Design and Fabrication of a Dual Condition PIN-ON-DISC Automated Wear Testing Machine

Uhuami Abdulwahab
Industrial Training Fund, Industrial Skills Training Centre, Lokoja, Kogi State, Nigeria
uhami1973@gmail.com

M. B Ndaliman, O. A Olugboji, & K. C Bala
Department of Mechanical Engineering, Federal University of Technology
Minna. Niger State, Nigeria
mbndaliman@yahoo.com, olugbojioluwafemi@futminna.edu.ng &
katsina.bala@futminna.edu.ng

Abstract

Wear is a dynamic and complex process that involves not only surface and material properties but operating conditions as well. Wearing of surfaces may lead to extra cost of maintenance or manufacturing process. This paper presents the design and fabrication of a dual condition PIN-ON-DISC wear testing machine. The machine is used to compute both the dry and lubricated surface contact of engineering material. The surface wear of Aluminum 6061 pin was examined together with the performance test based on different loads, speeds and time. The paper also analyzed the wear resistance, pin wear rate, and specific wear rate of the pin of Aluminum 6061. During the experiment, the pin was subjected to different performance test at constant sliding speeds of 0.158m/s at the forces of 5N. The testing the pin was removed after 300 seconds and the final volume of the pin was computed. The results indicates a wearing rate per second under applied force of 5N at 0.158m/s sliding speed of 4mm diameter Aluminum 6061 pin during lubricated condition as $20.5\mu mm^3/ms$. Using the pin-on-disc designed by this study, the lubricated surface reduces wear to 54%. At sliding speed of 0.158m/s and sliding distance of 568.8m, the specific wear rate of 4mm diameter pin with lubricated surface has least wearing rate. The specific wear rate test of the Aluminum 6061 pin was 0.2428×10^{-3}mm^3/Nm. The contribution of this research will greatly profits indigenous Material design and Tribology technology.

Keywords
PIN-ON-DISC, Wear Testing Machine, Aluminum 6061, wear resistance.

1. Introduction

The PIN-ON-DISC wear test is a method of characterizing the frictional force and its coefficient and the rate of wear between the contacting surfaces of materials (Abdul *et al.,* 2015). During the test, the weight loss is continuously measured and stored and the wear rate is calculated.

According to Abdul *et al.* (2015), pin wear tester is essential to the development of innovative and enhanced cost-effective applications in engineering design. For example, design of frictional and wearing forces of the materials in contact. The purpose of pin wear tester research is to minimize or eradicate losses available from wear and friction of engineering material surface (Saleh et al. 2021).

Tribology is a study of friction, wear and lubrication between two interacting surfaces in relative motion and of relative subjects and practices (John, 2008). It includes the study and application of the principles of friction, lubrication and wear. Tribology is a branch of mechanical engineering (Saleh, et al., 2021). The tribological interactions of a solid surface's exposed face with interfacing materials and environment may result in loss of material from the surface. The process leading to loss of material is known as "wear" (Amit Swamy et al. 2022). Major types of wear include abrasion, friction (adhesion and cohesion), erosion, and corrosion. Wear can be minimized by modifying the surface properties of solids by one or more of "surface engineering" processes (also called surface finishing) or by use of lubricants (for frictional and adhesive wear). Contacting elements of structures are very common in technology. Many mechanical devices and mechanisms are constructed with the aid of component parts contacting one with another. Contact regions occur between tools and work pieces in machining processes. Loads, motions and heat are transmitted through the contacts of structures. Friction and wear accompany any sliding contact. It has been agreed that wear cannot be totally prevented (Chanakyan, et al.).

1.1 Objectives

The objective of this paper is to design and fabricate of a dual condition pin-on-disc wear testing machine that can be used to determine surface wear of engineering material being subjected to variable parameters such as load, time and speed in a laboratory. The developed machine was used to evaluate the effect of changing the load on the rate of wear in both dry and wet condition on Aluminium 6061.

2. Wear

Wear is a dynamic and complex process that affects not only surface and material properties, but also operating conditions (Anandakrishnan et al. 2021). Technical material wear includes nut and bolt wear experienced by the machinery used in the workshop (Saleh et al. 2018). Wear test is usually adopted as a simple measure of workability of material in use. Materials behave differently in friction state so it may be significant to perform mechanical tests which simulate the condition the material will experience in actual use (Wang et al. 2021).

