\mu_s = \tan \theta \quad (2)$$

μ_s is the static coefficient of friction [26].

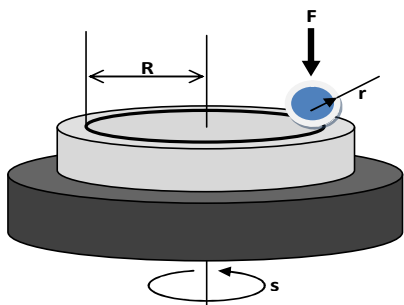


Figure 1: The standard ball-on-disk setup

Various researches have been carried out in similar reports using different materials as steel, cast iron and other aluminium alloys. However, the current work is targeted at evaluating the frictional behaviour of cast Al-Si-Cu-Zn alloy as a material for application in automobile hydraulic brake/clutch master systems and hydraulic fluid pumps.

In practice, the material loss is defined from the shape of the wear track.

Variations around the wear track can be caused by debris and plastic deformation [27]. The

approach seeks to examine the friction characteristics of Al-Si-Cu-Zn alloy in dry and wet contacts (DOT4) using standard tribometer for small applied loads

II. Materials and Methods

A. Materials sources and preparation

In the study, castings were prepared from the sourced wrought aluminium alloy in accordance with ASTM B26/B26M-05 specification for aluminium sand castings. The as-cast alloy samples obtained were cut from the bulk material. The surfaces of the specimens (25 mm diameter by 10 mm thickness cylinder size) were grinded and polished with 0.2 μm fumed silica suspension to get uniform and smooth mirror-like finishing using automatic polishing machine (Saphir 550, ATM, Germany).

The samples were analysed in the solid form and characterised by X-Ray Fluorescence (XRF) spectrometric method based on ASTM E1251 standard using the Rigaku ZSX Primus II model of XRF machine. The composition of the aluminium alloy specimen and chemical properties of hydraulic fluid (DOT4 Fluid) are respectively shown in Tables 1 and 2. The data of XRD phase analysis of the cast Al-Si-Cu-Zn alloy using Rigaku Ultima IV model are presented in Table 3.

Table 1: Composition of aluminium specimen

Metal	Mass %	Metal	Mass %	Metal	Mass %
Al	74.0161	Cu	2.0080	Co	0.0093
Si	19.1539	Zn	1.7941	Ti	0.0445
Fe	2.1194	Mn	0.3587	Mg	0.0247
Ni	0.0625	Cr	0.0421	Trace metals	Balance
Sn	0.0323				

Table 2: Analyses of DOT4 Fluid

Composition	% vol	Other properties	Units
Triethylene glycol butyl ether	10-30	Density	0.999g/cm ³
Triethylene glycol methyl ether	5-25	Specific Gravity	1.000 to 1.070
Triethylene glycol	0-10	pH	10.0 – 11.5
Polyethylene glycol methyl ether	0-15	Water Solubility	Soluble
Polyethylene glycol Butyl Ether	0-15	Boiling Point	248.9 °C
Diethylene glycol	5-15	Flash point	>135 °C
Dilsopropaolamine	0-1	Physical state	Liquid
Diethanolamine	0-1		
Borate Ester	30-50		

Source: Manufacturer- KMCO DOT4 Brake Fluid SDS No 30357

Figure 2 shows the laboratory set up for (a) wet and (b) dry frictional wear tests (Anton Paar G74IB001EN-B User manual). The distance h depends on the sample height and also the length of ball holder (Figure 2a). The frictional sliding wear tests were performed using the standard tribometer with and without DOT4 brake fluid under different environment but similar loading conditions. The applied normal load was varied from 1 to 10N for the studies. The morphology and wear track patterns resulting from the rotational (single way) motion of the 6mm diameter ball against aluminium alloy surfaces were examined using Zeiss Observer-7 metallurgical microscope. In this study, more comprehensive and detailed results/ graphical data and interpretations of frictional coefficient (CoF) for dry and wet (in DOT4) sliding were generated via standard tribometer (Anton Paar TRB Model) installed with InstrumX 7.3.13 version software



Figure 2: The laboratory set up for (a) wet wear and (b) dry wear test (Anton-Paar G74IB001EN-B User manual)

Table 3: XRD of phase analysis of the cast Al-Si-Cu-Zn alloy

Phase name	Formula	Phases	Phase name	Formula	Phases
Aluminum Copper	Al ₄ Cu ₉	Al _{4.2} Cu _{3.2}	Silicon	Si	Si,
Aluminum Copper Zinc	Al _{4.2} Cu _{3.2} Zn _{0.7}	Al, Al _{4.2} Cu _{3.2} Zn _{0.7}	Silicon Copper	Cu ₉ Si	Cu ₉ Si
Aluminum Silicide	Al _{0.41} Si _{0.09}	Al _{0.41} Si _{0.09}	Zinc	Zn	Zn,
Aluminum Silicon	(Al ₉₉ Si) _{0.04}	(Al ₉₉ Si) _{0.04}	Copper Zinc	Cu ₅ Zn ₈	Cu ₅ Zn ₈
Copper Silicide	Cu _{0.9} Si _{0.1}	Cu _{0.9} Si _{0.1}	gamma-Al ₄ Cu ₉	Al ₄ Cu ₉	Al,
Copper Silicon	Cu _{0.83} Si _{0.17}	Cu _{0.83} Si _{0.17}	Iron	Fe	Fe, Si

