TRIBOLOGICAL PERFORMANCE OF HYBRID COMPOSITES BASED ON PALM OIL FIBRES AND ALUMINA POWDER BLEND

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TRIBOLOGICAL PERFORMANCE OF HYBRID COMPOSITES BASED ON PALM OIL FIBRES AND ALUMINA POWDER BLEND

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A report submitted
in fulfilment of the requirements for the degree of
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DECLARATION

I declare that this project report entitled "Tribological Performance of Hybrid Composites Based on Palm Oil Fibres and Alumina Powder Blend" is the result of my own work except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

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APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature : ……...

Supervisor's Name : ……...

Date : ……

DEDICATION

To my beloved father, mother and brother.

ABSTRACT

Nowadays, the green technology is important and expected due to global warming threaten. The usage of agricultural waste product in industry manufacturing process is increased and more environmental friendly. The production of hybrid composites based on palm oil fibres from agriculture waste and alumina powder blend is considered as the substitution of materials which have large potential towards zero waste strategy as well as the composites can provide the better properties compared to one of material alone. The absent of hybrid composite which can provide high friction with low wear rate ability without using the lubricant is being focused due to low wear rate can extend the lifespan of tools. Thus, literature study on hybrid composites and applications has an enormous potential to explore the benefits of hybrid composites. The objectives of this project research were included the determination of the optimal composition ratio and investigation of tribological properties of hybrid composites based on palm oil fibres and alumina powder blend. The comparison of tribological properties in terms of coefficient of friction and specific wear rate is conducted in between hybrid composites and conventional composite, SK-2 carbon steel disc. The composition of specimen is focused in three categories such as 50 wt.%, 60 wt.% and 70 wt.% of composite reinforced with 50 wt.%, 40wt% and 30 wt.% of epoxy respectively. The physical-mechanical properties of specimen are determined using the physical testing and followed by carry out tribological testing using ball-on-disc tribometer where the testing parameters are set with 400rpm sliding speed, 49.05N applied load and 3000m sliding distance to investigate the tribological performance of hybrid composite. Then, the manual calculation is performed to determine the specific wear rate of specimens while the wear morphology of the specimens is studied through the optical micrographs of worn surface which is captured using 3D non-contact profilometer. The collected data were analysed through qualitative and quantitative approaches. From the study, the optimal composition ratio with 35 wt.% of palm oil fibres, 35 wt.% of alumina powder and 30 wt.% of epoxy is obtained for the hybrid composite with high friction and low wear rate in tribological properties.

ABSTRAK

Teknologi hijau ialah teknologi yang penting pada masa kini dan ini disebabkan oleh ancaman pemanasan global yang nyata. Penggunaan produk sisa pertanian dalam proses pembuatan industri semakin meningkat dan penggunaan ini adalah mesra alam sekitar. Pembuatan komposit hibrid berasaskan campuran serat minyak kelapa sawit daripada sisa pertanian dan serbuk alumina boleh dianggapkan sebagai penggantian bahan yang mempunyai potensi yang tinggi untuk menghapuskan sisa pertanian. Komposit hibrid dapat memberikan sifat-sifat yang lebih baik berbanding dengan komposit yang terdiri daripada satu jenis bahan sahaja. Kekurangan komposit hibrid yang mempunyai pretasi tribologi dengan geseran yang tinggi dan kadar haus yang rendah tanpa menggunkan pelincir adalah topic yang diberikan tumpuan kerana kadar haus yang rendah dapat memperpanjangkan tempoh umur alat. Oleh demikian, kajian kesusasteraan mengenai komposit hibrid dan aplikasinya teleh dijalankan, ia mempunyai potensi yang tinggi untuk memberi peluang dalam penerokaan manfaat yang diberikan oleh komposit hibrid. Objektif penyelidikan projek ini termasuklah menjalankan kajian mengenai nisbah komposisi yang optimum dan sifat-sifat tribologi dalam komposit hibrid berasaskan campuran serat minyak kelapa sawit dan serbuk alumina. Perbandingan sifat-sifat tribologi antara komposit hibrid dan komposit konvensional, cakera keluli karbon SK-2 pun telah dijalankan. Komposisi yang digunakan dalam pembuatan spesimen telah difokuskan dalam tiga kategori, iaitu 50 peratus berat komposit dengan 50 peratus berat epoksi, 60 peratus berat komposit dengan 40 peratus berat epoksi dan 70 peratus berat dengan 30 peratus berat epoksi. Ujian fizikal dijalankan untuk mengkaji sifat-sifat fizikal dan mekanikal dalam komposit hibrid manakala ujian tribologi yang menggunakan "ball-on-disc" dijalankan dengan parameter yang ditetapkan dengan kelajuan 400rpm, beban ujian sebanyak 49.05N dan jarak jauh 3000m untuk mengkaji prestasi tribologi bagi komposit hibrid. Pengiraan manual dijalankan untuk menggira kadar haus spesifik bagi komposit hibrid manakala kajian morfologi bagi permukaan spesimen dijalankan dengan menggunakan "3D non-contact profilometer". Data yang dikumpulkan dalam kajian telah dianalisiskan dengan kaedah kualitatif dan kuantitatif. Nisbah komposisi yang optimum bagi komposit hibrid ialah 35 peratus berat serat minyak kelapa sawit, 35 peratus berat serbuk alumina dan 30 peratus berat epoksi, ia mempunyai geseran ynag tinggi dan kadar haus yang rendah dalam prestasi tribologi.

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Equation 4.1 - $D = 2\pi(\mathrm{r})(\mathrm{N})(\mathrm{t})$

Equation 4.2 - $COF = \frac{Friction\ force\ (N)}{Normal\ force\ (N)}$

Equation 4.3 - $V = \pi r^2 T$

Equation 4.4 - $\rho = \frac{M_a}{V}$

Equation 4.5 - $M_{loss} = M_b - M_a$

Equation 4.6 - $V_{loss} = \frac{M_{loss}}{\rho}$

Equation 4.7 - $k = \frac{V_{loss}}{W \times D}$

LIST OF ABBREVIATIONS AND SYMBOLS

COF	-	Coefficient of Friction
°C	-	Degree Celsius
ρ	-	Density of specimen
W	-	Load applied
µm	-	Micro-meter
nm	-	Nano-meter
N	-	Newton
POF	-	Palm Oil Fibre
Pa	-	Pascal
r	-	Radius of specimen
RPM	-	Rotation per Minutes
D	-	Sliding distance
k	-	Specific wear rate
Ra	-	Surface Roughness
T	-	Thickness of specimen
t	-	Time
wt.%	-	Weight Percent

CHAPTER 1

INTRODUCTION

1.1 Background

Hybrid composite is a mixture of two different material at various composition ratio. Hybrid composites have generated the significant interest for a researcher since the 1970s. The percentage difference or composition ratio in hybrid composite is directly affected the performance of composite (Harris, 2003). The important criteria for the effective use of hybrid composite are related to life durability. Thus, the method of combine two or more types of varied materials to develop the new types of hybrid composites and the hybrid composites are found the widest application use to the present time. The hybrid composites have the high probability to create the new tribological properties after combination (Shalin, 1995).

In this project, the hybrid composite based on palm oil fibres and alumina powder blend is used to test in term of tribological performance. The palm oil fibres are classified as the natural fibre and the natural fibre polymer composites have numerous application in almost all field of engineering (Chand, 2008). The advantages of using natural fibres compared to synthetic fibres include low cost with their low density, good relative mechanical properties and less damage of tool wear in machining operations. Thus, the palm oil fibre is useful and shown an enormous potential as a reinforcing material because our country, Malaysia is the plantation base for palm oil and the material can be obtained easily compared to other fibre (Mohanty, 2005). The alumina powder blend or it can be called as aluminium oxide is commonly used in engineering processes. Due to the desired properties

of alumina powder composites, such as low weight and high specific strength, they have received a great interest in the recent years in engineering industry. Among the ceramic reinforced materials, alumina powder is the second most used in metal matrix composites due to the better corrosion and elevated temperature resistance in performance when compared to silicon carbide material (Rahimian, 2011).

There is increased awareness about the properties of natural fibre-based hybrid composite to meet the engineering requirements (Mittal, 2016). The natural fibre-based hybrid composite will be able to be classified as a suitable material in manufacturing of engineering product with maximum usage of natural fibres. In this project, the study is focused on the tribological performance of hybrid composite which is based on palm oil fibres and alumina powder blend in term of wear rate and coefficient of friction analysis by using ball-on-disk tribometer, hence to provide the optimal composition ratio for hybrid composite which is having the superior tribological performance with high friction and low wear rate.

1.2 Problem Statement

The demand of searching the suitable material or hybrid composites which can be operated in machine parts without using the liquid lubricant as a medium to increase the wear performance of the composites. The absent of hybrid composite which can meet the requirement of high friction and low wear rate in the automotive industry is being focused, due to the expected hybrid composites are environmental-friendly which can be targeted as reducing waste instead of replacing with new one after a short lifespan. In general, the research in creating the more efficient hybrid composite in term of wear performances can lead to determine the solution in overcoming these problems. The hybrid composite with efficient tribological performance is highly demanded in automotive industry, the high

friction, high temperature resistance and low wear loss hybrid composite is suitable to be used as manufacturing material for bearing or brake pad in automotive parts to replace the conventional materials. Thus, the study in tribological performance of hybrid composite is important and it will be an interesting topic by using the ball-on-disk tribometer.