Wear is among the most significant factors in processing of engineering materials (Kalpakjian and Schmid, 2009). Stolarski (2000) defined wear as loss of material from contacting bodies in relative motion. It is controlled by the properties of the material, the environmental operating conditions and the geometry of the contacting bodies. The wear mechanisms are in two groups. The first dominated by the mechanical behaviour of materials, and the second defined by the chemical nature of the materials (Saleh et al. 2020). Figure 1 shows the wear testing machine developed.

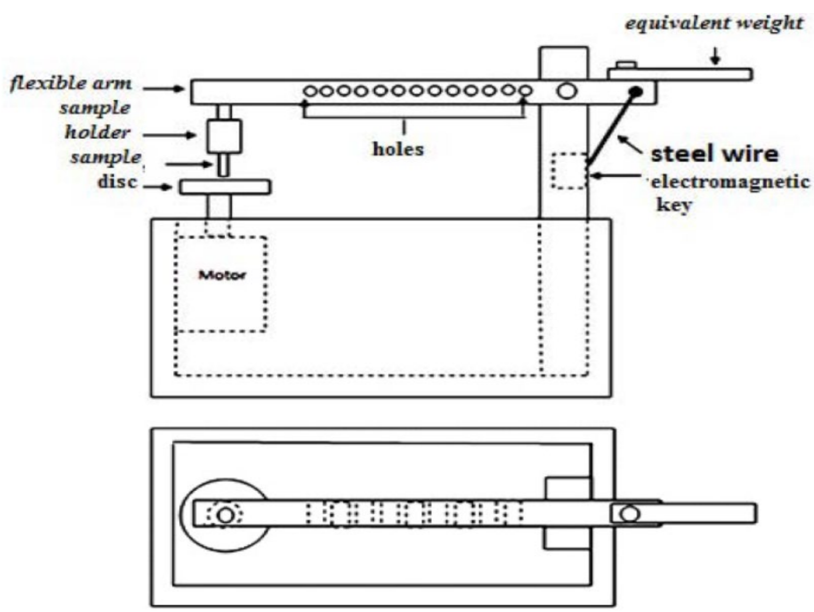

Figure 1: Wear Testing Machine (Nassar and Nassar, 2011)

El-Mahallawi and Shash (2017) considered effect on wear on dry surfaces. Different number of experiment was conducted by using a pin-on-disc machine using wear and friction monitor TR-20 model. The pin was held against the counter face of a rotating disc (EN31 steel disc) with wear track diameter of 60 mm. This provides an insight on how to design a good pin on disc wear testing machine. The present study adopted the rotating disc using steel with diameter 100mm and thickness of 8mm. This was according to ASTM-G99 that requires rotating disc which must be within 165mm by diameter and 8mm of thickness size (ASTM, 2000).

3. Materials and Methods

3.1 Materials

The materials used in carrying out the experimental analysis include:

i. Pins of 25mm long and diameters of 4mm. The pin materials is of Aluminum alloy (Al 6061) with composition shown in table 1 and specifications in table 2

Table 1 Aluminum Alloy 6061 Composition (SEDI, 2011)

Aluminum alloy 6061 Component	Weight %
Percentage of Aluminum	96.20
Percentage of Magnesium	1.20
Percentage of Silicon	0.75
Percentage of Iron	0.70
Percentage of Copper	0.40
Percentage of Zinc	0.25
Percentage of Titanium	0.16
Percentage of Manganese	0.14
Percentage of Chromium	0.20

Table 2 Specification for Aluminum 6061 (SEDI, 2011)

Specification	**Unit**
Elasticity Modulus (GPa)	70
Density (kg/m^3)	2700
Thermal conductivity (W/mK)	173
Melting Temperature (^oC)	585
Poisson Ratio (υ)	0.33
Tensile strength MPa	125
Yield strength MPa	55
0.2% Proof strength MPa	100

ii. Disc size of diameter size 170mm, thickness of 10mm and surface wear track radius of 50mm and 40mm respectively.

iii. Applied force of 5N using laboratory dead weight of 0.51kg, 0.82kg and 1kg
iv. Gear oil as anti-wear additives oil (Monograde SAE 80)

3.2 Methods

Shaft Shear Stress Analysis

The shaft shear stress is designed based on Guest' theory known as law of maximum shear stress, (MSS) theory and it is given by (Budynas and Nisbet, 2011).

$$\tau_m = \frac{1}{2}\sqrt{{\sigma_b}^2 + 4\tau^2} \qquad (1)$$

$$\sigma_b = \frac{32M}{\pi d^3} \qquad (2)$$

$$\tau = \frac{16T}{\pi d^3} \qquad (3)$$

Where:
τ_m is maximum shear stress in N/m^2, τ is mean shear stress in N/m^2, σ_b is bending stress in N/m^2, M is bending moment in Nm, d is solid diameter in m and T is is torque in Nm.