Source: Manufacturer- KMCO DOT4 Brake Fluid SDS No 30357

III. Results and Discussion

A. Compositions and properties of Al-Si-Cu-Zn alloy and fluid

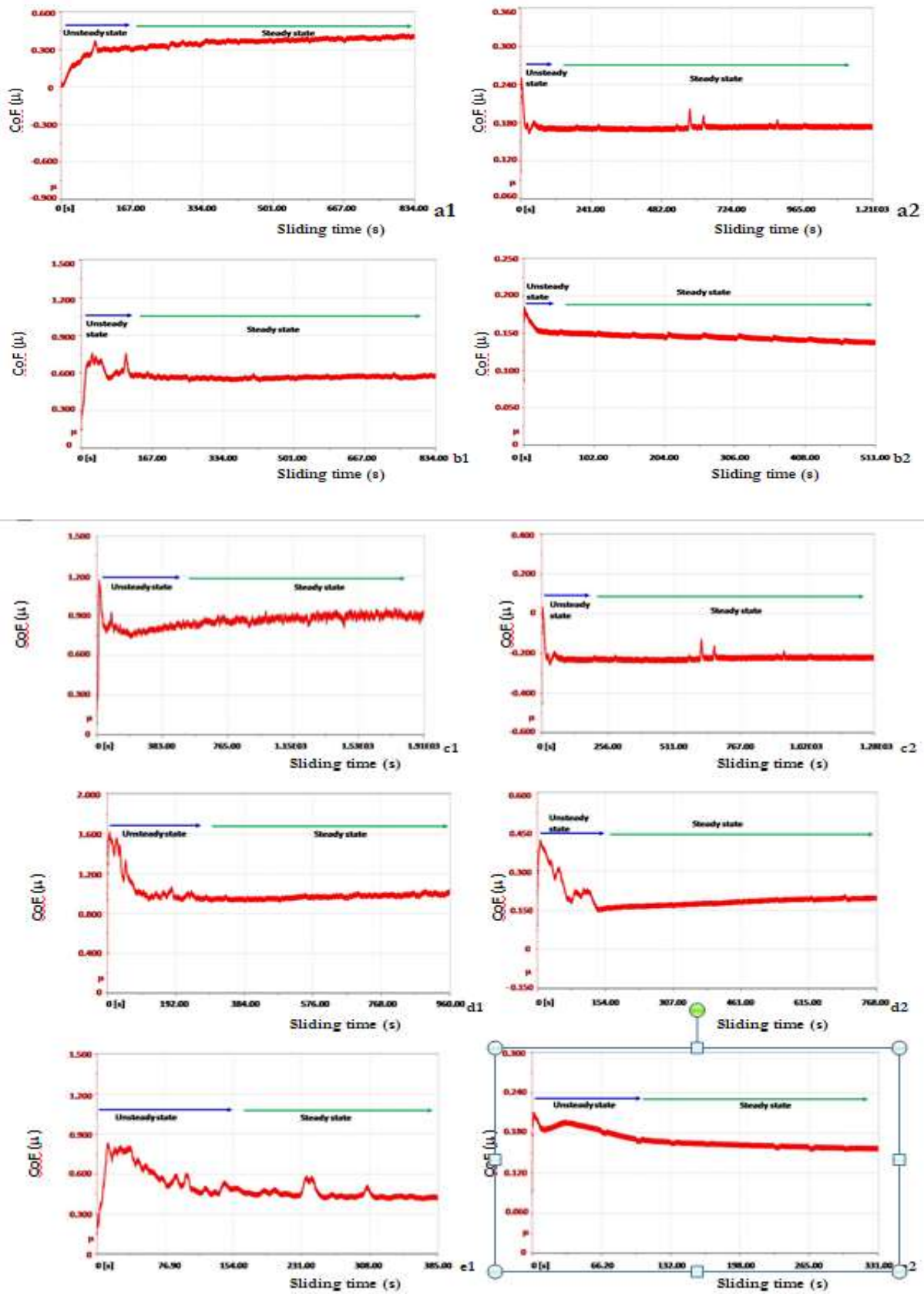
The chemical composition of aluminium alloy specimen is illustrated in Table 1. The sample contains aluminium (Al) as the major metal and high contents of three other principal alloying elements such as silicon (Si), copper (Cu), and zinc (Zn); beside iron (Fe) reported to have dissolved into the melt due to the casting practice [23]. Table 2 shows the constitutional properties of DOT4 Fluid. It is evident that the fluid is highly alkaline. The fluid has relative similarity in composition with the DOT3 fluid used in previous report [23] but different from non water absorbing SAE 20W-50 and SAE 90 engine oils and other lubricants reported [2-4,6,17,20].

The present material (cast Al-Si-Cu-Zn alloy) has enhanced metallurgical properties than cast specimens produced from A6061 aluminium alloy (containing 0.32-0.72% Si and 0.10-0.18% Cu) sourced from recycled scrap and new brake cylinder callipers [23]. The previously reported as-cast A6061 test samples were characterised by poor metallurgical qualities (due to variation in weight and density, low HBN, low tensile strength, high porosity, irregular microstructure and casting defects). In contrast to the graphical friction CoF properties generated from standard tribometer used in the current study, the weight loss measurements were formerly used to calculate the wear loss with and without DOT3 brake fluid based on the usage of weight loss, density and wear volume parameters used by [28]; the results seemly less precise due to unaccounted losses to machine operation. In addition, the present material contains lower Al (74.0161%) with higher amount of 19.1539% Si, 0.0247% Mg, 2.1194% Fe, 0.3587% Mn, 2.0080% Cu, 1.7941% Zn, 0.0421% Cr and 0.0445% Ti, beside other trace metals such as Co (0.0093%), Ni (0.0625%) and Sn (0.0323%) which are responsible for better tribological resistance in the current cast Al-Si-Cu-Zn alloy specimen; as against 98.44 %Al, 0.32 %Si, 0.29

%Mg, and 0.16 %Fe with equal amount of 0.001% of other alloying elements (Mn, Cu, Zn, Cr and Ti) present in previous reported A6061 alloy samples.

