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A Review on Tribological Wear Test Rigs for Various Applications

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Abstract: To mimic a tribosystem setup to the real time model while taking into consideration the subject of green tribology, many tribological wear test rigs are invented. The current work is a dedicated review on the latest development of various tribological wear test rigs build for numerous applications. With the aid of diagrams, the working principles of the machines which are built on specific standards are discussed. Their operating parameters associated with related research using these machines are also included. In addition, recommendations and directions for improvements in tribology machines are reported.

Keywords: Tribology; Machine design; Testing parameters; Automation; Green Engineering

1. Introduction

When industrial revolution started to come into sight in the 18th century, human beings started to depend more and more on machines, in order to improve their lifestyle, production capability and agility, quality and quantity. Therefore, Continuous and Sustainable Development Improvement (CSDI) is really needed in order to achieve the growing needs of human beings with environment preservation [1]. One of the main principles that an engineer or a scientist must comprehend is the conservation of energy. Upon understanding this principle, a scientist or an engineer will get to know how a machine operates and transform its energy. Working mechanisms in machines will tend to be exposed to wear, heat, and friction. An expert reported that a huge amount of money will be saved in industry if the study of wear, friction, and lubrication is taken into consideration [2]. In definition, tribology is a physical science studies the effects occur to materials that reduce its lifetime; effects such as wear, friction, and lubrication between surfaces in motion [3]. Every application has surfaces in contact and in relative motion (e.g. sliding, rolling, impacting) [4]. Tribology objectives are to control, reduce, and improve a particular wear behavior of a material. The characteristics of the different materials differ due to their quantum differences. Hence, the coefficient of friction differs from one material to another. The field of Tribology is very important in the 21st century, as tribology science helps to understand the behavior of materials subjected to friction, wear, and lubrication, which in turn it gives the ability to reduce the wear-tear and achieving the target of having better performances with lesser power consumptions, and sustainability of a living [5]. It does that by simulating the real time tribo-conditions under controlled parameters [6], for example: if a researcher wants to test the wear lifetime of a tire, or to make sure that the tire has the specific amount needed to make the car grip the road, it is not logical to take the car and drive it for hundred kilometers then observation to be made to see how good is the tire performance, instead simulating this by using tribotestings are more time and cost effective, whereby, researchers can set the environment needed for the tire to be tested, such as: Temperature, roughness of the road, and so on. There are so many techniques for tribology study depends on the contact mechanisms between bodies in motion, contact mechanism such as: point contact, line contact, and plane contact [7].

For the current work, seven different types of wear namely abrasive, adhesive, erosive, fatigue, oxidative, fretting, and corrosive are explained. Each type of wear tells about how the conditions of wear between the surfaces in contact, whether it is a form of mechanical wear, chemical wear, thermal wear or a combination of different types of wear. Based on observations, most of the wear study are based on adhesive, abrasive and erosive. Adhesive wear happened between two hard materials moving with respect to each other. Abrasive occurs between hard and soft materials, and erosive happened due to the chemical reactions occur to the

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surfaces due to the surroundings of environmental and temperature effects. Erosive wear becomes oxidative wear when it is exposed to oxygen, corrosive wear when it is exposed to corrosive fluids, fretting wear comes when small oscillation of high frequency occurs [8]. Applications of tribology wear includes but not limited to the following sectors or engineered products: automotive, space shuttles, semiconductors, brake pads, piston rings, hinges, material coatings, fabrics, electrical and electronic components, rail roads, aircraft, turbines, combustion chamber in an engine and cam shafts. The aim of this review is to discuss the various tribological wear test rigs, with the aid of diagrams, standards, and related research works, to report existing tribological wear test rigs' operating parameters, and to propose automation system in the tribological wear test rigs, with the aid of published research works references. The following section illustrates some common types of wear encountered in our everyday life.

1.1 Abrasive and Adhesive Wear of a Hinge

In order to enable the door to open and close smoothly, a hinge is normally used, as illustrated in Fig. 1. However, two types of wear are experienced by the hinge; abrasive and adhesive, which results with declining the smoothness of opening and closing the door. Abrasive happened between a metal and a rubber, whereby metal is pushed to the rubber by the fact of the weight of the door, in which it results with scratching the rubber and deteriorating its material. Adhesive happened between a metal and a metal, whereby two hard materials are pushed and rotated together in which it results in galling or scuffing.

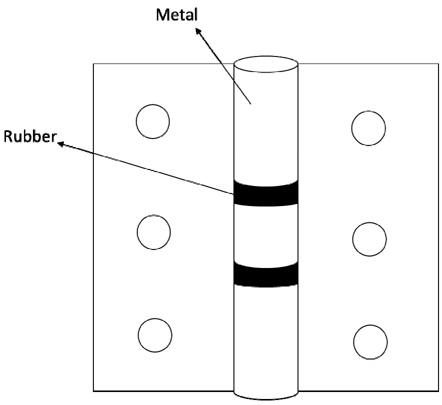

Fig. 1 Hinge for sliding applications of a door

1.2 Eyeglasses

Two common types of wear happen in eyeglasses which are adhesive and erosive. Adhesive wear, by the fact of opening and closing the glasses' temples, adhesive will occur on the hinge, in which it results with deteriorating the flexibility of opening and closing of glasses' temples. Erosive, by the fact of sweating, perspiration will make chemical reactions with the eyeglasses, in which in turn, it will cause erosion wear to it, as illustrated in Fig. 2.

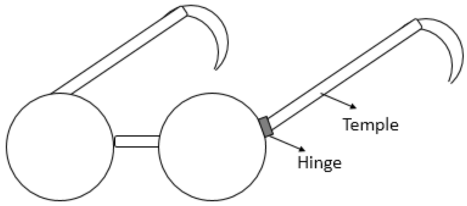

Fig. 2 Schematic drawing of eyeglasses

1.3 Cracks on a wall

One of the reasons that cracks occur on a wall is the chemical reactions between wall's paint with the atmosphere. Here, tribology comes into study the best paint and coating that can resist the atmospheric chemical reactions. Choosing paint for a wall depends on whether the wall is in indoor or outdoor environment, and what possible chemical reactions is the wall exposed to [9], Fig. 3 shows a wall's cracks, due to exposure to chemical reactions in outdoor environment.

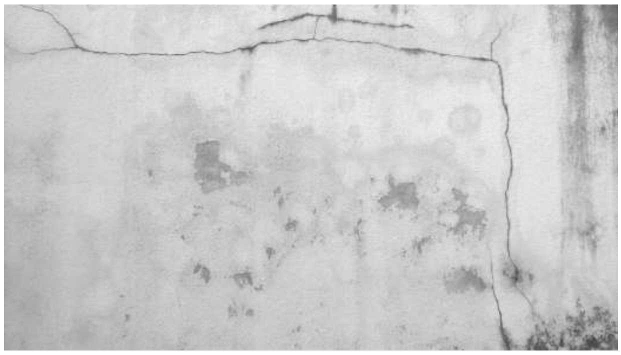

Fig. 3 Real picture showing a wall exposed to outdoor environment

1.4 Head lights of a car

When cars move in the road, a counter force resisting the movement is occurred. One of the resisting forces is air, air contains of several particles, such as: dust. When cars move fast, the dust hits the car strongly, in which it results with deteriorating the body of the car. One of the body parts of the car that majorly affected are the headlights, whereby dust hitting the headlights cause impurities shown in the headlights' cover, where it will affect the strength of the light in cars' head lights. Cars which are driven in desserts are more likely to have this erosion, as illustrated in Fig. 4.