By substituting equations (3.2) and (3.3) into equation (3.1) gives:

$$\tau_m = \frac{1}{2}\sqrt{\left(\frac{32M}{\pi d^3}\right)^2 + 4\left(\frac{16T}{\pi d^3}\right)^2} = \frac{1}{2}\sqrt{\frac{32^2M^2+4(16T)^2}{\left(\pi d^3\right)^2}} = \frac{1}{2}\sqrt{\frac{2^{10}M^2+2^{10}T^2}{\left(\pi d^3\right)^2}}$$

$$\tau_m = \frac{2^5}{2\pi d^3}\sqrt{(M^2 + T^2)} = \frac{16}{\pi d^3}\sqrt{M^2 + T^2}$$

Divide both sides by $\frac{\pi d^3}{16}$ gives:

$$\tau_m\left(\frac{\pi d^3}{16}\right) = \sqrt{M^2 + T^2} \qquad (4a)$$

Khurmi and Gupta (2012) expressed that T_e is the equivalent twisting moment of a shaft given as

$$T_e = \sqrt{M^2 + T^2} \qquad (4b)$$

The maximum shear stress (MSS) is:

$$T_e = \tau_m\left(\frac{\pi d^3}{16}\right) \qquad (5)$$

Equation 5 is the equivalent twisting moment acting on shaft that rotates the disc as shown in Figure 2.

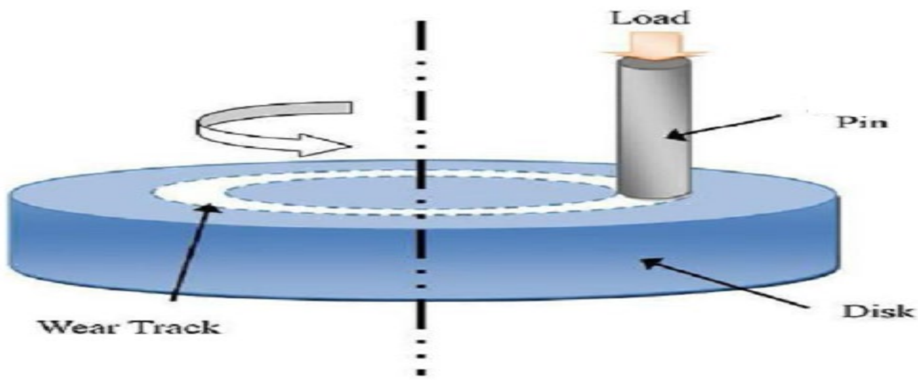

Figure 2: Pin on disc wearing set-up

Factor of safety (FOS) for designing the shaft is given as (Khurmi and Gupta, 2005).

$$\boldsymbol{FOS = 0.5\sigma_y/\tau_m} \quad (6)$$

Where:
σ_y =Yield stress at yield point (N/m^2)

Electric motor

The strength of the shaft depends on maximum torque (T_m) which can be transmitted through electric motor and this is given as (Harris and Piersol, 2002):

$$\boldsymbol{T_m = P_m/\omega} \quad (7)$$

$$\boldsymbol{T_m = \alpha T_a} \quad (8)$$

$$\boldsymbol{\omega = 2\pi N/60} \quad (9)$$

Where:
α is multiplicative factor, $T_a is$ allowable torque in Nm, ω is angular velocity (rad/s), N is number of revolution and $P_m is$ maximum power

The horse power (HP) of the electric motor is determined as (Harris and Piersol, 2002):

$$\boldsymbol{HP = \omega/2\pi} \quad (10)$$

Shaft diameter

The shaft diameter is determined as (Budynas and Nisbet, 2011).

$$\boldsymbol{T_m = \frac{\pi d^3}{16}\tau_m} \quad (11)$$

$$d = \sqrt[3]{\frac{16T_e}{\pi\tau_m}} \quad (12)$$

This is the required diameter of the shaft that helps in rotating the disc mounted on the developed wear testing machine.