B. Wet and dry frictional properties of Al-Si-Cu-Zn alloy

For the purpose of extensive study and comparison of the frictional CoF under dry and wet (in DOT4) sliding conditions; application of 1N, 2N, and 5N loads are studied and reported in the current work. Report of cast AA6061 samples previously prepared according to ASTM (G 119-04) procedure with or without MgFeSi inoculants show moderate wear resistance, with and without DOT3 brake fluid [29]. It was reported that the wear cycles range from 73500 cycles (with DOT3 brake oil) and from 30625 cycles (without DOT3 brake oil) to about 3,100,475 wear cycles with accompanied insignificant material volume loss (0.00213 mm^3). Similarly, at the initial stage there were very short active periods (10 minutes) when no wear was experienced which clarified when the material is functionally perfect for the automobile cylinder application. The cast AA6061 alloy has considerably higher wear rate ($\text{mg/mm}^2/\text{min}$) of about $8.00\text{E}-03$ (without DOT3 oil) compared to $1.2\text{E}-06$ (with DOT3 oil) respectively. From the macro-graphic studies, the wear jig did not make deep cuttings on pistons without DOT3 oil as observed in the present study (Figures 4) using tribometer with and without DOT4 oil [23,29]. In addition, the graphical friction CoF properties of the Al-Si-Cu-Zn alloy for the 3, 4, 6, 8 and 10N are elaborately illustrated as compared with the results briefly reported previously under wear behaviours of the similar aluminium base AA6061 and Al-Si alloys by weight loss method [23,24,29]. However, the present study material has more significant CoF changes during dry contacts (without DOT4 oil) than in wet contacts (with DOT4 oil) when subjected to both increasing load and wear time as compared with previous results of other materials on dry and wet contacts in DOT3 oil.