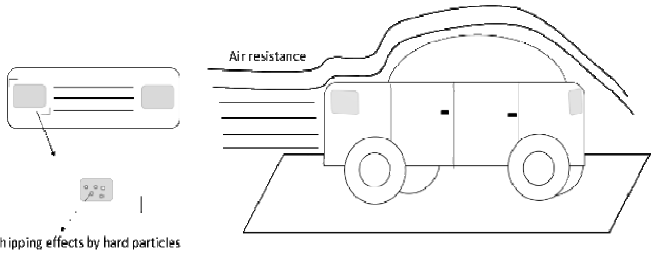

Fig. 4 Schematic drawing of head lights exposed to erosion

1.5 Wheels and roads in contact

The fact that one of the reasons to make cars move in the road is to have tires having a good grip on the road, in order to make tires to have a good grip, tires must acquire a suitable acceptable friction with the road. Tribology science ensures that, furthermore, it enables the study of three bodies, in Fig. 5 an example of third body is introduced between a tire and a road in contact.

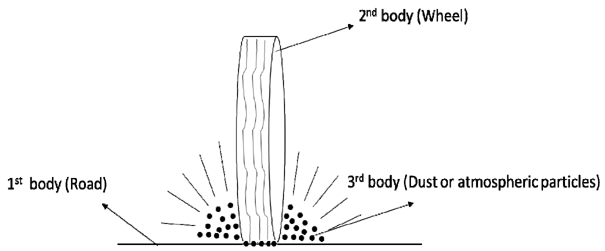

Fig. 5 Schematic drawing of a wheel and a road in contact with an introduction of dust or atmospheric particles as 3rd body (2 & 3 bodies friction)

2. Testing Methods in Tribology

Several standards are set in order to ensure the best performance and effectiveness of Tribology study. Standards such as International Organization for Standardization (ISO), American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM), Deutsches Institut für Normung (DIN), Japanese Industrial Standards (JIS), Society of Automotive Engineers (SAE), International Electrotechnical Commission (IEC), American Foundry Society (AFS), British Standard European Norm (BS EN), China National Standard (GB), and International Petroleum (IP) test methods are some common organizations that regulates and defines a specific tribological wear test rig to mimic real time conditions for various applications. Standards define testing parameters, such as: applied load, surrounding temperature, sliding velocity, contact surfaces, contact temperature, sliding conditions, repeated cycles (distance), wet/dry environment, electrification, and specimens' sizes and shapes.

Techniques used in tribology machines differ majorly from one to another by the contact mechanism, area/plane, line/linear, and point contact in between tested material and the applied counter-face [7], [10]. Before performing any tribological experiments, scientists first need to define the tribotest used for the experiment, and to ensure that tests are performed under the right conditions. Sensors are important in tribology studies, as sensors collect and present data that will help scientists to observe and understand the behavior of each material under a specified wear test. Sensors and data include: Temperature using temperature sensors, load cell to detect the forces, a tachometer to measure the rotation speed, a torque sensor to measure the torque, pressure transducer, angle measurement sensor, a profilometer to measure the peaks and valleys of a surface profile, Linear Variable Displacement Transducer (LVDT) to measure the linear displacement, acoustic sensor to evaluate the noise generated by the study, weighing machine to measure the weight of a specimen before and after the test. Moreover, a microscope is used to detect the surface damage, and a computer software for data collection, data storage, and data analysis. Furthermore, intelligent systems can be created by neural computing and knowledge-based systems to analyze the wear behavior or optimize them. A previous study makes used of a Genetic Algorithm (GA) as a tool for optimization of wear depth of electroless Ni-P-W coating under dry and lubricated conditions [11]. Whereby, another study monitored the wear performance in a turning machine with a carbide as an insert tool and mild steel specimen, using the method of Hilbert–Huang Transform (HHT) by taking inputs from a very sensitive microphone, artificial neurons were trained to categorize the conditions of the wear [12], It was found that the position of a sensor in any experiment is very critical for accuracy of data collection, therefore researchers must clearly define the frame of reference of the sensor with respect to the part that is going to sense (local measurement, global measurement).

Referring to a work done by Samyn and Tuzolana [7], the considerations and observations conducted for a typical tribological tests are as follow:

i. Motion (linear, rotary, reciprocating, oscillating, or a combination).
ii. Repeatability type (unidirectional, bidirectional).
iii. Contact geometry (point, area, line, or a combination).
iv. Environment (e.g. wet, dry, 3rd particles introduced (e.g. sand), slurry, electrification, low temperature, high temperature, pressurized, lubrications and their viscosities).
v. Atmosphere (e.g. hydrogenated, carbonized, vacuumed, oxidized, argon).
vi. Wear (abrasive, adhesive, erosive, fatigue, oxidative, fretting, corrosive, or a combination).
vii. Area of study specification (e.g. ball screw, teeth, biomaterials).
viii. Duty cycle (continuous, periodic).
ix. Mechanism (e.g. belt drive, hydraulic, power screw, chain drive, spur gear, rack and pinion, gear train, cam and cam follower, crank rocker mechanism).
x. Contact area (constant, variable).
xi. Material type and structure (e.g. rubber, steel).
xii. Dissipation of energy (e.g. heat sink).

When performing a tribology test, it is important to note that the test samples will act independently, as they are natural fibers composites. Hence, the contents of chemical composition in them differ from fiber to fiber. That's why we need to tribology test three times and obtain the average. This is specified in ASTM G99 standard [13].

Some machines are followed by "tribo" or "tribometer" in its name, but it doesn't necessarily mean that it is meant for tribology testing, but rather used for applying a certain environment or atmosphere to the tribotestings, used as an instrument to observe the behavior of the materials after tribotestings and used to define the type of focused field in tribology study. Some machines and tests are done based on standards and some are not, however it is better to use standards when the test is applied, unless proposition of a standard to a worldwide certified organization is intended.

Out of a survey of nearly ten manufacturing companies related to tribology, not all machines have the same parameters, machines differ majorly in speed range, load range, mechanism of applying the test, and limitations of environment and atmosphere. Some machines available in the market are classified as Universal Testing Machines (UTM). The UTM can do many different setups and tests where these kinds of machines are more economical, as researchers do not have to buy different machines for different setups. Furthermore, accessories are provided for UTMs to enable the specific environment and atmosphere needed for the specified test. Precise tribological wear test rigs machines mostly use electrical devices with closed loop control systems. The following section is a compilation of works related to common tribology testing methods. The basic working operation of the tribological wear test rig, its standard used, parameters of the machine setup and reported research using the machine will be discussed.

2.1 Pin-On-Disc (POD)

POD tribological wear test rig as shown in Fig. 6, is designed based on ASTM G99 standard [13]. The standard suggested that pin specimen to be in the size of 1×1×2 cm^3, but some researchers use different dimensions based on the application of their study. The size of the pin specimen may vary from 2 mm to 10 mm in diameter, and disc specimen from 30 to 100 mm in diameter with a thickness of 2 to 10 mm. POD test is one of the most common test in tribology study, and it consists of several important parts. The setup incorporates a linearly imposed pin specimen of a specified material by method of applying weights normal to the pin to push the pin specimen to a rotating disc specimen of a specified materials powered by an AC motor or a servo motor. The setup is mounted such a way that the vibration effects will not affect the test. Another mechanism for applying load is by using pneumatic, hydraulic, or power screw. ASTM G99 suggests that the motor's speed to be in the range of 60 to 600 rpm. The wear test cycles simulate the distance cut of the two imposed specimens, these test cycles help researchers to know the wear performance of the two materials during the sliding process subjected to a specified velocity, temperature, lubricant, load, pressure, duration, and friction. Currently, there exists different types of POD tribometer, these differences are due to the type of motion, limitations, and applications. From the survey, POD machines subjected to nano testing samples are also available, for testing materials at very low contact pressures. Another for medium to high contact pressures. Based on observations of machines from different manufacturing companies available in the market, existing standards and some works reported, the parameters available for POD tests are described below.