Pulley arm and Groove

The pulley arm design is based on assumption that weight of the pulley block is small as compared to the weight of load to be lifted and this is neglected (Harris and Piersol, 2002). This is analyses mathematically through velocity ratio (VR) which is given by (Harris and Piersol, 2002):

$$VR = 2^n \quad (13)$$

$$VR = y/x \quad (14)$$

Equating equations (3.13) and (3.14) gives:

$$2^n = \frac{y}{x}$$
$$y = 2^n x \quad (15)$$

Where:
n = Number of pulley, y *is* Distance moved by the effort (P) in lifting load (W) in m, x *is* Distance moved by the lifting load (W) in m and by letting the mechanical advantage be,

$$MA = W/P \quad (16)$$

Efficiency (η) is the ratio of output (O) and input (I) of the design pulley

$$\eta = MA/VR \times 100\% \quad (17)$$

Power transmitted by the pulley is (Harris and Piersol, 2002).

$$P_p = (T_1 - T_2)v \quad (18)$$

Where:

T_1 *is* Tension in the tight side in Newton, T_2 *is* Tension in the slack side in Newton and v *is* Velocity of the rope in m/s

Fibre Rope

The rope is open type and the angle of contact between rope and pulley groove is (Harris and Piersol, 2002).

$$\theta = (180^\circ - 2\alpha)\pi/180 \text{ in rad} \quad (19)$$
$$\alpha = \sin^{-1}\left(\frac{r_1 - r_2}{x}\right) \quad (20)$$

Where:

r_1 *is* Radius of driving pulley in m, r_2 *is* Radius of driven pulley in m and x *is* distance between the pulley driving and driven pulley in m.

4. Fabrication

The development of dual condition pin-on-disc wear testing machine was fabricated through following manufacturing processes:

i. Bending of required mild steel and angular bar into designed shape.
ii. There are four pulleys which were mounted and served as medium of weight insertion on the pin.
iii. The wet condition was possible by incorporating pumping mechanism that include electric motor (0.5 Horsepower) and hose pipe. This aids pumping the lubricant (gear oil) into surface disc during wet condition.
iv. The electric motors for pumping and rotating disc was placed at lower part of the standing support of developed machine while the pulley system is placed at the upper part of the machine.
v. The developed Pro-e design for the fabrication is attached in this thesis.
Plate IV below shown the Scanning Electron Microscope (SEM) for the wear track on the disc at dry and wet condition.