1.3 Objective

The objectives of this project are as follows:

a. To determine the optimal composition ratio of hybrid composite based on palm oil fibres and alumina powder blend with high friction and low wear rate.
b. To investigate the tribological properties of the hybrid composite based on palm oil fibres and alumina powder blend.
c. To compare the tribological performance of hybrid composites with conventional composite, SK-2 carbon steel disc.

1.4 Project Scope

The project research is limited to the study of tribological performance of hybrid composites based on palm oil fibres and alumina powder blend which is focused in wear friction and wear rate of the hybrid composite. Hence, the tribological testing in this project is carried out using the parameters as stated as below:

a. Materials: Palm Oil Fibres, Alumina Powder Blend and Epoxy
b. Materials composition:
    - 50 wt..% of composite and 50 wt.% of epoxy
    - 60 wt.% of composite and 40 wt.% of epoxy
    - 70 wt.% of composite and 30 wt.% of epoxy
c. Machine: Ball-on-disk Tribometer

d. Load applied: 49.05N

e. Sliding speed: 400rpm

f. Sliding distance: 3000m

g. Sliding temperature: Room temperature

h. Sliding condition: Dry sliding

i. Surface roughness: 0.2µm – 0.8µm

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is discussed the literature review for project title keywords based on previous research or reference from books. In this chapter, the selected keywords such as tribological performance, hybrid composites, palm oil fibres and alumina powder blend are used for further discussion. The purpose of literature review is to provide background information on the issues to be considered in this project and to emphasize the relevance of the present study. The wide range of explanation in details are important to provide the sufficient of information before the experiment is conducted to test the tribological performance of hybrid composites.

2.2 Tribological Performance

Tribological performance is an important term in tribology which is included the study of friction, lubrication and wear of the materials. The tribological performance is a significant parameter for hybrid composites and it can be tested by using pin/ball-on-disc tribometer. Thus, the terms of friction and wear will be studied in tribological testing because this criterion can differentiate the usage of hybrid composites in industry or real-life application. Stachowiak (2005) states that the tribological process is a contact process where two surfaces are in relative motion and it involves the friction, wear and deformation mechanisms at different scale levels and of different types. The study of tribological performance is significant in engineering fields where it allows the researcher to explore the tribological properties of material or composite, hence the research can provide the improvement to reduce the friction and wear in machine.

In tribological performance, the friction term of material is important in tribology can be defined as the resistant force to the relative motion of two solid surfaces or fluid layers. Neglecting the wear processes in tribology, friction rises from the transfer of collective translational kinetic energy into nearly random heat motion. The concept of friction is illustrated in Figure 2.1. The sliding or slipping may or may not occur in between two solid body surfaces because it depends on the conditions where the applied force can overcome the friction force which is opposing it (Peter, 2008). In this project, the sliding friction in dry condition is focused in the study of tribological performance of hybrid composites. Persson (2013) stated that the sliding friction is mainly depends on the physical properties which included the surface roughness of materials. During sliding processes, two bodies which are generally in contact over very small discrete areas where the sliding friction is ouccured in between the contact surface. The sliding friciton occurs in between the contact surface will transform the kinetic energy in desired motion into the heat energy or mechanical energy where it is caused the wear of contacting bodies (William, 2010). The sliding friction of a material can be related to determination of coefficient of friction where the applied force is included in calculation. Based on the law of frcition, the depence of of the frcition force upon normal load applied is proven and it is significant in generation of coefficeint of friction (Bartenev, 1981). However, the coefficient of friction of a material or composite is independent of the apparent area of contact. Moreover, the coefficeint of friction is often nearly velocity independent unless the sliding velocity is very low, where the thermal activation becomes very important and could affect the result in testing. Therefore, the friction force of composite is important in tribological performance where it can classify the properties of composite. Besides, Niklas (2001) research found that the friction is required to be measured in the stable, steady-state conditions so that the results are useful in characterizing the long-term properties of the system.

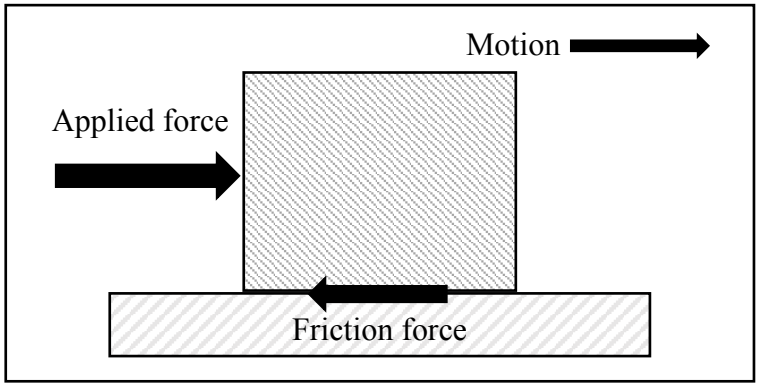


Figure 2.1: Concept of friction force

In tribological performance, the wear of a material or composite is a significant outcome in tribological testing. Bayer (2004) studied that the wear can be recognized as the process which included loss of material from a surface, transfer of materials from one surface to another or movement of material within a single surface. Hence, a simple statement or explanation regarding the wear term in tribology is that wear is a damage to a solid surface and generally involving the progressive loss of material. However, the wear of a material also can lead to the change in geometry or dimension of a part as results of plastics deformation. Wear is not a material property not it is a unique physical mechanism. The materials can be wear by variety of mechanisms and wear behaviour can be influenced by material properties and operational parameters (Bharat, Principles and Applications of Tribology, 1999). Study of wear is a common and useful practice in engineering because it is related the performance of a designed materials. Furthermore, the study in wear performance can lead to discover the wear behaviour and wear mode of a composite. The wear is one of the important characteristics in engineering design such as automotive design. The selection of materials is based on the wear performance or wear behaviour criterion, so that the linear relationship in between of design and wear (Bayer, 2004). The wear can be classified into various form which included lubricated wear, unlubricated wear, severe wear, mild wear, sliding wear, rolling contact wear and impact wear. However, the wear processes involve the wear mechanisms in term of abrasion, adhesion, fatigue and oxidation (George,

2004). The wear mechanism of adhesive wear and abrasive wear which is commonly happen in tribological testing are presented in Figure 2.2. According to Bharat (2002), adhesive wear is occurred when two nominally flat solid bodies are in sliding contact with or without lubracation where the asperitiy is contacted at the interface and these contacts are sheared by sliding such as tribological testing using ball-on-disc tribometer. The sheared contacts are caused the detachment of a fragment from one surface and attachment to the other surface as well where the process in known as material transfer. Furthermore, Karl (1987) presented that the abrasive wear is a type of material removal mechanism which is similar to the grinding in manufacturing process. During the sliding process, the hard asperities or particles of a rough, hard surface are penetrated into the softer surface under normal applied force and damage the interface by plastic deformation. For the abrsive wear, the scratching effect which is usually appears on softer surface can be observed as a series of grooves parallel to the direction of sliding.

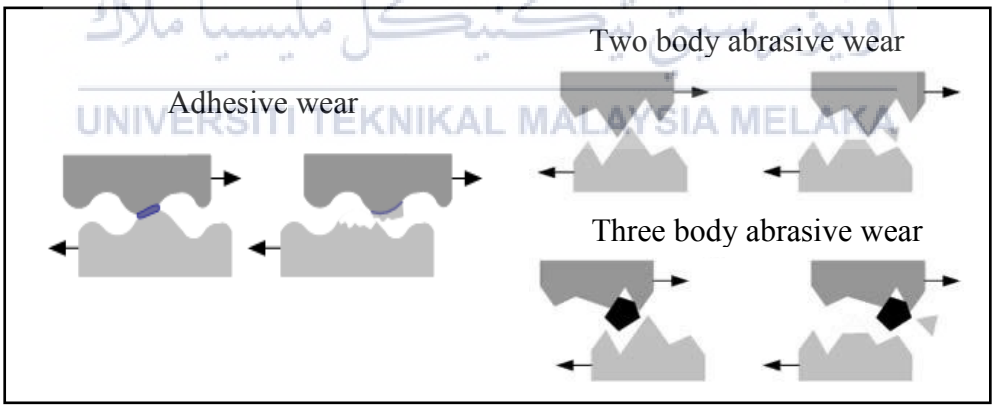


Figure 2.2: Concept of adhesive wear and abrasive wear

2.3 Hybrid Composites

Hybrid composites can be defined as the combinations of two or more materials assembled in nanometer or molecular level as to have characteristics which are not offered

by any one materials alone, besides the compounds is a mixture of organic and inorganic in nature (Ashby, 2005). Another study by Yamada (1989) defined the hybrid composites as a mixtures of two or more materials by new electron orbitals formed between each material and the hybrid composites are created with new properties as well. Hybrid composites must have superior functions or better properties while comparing to traditional composites so there is more option in selection of materials in manufacturing. The categorization of hybrid materials and their related materials in detail is shown in Table 2.1.