For Nano POD tribometer, applied load and sliding speed ranges from 5μN - 1N, and 1 - 200 rpm respectively. For micro tribosystem, applied load and sliding speed ranges from 0.01 - 10 N and 3000 rpm respectively. For medium to high contact applications, load and sliding speed ranges from 0.25 - 1000 N and 1 - 5000 rpm respectively.

Related works based on setups explained above had been carried out by numerous researchers. For instance, Marklund and Larsson [14] tested a wet clutch system using a POD setup. A thermocouple was placed inside the test specimen in order to capture temperature readings during the sliding wear test of the sintered bronze specimen subjected to a steel disc at a speed of 0 - 318 rpm for 10 mins under 22º – 100º C, 4.0 – 8.0 MPa, and 0 – 49 N frictional force. Verma et al. tested the wear behavior of brake pad material dry sliding against a cast iron disc. The diameter of brake pad pin specimen was around 0.62 cm with a height around 0.7 cm. The abrasion test done under standard room temperature and humidity, when oxidation occurred the wear becomes adhesive due to high material removal, the test done with 3.14 m/s velocity for 50 mins, and a pressure of 0.5 MPa, and 2.0 MPa [15]. In [16], Djoufack et al. investigates the wear behavior of hydrogenated diamond like-carbon (DLC) coating in DLC/steel tribological contact in the POD model test under GDK650 and EN590 diesel fuel lubrications, (DLC)/Steel test done with 40º C - 120º C temperatures, 0.4 m/s - 1.4 m/s speed, and 40 MPa to 120 MPa pressure. The disc diameter was 7 cm with 0.5 cm thickness, and the diameter of the pin was 0.18 – 0.21 cm. Nuraliza et al. used POD with these testing parameters: different applied load of (10N, 50N, 100N), and a speed of 3 m/s [17]. Whereby, Sapawe et al. performed the study using POD tribometer with 5N, 20N, 40N, and 80N applied loads [18].

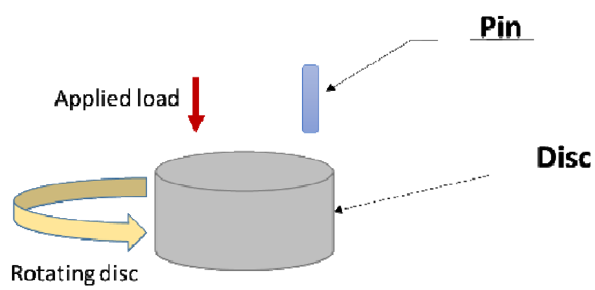

Fig. 6 Schematic drawing of a POD

2.2 Continuous Abrasion Test (CAT)

CAT is a set of tribotesters that apply the tribology study in a continuous rotating wheel for various conditions and environments. Tribotesters such as: Dry Sand Rubber Wheel (DSRW), Dry Sand Steel Wheel

(DSSW), Wet Sand Rubber Wheel (WSRW), and Wet Sand Steel Wheel (WSSW). DSRW was first developed by Stevenson Hutchings in 1996 as illustrated in Fig. 7 [19], and it is widely used for abrasion test [20]. DSRW is based on ASTM G65 standard [21], WSRW is based on ASTM G105-2 [22], and WSSW is based on ASTM B611 [23]. ASTM G65 recommends sand particles to be 200 - 300 μm with a feed rate of 300 to 400 gm^{-1}, and hardness degrees of rubber (IRHD) to be 58 to 62. A specified load is put in a lever arm to create a force that will push a specimen against a rotating rubber wheel. This will cause a friction between two bodies, the wheel and the specimen, sand is introduced to make the system with three bodies friction. Based on the literature survey, the sample are simple blocks of 55 x 24 x 12 cm^3, disc diameter to 22.3 - 22.5 cm, load to 130-45 N, and speed to 214 rpm. These machines can be used for testing rollers, bushes, bearings, sealing, rigs, tires, and coatings. Gore and Gates performed various experiments using DSSW and DSRW on different types of materials with different characteristics [24]. Michaela et al. observes the abrasive behavior of different coatings in low and high stress abrasion using DSRW and DSSW [25]. Varga et al. used DSSW configuration, the steel wheel's diameter was 23.2 cm with 1.2 cm width. the test performed under temperatures of 300° ,500° ,600°, and 700° C, force of 45 N, and speed of 1 m/s [26].

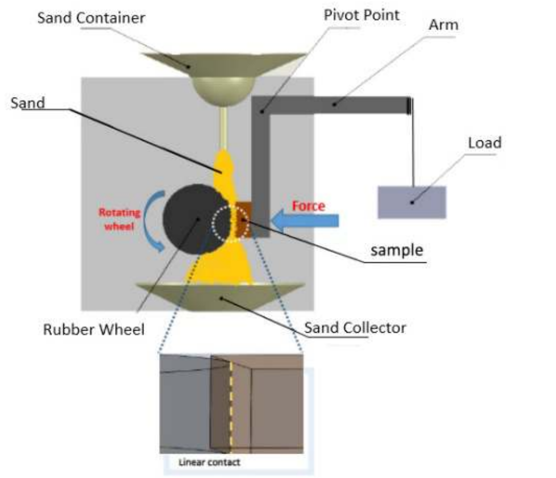

Fig. 7 Schematic drawing of a Dry Sand Rubber Wheel (DSRW)

2.3 Block on Ring (BOR)/Rotating Wheel Apparatus (RWA)

BOR as illustrated in Fig. 8, consists of a block specimen with standard size of 1×1×5 cm^3 that is pushed to the side of a rotating ring. Hydraulic system or Servo motor are used as ways to put load on the Block. Based on the literature survey, and available standards, the range of applying load is 20 - 10,000 N, and speed range is 60-3,600 rpm. BOR is used in any test with wear behavior of sliding/rolling such as: tires, bearings, camshafts, pulleys. The possible standards that can be used for BOR are: ASTM G77, ASTM D2509, ASTM D2782, ASTM D2981, ASTM G137-97, ASTM D2714, ASTM D3704, and ASTM G176 [27] – [34].

The followings are some selected works reported on using BOR test technique. Angelini et al. studied the influence of treatment temperature/time on micro structural features and dry sliding behavior of Low-Temperature Plasma Carburized (LTPC) treated martensitic stainless steel AISI420. AISI420 sample block were cut in cylindrical shape height of 1 cm and 5.08 cm diameter, the test was carried out under 350° – 500° C temperature, applied loads of 5 N and 10 N, with a speed of 0.3 m/s, and a pressure of 40 – 60 MPa [35]. Wirojanupatump and Shipway conducted abrasive wear using Rubber and steel wheel to mild steel in dry and wet conditions. The mild steel specimens' sizes were 1.27 × 5.6 ×0.5 cm^3. The abrasive tests were conducted under 23 -75 N applied load, and 125 – 150 μm particle size [36].