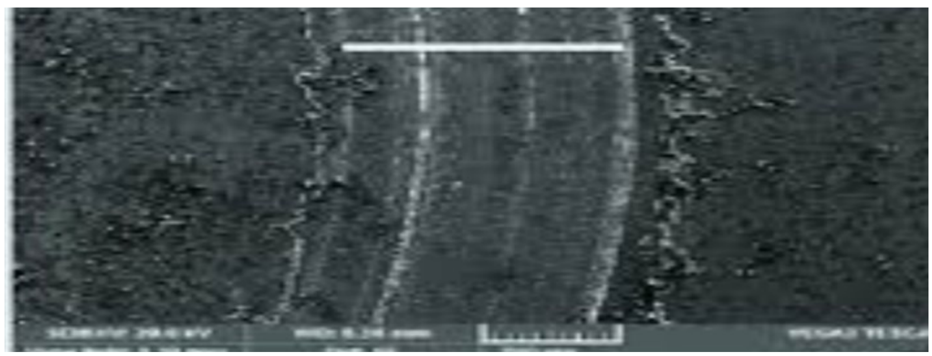

Plate I SEM for the dry condition on pin-on-disc wear testing machine

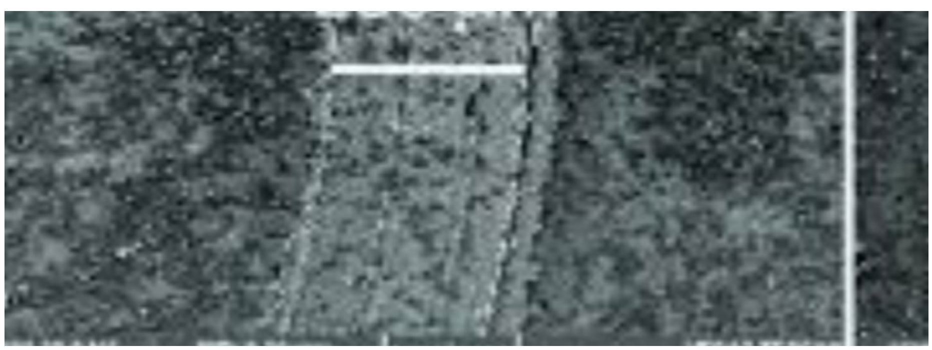

Plate II SEM for the wet condition on pin-on-disc wear testing machine

4.1 Sliding wear testing

The dry sliding wear tests was conducted for the aluminum alloy pin material using the developed wear test machine. The pin material is 25mm of height with diameter of 4mm. The steps include (ASTM G99, 2003):

i. The surfaces of the pin sample was cleaned by emery paper (grit size 320 Fine),
ii. The surface of the disc was cleaned with acetone,
iii. The digital weighing scale was set to be zero,

iv. The pin was held against the counter face of disc mounted on rotating shaft with wear track diameter of 100 mm,
v. Pulley load or dead weights used include 0.51 kg, 0.82kg and 1kg. The experiment was carried out at constant nominal speed of 0.158 at interval of 5 minutes (300s) and
vi. The number of experiment carried out was average of 12 experiments on a pin material.
vii. The volume and rate of wear was computed based on Windarta *et al.,* 2011:
viii. Average value for the results of the parameter is shown for the pin material.

4.2 Wet wears testing

The same procedure as above was followed, however the difference was at step five of section and gear oil was introduced into the experiment. This was possible through the use of pumping mechanism incorporated into developed machine.

5. Results and Discussion

This section presents the results and discussions of the findings.

Figure 3 shows the designed and developed dual condition pin-on-disc wear testing machine. The machine is used to compute the rate of wear on Aluminum 6062 pin's surface.

Figure 3: Dual Condition Pin-On-Disc Wear Testing Machine

The dual condition PIN-PIN-DISC means the wear testing machine can operate under the dry and wet conditions. The machine is made up of the experimental container, rotating disc, pumping (pipe) mechanism, pin holder, supporting base, pulley, pulley arm, industrial lubricating oil tank and two electric motors. Wear test is possible by inserting the pin into the pin holder for a variable time with the pulley mechanism mounted on the machine. The pins were exposed to various loads, times, and slide distances during the experimental phase used to test surface wear behavior.

5.1 Aluminum 6061 Surface Wear Analysis (SWA)

Aluminum 6061 pins with a diameter of 4 mm were subjected to wear analysis under dry and wet surface wear test conditions. The influence of sliding speed and force on the pin was determined to estimate the wear coefficient of Aluminum 6061. The testing was done under the applied force of 5N on pin diameter 4mm at sliding speed of 0.158m/s and the results of the dry and wet SWA is shown in Table 4.1 and 4.2 respectively.

As both the time t (s) and the sliding distance $x_s(m)$ increase, the pin volume loss (V_l) increases and the wear rate (ω) decreases. Table 3 shows that Aluminum 6061 with a diameter of 4 mm exposed to 0.158 m / s has a volume loss of 21.6204 mm3, a wear rate of 0.1520 mm3/m, a wear resistance of 6.58 m/mm3, and a specific wear rate of 3.04×10^{-2} mm^3/Nm after 900s. With a force of 5N applied, the pin covered a slide distance of 142.2m.

Table 3: Dry SWA of Aluminum 6061's Diameter 4mm at 0.158m/s (5N)

t	x_s	h_l	V_l	ω	ω_r	$\omega_s \times 10^{-2}$
(s)	m	mm	mm^3	mm^3/m	m/mm^3	mm^3/Nm
300	47.4	1.52	19.1064	0.4031	2.48	8.06
600	94.8	1.61	20.2377	0.2135	4.68	4.27
900	142.2	1.72	21.6204	0.1520	6.58	3.04
1200	189.6	1.80	22.6260	0.1193	8.38	2.39
1500	237	1.83	23.0031	0.0971	10.30	1.94
1800	142.2	1.84	23.1288	0.0813	12.30	1.63
2100	331.8	1.85	23.2545	0.0701	14.27	1.40
2400	379.2	1.90	23.8830	0.0630	15.88	1.26
2700	426.6	1.94	24.3858	0.0572	17.49	1.14
3000	474	1.97	24.7629	0.0522	19.14	1.04
3300	521.4	2.10	26.3970	0.0506	19.75	1.01
3600	568.8	2.12	26.6484	0.0469	21.34	0.94

After experimental period of 3600s the pin volume loss was 26.6484mm^3, rate of wear of 0.0469 mm^3/m, resistance of wear rate of 21.34 m/mm^3 and specific rate of wear of 0.94×10^{-2} mm^3/Nm and with sliding distance of 568.8m under applied force of 5N. It is indicated that surface behavior of Aluminum 6061 pin's rate of wear (ω) reduced to 88.37% after 3600s.