Table 2.1: Categorization of hybrid materials

Composites	Mixture of materials consisting of matrix and micron-level dispersion
Nanocomposites	Sub-micron level mixture of similar kinds of materials
Hybrids	Sub-micron level mixture of various kinds of materials
Nanohybrids	Atomic or molecular level mixture of varied materials with chemical-bonds between the varied materials

Moreover, Nanko (2009) presented that there is no strict definition of hybrid materials however the definition of hybrid materials is required an atomic or nanometer-level mixture of materials. Thus, the classification of materials by different scale levels are proposed to define a clearer boundary for hybrid materials or hybrid composites as in Figure 2.3.

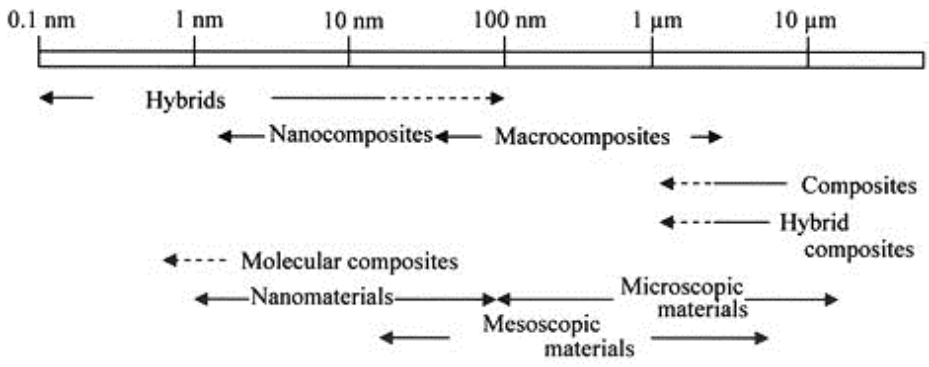


Figure 2.3: Classification of materials at different scale levels

Besides that, the present type of hybrid materials can be categorized into three categories such as structurally-hybridized materials, materials hybridized in chemical-bond and functionally-hybridized materials. (Hagiwara, 2000) The Figure 2.4 as below shows the realtionship between three types of hybrid materials.

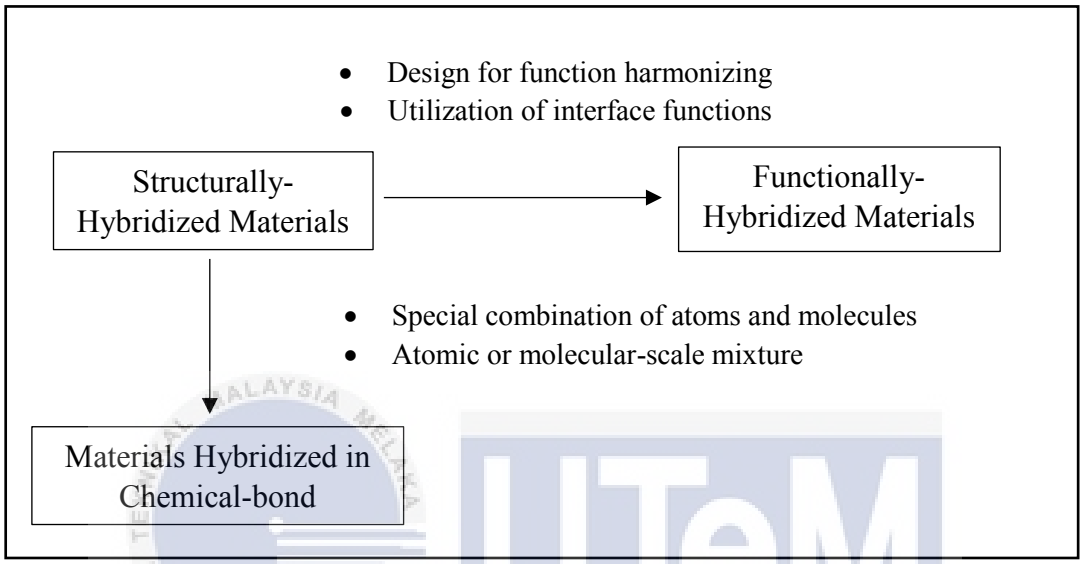


Figure 2.4: Relationship between structurally-hybridized materials, materials hybridized in chemical-bond and functionally-hybridized materials

The historical research on hybrid composites was focused on carbon and glass fibres and this research leds the awareness that the use of mixture can allow properties better than those previous expected from the application of the rule of mixtures. As an example in Summerscales (1978) study presented that the incoporation of glass fibres in carbon fiber reinforced laminates was stated to improved properties and to increase the failure strain of carbon fibers in tension. The hybrid effect is very effective in mixture of composites, there are 40% increase of the failure strain of the carbon fiber layers in a hybrid composites based on carbon and glass compared to the reference carbon fiber composite. It shows that the hybrid composites can create the better properties than single material alone.

Vijay (2017) summarized that the usage of hybrid composites has increased in different industries which are ranging from aerospace, wind energy, transportation, naval,

and defence structures. The selection of using hybrid composites is the optimal choice because the hybrid composites have the ability to broaden then occupied areas of material-property space and it can also provide the properties tailored to meet the specific requirements and needs in industry.

The fabrication of hybrid composites is a chance to create the development in engineers and manufacturers, due to fabrication process can use many approaches such as injection moulding, compression moulding and casting from solvents. Thus, the increment in hybrid composites usage in industry can lead the development or implementation of innovative technology in manufacturing the composites with low cost and less time (Hanieh, 2017).

2.4 Palm Oil Fibres

Palm oil is one of the famous agricultural product in Malaysia and it is also the main export product to other country. Palm oil is an edible oil which is derived from the flesh of the fruit of the oil palm. Globally, Malaysia is one of the largest producers and exporters of palm oil accounting for 11% of the world's oil and fat production and 27% of the export trade of oils and fats. The palm oil industry generates a large quantity of waste consisting of around 90% of biomass waste and only around 10% of the palm oil. The palm oil has many usages in human daily life activities. Palm oil has a high resistance to oxidation and a long shelf life. These special properties allow the palm oil particularly suitable for use in hot climates such as Malaysia. In a traditional way, the palm oil has been used in non-food field such as the manufacture of soaps and detergents and in the production of greases, lubricants and candles. Besides, the property of highly saturated nature in palm oil allow it to replace the trans fats or butter in uses where the solid fat is desirable and suitable for making pastry dough and baked goods (Casimir, 2012). Figure 2.5 shows the palm oil before process.

Figure 2.5: Palm oil

Moreover, the use of palm oil in biofuels industry has provide the significant usage in non-food where the palm oil can be used as feedstock to produce biodiesel and act as an alternative mineral oil for power stations use. The biofuels are a new generation of fuels that derive energy from the carbon fixed in vegetation and algae such as palm oil. Palm oil biodiesel can be classified as the optimal biofuel because it offers an alternative source of energy that can reduce current dependence on non-renewable fossil fuels and, depending on the feedstock and processing used, may reduce greenhouse gas (GHG) emissions (Chow, 2002). Besides, Basiron (2007) reported that the introduction of palm oil biofuels creates the new market demand due to the high prices of petroleum in some country in European Union. Althought the palm oil biofuels industry is being related to environmental issues, which are being exploited and propagated as anti-palm oil campaigns by environmental NGOs, the palm oil biofuel is still acceptable by most of the country around the world. There are a number of advantages in using palm oil for the production of biofuel. The combustion of palm oil biofuel does not increase the level of carbon dioxide in the atmosphere compared with fossil fuels as the oil is merely returning carbon dioxide obtained earlier from the atmosphere through photosynthesis. Hence, the biofuel is regarded as carbon neutral.

The achievement in palm oil also some goes to palm oil fibres. The palm oil fibres are derived from the palm oil fruits. Sobral (2004) studied shows that the palm oil fibres as

shown in Figure 2.6 consist of a series of thin strands and leathery skin which surrounds the kernel and provides a reinforcement for the outer fleshy part of the fruit.

Figure 2.6: Palm oil fibres

In conventional way, the palm oil fibres always used to burn to provide fuel for household cooking in village areas. However, when the advent of electrical and gas cooker to household, the palm oil fibres are remained as waste to be decomposed. Therefore, the palm oil fibres are expected to be used in manufacture of paper or ropes due to palm oil fibre is an insoluble typed of fibre. According to Sobral (2004) studies, the palm oil fibres is the fibres which can give the best bond strength and be most durable fibres compared with coconut fibres and sugar cane fibres. When the green technology of material science is remarkable in achievements, the usage of palm oil fibres are being emphasized to use in industry. Shinoj (2011) presented that the palm oil fibres extracted from the empty fruit bunches is proven as a good raw material for bio-composites. The cellulose content of palm oil fibres is in the range of 43%–65% while the lignin content is in the range of 13%–25%. Throughout the research, the palm oil fibre is hard, tough and its porous surface morphology is useful for better mechanical interlocking with matrix resin for composite fabrication. To achieve a better result, the alkali treatment is suitable and the most common treatment for palm oil fibre to improve the fibre-matrix interfacial adhesion. According to

Mohanty (2005) research, the palm oil fibre has shown an enormous potential as a reinforcing material and it can provide the high wear resistance in use. This allow the palm oil fibres to mix with other materials to produce the high strength composites and high wear resistances. Furthermore, palm oil fibre is one of the natural fibres which have proved to be an excellent reinforcement in polymers. However, the main disadvantage of the natural fibres to be used as reinforcement in polymers for structural applications is their hydrophilic nature. In real life applications, the advantages of palm oil fibres in mechanical properties and mechanical performance allow it to be used in industry with minimal cost due to palm oil fibres are categorised as agriculture waste for palm oil plantation and production.