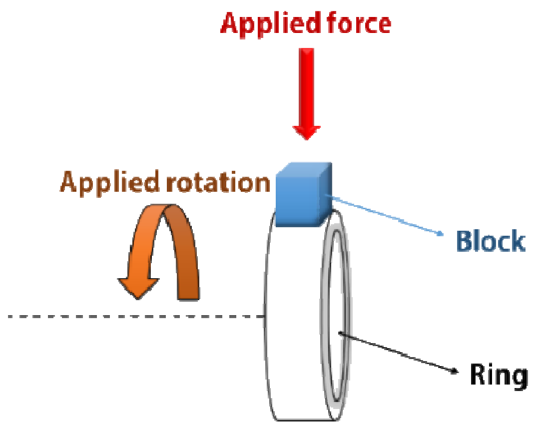

Fig. 8 Schematic drawing of a Block on Ring (BOR)

2.4 Ball on Disc (BOD)/Ball on Flat (BOF)

BOD configuration as shown in Fig. 9, is based on ASTM G133 - 05, and ISO 7148 [37], [38]. The ISO 20808 is a possible standard to be used for BOD configuration as well [39]. The BOD is basically consisting of a ball imposed to a rotating or sliding disc that is usually powered by an AC servomotor (e.g. 0.4 kw servo motor). The BOD is an alternative method of testing for twin disc tribometer, whereby BOD shares the same advantages as twin disc tribometer, but controlling tribology tests using BOD tribometer is less difficult compared to twin disc tribometer [40]. BOD can be used to do fretting wear test. The standard ball's diameter is 2.0647 cm, and the disc's diameter is 6 - 10.1 cm. ASTM G133 – 05 suggests two procedures for two different test parameters, unlubricated wear testing at 22° ± 3° C, and lubricated wear testing at 150° ± 2° C. It is recommended to use 25 N normal force with duration of test for 16 mins, 40 sec. whereby for the second one 200 N normal force with 33 mins,.20 sec duration of test is recommended. For Micro tribosystem 0.01 - 10 N applied load, 3000 rpm speed, plate specimen sizes up to 1.2×1.2×1.1 cm^3, ball specimen 0.1 - 0.3 cm. And for Medium to large tribosystem, 0 - 1 kN, 1800 rpm.

Wang et al. used BOD tribometer in dry sliding conditions to study the behavior of GCr15 steel against ultra–high molecular weight polyethylene (UHMWPE), polytetrafluoroethylene (PTFE), Phenolic, phenyl p-hydroxybenzoate (PHBA), poly-etheretherketone (PEEK), and polyimide (PI) polymers. The specimen's diameter GCr15 steel was 1 cm with roughness of 0.025 µm, the tested polymers' diameter was 2.5 cm, with thickness of 0.8 cm, and the normal load was 10 N [41]. This work was done by Björling et al. using a ball on disc tribometer to investigate the circular EHD contact created by ball on disc. The goal of this paper is to show differences in friction data between gear test and ball on disc test. The disc's diameter was in 10.16 cm, and the balls were in diameter of 2.063 cm under different types of lubricant. The test was performed under 76 N load, speeds of 1 m/s to 4 m/s, with temperatures of 40º and 70º, pressure of 1.24 GPa, and 0.0002 - 1.2 Slide to Roll Ration (SRR) [42]. EHL tribological systems is presented by Björling et al. with different parameters and conditions. The ball's diameter was 2.0637 cm, and the disc's diameter was 10.1 cm diameter. The tests were performed under 0.34 m/s and 9.6 m/s speed, and 0.02% to 49% SRR [40].

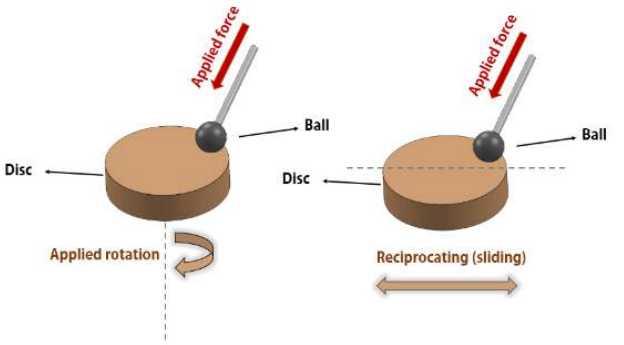

Fig. 9 Schematic drawing of a Ball on Disc (BOD)

2.5 Four Ball Tribotester (FBT)/Ball on Three Balls test (B3B)

B3B test as shown in Fig. 10 started in 1940's to test greases' properties, wear, and friction [43]. B3B plays a very valuable role in determining the effectiveness of various coating designs. The test balls' diameter is 1.27 cm according to ASTM D4172 and ASTM D2266 [44], [45]. The standard speed is 1760 rpm, and the wear is mostly adhesive. three balls are put in a holder and the fourth ball is rotated (by using an AC servo motor such as: 1.5 kw servo motor), and pushed towards the center of the three balls, the scars occur on the balls after the experiment are evaluated and studied. Load step in DIN standard is suggested to be 200 N, and in Europe the speeds used are 1450 rpm (acc. to DIN 51350-T5), 1200 rpm and 1760 rpm (acc. to ASTM D2266) [43]. B3B is best for testing tiny specimens and fragile materials [46]. Take note that, the effect of heat generated during the experiment can cause the four balls to be melted together, and malfunction of the tribometer may occur, therefore a certain lubricant is applied to avoid that. Possible standards for B3B are: ASTM D2783, ASTM D2596, ASTM D5183, IP 239, ISO 11008, DIN 51350-4 [47] - [50]. Based on the literature survey, the speed range can be up to 3,000 rpm, and load range up to 12,000 N.

Talib et al. used FBT in ASTM D4172, with 392N normal load, rotational speed of 1200rpm, and 75º C for a duration of one hour [51]. Li et al. used the B3B configuration with balls' diameter of 1.27 cm, 1450 rpm speed, and 30 mins duration of the test. The balls used for the study was made of GCr 15 bearing steel [52]. Hu et al. examined the wear on balls made with the ASTM E52100 bearing steel, under constant load of 250 N, and 1450 rpm speed [53] using this setup.

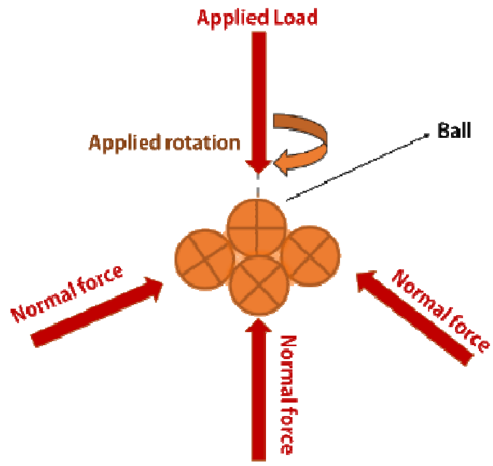

Fig. 10 Schematic drawing of a Ball on Three Balls (B3B)

2.6 Twin Disc Tribometer (TD)

Twin disc tribometer consists of two discs' specimens rotating on each other, with an applied force towards each of the disc specimens, as illustrated in Fig. 11 (a). Twin Disc tribometer has synonym names as: Rolling Sliding Apparatus (RSA), Disc on Disc (DoD), Ring on Ring (RoR), Twin Ring test (TR), Roll on Roll, and Gear to Gear (GG). Possible standard for this setup is GB 10622-89 [54]. Based on the literature survey, velocity usually sets up to 7.5 m/s, load up to 7100 N, and disc specimen's diameter up to 8 cm. Mostly this tribometer is used for improving wheel/rail contact as shown in Fig. 11 (b). Due to the symmetrical contact between the two specimens, this tribometer is applicable model to find out the wear characteristics of materials [55].