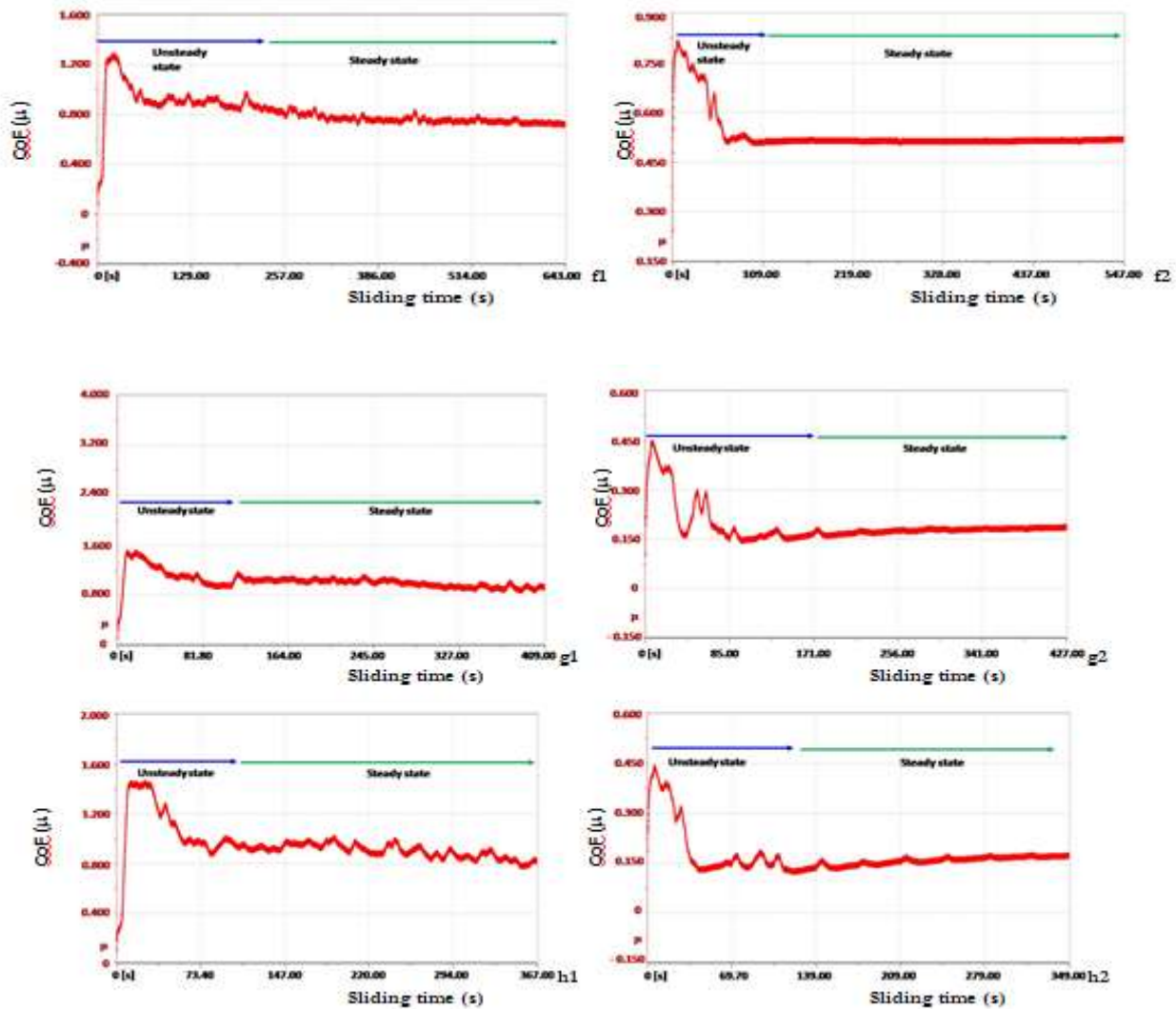


Figure 3: Graphical friction CoF (μ)-sliding time (s) properties of Al-Si-Cu-Zn alloy showing dry a(1)-h(1) and wet a(2)-h(2) contacts in DOT4 brake oil using tribometer for different applied loads (1, 2, 3, 4, 5, 6, 8 and 10N).

Figures 3 (a1-h1) and (a2-h2) show the graphical data representation of friction coefficient CoF, (μ) against sliding time (s) for the cast Al-Si-Cu-Zn alloy at three different loads and sliding wear (dry and wet) conditions. The CoF for the dry and wet wears using standard tribometer were compared at different loading conditions. Figure 3(a1) presents the dry contact of 1N applied load using wear track radius $R = 4.58$ mm and linear speed, $V = 4.80$ cm/s, the μ

increased at from 0.009 to 0.360 within the first 80.3 s and an average CoF, $\mu = 0.415$ value was gotten after 834 s frictional contact time. Comparatively, for experiment run at 3.17 mm radius and 3.32 cm/s linear speed; the CoF-sliding time curve of the wet sliding wear under the same load application (Figure 3a2) shows that CoF reduced from 0.218 to 0.165 within the first 29.3 s of contact until a stable mean CoF, $\mu = 0.174$ value was recorded after

39.9252 m wear distance (cycle = 2004.84) and 1204.13s time.

The increase in the applied load to 2N led to sharp rise in CoF value from dry wear (Figure 3b1). With a radius $R = 4.58$ mm and linear speed $V = 4.80$ cm/s, the μ increased from 0.150 to 0.748 within the first 25.5 s and an average CoF, $\mu = 0.571$ value was obtained after 834 s. In contrast, for the wet test (Figure 3b2) run with 7.56 mm radius worked at 7.92 cm/s linear speed at 2N; CoF declined from $\mu = 0.182$ to $\mu = 0.152$ after the early 20.0 s of rubbing giving an average CoF, $\mu = 0.146$ value after 511s.

For the period of dry sliding with applied 3N load (Figure 3c1) the CoF rises to maximum, $\mu = 1.2$ within the earliest 20 s and average of $\mu = 0.9$ was obtained after 1911 s of rubbing. Relatively for wet (DOT4 brake fluid) experiment under the same loading condition in Figure 3c2, within earliest 10 s of contact, the CoF reduced to and become stable at about $\mu = 0.2$ and 40 m contact distance and 1276 s sliding time.

Increasing normal applied load to 4N, for dry contact wear (Figure 3d1); the CoF increased to $\mu = 1.2$ maximum in the earliest 10 s with an average CoF, $\mu = 0.998$ attained after 960 s. Meanwhile, CoF declined to $\mu = 0.16$ at about 140 s of contact and become stable at average $\mu = 0.19$ value after 770 s for the wet test run at 4N load (Figure 3d2).

The 5N loading dry and wet sliding wear CoF-sliding time curves are presented in Figures 3(e1) and 3(e2) respectively. With tribometer ball set at a radius of 10.06 mm and running at linear speed of 10.53 cm/s, 39.97 m distance, cycle of 633; and additional increase in load to 5N also changed CoF, μ from 0.157 to 0.823 during the early 12.9 s contact sliding time. Thereafter, CoF stabilised to an average CoF, $\mu = 0.4997$ value after 385 s wear period.

Under the dry wear, (Figure 3e1), CoF-sliding time curve trend shows more fluctuations than any of the Figures 3a1 and 3b1. There may be

the possibilities of more formation of wear debris which plays active roles in the wear and on the other hand, the braking of the formed oxide layer on the cast Al-Si-Cu-Zn material surface-ball interface cause wear. In contrast (Figure 3e2), with the wet wear, ball set at radius of 11.70 mm and linear speed of 12.25 cm/s, there was at 1.81 s early sliding time, an increase in μ from 0.095 to 0.209. Like every other wet sliding wear cases, there was reduction in CoF value (from 0.4997) obtained in the 5N dry wear (Figure 3e1) to CoF of 0.1689 at 34.33 m sliding distance and 544 cycles after 331 s total sliding time under wet sliding (Figure 3e2).

Increasing the force to 6N again changed CoF $\mu = 0.92$ value within the earliest 60 s of contact (Figure 3f1). The CoF value rise and fall but later stabilised to average value of $\mu = 0.82$. As compared with dry contact (Figure 3f1), the DOT4 oil contact reduced the CoF to $\mu = 0.51$ at about 550 s and 40 m sliding distance as shown in Figure 3(f2).

At 8N (Figure 3g1), CoF increased to maximum $\mu = 1.5$ in the earliest 10 s and diminished to average value of $\mu = 1.03$ after about 410s of frictional contact. However, the CoF later stabilised after series of fluctuations between $\mu = 0.42$ and 0.16 during the wet contact in Figure 3(g2). Consequently, the CoF dropped from 0.423 to 0.176 within the first 40.6 s of contact to get stable CoF value of $\mu = 0.233$ after wear cycle = 706.56 (39.94 m distance) for 426.30 s.