2.5 Alumina Powder Blend

Alumina powder blend can be defined as aluminium oxide which is a chemical compound with formula Al_2O_3. Aluminium oxides are specified defined as aluminium (III) oxide but commonly called as alumina. According to Davis (2010) studies, aluminium oxide or alumina is the only oxide formed by the metal aluminium and it occurs in nature as the minerals such as corundum (Al_2O_3), diaspore (Al_2O_3•H_2O), gibbsite (Al_2O_3•$3H_2O$); and most commonly known as bauxite, which is an impure form of gibbsite. The first isolated alumina or aluminium oxide is done by extracting it from natural clay using sulphuric acid in 1754. Moreover, the manufacturing of alumina was first started in 1860 by using the Sainte-Claire Deville process that consisted of attacking bauxite by sodium carbonate followed by the precipitation of alumina hydrate. Besides, there is another important development which the perfection of the process of electrolyzing alumina into aluminium in is 1886 and the process is still used until today. Figure 2.7 shows the aluminium oxide powder.

Figure 2.7: Aluminium oxide powder

The commonly-used aluminium oxide is produced through the Bayer process starting from bauxite, which mainly consists of hydrated aluminium. In the Bayer process, crushed bauxite is treated with caustic aluminate solution containing soda. Next, the dissolution reaction is generally conducted under pressure at temperatures ranging from 140 to 280°C. The caustic solution reacts with the aluminium hydroxide so that the impurities can be separated by sedimentation and filtration, leaving a clear solution. After precipitation of the hydroxide, aluminium oxide powders can be obtained through heat treatment at the transition temperatures (Shirai, 2009).

Based on the research from Auerkeri (1996), the properties of alumina in fused condition where the alumina is produced after being melted and re-crystallized has the identical chemical and physical properties with natural corundum. It is a very hard material and its hardness is exceeded only by diamond and a few synthetic substances such as carborundum, and silicon carbide. Thus, it lends itself for use as an abrasive material.

The structure of alumina is familiar with the powder blend form. The structure of aluminium oxide has two types of sites which are consist of hexagonal and octahedral in which it holds the atoms. Hexagonal sites are the corner atoms in the cell while the octahedral sites are present between two layers of vertical stacking. Aluminium cations are in 2/3 of the octahedral sites, and oxygen anions are in 1/3 of the octahedral sites. Each oxygen is shared

between four octahedra. Due to the presence of oxygen in octahedral sites permits strong bonding, therefore, gives rise to the characteristics of the properties of alumina compared with other materials. Figure 2.8 and Figure 2.9 show the hexagonal and octahedral structure alumina oxide respectively.

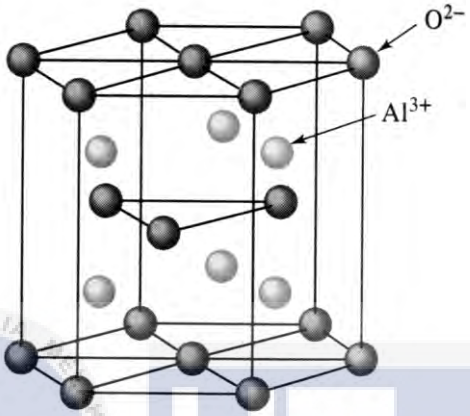


Figure 2.8: Alumina in hexagonal structure

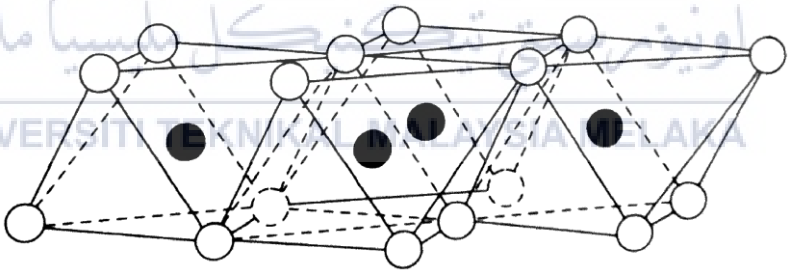


Figure 2.9: Alumina in octahedral structure

The alumina has wide usage in applications such as ceramics, refractory uses, chemical industry, catalyst and the glass industry. More than 90% of alumina produced worldwide is utilized in the production of aluminium. The varied applications of alumina are due to its abundance and its multiple forms as well as its properties of stability, purity, refractoriness, and chemical inertia. The ceramics field are the wide-ranging use of alumina,

the alumina can use as insulating material because the dielectric and excellent thermal shock properties of Alumina make it an excellent choice as an insulating material. For the electronics field, alumina is used in the electronics industry for passive components such as interconnection, resistances, and capacitors. Furthermore, the alumina also used as a substitute material for several applications such as ceramic cutting tools due to the excellent mechanical properties of alumina. Alumina-based ceramics are also used for making extrusion and sanding nozzles and for parts of machine particularly in the mining industry where wear resistant qualities are critical. In military uses, the shock-resisting quality of alumina-ceramics makes them useful as armour plating for protection of tanks and helicopters as well as for bullet-proof jackets and in aeronautics for protection of hydraulic parts (Davis, 2010). As highlighted by Dorre (1984), the aluminium oxide or alumina is one of the most cost effective and suitable for wide used in engineering field. The key properties of alumina such as hard, wear-resistant, good thermal conductivity, high strength and stiffness are allow it to be mixed with other materials to form composites.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will cover up the methodology of determine the tribological performance of hybrid composites based on palm oil fibres and alumina powder blend. This project starts by studying the previous research done by other researchers and record the optimal method to prepare the specimen for tribological testing. The parameters used in specimen preparation is significant and it will affect the outcome of the specimen in tribological testing. Besides, the flow chart of methodology is prepared to ensure the experiment set up and testing is follow the correct pathway to obtain the result from tribological testing. All the data obtained with average value and the data will be used in further calculation to obtain the final result for this project.

3.2 General Experiment Setup

Figure 3.1 shows that the flow chart of the methodology which starts from specimen preparation until analysis data and result based on testing outcome. The experiment is setup based on the study on previous research and journal article, all the related parameters in experiment are referred to be used in this project. Besides, the specimen preparation in this project is required to use the diverse set of parameter values to determine the optimal and suitable parameters such as temperature and pressure for hot-pressing machine. The specimen preparation is using the same parameters to ensure the preparation conditions are keep constant throughout the project. After the specimens are prepared, the curing process

with one-week duration is required to observe the changes on specimen such as crack on surface or side. If the cracks happen on specimen surface, the specified specimen is required to repeat the preparation to obtain the complete specimen. However, if the specimen is failed to achieve the requirements, the justification of failure should be provided to explain the reasons for the failure. The process will be continued for the specimens in good conditions by carry out the laser stamping process to cut the screw hole for attach use in ball-on-disc tribometer. The laser stamping process is required to conduct using laser stamp machine and specified drawing for cutting on specimens. Then, the project is followed by carry out the physical testing such as hardness test, surface roughness measurement and density measurement. Then, the tribological testing is conducted for specimens by using ball-on-disk tribometer with specified parameters such as load, sliding speed and distance to simulate the dry sliding condition in testing process. After the tribological testing, all the specimen and SKF stainless-steel ball will be processed with wear morphology on the worn surface of specimens and SKF stainless-steel ball by using 3D Non-contact Profilometer. The optical micrographs of worn surface are captured and discussed in Chapter 4. All the data and result will be analysed and elaborated in discussion part of this project report.