Andersson and Hemming performed a test for cast iron discs with two different grades against steel in lubricated contact. The fatigue and wear tests were carried out under applied force of 450-500 N, 3 m/s lower disc (Cast iron) velocity, 48 hrs. duration, and 1 – 51 number of tests [56]. Seo et al. used TD to test the contact wear and fatigue of two types of rail materials UIC 60, and KS 60. The fatigue test was done under 1100 MPa pressure, 500 rpm speed, and 0.01 – 0.45 C.O.F [57]. Gallardo-Hernandez and Lewis tested wheel/rail contact in different conditions wet, dry, and oily. UIC 60 900A rail steel was the material used for the wheel specimens, with 4.7 cm diameter and 1 cm contact width. The fatigue was set to 400 rpm speed, 1500 MPa, and slips of 0.5 % to 5 % [58]. Wang et al. simulated wheel/rail under dry and wet conditions. The fatigue tests were carried out under 1400 N – 2500 N normal force, 1050 – 1194 MPa contact stresses, 60 – 120 km/hr speed, 0 - 200 N lateral force, 18º- 23º C, and 50% – 70% humidity [59]. Fontanari et al. studied different pairs of materials, such as: 42CrMo4V against 42CrMo4V, and GJS- 700-2 against 42CrMo4V. Velocity of the first disc was 4.14 m/s with a diameter of" 5.4 cm, where by the second disc was 2.6 cm diameter with velocity of 0.39 m/s The test was carried out under temperature of 80º C [60]. Zanoria examined of abrasive wear in track-type machine where sand as a third body particle was introduced. The study parameters were set at 137 - 1656 N applied force and 200 rpm angular speed [61].

DOD can become Gear to Gear tribometer (GG) by simply changing the configuration to put gears instead of discs as shown in Fig. 11 (c). C. M. C. G Fernandes and co-workers studied the effect of gear oil with [BMP][NTf2] ionic liquid on the performance of two meshing gears, in order to improve the wind turbine gear box. The tests were performed under two different loads 700 N and 7000 N, with five different velocities 150 rpm, 300 rpm, 600 rpm, 900 rpm, and 1200 rpm [62]. Brandão and co-workers performed seven tests on spur gears, in order to confirm the effects of load and a thick basestock. The tests were performed under lubrication, and these parameters: 750 rpm speed of pinion, and normal force of 6373 N [63]. Jolivet and co-workers examined the effect of the viscosity of lubricants and the roughness of gear tooth on vibration of automotive gears. 1500 rpm speed, and 8 Nm applied load were the parameters of conducting the tests [64].

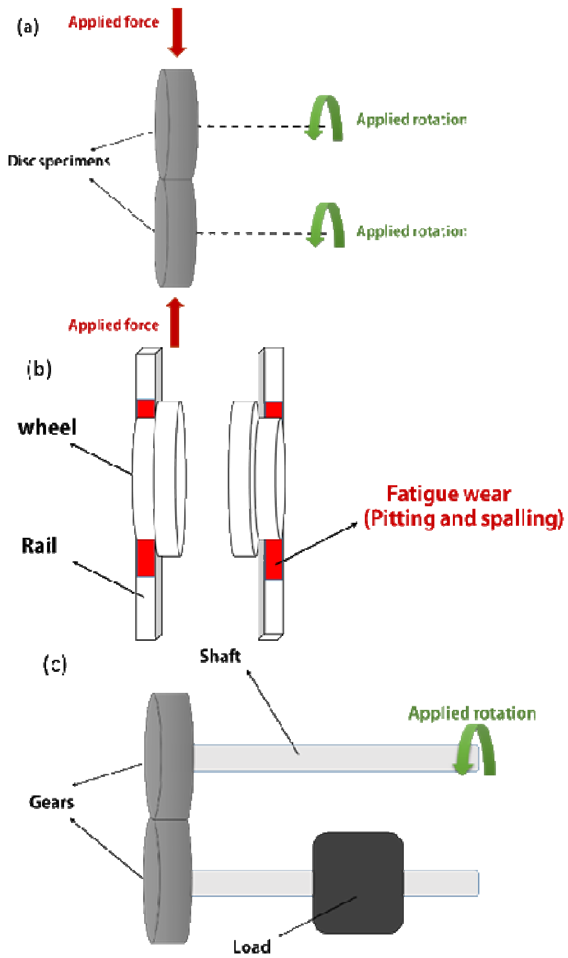

Fig. 11 (a) Schematic drawing of Disc on Disc (DOD) tribometer; (b) Schematic drawing of Upper view for wheel/rail configuration; (c) Schematic drawing of Gear to Gear (GG) tribometer.

2.7 Testing a piston ring assembly in automotive engines

A Piston Ring tribometer as illustrated in Fig. 12, is built based on ASTM G181 [65]. The following parameters are recommended by ASTM G181: 100º ± 2º C, and 20 - 200 N applied load. Available machines in market can apply load up to 500 N with max. piston ring velocity 5 m/s. Piston-Ring tribometer mechanism is basically consist of a linearly motion with a bidirectional repeatability, that simulates the abrasive and adhesive wear between a piston ring and a cylinder.

Ali et al. tested nanoparticles lubrication with the assembly of a piston ring. The tests were carried out under 30 - 250 N load, 0.65 – 5.43 MPa contact pressure, and 50 – 800 rpm speed [66]. Söderfjäll et al. used heavy duty diesel engines to design a high-speed cylinder liners and piston rings. The tests were carried out under 300 – 1500 rpm speed, and 80º C temperature [67]. P. Olander et al. examined Sulphur in rig specimen where the tests were carried out under 15-150 N of applied load, 0.75 – 7.5 MPa of contact pressure, 0 – 0.6 m/s of sliding speed and at operating temperature of 140º – 200º C [68].

2.8 Pin on Plate (POP)

POP setup as illustrated in Fig. 13, consists of a pin imposed to a reciprocating movement of a plate. Other synonyms to Pin on Plate as follows: Pin on Flat (POF), and Flat on Flat (FOF). ASTM G99-05, and ASTM G133-05 standards can be used to evaluate the wear performance of POP setup during and after the test [13], [69]. ASTM F732 gives guidelines for reciprocating test mode [70]. Possible standard to be used in POP setup is ASTM G132 [71]. Based on the literature survey on various setups and standards, Pin specimens' size can be up to 1.5 cm, reciprocating plate specimens' size up to 1.2×1.2×1.1 cm^3, speed can be set up to 2000 rpm, and load up to 200 kg.

Joyce et al. presented some works done using (POP) by performing a test on polytetrafluoroethylene (PTFE) against stainless steel where the applied force on the pin specimen was 40N with a diameter of 0.6 cm, and the wear factors were (2.3 – 5.2) × 10^{-5} mm^3/Nm [72]. Another study was carried out a cross-linked polyethylene (XLPE) against XLPE where the test was set under 1 Hz reciprocating speed, 37° C temperature, 40 N applied load, and 2.04 MPa nominal stress [73].