Expectedly, 10N loading resulted in increase but with constant instability in the CoF curve for dry wear (Figure 3h1). The CoF declined from the maximum ($\mu_{\max} = 1.5$) to more stable CoF $\mu = 0.82$ value attained within the earliest 15 still about 400 s contact time. In contrast, CoF declined from $\mu = 0.44$ to $\mu = 0.13$ and thereafter remained stable at $\mu = 0.16$ before the earliest 50 s of wet contact. From the experiment, an average CoF ($\mu = 0.193$) was recorded within the 360 s of entire wet contact in DOT4, run under 10N loading (Figure 3h2).

The outcomes of the research agree with the reports of [27] on the effects of lubrication on CoF-time and wear resistance of aluminium alloys exposed to small range of changing frictional force where the coefficient of friction values varied between 0.3 and 0.4 for all the samples for the varying frictional force in the range of 5 to 8 N. In addition, the study reported that wear resistance and load carrying capacity of Al-Si alloys are enhanced with the increasing Si content. Meanwhile, the behavioural enhancement in the present study

can be ascribed to the significance of the alloying element compositions (Cu, Si etc) in the present test specimen and the cumulative effect of lubrication in DOT4.

C. Optical examinations of wear properties

The wear scar of surfaces of the dry and wet (DOT4 brake oil) friction contacts with alumina ball under eight (8) different applied normal loads (1, 2, 3, 4, 5, 6, 8 and 10N) are presented in the optical micrographs (OM) in Figure 4 (b1) to 4(i2).

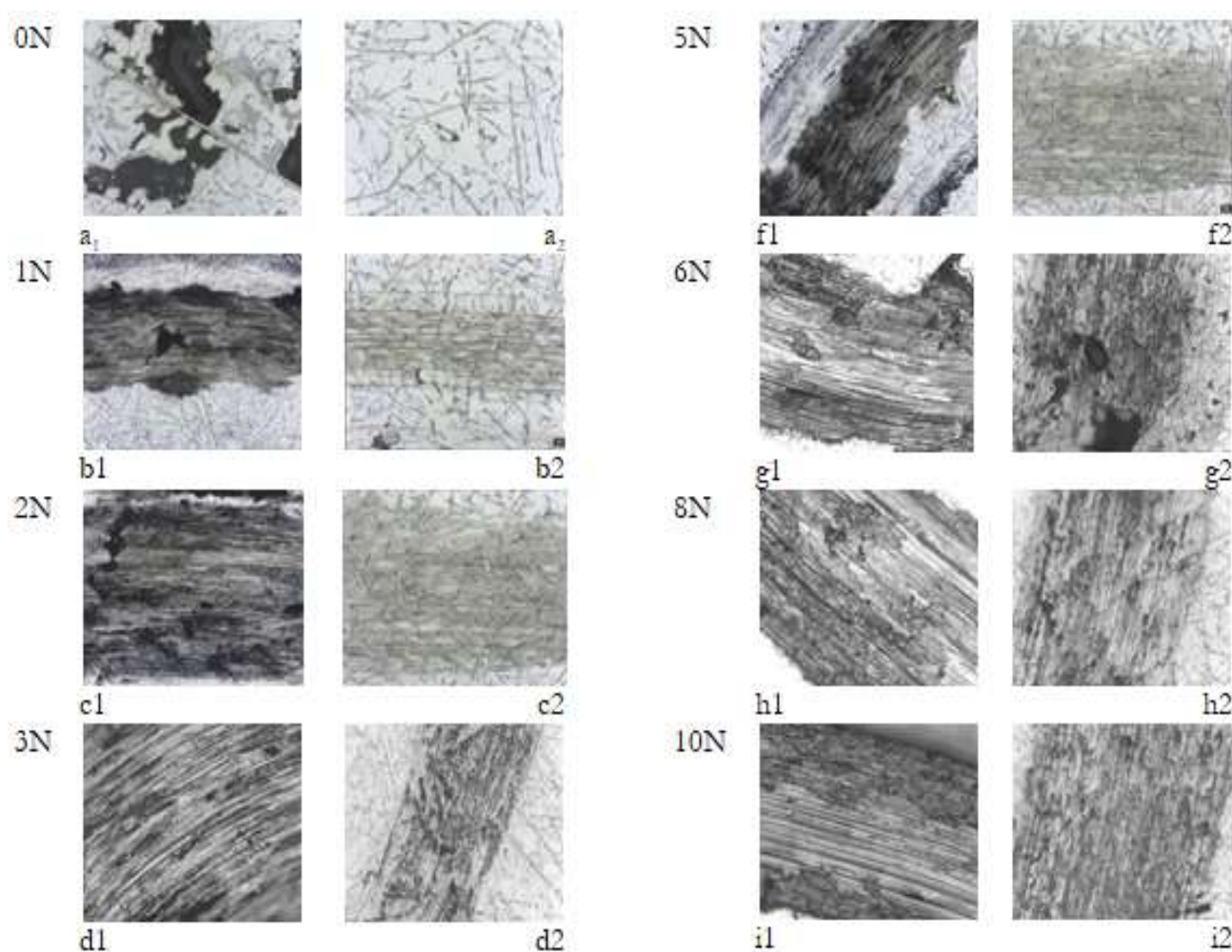


Figure 4: Optical micrographs of samples before wear test (a1, i2) and wear scar patterns dry sliding (x10) (b1-i1); and wet sliding (x20) (b2-i2) in DOT4 brake oil under applied load variations (1, 2, 3, 4, 5, 6, 8 and 10N)