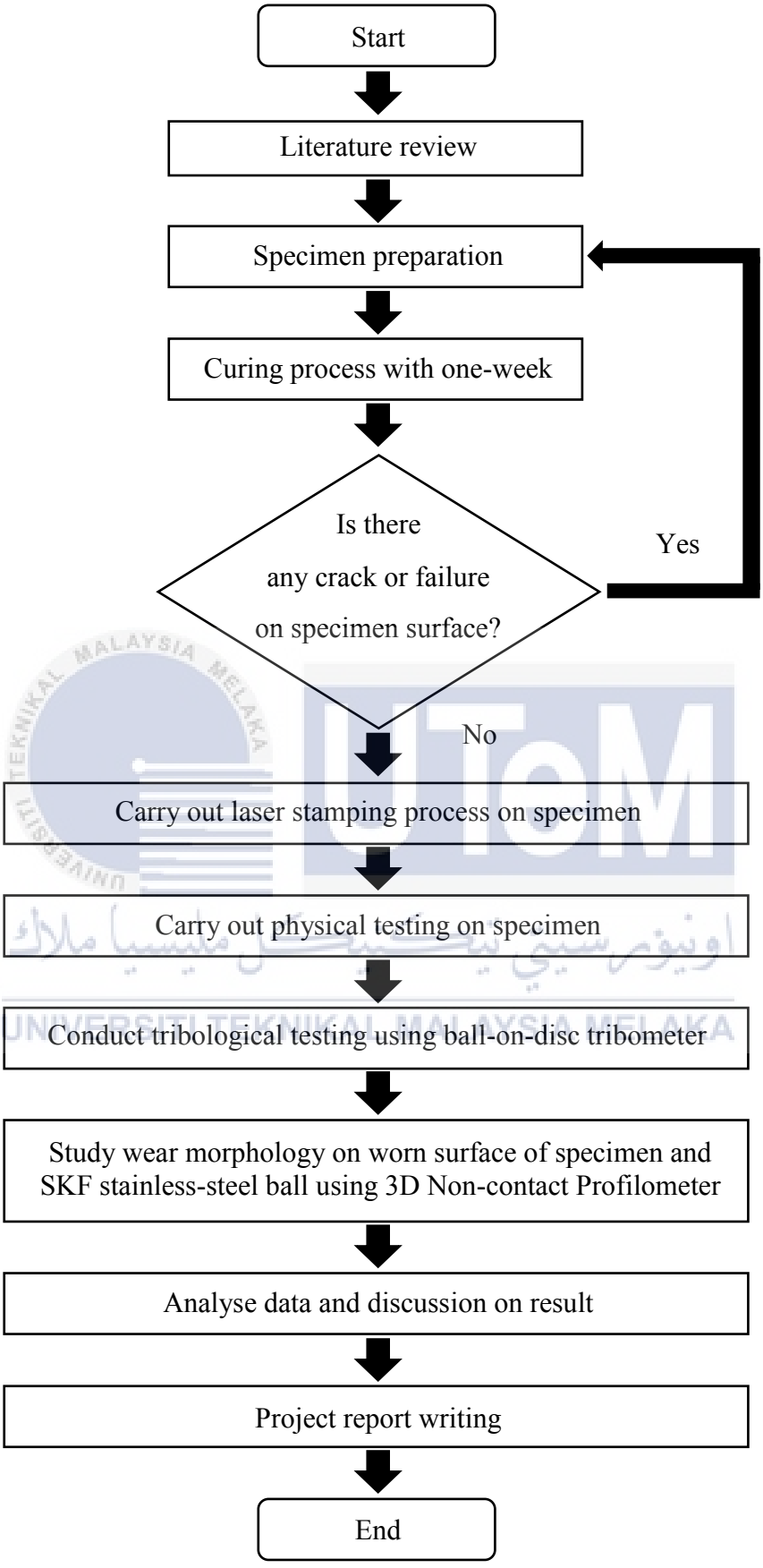


Figure 3.1: Flow chart of methodology

3.3 Preparation of Palm Oil Fibres and Alumina Powder Blend

In this project, the palm oil fibres are used as one of the materials to mix with others to form composites. For the fibre preparation, all extracted fibres from palm oil as shown in Figures 3.2 were cut into lengths of 2-3mm as shown in Figure 3.3.

Figure 3.2: Palm oil fibres before cutting

Figure 3.3: Palm oil fibres after cutting

For the alumina powder blend, this project is used the nanoparticle size (1 - 100nm) aluminium oxide powder. There is no need further process or preparation to obtain the alumina powder blend. Figure 3.4 shows the example of nanoparticle size alumina powder blend.

Figure 3.4: Nanoparticle size alumina powder blend

3.4 Preparation of Specimen

For specimen preparation, the composition ratio of hybrid composite with 50 wt.% of composite reinforced with 50 wt.% of epoxy is carried out at first stage, 60 wt.% of composite reinforced with 40 wt.% of epoxy is carried out at second stage and 70 wt.% of composite reinforced with 30 wt.% of epoxy is carried out at final stage.

The total weight of specimen is set as 40 grams and the mixture ratio of epoxy (resin and hardener) used is 4 : 1 for all specimen preparation. Hence the weight of materials that required to be mixed can be calculated and shown in Table 3.1.

Table 3.1: Weight of composition in hybrid composites

Specimen No	Weight of Palm Oil Fibres (g)	Weight of Alumina Powder (g)	Weight of Epoxy		
			Resin (g)	Hardener (g)	Total (g)
1	10	10	16	4	20
2	20	0	16	4	20
3	0	20	16	4	20
4	12	12	12.8	3.2	16
5	24	0	12.8	3.2	16
6	0	24	12.8	3.2	16
7	14	14	9.6	2.4	12
8	28	0	9.6	2.4	12
9	0	28	9.6	2.4	12

The high-density epoxies which consist of West system 105 epoxy resin (105-B) and West system 206 slow hardener (206-B) were selected due to their great processing characteristics, superior strength, excellent performance at elevated temperatures, and high solvent resistance, all the characteristics are commonly required by the composite fabrication industries. Moreover, the mixture ratio of epoxy (resin and hardener) used in this project is 4 : 1 because the ratio is ideal for mixed up two materials for hot-pressing process. The compressible mould for specimen preparation is required to clean with acetone to remove the impurities on mould surfaces followed by wiped the mould removing wax on the inner surface for easier the process to remove specimen from mould. When the mixture of composites is poured into mould, the compressible mould will be located at hot press machine with 80°C for upper and bottom plates. The amount of 2MPa compression pressure is applied for the hot-pressing process for 60 minutes. After the hot-pressing process, 15 minutes of cooling duration are required for mould to cool down before the specimen is extracted from mould. Then, the specimens are left to undergo the curing process at room temperature for one-week duration.

3.5 Laser Stamping Process

The laser stamping process is carried out using the laser stamping machine where the process is applied to cut the screw holes on specimen. The dimension of screw holes as shown in Figure 3.5 is used in laser stamping process on specimens where the screw holes are fit with holes in ball-on-disc tribometer.

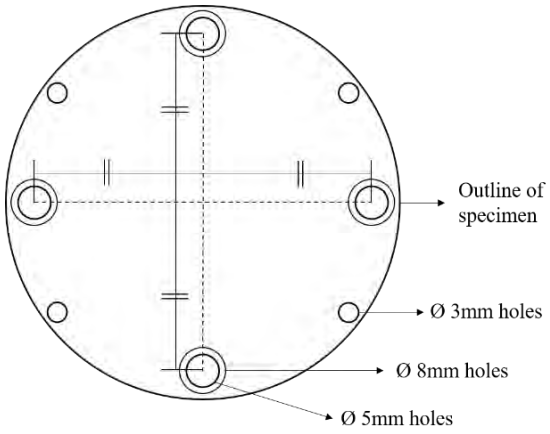


Figure 3.5: Dimension of screw holes on specimen

3.6 Physical Testing on Specimen

The physical testing in this project consists of surface roughness test and hardness test which is significant to know the physical properties of specimen.

Surface roughness test is carried out using profilometer on the polished surface of specimen. The method used for surface roughness testing is direct measurement method. The data is obtained by using a stylus drawn along the surface while the stylus motion perpendicular to the surface of specimen. This method requires interruption of the machine process and the sharp diamond stylus may make micro-scratches on surfaces. The unit for surface roughness is Ra. As described in ASME B46.1, Ra is the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. The surface roughness testing is important due to roughness plays a key role in the interaction of specimen with its environment. The observation on specimen's surface is carried out after curing process to ensure the surface is complete and without crack. The specimen in good condition is polished manually by using the sandpaper grade 1500, 2000 and 3000 to achieve the flat and clean surface. When the manual polish process is done, the surface roughness data in parameter Ra is collected in average value by using

profilometer. The value of surface roughness on the specimen testing side should be less than or not exceed than the range of 0.2µm – 0.8µm and less is usually recommended.

For the hardness testing, the durometer scale digital hardness tester is used. The durometer measures the depth of an indentation in the material created by a given force on a standardized presser foot. This depth depends on the hardness of the material, its viscoelastic properties, the shape of the presser foot, and the duration of the test. Besides, the durometers can be able to do the measurements of the initial hardness, or the indentation hardness after a given period. While using the durometer, user should be always alert that the basic test requires applying the force in a consistent manner, without any shock during the measurement of hardness.

Moreover, the weight of specimen is measured by using analytical balance and the values are recorded before and after the tribological testing for further calculation use.

3.7 Tribological Testing on Specimen

The tribological testing in this project is carried out using the ball-on-disc tribometer. Ball-on-disc tribometer is a test instrument designed for accurate and repeatable tribological characterization of bulk materials, coatings and lubricants. The machine compiled with the easily changeable holders allow users to quickly change the nature of tribological contact to something that is relevant to their application.

Before carrying out the tribological testing, the preparation of tribological testing for specimen is conducted to ensure the testing process undergoes smoothly. The tribological testing is required the stainless-steel bearing ball to be used in ball-on-disc tribometer. Therefore, the stainless-steel bearing ball from SKF manufacturer as shown in Figure 3.6 is selected and cleaned using an ultrasonic bath cleaner. The SKF stainless-steel bearing ball is placed in a beaker with hexane acid for 5 minutes duration with 40°C heating temperature.