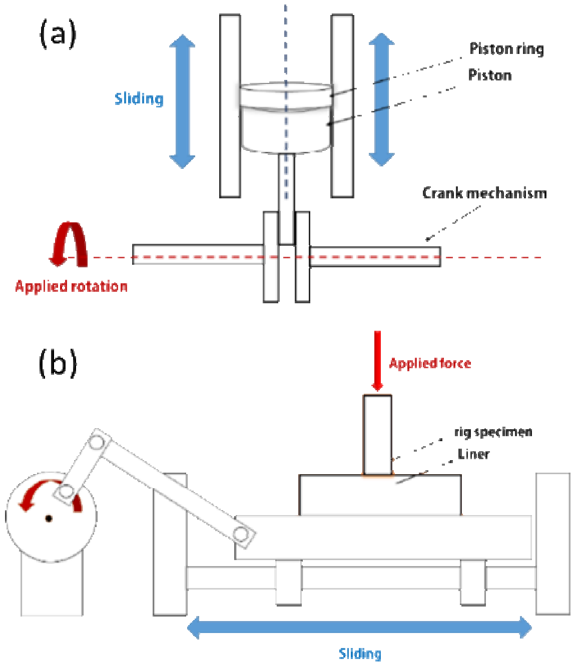

Fig. 12 (a) and (b) Shows schematic drawings of possible configurations for Piston Ring tribometer

One of the methods to increase the wear performance between two bodies in contact is by supplying electric power to both studied specimens one as anode and the other as cathode, these types of study is called tribo-electrification [74]. POP can become a reciprocating tribo-electrification apparatus by applying DC power source to both the pin and the specimen as shown in (c) Fig. 13. In tribo-electrification, Alternating Current (AC) with a certain amplitude and frequency, or Direct Current (DC) can be used based on the experimental test, as an example, examination of electrical sparking between surfaces in bearings can be performed [75]. Chiou et al. done some adhesion experiments using POP, whereby the displacement of the slider was set to 0.7 cm, and the range of applied voltage to -40 µV to 20 µV. Pure Pt, Ti, Fe, Mo, and W hard metal pairs were tested under tribo-electrification in dry environment. The test parameters were set to be 30 N applied load, and 50 mm/s speed [76]. Pure Al, Cu, Ag, Zn, Au, and Pb soft metal pairs were tested under tribo-electrification in dry environment. The materials were examined under the effect of load [77], and speed [78]. In [77], the test was set with an average speed of 40 mm/s, 10 – 90 N applied load. Whereby in [78], the applied load is set to be 30 N, with a V_{max}=55 mm/s. POP can also be used for scuffing tests, as Olander and Jacobson reported [79].

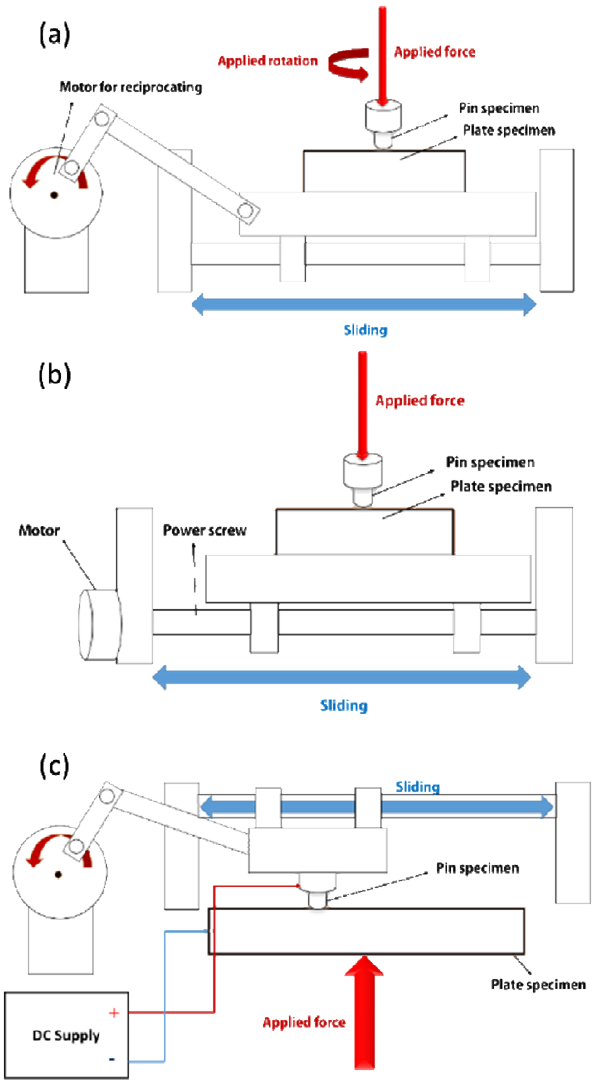

Fig. 13 (a), (b) Shows schematic drawings of possible configurations of Pin On Plate (POP) tribometer; (c) shows schematic drawing of Pin On Plate (POP) tribometer under electrification

2.9 Scratch Test

One of the common testing methods for adhesion wear is scratch test as shown in Fig. 14. Scratch test consists of a pin imposed to a plate that can travel in X, Y, and Z directions by using motors (e.g. servo motors). Based on the literature survey on machines in market and standards, applied load can be up to 25 N, speed up to 200 rpm, and the maximum size of test specimen is 10 × 15 × 5 cm^3. Possible standards for scratch test include: ASTM D7187, ASTM C1624, ASTM D7027-05, and ISO 20502 [80] – [83].

Xu et al. tested the scratch/abrasion of ferrite–martensite. The test parameters were set to be: 0 -25 N applied load, and 200 rpm speed. [84]. Zhu and co-workers tested hydrogenated nitrile butadiene rubber (HNBR) scratch with linearly increasing depth under ambient temperature (around 25° C), and 0.01 cm scratch tip. The length of scratch was set to be 100 mm, with a speed of 25 mm/s [85]. Xu et al. examined scratch and abrasive wear in a lean C-Mn construction steel. The test parameters were set to be, 0 - 25 N applied load, and 200 rpm speed [86].

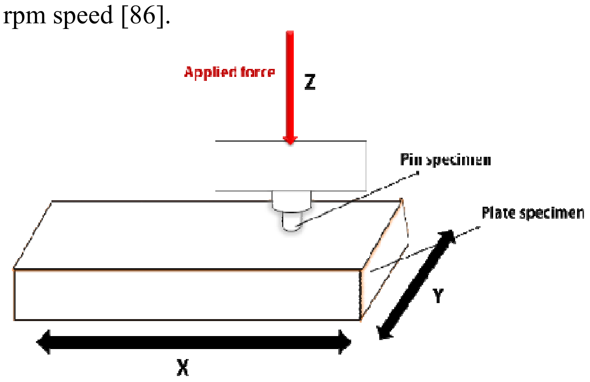

Fig. 14 Schematic drawing of Scratch Test tribometer

2.10 Taber Abraser (TA)

A Taber Abraser or Abrasion Resistance Tester (ART) is a machine that consists of two abrasive wheels with a rotating stage as illustrated in Fig. 15, whereby abrasive wheels are rotated by the applied rotation from the rotary stage, which usually rotated 60 rotations/min, and the normal force range of TA is 2.5 - 10 N [87]. TA was developed in 1930's to accelerate the wear testing, the machine is designed according to ASTM G195-13a [88], [89]. Possible standards for TA include: ASTM D 4060-95, ISO 5470-1, DIN 53754, and ASTM F1978-00e1 [90] – [93]. Taber Abraser is popular for testing the resistance of materials and coatings subjected to abrasion wear. Test specimens' can be circular or square in shape, for circular shapes the diameter is set to be 11 cm, and for square shapes the size is 10 cm × 10 cm. Applied loads can be up to 1 kg [94].