The microstructure of polished surface of cast alloy (control) prior to the dry and wet wear tests are shown in Figures 4(a₁) and 4(a₂). Although, the asperities due to frictional contact wear appeared to be proportion to the amount of load, the DOT4 brake oil trimmed down the effects of load increase on friction coefficient (CoF) and wear loss as compared with the dry contacts. Despite the increase in loading from 1N to 10N, DOT4 brake fluid was able to influence a reduction in the frictional wear. This can be attributed to the substantial amount of Cu (2.0080%) in the material, leading to exhibition of self lubricating and high thermal stability properties in the cast aluminium based silicon-copper-zinc (Al-Si-Cu-Zn) alloy as compared with other studies on similar or different alloys and lubrication fluid systems. Researchers [30] discussed wear mechanisms of the cast hypereutectic Al-Si-Cu alloy using a pin on disc tribometer under lubricated sliding conditions was characterized by fracture and spallation, the intermetallic compounds and the primary silicon phases from the matrix. Under that test condition, the wear rate of the material corresponded to a mild wear regime. Unfortunately, the increase in temperature of the components causes a reduction in strength of Al-Si alloys in practical automotive operational applications [31,32] to promote micro-structural stability by precipitation hardening and to overcome this problem elements such as Cu, Mg, Fe and strontium were added.

Likewise, [3] investigated wear of an Al alloy LM25 (with 7%Si, 0.05%Fe, 0.22% Cu, 0.13% Mn, 0.40% Mg, 0.12% Ni) in two body dry and SAE 20 W 50 and SAE 90 lubricated sliding wear tests by using a Pin on the disc machine. In similarity to the current study (Al-Si-Cu-Zn alloy), load and speed increase show that the wear rate increased with severe surface deformation with the pits formation observed under dry condition but showed mild surface delamination under lubricated conditions showing that lubricants (SAE 20W50 and SAE90) absorbs heat that was generated at the

specimen-disc interface, thus trims down friction considerably and making the amount of wear to be very low or almost negligible under lubricated sliding situation. In like manner, it is expected that the DOT4 oil temperature affects the probability of adhesion, oxidation, wear rates, and CoF, while friction, and wear decrease with increase of the running time at room temperature and under lubrication conditions as in SAE 20W 50 and SAE90; and thus validates that the lubricant temperature has a significant role in wear mechanism established by [2].

In a related trend, cast Al-Si-Cu-Zn alloy material used in the present study also contains Fe, Ni and Cr (Table 1); experimentally, [33] had investigated the effects of adding these three elements on the wear behaviour of hyper-eutectic Al-Si automotive alloy studied and established that Fe addition increases the wear rate by forming needle beta intermetallics; while Cr addition changes the beta intermetallics into the modified alpha phases and thus diminished the negative effect of iron as it recovers the strength and wear resistant properties. The report shows long parallel grooves along the sliding direction caused by the abrasion of entrapped particles seen on the worn surfaces, clearly suggesting abrasive wear as well as cracks with grooves and material dislodgment indicating combination of abrasion and delamination as is also observed in the optical micrographs of samples wear scar patterns for dry and wet sliding in DOT4 brake oil under applied load variations (Figures 4 (a1-i1) and (b1-i2) in the present report.

In all cases, the effects of friction due to impressed loading on DOT4 brake oil lubricated interfaces are less intensive than the dry contact surfaces (Figures 4b1 to 4i2). The effects of applied normal loads on the severities of wear due to friction contacts were better examined from the optical microscopic (x10) and (x20) magnifications for dry contact in air (Figures 4a1-i1) and wet sliding in DOT4 brake oil (Figures 4a2-i2) respectively.

Under all loads, the observed wear scars on the dry substrate are of abrasive mode (Figures 4

a1-i1) and severe as compared with the adhesive mode and mild wear scars observed on wet sliding case (Figures 4g2, h2 and i2). The load controlled the rigorousness and natures of wear observed from the optical microscopy (OM) studies. The OM images clearly show that the asperities observed during the dry sliding are proportionally dependent on the amount of load applied (Figures 4 g1, h1 and i1).

Comparing the wear behaviour of the cast Al-Si-Cu-Zn alloy with other material such as ADI; the presence of some copper inter-metallic phases such as $\text{Al}_{4.2}\text{Cu}_{3.2}\text{Zn}_{0.7}$, $\gamma\text{-Al}_4\text{Cu}_9$, Al_4Cu_9 , $\text{Cu}_{0.83}\text{Si}_{0.17}$, $\text{Cu}_{0.9}\text{Si}_{0.1}$, Cu_5Zn_8 and Cu_9Si in the alloy as observed in the XRD of phases present in cast aluminium alloy specimen (Table 3) must have contributed to the enhanced tribological properties of the alloy in similar way the inter-metallic phase improved the wear of cast iron with addition of aluminium in ADI reported by [34]. It was commented that formation of intermetallic compounds and austempering processes improved the wear resistance of the alloy by adding aluminium to the ductile iron. In addition, the single step austempered alloy has slightly lower CoF than the two-step austempered alloy.