Figure 3.6: SKF stainless-steel bearing balls

As described in ASTM G99-17, the standard test method for wear testing with ball-on-disc apparatus. The experimental procedure for using ball-on-disc tribometer is as the following:

i. The specimen is cleaned and the burns from circumference are removed by using the fine grade emery paper.
ii. The weight of specimen is determined by using the analytical balance.
iii. The specimen is placed and set in holding area with screws.
iv. The stainless-steel ball is clamped to loading lever tip by hardened jaws. The ball is ensured to contact the specimen's surface.
v. The setting of sliding velocity and sliding distance are set before the testing is started.
vi. The desired load is applied and placed on loading pans slowly without any shaking.
vii. The test is conducted by pressing the start button on controller and note the observations during testing.

In this project, the parameters required to set in ball-on-disc tribometer setting are shown in Table 3.2. The parameters are set for simulate the testing in critical and dry sliding conditions such as high speed and long distance so that the tribological performance of hybrid composites can be analysed as well.

Table 3.2: Tribological testing parameters

Parameters	Sliding velocity (rpm)	Load (N)	Sliding distance (m)
	400	49.05	3000

Before the tribological testing is carried out, the sliding duration is determined by using the Eq. 4.1 and set in tribometer to complete the testing.

$$D = 2\pi(\mathrm{r})(\mathrm{N})(\mathrm{t}) \quad (4.1)$$

where the D is sliding distance (m), r is radius of wear track (mm), N is the sliding speed (rpm) and t is total sliding time (min). The radius of wear track is different for each specimen, but the initial radius parameter is set using 20mm where the diameter of wear track is 40mm. The specimen will be tested using the initial parameter which is 20mm as radius of wear track to achieve the steady state of tribological testing. If the steady state condition is not able to be achieved, the radius of wear track will be set to smaller than previous. Table 3.3 shows that the total sliding time for the 9 pieces of specimen and SK-2 carbon steel disc.

Table 3.3: Radius of wear track and total sliding time for specimens in tribological testing

Specimen No	Radius of wear track (mm)	Total time required in tribological testing (min & sec)
1	10	119 min 22 sec
2	20	59 min 41 sec
3	15	79 min 35 sec
4	20	59 min 41 sec
5	20	59 min 41 sec
6	10	119 min 22 sec
7	20	59 min 41 sec
8	20	59 min 41 sec
9	-	-
SK-2 carbon steel disc	20	59 min 41 sec

The data that collected from tribological testing is being processed to obtain and determine the coefficient of friction on steady state. The coefficient of friction (*COF*) is calculated using Eq. 4.2.

$$COF = \frac{Friction\ force\ (N)}{Normal\ force\ (N)} \tag{4.2}$$

Then, the calculation of specific wear rate, *k* for each specimen is conducted using the following equations which are shown as below to obtain the value for comparison purpose.

$$V = \pi r^2 T \tag{4.3}$$

Equation 4.3 is used to calculate the volume of specimen, V (mm^3) where r is the radius of specimen (mm) and T is the thickness of specimen (mm).

$$\rho = \frac{M_a}{V} \tag{4.4}$$

Equation 4.4 is used to calculate the density of specimen, ρ (g/ mm^3) where M_a is the mass of specimen after tribological testing (g) and V is the volume of specimen (mm^3).

$$M_{loss} = M_b - M_a \tag{4.5}$$

Equation 4.5 is used to calculate the total mass loss of specimen, M_{loss} where M_a is the mass of specimen after tribological testing (g) and M_b is the mass of specimen before tribological testing (g).

$$V_{loss} = \frac{M_{loss}}{\rho} \tag{4.6}$$

Equation 4.6 is used to calculate the total volume loss of specimen, V_{loss} (mm^3) where M_{loss} is the total mass loss of specimen in tribological testing (g) and ρ is density of specimen (g/ mm^3).

$$k = \frac{V_{loss}}{W \times D} \tag{4.7}$$

Equation 4.7 is used to calculate the specific wear rate of specimen, k (mm^3/Nm) where V_{loss} is the total volume loss of specimen in tribological testing (mm^3), W is the load applied in tribological testing (N) and D is total sliding distance (m).

At the final stage, the optical micrograph of the specimen's worn surfaces is observed and analysed using 3D Non-contact Profilometer and the discussion on wear mechanism is performed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results that obtained from the physical and tribological testing are presented in table and graph. The quantitative data and the result obtained from manual calculation, mechanical testing and tribological testing for this project are presented in the following sub-topic. The data and result are included the images of specimen before testing and after testing, surface roughness of specimens, hardness of specimens, thickness of specimen, mass of specimen before and after tribological testing, friction force, coefficient of friction, specific wear rate and wear morphology of each specimen. The data obtained from the mechanical testing and tribological testing are being used in calculation to present the final stage result of testing according to the standard of scientific writing.

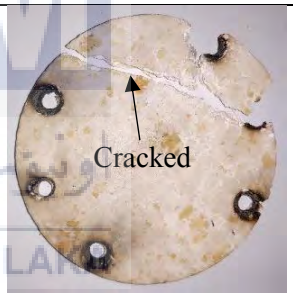
Furthermore, the discussion and analysis of data are carried out to present and justify the findings in this project. The result and discussion are important to study and justify the research findings which can related to background theory, scientific theory and logic of science. The discussion and analysis are carried out with using good engineering judgment in research findings and suitable comparison with similar research.

4.2 Specimen

There are total of 9 pieces of specimen are prepared for this project. Table 4.1 shows the specimen composition and image before and after tribological testing

Table 4.1: Specimen composition and image before and after tribological testing

Specimen No	Composition	Before tribological testing	After tribological testing
1	25 wt.% of palm oil fibres 25 wt.% of alumina powder 50 wt.% of epoxy		
2	50 wt.% of palm oil fibres 50 wt.% of epoxy		
3	50 wt.% of alumina powder 50 wt.% of epoxy		
4	30 wt.% of palm oil fibres 30 wt.% of alumina powder 40 wt.% of epoxy		
5	60 wt.% of palm oil fibres 40 wt.% of epoxy		

6	60 wt.% of alumina powder 40 wt.% of epoxy		
7	35 wt.% of palm oil fibres 35 wt.% of alumina powder 30 wt.% of epoxy		
8	70 wt.% of palm oil fibres 30 wt.% of epoxy		
9	70 wt.% of alumina powder 30 wt.% of epoxy		

As shown in Table 4.1, the specimen no. 9 is cracked after the laser stamping process is conducted. Based on the observation, the specimen's surface is not compact and covered with alumina powder when it is removed from mould after 60 minutes duration in hot-pressed. The specimen no. 9 composition consists of 70 wt.% of alumina powder and only 30 wt.% of epoxy which could cause the minimal bonding effect in the composite. The epoxy is performed as the adhesive agent in composite material and it is necessary to be satisfied with an optimal amount to ensure the adhesive effect is effective (Petrie, 2005). Therefore,

the tribological testing for specimen no. 9 is not completed after repeat the preparation of specimen several times using the same composition.

In this project, the tribological testing is carried out using the pre-set parameters and the testing diameter for each specimen is different due to the limitations on specimen during tribological testing. Thus, the testing diameter for each specimen is set on 20mm, 30mm and 40mm. Each testing diameter is used until the tribological testing of specimen is reached the steady state where the difference of frictional force is in minimal value and the trend is constant for a specified duration.

Meanwhile, a piece of SK-2 carbon steel disc is used in the tribological testing to allow the comparison between hybrid composite and conventional metal-polymer composite. SK-2 carbon steel disc is a metal matrix composite which is high carbon and low alloy steel. Table 4.2 shows that the image of SK-2 carbon steel disk before and after tribological testing.

Table 4.2: Image of SK-2 carbon steel disc before and after tribological testing

Specimen	Before tribological testing	After tribological testing
SK-2 carbon steel disc		

4.3 Physical and Mechanical Properties of Specimen

The physical-mechanical properties of specimen are included the surface roughness, hardness, thickness and mass. The physical-mechanical properties are significant for researcher to study the hybrid composites where it is related to the tribological testing result.

4.3.1 Surface Roughness of Specimen

The surface roughness testing is one of the physical testing which is conducted in preliminary stage for all specimens after the manual polishing process. Manual polishing is carried out to ensure the ground surface roughness of specimens can achieve 0.8µm or less than it to achieve the requirement which stated in ASTM G99-95a (Standard Test Method for Wear Testing with a Pin-on-Disc Apparatus). Table 4.3 shows the surface roughness for all specimens and the bar chart is presented in chart as shown in Figure 4.1.

As shown in Figure 4.1, the specimen no. 8 had highest surface roughness, 0.612µm while the specimen no. 3 had the lowest surface roughness, 0.209µm. By comparing the specimens based on the composition ratio, the specimen no. 2 had the highest surface roughness value among the three specimens with 50 wt.% of composite and 50 wt.% of epoxy. It is because the specimen no. 2 consists of 50 wt.% of palm oil fibres as composite reinforced with 50 wt.% of epoxy. Besides, the specimen no. 4 which consists of 30 wt.% of palm oil fibres, 30 wt.% of alumina and 40 wt.% of epoxy had the highest surface roughness value among the three specimens with composition of 60 wt.% of composite and 40 wt.% of epoxy. In category of specimen with 70 wt.% of composite and 30 wt.% of epoxy, specimen no. 8 which consists of 70 wt.% of palm oil fibres and 30 wt.% of epoxy had the highest surface roughness value.