Suzuki and Ando examined metal nitride against glass by using Taber Abraser. The 2 mm substrate was made of soda lime silica sheet glass. The test parameters were 4.9 N applied load, and 50 mm/min sliding speed [95]. The Taber test is among the most common tests to evaluate the abrasion resistance of coatings. Rossi et al. used artificial sand as an abrasion element against organic coatings, the design of Taber Abraser was modified to include an electrical contact. The applied load was 1 kg for the test [96]. Cambruzzi et al. abrasion happened to organic coatings using Taber Abraser with three body contact: rubber wheel, organic coated sample with dimension of 10 cm × 10 cm, and sand as the third body [97]. Jumahat et al. used ART which is a similar tribometer to TA, and it can take more applied load. ART was used with these parameters: 20 N applied load, and 1.4 m/s speed [98].

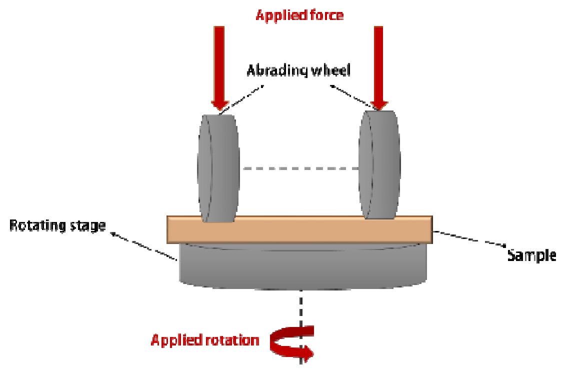

Fig. 15 Schematic drawing of a Taber Abraser tribometer.

2.11 Jet Impingement Tribometer (JIT)

JIT as illustrated in Fig. 16 (a), is a machine that consists of an ejector with specifically designed nozzle, whereby gases or liquids can be impinged to a tested specimen with specific tribology study parameters. Ejectors are placed in an angle specified by the researcher. JITs differs by angle of placed ejectors, distance between ejector and tested specimen, ejector's nozzle design, pressure, speed, temperature, and the type of impinging materials. Possible standards for JIT include but not limited to: ASTM G76, ASTM G73-10, ASTM G73-98, and ASTM G211-14 [99] – [102]. Upon the survey, JIT comes in a speed up to 250 m/s, pressure up to 320 bar, nozzle diameter up to 3 mm, angle of impingement ranges from 15º – 90º, temperature up to 950º C, and standoff distance between a nozzle and a specimen up to 20 cm.

Zhao and co-workers studied the erosion-corrosion of Fx65 steel. The diameter of the nozzle was 0.4 cm, the specimen was 0.5 cm far from the nozzle, and the test parameters were 20 m/s speed, and 50º temperature [103]. Hossain et al. studied the wetting delay of a brass block under high temperature. The jet was place 2.3 cm away from the specimen, with jet diameter 0.1 cm. the test was carried out under 250º – 450º temperatures, and 3 m/s, 5 m/s, and 10 m/s speeds [104]. Gant et al. observed the erosion of tungsten carbide and carbon steel. The tests were carried out under 60 – 240 rpm, and 2 - 4 bar pressure [105]. Cavitation, erosion, and slurry wear were examined by Sugiyama et al. for SCS6 metal. The jet nozzle was 0.3 cm and 2.5 cm far from the specimen that was inclined in angles ranges from 90º – 15º. The test parameters were 25º ± 1º C temperature, and 10 – 40 m/s slurry jet velocity [106]. Another type of JIT is Spray Jet Apparatus (SJA) as illustrated in Fig. 16 (b). Fujisawa, Yamagata, Wada et al. used SJA to examine an aluminum specimen (Al070) by simulating Liquid Droplet Impingement (LDI) erosion using SJA. The distances between the jet nozzle and the specimen were 27 cm and 48 cm. The erosion test was carried out with the following parameters, 16 - 28 MPa pressure, and 179 - 237 m/s nozzle exit velocities [107].

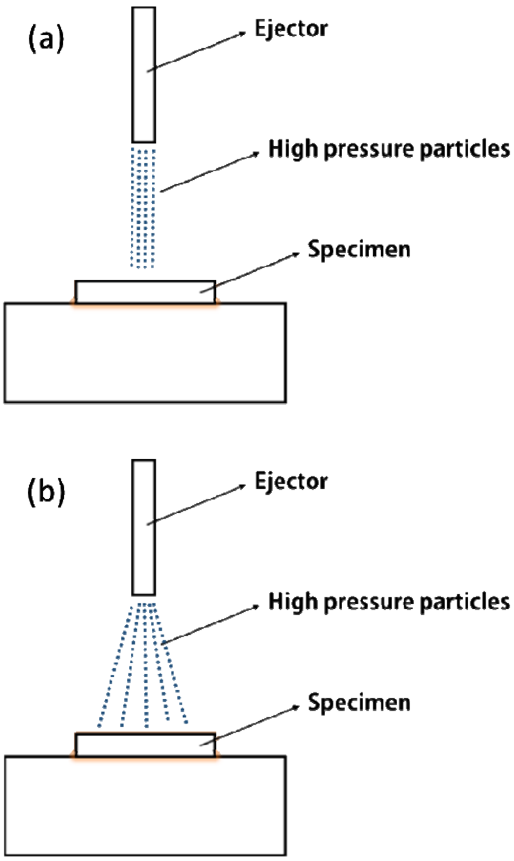

Fig. 16 (a) Shows schematic drawing of a Jet Impingement Tribometer (JIT); (b) show schematic drawing of a Spray Jet Apparatus (SJA)

3. Tribotronic System

Glavatskih and Höglund proposed a new concept for development of tribology machines, called tribotronic system. Tribotronic system is a combination of mechatronics, electronis, and control engineering in order to improve the accuracy of studies of surfaces in contact, as well as to improve machines subjected to tribology during operation [108]. Other names to tribtronics system might be: automation in tribology machines, active tribology, and Computer controlled tribology tests. Schmitz et al. discussed about the concept of Automation of Automation (AoA), that helps in the transition from skilled labor needed for a certain operation, into a fully computerized system for the intended operation [109]. Therefore, before an engineer or a scientist decides to automate a tribology machine, a sufficient knowledge must acquire about what to automate. What is meant by automated and manually operated tribology testing machine is automated means no need for a human involvement, manually means need for a human involvement. Lindstr et al. defined different levels of automation based on four roles of handling by a human or by a computer [110]. Two types of machines are available in tribology testing machines market:

- Manually operated tribology machine
  - Operator changes testing specimens manually.
  - Operator collects the data from sensors and recorded down manually.
  - Operator can analyze the data manually or automatically by inserting the data to a computer.
- Semi-automated operated tribology machine:
  - Operator changes testing specimens manually.
  - Computer collects and stores data.
  - Operator can analyze the data manually or automatically by inserting the data to a computer.

It is proposed to develop the tribo-testing machines to fully automated machines, with changing specimens automatically, by the means of robotic arms for example. Fig. 17 illustrates the differences between Automated, Semi-Automated, and Manually operated tribology testing machines.