Comparatively, the present Al-Si-Cu-Zn alloy has lower amount of Zn (1.7941%) than Al-Zn alloy earlier reported [35]. The Al-Zn alloy yielded higher average CoFs of 0.1591, 0.413, 0.0739 and 0.4793 under the 1, 3, 5 and 10 N applied loads thus reflected lower resistance to friction due to influence of high Zn amount present in the Al-Zn alloy as compared to what was obtained from the reported AA6061 and rolled steel with or without DOT3 or DOT 4 brake oil [23] and in the present study material. Conversely, in the present study, lower loads (1 N to 10 N) were applied in combination with the DOT4 brake oil which is more temperature sensitive than the 5 N to 50 N, 50-80 N and 80-100 N loading in SAE20W50 lubricating oil reported [4]. In the former case, the CoF of hypereutectic Al-25Si alloy /steel decreased with increased normal load from 5 N to 50 N; the primary Si particles size and distribution found

in the wear track of Al-25Si alloy was responsible CoF for reduction at higher normal applied loads. The present study produced lesser wear effects; the observed wear tracks obtained under a single pass rotational action of the wear ball seems to be of mild abrasive as shown in Figures 3 and 4; as compared with result reported under the reciprocating loading by [1].

IV. Conclusion

The study explores the friction properties of Al-Si-Cu-Zn alloy in dry and wet contacts (DOT4 brake oil) using standard tribometer for eight different applied loads (1, 2, 3, 4, 5, 6, 8 and 10N). Subsequently, conclusions are drawn from the research findings as follows:

The graphical method and the optical microscopy used gave substantive comparative analyses of the friction characteristics of the alloy under investigation. The graphical data obtained for the relationships of CoF and time as well as the surface morphologies resulting from the friction effects revealed the asperities. Increased normal force, F_n loading has noteworthy effect on the CoFs for both dry and wet sliding. The CoF stabilized over wide range of time or cycle similarly for wet and dry situations. The results correlate with the reports on the wear rate behaviours obtained by weight loss method.

Even with the increasing applied load, DOT4 brake oil influenced in the reduction of the frictional coefficient. The considerable amount of Cu present in the Al-Si-Cu-Zn alloy enhanced its self lubricating capacity and thermal stability at high loading that could have generated significantly high temperature due to frictional contact.

Based on the findings from the study, the material shows higher level of frictional resistance at higher loading for longer wear cycles. This implies that the material will serve more effectively and suitably as material for brake cylinder and piston for automobile applications.

Acknowledgments

Special thanks to the Centre of NanoEngineering and Tribocorrosion, University of Johannesburg, Johannesburg, South Africa for the provision of laboratory equipment used. The Management of the Premier Wings Engineering Services, Ado Ekiti, Nigeria is appreciated for providing the materials and workshop services used for the work.

References

- [1] Islam A. and Farhat Z. Wear of A380M aluminum alloy under reciprocating load. *Journal of Materials Engineering and Performance*, Vol. 19, No 8, 2010 pp1208–1213.
- [2] Al-Araji N., Sarhan H. Effect of temperature on sliding wear mechanism under lubrication conditions, *International Journal of Engineering*, Vol.5: 2011 pp176–184.
- [3] Bharathi V., Ramachandra M., Srinivas S. Comparison of dry and wet sliding wear behavior of squeeze cast aluminum alloy. *Indian Journal of Advances in Chemical Science S1*, 2016 pp101-106
- [4] Kumar P, Wani M.F. Friction and wear behaviour of hypereutectic Al-Si alloy/steel tribopair under dry and lubricated conditions. *Jurnal Tribologi*. Vol.15 2017 pp21-49.
- [5] Wani, M.F. and Anand, A. Life-cycle assessment modelling and life-cycle assessment evaluation of a triboelement. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Vol.224 No11, 2010 pp1209-1220.
- [6] Farhanah, A.N. and Bahak, M.Z., (2015). Engine oil wear resistance. *Jurnal Tribologi*, Vol.4, 2015 pp10-20.
- [7] Ghazali M J, Rainforth W M, Jones H. The wear of wrought aluminium alloys under dry sliding conditions. *Tribology International*, Vol.40, 2007 pp160–169.
- [8] Gibson P.R, Clegg A.J. and Das A.A. Wear of cast Al-Si alloys containing graphite. *Wear*. Vol.95 No.2, 1984 pp193–198.
- [9] Abouei V., Shabestari S.G. and Saghafian H., Dry sliding wear behaviour of hypereutectic Al-Si piston alloys containing iron-rich intermetallics. *Materials Characterization*, Vol.61 No 11, 2010, pp.1089-1096.
- [10] Alshmri, F., Atkinson, H.V., Hainsworth, S.V., Haidon, C. and Lawes, S.D.A. Dry sliding wear of aluminium-high silicon hypereutectic alloys. *Wear*, Vol.313 No 1, 2014 pp106-116.
- [11] Haque, M.M. and Sharif, A., Study on wear properties of aluminium–silicon piston alloy. *Journal of Materials Processing Technology*, Vol.118 No.1, 2001 pp 69-73.
- [12] Kumar, K.G., Influence of Refinement and modification on dry sliding wear behavior of hypereutectic Al-Si cast alloys. *Advanced Materials Research*, Vol.685, 2013 pp112-116.
- [13] Nuraliza, N., Syahrullail, S. and Faizal, M.H. Tribological properties of aluminum lubricated with palm olein at different load using pin-on-disk machine. *Jurnal Tribologi*, 9, 2016 pp45-59.
- [14] Sapate S.G, Uttarwar A, Rathod R.C, Paretkar R.K. Analyzing dry sliding wear behaviour of copper matrix composites reinforced with pre-coated SiC particles. *Mater Des*. Vol. 30, 2009 pp376–386.
- [15] Nuruzzaman D. M and Chowdhury M. A Friction coefficient and wear rate of copper and aluminum sliding against mild steel. *International Transaction Journal of Engineering, Management, Applied Sciences and Technologies*. Vol.4, No. 1, 2013 pp029-040.
- [16] Kandeve M., Vassileva L, Rangelov R., Simeonova S., Wear-resistance of Aluminum Matrix Microcomposite Materials, *Tribology in industry*, Vol.33, No. 2, , 2011 pp57-62 .
- [17] Rumierz J. Lubricants for Rolling-Element Bearings, In *Friction, lubrication and wear*