Table 4 shows the Aluminum pin diameter 4mm diameter under wet or lubricated condition at sliding speed of 0.158m/s through applied force of 5N.

Table 4: Wet SWA of Aluminum 6061's Diameter 4mm at 0.158m/s (5N)

t	x_s	h_l	V_l	ω	ω_r	$\omega_s \times 10^{-2}$
(s)	m	mm	mm^3	mm^3/m	m/mm^3	mm^3/Nm
300	47.4	1.06	13.3745	0.2822	3.5441	5.6432
600	94.8	1.13	14.1664	0.1494	6.6919	2.9887
900	142.2	1.20	15.1343	0.1064	9.3959	2.1286
1200	189.6	1.26	15.8382	0.0835	11.9711	1.6707
1500	237	1.28	16.1022	0.0679	14.7185	1.3588
1800	284.4	1.29	16.1902	0.0569	17.5662	1.1385
2100	331.8	1.30	16.2782	0.0491	20.3832	0.9812
2400	379.2	1.33	16.7181	0.0441	22.6820	0.8818
2700	426.6	1.36	17.0701	0.0400	24.9911	0.8003
3000	474	1.38	17.3340	0.0366	27.3451	0.7314
3300	521.4	1.47	18.4779	0.0354	28.2175	0.7088
3600	568.8	1.48	18.6539	0.0328	30.4923	0.6559

The 4mm diameter of Aluminum 6061 subjected to 0.158 m/s had volume loss of 15.1343 mm^3, rate of wear of 0.1064mm^3/m, resistance of wear rate of 9.3959m/mm^3 and specific rate of wear of 2.1286 $\times 10^{-2}$ mm^3/Nm after 900s. The pin has covered a sliding distance of 142.2 m under applied force of 5N. After experimental period of 3600s the pin volume loss was 18.6539mm^3, rate of wear of 0.0328 mm^3/m, resistance of wear rate of 30.4923 m/mm^3 and specific rate of wear of 0.6559$\times 10^{-2}$ mm^3/Nm and with sliding distance of 568.8m under applied force of 5N. It is indicated that surface behavior of Aluminum 6061 pin's rate of wear (ω) reduced to 88.38% after 3600s.

5.2 Effect of Sliding Speed and Applied Force

The effect of constant sliding speed is considered on the Aluminum pin at varying applied force and varying diameter. Figures 4.1 illustrate the graph of rate of wear (mm^^{3}/m) and sliding distance (m).

Figure 4 show the Aluminum 6061 diameter 4mm pin "4d5(dry)" under applied force of 5N without lubricating surface at sliding distance of 142.2m at 900s. The rate of wear in this pin was 0.152 mm^^{3}/m and this reduced to 28.6% in comparing with 4d8(dry) above. In this case there is reduce force but the wear can be only being limited to 28.6% under this dry condition. If by changing the condition to lubricated surface of 4d8(dry) by 4d80(wet), the rate of wear of 4d8(wet) was 0.1490 mm^^{3}/m. This led to only 30.01% reduction of rate of wear and this means wearing at surface is reduced using lubricating oil and tends to reduce more if with increase in surface contact area.