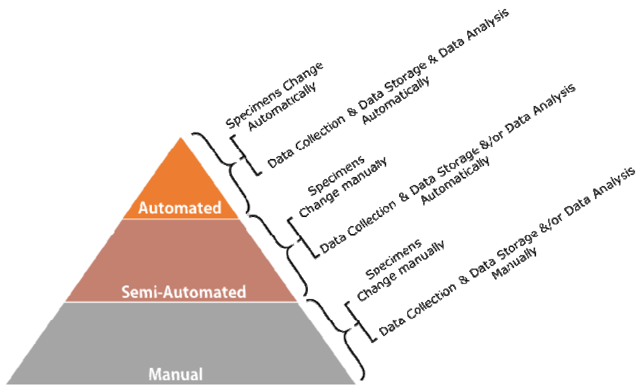

Fig. 17 Differences between Automated, Semi Automated, and Manually operated tribology testing machines

Fig. 18 shows the sequence of data handling in a very simplified way, in order to enable a better understanding of the topic. Data types are divided into three main sections, data collection from sensors and feedbacks, data storage in a memory, and data analysis of the collected data. Digital image processing plays a vital role for detections of different types of wear automatically [111].[112].

Choi and Kim analyzed five different types of surfaces' corrosion using the method of image processing by classifying each surface damage into three classifications, namely: Shape features, Color, and Texture. In the analysis Hue, Saturation, Intensity (HSI) model was used for the color features of the surfaces after corrosion, as HSI enables to characterize the brightness level of each surface, which in turn it helps to prevent the irregularities of brightness levels when capturing images. Co-occurrence matrix was used for the texture and shape analysis of the corroded surfaces. Choi and Kim claimed that digital image processing is vital for the analysis of surfaces' corrosions [113]. Ribeiro et al. used the technique of image processing to investigate the erosion of surfaces after being subjected to Jet Impingement Tribometer (JIT). The analysis of image processing gave the ability to show the comparisons of the changes in the surfaces subjected to erosion, and how the impingement slurry flows into the tested surfaces [114]. Wang et al. used the method of image processing to analyze the defects on steel balls surfaces [115].

Sound processing technology is a great method for wear examination because of its ability for response in real time without process interruption and it is predicted to be used as a method for future studies in the field of tribology [116]. Jomdecha et al. used the method of sound processing Acoustic Emission (AE) to find the types and locations of four different types of corrosion [117]. Tian et al. examined four different types of metals subjected to dry sliding using the method of sound processing [118]. Saeidi et al. used the sound processing on examination of scuffing happened between materials tested using Flat-On-Flat (FOF) set up [119].

Artificial Neural Network (ANN) is a marvelous method for saving time for experiments, whereby after the neurons are trained and the data are collected, a prediction of materials' wear behavior can be made easily, without the need of performing experiments, which it results in saving time and costs [120]. Kumar et al. used the method of ANN in order to anticipate the loss of Sintered Cu-SiC composited due to abrasive wear [121]. Yetim et al. used ANN to predict the properties of wear in plasma nitriding, and in the paper it is concluded that ANN prediction was similar to the results obtained after doing the experiment [122].

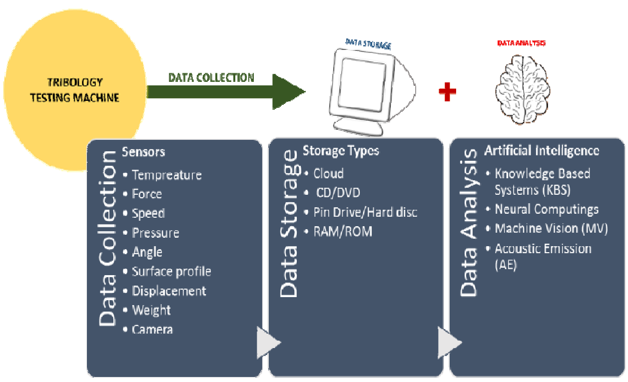

Fig. 18 Data types with examples

Below are some critical questions that should be asked before making a decision to apply automation in tribology testing machines.

- ✓ Why:
  - Why specimens are needed to be changed automatically?
  - Why to classify different types of tests?
- ✓ When:
  - When human interruptions get in?
- ✓ Where:
  - Where the automation takes part?
  - Where the sensors should be located?
- ✓ What:
  - What are the specimens needed to be changed automatically?
  - What sensors are going to be used?
  - What software frameworks are intended to be facilitated?
  - What mechanisms should be designed?
  - What accessories could be added to change environment or atmosphere of the designated tests?
- ✓ How:
  - How the machines are controlled?
  - How to make machines easy to operate?
  - How electricity is supplied?
  - How to make a friendly user interface?
  - How to read sensors' measurements?
  - How to train the system to classify different types of wear, tear, and scars?

4. Outlook of this study

From the review done, it is crucial to have an automated tribology wear test rig based on the benefits proposed below:

- Performing multiple tests at the same time.
- Researchers don't have to sit beside the experiment and observe it all day, remote observations are better.
- Safety of researchers, as researchers don't need to mount the specimens, or being within the test working envelope.
- Care of handling specimens, for example: using robotic arms to move a specimen from one place to another precisely.
- Data analysis from computers can help human beings to push beyond their limits, as computers can observe in more detailed characteristics of studied specimens.
- Time savings, such as: idle time by implementing automated changing specimens, down time as a computer software will be trained to avoid the causes of a down time, or to alert an operator when the checkup time is needed for the tribology testing machine and saving the setup time as setups of different tester will be done automatically.
- Cost savings, as the need of expertise to operate the testing machine will be lesser if the knowledge and concepts of automation are utilized in this field.

5. Summary of literature survey

Upon conducting the literature survey on the types of machines available in the market and the types of standards used, few statements can be made as a summary of the literature survey. Which are listed below:

- Certain applications require specific tribology machines and tribological setups.
- Developing tribology machines is really needed to overcome the continuous arising challenges in industrial sectors.
- Tribology science is extremely important to achieve the desired quality.

- When suffixes “Tribo”, or “Tribometer” are used, it doesn’t necessarily only to be adopted for defining tribology machine testers, it is also used for instruments or accessories needed for tribology studies, or even the type of specified tribology study.
- A study of parameters such as: speed, load, and mechanism, is important before launching an experiment, in order to decide which tribomachine suits the experiment.
- Tribology falls in our daily life, no one can escape from tribology, because wear and tear are part and parcel of a material during the material’s life span [123].
- In order for a new material to be implemented in the market, material has to be subjected to wear performance, hence tribology comes in, and different setups are available for applications of the material will be subjected to.
- It is also noticed that tribology experiments require lengthy setup time, involving human or the machine itself. Thus, when there is a human involvement, the setup time even comes longer, because somebody has to take the data, the measurement has to be done by a human and so on and so forth.

From the above, it is proposed that future researches on tribology machines to be carried out mainly to automate tribology machines. Applying automation principles to tribology machines will reduce setup time, idle time, and down time of the setups. This can in return contribute to ‘Green Engineering’ as the machine utilizes less operation time, low man power and low machine power consumption due to energy efficient automation hardware being utilized.

6. Conclusion

In this paper, various tribological wear test rigs are discussed, with the aid of diagrams, standards, and related research works. As well as, existing tribological wear test rigs’ operating parameters are reported. Challenges on making this review article were faced on combining various machines that has the same operation but different names, as well as finding the operation standards, and noting the parameters’ range of the machines. After reviewing and combining all the different tribomachines It is noted that tribomachines need more developments on the time it consumes to do tribological experiments. Setup-Time, Idle-Time, and Down-Time are some of the challenges needed to overcome and reduce. Therefore, automation in tribological wear test rigs is proposed, as automation gives more efficient tribological studies by automating the process of setup-time, reducing the down-time and idle-time for every tribological wear tests studies.

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