- technology, Vol 18, ASM Handbook. ASM International, USA. 1992
- [18] Rendahl B.O and LeBozec N. Corrosion resistance of automotive materials: from laboratory to field exposures. Eurocorr 2011, No 1033. Stockholm, Sweden. 2011
- [19] Tung S, and Totten G.E., Ed. ASTM automotive lubricant and testing handbook. ASTM International, West Conshohocken, PA, 2013,
- [20] George, N.J., Obianwu, V.I., Akpan, A.E. and Obot, I.B., Lubricating and cooling capacities of different SAE 20W–50 engine oil samples using specific heat capacity and cooling rate. Archives of Physics Research, Vol.1 No 2, 2010 pp 103-111.
- [21] Wong, V.W. and Tung, S.C., Overview of automotive engine friction and reduction trends—Effects of surface, material, and lubricant-additive technologies. Friction, Vol.4 No1, 2016, pp1-28.
- [22] Bosch R. Bosch Automotive Handbook. 7th Ed. Bentley Publishers, Robert Bentley, Inc., Cambridge, MA, USA. 2007
- [23] Ajibola O.O, Adewuyi B.O, and Oloruntoba D.T. Wear behaviour of sand cast eutectic Al-Si alloy in hydraulic brake fluid. International Journal of Innovation and Applied Studies, 6 (3) 2014 pp420-430
- [24] Ajibola O.O , Aribo S., Ige O.O, Akinribide O.J, Akinwamide S.O., Olubambi P.A., Wear behaviour of cast aluminium silicon (Al-Si) alloy in Dot 4 brake fluid. IOP Conf. Series: Materials Science and Engineering Vol.628, 2019 ID 012012,
- [25] Ajibola O.O, Oloruntoba D. T, Adewuyi B.O, “Effect of polishing grits, temperatures and selected activators on electroless-nickel deposition on cast aluminium substrates”. Journal – The Institution of Engineers, Malaysia, Vol. 76, No. 1, 2015 pp38-46.
- [26] Anton-Paar G74IB001EN-B TRB User Manual, Tribometer Software Version 7, pp1-141,
- [27] Mathavan J.J., and Patnaik A. (2016). Analysis of wear properties of aluminium based journal bearing alloys with and without lubrication, IConAMMA-2016, IOP Conference Series: Materials Science and Engineering. Vol.149, 2016 ID 012052
- [28] Sharma S.C, Girish B.M, Kamath R and Satish B.M, Graphite particles reinforced ZA-27 alloy composite materials for journal bearing application. Wear, Vol.219, 1998 pp162-68.
- [29] Ajibola O.O, Ige O.O, Olubambi P.A, Wear and Corrosion of Wrought A6061 Aluminium Alloy in DOT3 Brake Fluid. International Journal of Engineering and Technology (IJET-UAE), Vol.7 No.2, 2018 pp 512-519.
- [30] Lozano D.E, Mercado-Solís R.D., Juarez-Hernandez A., Hernández-Rodríguez M.A.L, Garza-Montes-de-Oca N.F., Wear mechanisms experienced by an automotive grade Al-Si-Cu alloy under sliding conditions. Ingeniería Mecánica Tecnología Y Desarrollo. Vol. 5 No. 3, 2015 pp339 - 345
- [31] Treviño M., Garza-Montes-de-Oca N.F., Pérez A., Hernández-Rodríguez M.A.L., Juárez, R. Colás A., Wear of an aluminium alloy coated by plasma electrolytic oxidation. Surface and Coatings Technology, Vol.206, 2012 pp2213-2219.
- [32] Lee J.A., Cast Aluminium alloy for high temperature applications, Automotive alloys The 132nd TMS Annual Meeting & Exhibition. 2003,
- [33] Kaiser M.S, Sabbir S.H, Kabir M.S, Soummo M.R, Al Nur M., Study of mechanical and wear behaviour of hyper-eutectic al-si automotive alloy through Fe, Ni and Cr addition. Materials Research. Vol.21 No. 4, 2018, e20171096
- [34] Adebayo A.O., Ajibola O.O., Owa A.F., Borisade S.G., Alaneme K.K., Oyetunji A. Characterization and dry sliding wear behaviour of 2.29 wt.% aluminium-alloyed ductile iron. Materials Today: Proceedings 38, 2021 pp.1152–1158

- [35] Ajibola O.O., Adebayo A.O., Borisade S.G., Owa A.F., Ige O.O., Characterisation and tribological behaviour of zinc-aluminium (Zn-Al) alloy under dry sliding reciprocating ball on disk tribometer. Materials Today: Proceedings Vol38, 2021 pp1140–1146.

Appendix

ASTM B26/B26M-05 Standard specification for aluminum-alloy sand castings, ASTM International, West Conshohocken, PA, 2005.

ASTM E1251-17 Standard test method for analysis of aluminium and aluminum-alloys by spark emission spectrometry. ASTM International, West Conshohocken, PA, 2017.