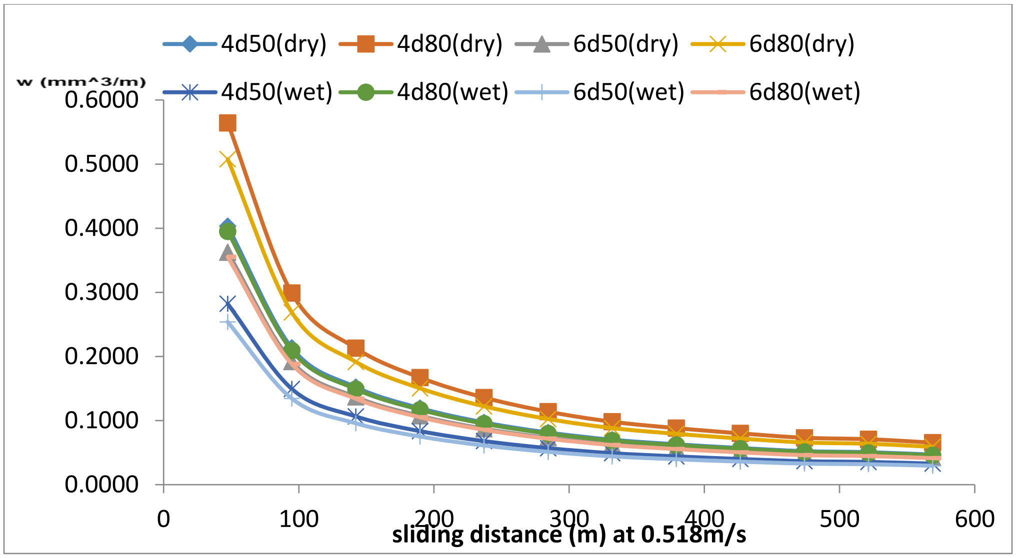

Figure 4: Effect of rate of wear on Aluminum 6061 Pin at sliding velocity of 0.158 m/s

6. Conclusion

The paper designed and fabricated a dual operational pin-on-disc wear testing machine. This machine can be used in the workshop for the analysis of surface wear on engineering material. The machine can be used on the dry, wet or lubricated surface contact of disc and pin. It has ability of 40mm and 50mm disc wear track, respectively. It was used for speed variation during experiment on the Aluminum 6061 for the wear parameters investigation.

The performance analysis was conducted for the surface wear behavior of the Aluminum 6061 pin. During the experiment, the pin was subjected to applied force of 5N at the interval of 300s and sliding speed of 0.518m/s. The findings indicates that increase in force increase the rate of wear at a fixed speed. With increase, the rate of wear is reduced. Also, the increase in surface area of contact and using a lubricated surface lead to wear reduction rate.

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Authors Biography

Engr. Dr. Uhuami Abdulwahab was born on 11th April, 1973 in Okehi Local Government, Kogi State, Nigeria. He obtained his masters and PhD in Mechanical Engineering with a distinction grade from Federal University of Technology, Minna, Nigeria in 2014 and 2021 respectively. He is a member of the Nigerian Society of Engineers (MNSE) and Registered Engineer with the Council for The Registration of Engineering in Nigeria (COREN). Presently, he work with Industrial Training Fund, Industrial Skills Training Centre, Lokoja, Kogi State, Nigeria as an Assistant Director/ Head of Training. He is an internal assessor at National Skills Qualification.

Engr. Professor M.B Ndaliman is a Professor of Mechanical Engineering at Federal University of Technology, Minna, Nigeria. He began his academic and research career at the FUT, Minna in 1991 and rose through the wrung of academic ladder to the exalted position of Professor on the October, 2017. He is at present, on Secondment as the Managing Director/CEO, Scientific Equipment Development Institute, Minna. He was a recipient of the best PhD Student in Engineering in 2014 at International Islamic University, Malaysia. He is a world class intellectual and design specialist, enlisted in the pre-eminent directory of Marquis who's who in the world 2014 edition.

Engr. Professor Oluwafemi Olugboji is a Professor of Mechanical Engineer at Federal University of Technology, Minna (FUT, Minna). He got his first appointment at FUT, Minna in October 1998. He was born on 24th December, 1972 in Emure Orun Local Government, Ekiti State, Nigeria. Engr. Professor Oluwafemi Olugboji is a member of the Nigerian Society of Engineers (MNSE), Council for Registered Engineers in Nigeria (COREN), America Society of Mechanical Engineer, USA, Institute of Mechanical Engineers, United Kingdom and an external assessor at Tshware University of Technology, Pretoria, South Africa.

Engr. Dr. K.C. Bala - FCILG, USA is a holder of Doctor of Philosophy degree (PhD) in Industrial and Production Engineering at Federal University of Technology, Minna (FUT, Minna). At present, he is a Lecturer with FUT, Minna. Engr. Dr. K.C. Bala is a member of the Nigerian Society of Engineers (MNSE) and Registered Engineer of the Council for The Registration of Engineering in Nigeria (COREN) and Member, Nigerian Institute of Mechanical Engineers (NIMechE).