The surface roughness of specimen will not highly affect the specific wear rate in tribological testing. However, it will affect the result of frictional force against time at starting period which can be identified as entrance region of tribological testing to achieve the steady state in testing.

Table 4.3: Surface roughness of specimen

Specimen No	Surface Roughness (µm)					
	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Average reading
1	0.251	0.246	0.261	0.239	0.245	**0.248**
2	0.401	0.398	0.405	0.403	0.389	**0.399**
3	0.213	0.190	0.211	0.210	0.223	**0.209**
4	0.422	0.456	0.411	0.399	0.372	**0.412**
5	0.211	0.311	0.276	0.298	0.409	**0.301**
6	0.222	0.287	0.255	0.311	0.410	**0.297**
7	0.543	0.483	0.512	0.388	0.489	**0.483**
8	0.512	0.622	0.633	0.591	0.702	**0.612**
9	0.487	0.566	0.387	0.531	0.334	**0.461**

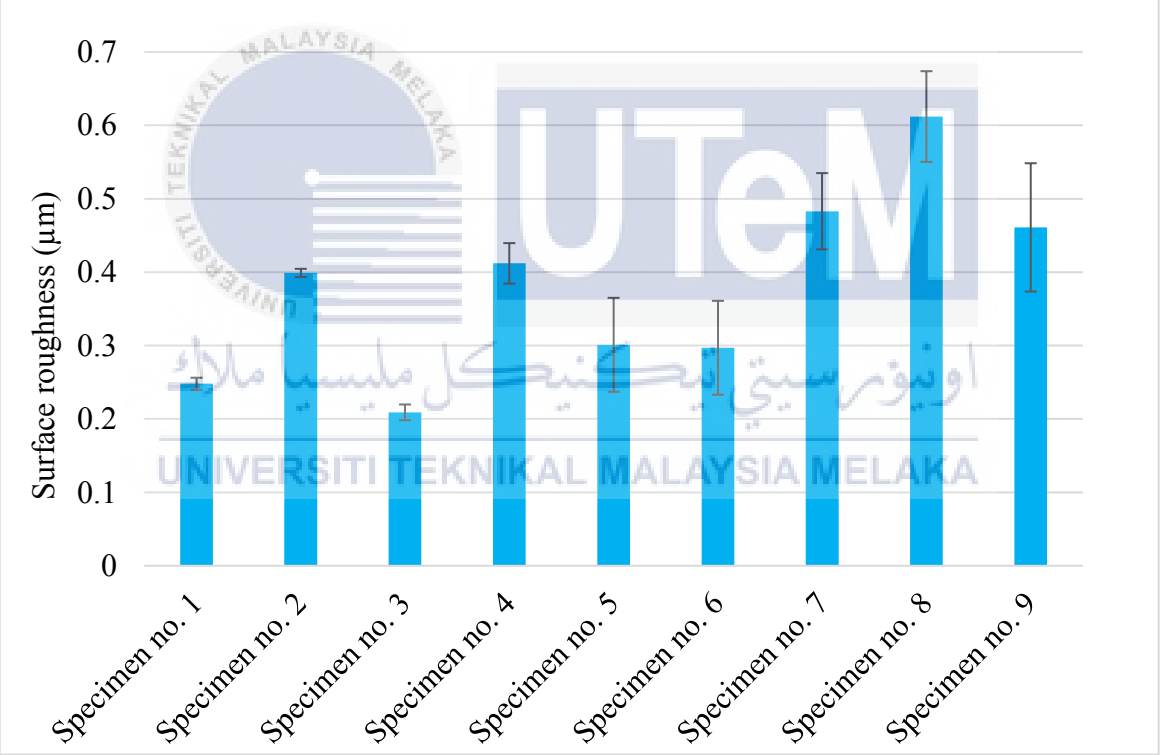


Figure 4.1: Bar chart of surface roughness versus specimen

4.3.2 Hardness of Specimen

The hardness test of specimens is conducted by using the durometer scale digital hardness tester. The value shown in durometer is needed to convert by referring to hardness conversion charts. Hence, the hardness unit is giga pascal, GPa. Table 4.4 shows the hardness value and the bar chart is presented in Figure 4.2.

As shown in Figure 4.2, specimen no. 3, no. 6 and no. 9 are the top three specimens where the hardness value is higher than other specimens. All these three specimens are the composite with pure alumina powder reinforced with epoxy. Based on the observation, alumina is a high strength and high hardness engineering material which can be categorized as effective and widely used material in engineering field. Therefore, the hardness value of specimen no. 3, no. 6 and no. 9 are reflected the mechanical properties of alumina during hardness testing. The pure alumina composite show that the strong ionic interatomic bonding which can obtain the higher hardness value compared with other specimens (Erhard, 1984).

Table 4.4: Hardness of specimen

Specimen No	Hardness (GPa)					
	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Average reading
1	7.502	8.405	7.649	7.571	7.208	**7.659**
2	6.934	6.865	6.796	7.071	6.522	**6.835**
3	8.248	8.562	8.326	8.405	8.640	**8.434**
4	7.718	7.208	8.248	8.885	7.502	**7.895**
5	7.208	7.355	7.277	7.649	6.934	**7.277**
6	8.248	8.483	8.728	8.405	8.101	**8.395**
7	6.796	6.267	6.728	6.394	6.590	**6.551**
8	7.208	7.355	7.424	7.502	7.277	**7.355**
9	7.502	8.101	7.649	8.248	6.590	**7.600**

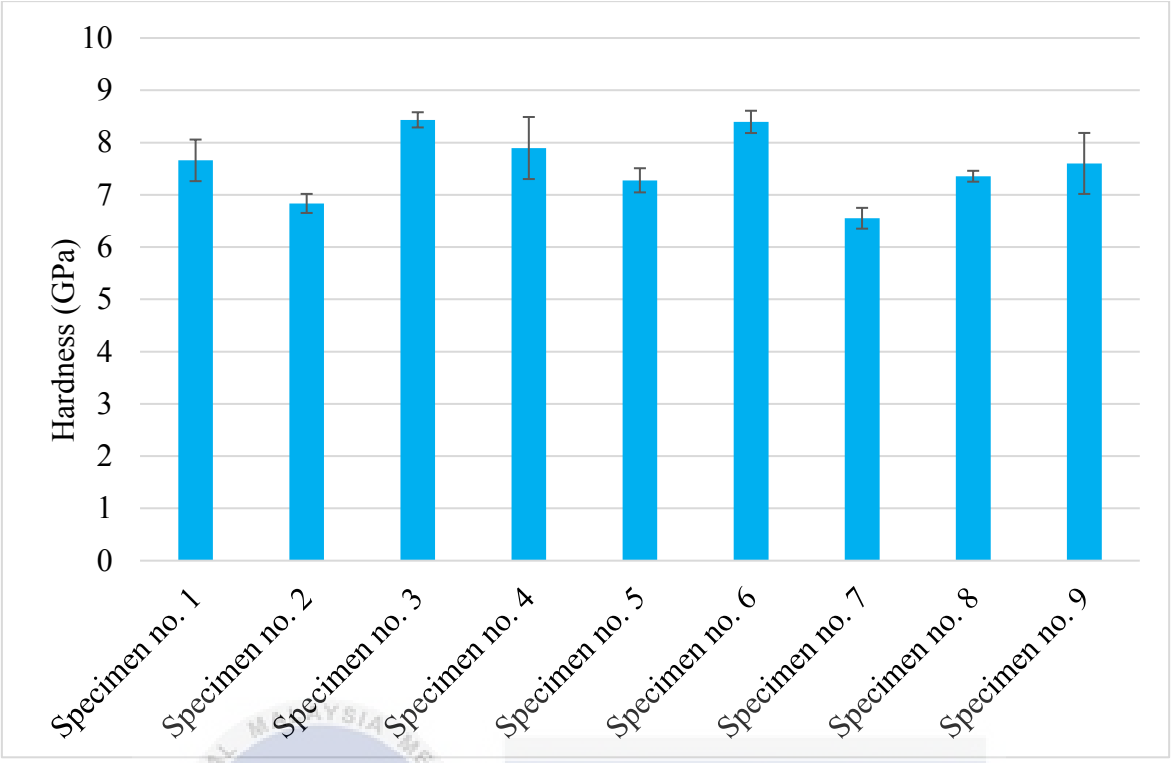


Figure 4.2: Bar chart of hardness versus specimen

4.3.3 Thickness of Specimen

The thickness of each specimen is measured in millimetre unit by using standard type of vernier calliper. The specific thickness which is required for tribological testing is in the range of 2mm to 10mm. Each disc sample will get the different thickness due to the preparation process and material composition ratio. The thickness value and bar chart are presented in Table 4.5 and Figure 4.3.

As shown in the Figure 4.3, the specimen no. 8 had the highest thickness value compared with other specimens. The reason of the thickness of specimen no. 8 is the specimen consists of 70 wt.% of palm oil fibres and 30 wt.% of epoxy where the adhesive effect is less effective for a pure palm oil fibres composite specimen. When the adhesive effect is lesser, the specimen with pure palm oil fibres will become thicker than others.

Table 4.5: Thickness of specimen

Specimen No	Thickness (mm)					
	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Average reading
1	3.5	3.5	3.4	3.5	3.6	**3.5**
2	7.0	6.9	7.0	7.1	7.0	**7.0**
3	4.5	4.5	4.4	4.6	4.5	**4.5**
4	5.0	5.2	5.0	5.0	4.8	**5.0**
5	7.0	7.0	7.0	7.0	7.0	**7.0**
6	5.0	5.0	5.2	4.8	5.0	**5.0**
7	5.5	5.5	5.5	5.5	5.5	**5.5**
8	7.5	7.5	7.5	7.5	7.5	**7.5**
9	6.0	6.0	6.0	6.1	5.9	**6.0**

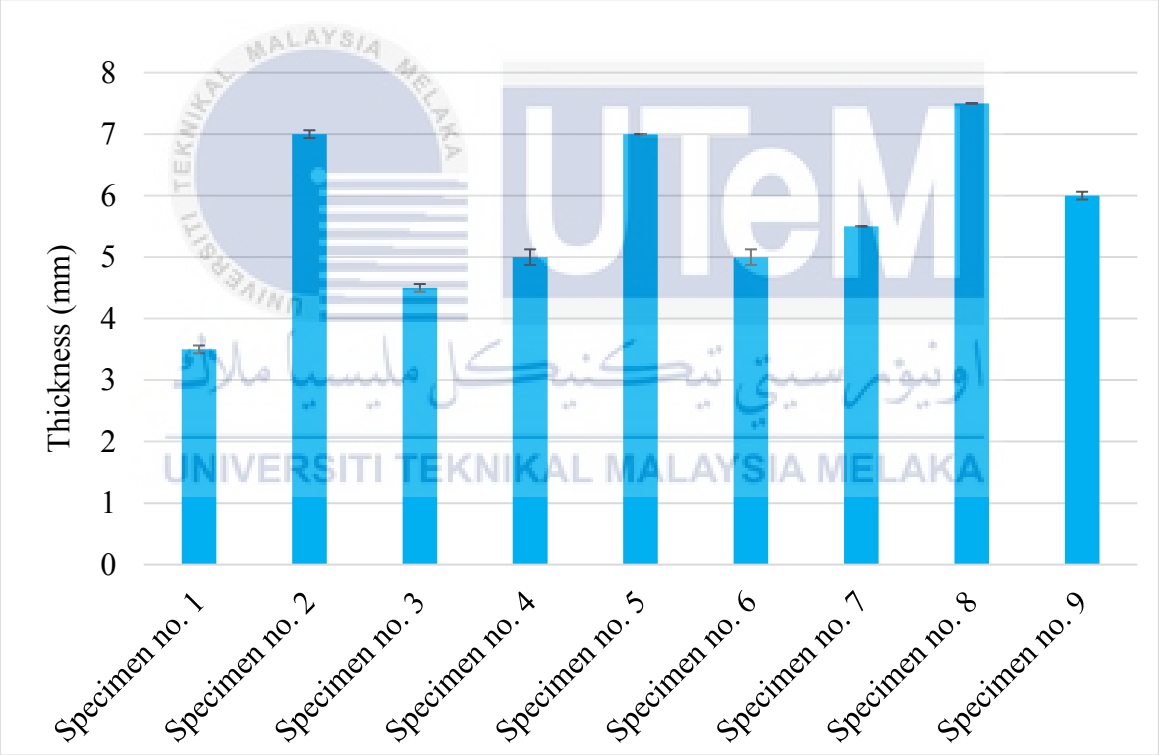


Figure 4.3: Bar chart of thickness versus specimen

4.3.4 Mass of Specimen

The mass of each specimen is required to measure before and after ball-on-disk testing. The measurement of specimen mass only can be conducted after it is being processed with laser stamping to cut the screw holes. The mass of each specimen before and after

tribological testing is recorded in Table 4.6 and the mass of SK-2 carbon steel disk before and after tribological testing is recorded in Table 4.7. However, the mass of specimen no. 9 is not recorded completely because the specimen is cracked after the laser stamping process to cut the screw holes on specimen. Therefore, the specimen no. 9 is only weighted before tribological testing.

Table 4.6: Mass of specimen before and after tribological testing

Specimen No	Mass of specimen (g)	
	Before tribological testing	After tribological testing
1	16.27	15.89
2	28.71	28.49
3	29.99	29.79
4	25.95	25.76
5	27.91	27.54
6	38.24	37.98
7	34.88	34.67
8	32.27	32.01
9	39.06	-

Table 4.7: Mass of SK-2 carbon steel disc before and after tribological testing

Specimen	Mass (g)	
	Before tribological testing	After tribological testing
SK-2 carbon steel disc	131.50	131.38

4.4 Coefficient of Friction

The specimens are processed with tribological testing using ball-on-disc tribometer with several stated parameters to obtain the result of friction force and coefficient of friction for each specimen. The parameters are set for simulate the testing in critical conditions such as optimal speed and long distance under dry condition so that the tribological performance of hybrid composites can be analysed as well. The testing parameters are set based on the

limitation of ball-on-disc tribometer in laboratory after a several times of testing using different value of parameters. Hence, the coefficient of friction of specimen is determined by carry out tribological testing where the steady state of friction force in the testing is used to determine the coefficient of friction value. The steady state of friction force is obtained when the minimal difference of friction force over a specified period can be determined. Based on the observation, the graphs of coefficient of friction versus time which shown in Appendix A are illustrated the running in time region with identical increment of friction force and followed by the fluctuation of friction force during tribological testing. Then, the trends are entered the steady state region where the minimal difference of friction force is identified. Hence, the average value of coefficient of friction for all specimens and SK-2 carbon steel disc in steady state is determined and presented in Figure 4.4 to be used in comparison and discussion.

Based on the observation from result, the specimen no. 7 (35 wt.% of palm oil fibres, 35 wt.% of alumina powder and 30 wt.% of epoxy) has the highest coefficient of friction value which is 1.3322 while the specimen no. 3 (50 wt.% of alumina powder and 50 wt.% of epoxy) has the lowest value which is 0.1544. Meanwhile, the coefficient of friction of SK-2 carbon steel disc can be classified as a datum value which is 0.5101 to be used in comparison with the different composition specimens.

In the category of 50 wt.% of composite and 50 wt.% of epoxy, the specimen no. 2 which is pure palm oil fibres reinforced with epoxy has the highest value of coefficient of friction while specimen no. 3 has the lowest value with the composition of pure alumina powder reinforced with epoxy. The smaller particle size of alumina and epoxy effect in specimen no. 3 will able to obtain the lower coefficient of friction. By comparing the coefficient of friction, the specimen no. 1 and no. 2 are higher than SK-2 carbon steel disc while specimen no. 3 is lower than SK-2 carbon steel disc. Thus, the comparison shows that

the hybrid composite has the average value of coefficient of friction from both pure palm oil fibres and pure alumina powder composites.

By comparing in the category of 60 wt.% of composite and 40 wt.% of epoxy, the specimen no. 4 has the highest value which is 0.5148 while specimen no. 5 has the lowest value. The difference of coefficient of friction value is smaller by comparing between specimen no 4, no. 5 and no. 6. In this comparison, the specimen no. 5 which is 60 wt.% of palm oil fibres and 40 wt.% of epoxy has the lowest value in coefficient of friction and it might be caused by the mixture of composition during specimen preparation. The lower coefficient of friction on specimen no. 5 is affected by the effect of epoxy in specimen and the result is out of expectation where pure palm oil fibres composite should obtain the higher value in coefficient of friction. However, the differences in coefficient of friction value between specimen no. 4, no. 5, no. 6 and SK-2 carbon steel disc are small when the comparison is made.

Furthermore, the specimen no. 7 has the highest value in coefficient of friction which is 1.3322 and specimen no. 8 has the lowest value which is 0.9575. In the category of 70 wt.% of composite and 30 wt.% epoxy, the specimen no. 9 is not able to be tested due to the failure of specimen after laser stamping process. The main materials for specimen no. 9 is pure alumina which is required the stronger adhesive effect in bonding during preparation. Therefore, the comparison is set in between specimen no. 7 and no. 8. Based on the observation, the specimen no. 7 has the outstanding performance with highest friction force and coefficient of friction which could be used in automotive braking pads development. Meanwhile, the specimen no. 8 has the almost similar result in coefficient of friction with specimen no. 2. However, the comparison in Figure 4.4 shows that the coefficient of friction of specimen no. 7 and no. 8 are higher than SK-2 carbon steel disc.

Based on the comparison result, the specimen no. 7 (35 wt.% of palm oil fibres, 35 wt.% of alumina powder and 30 wt.% of epoxy) has the highest coefficient of friction value and it is selected as the optimal composition ratio for hybrid composite because it has the higher friction than pure palm oil fibres composite. The hybrid composite with higher sliding friction is useful in industry where the study shows that the performance of hybrid composite is always better than pure material composite (Persson, 2013).

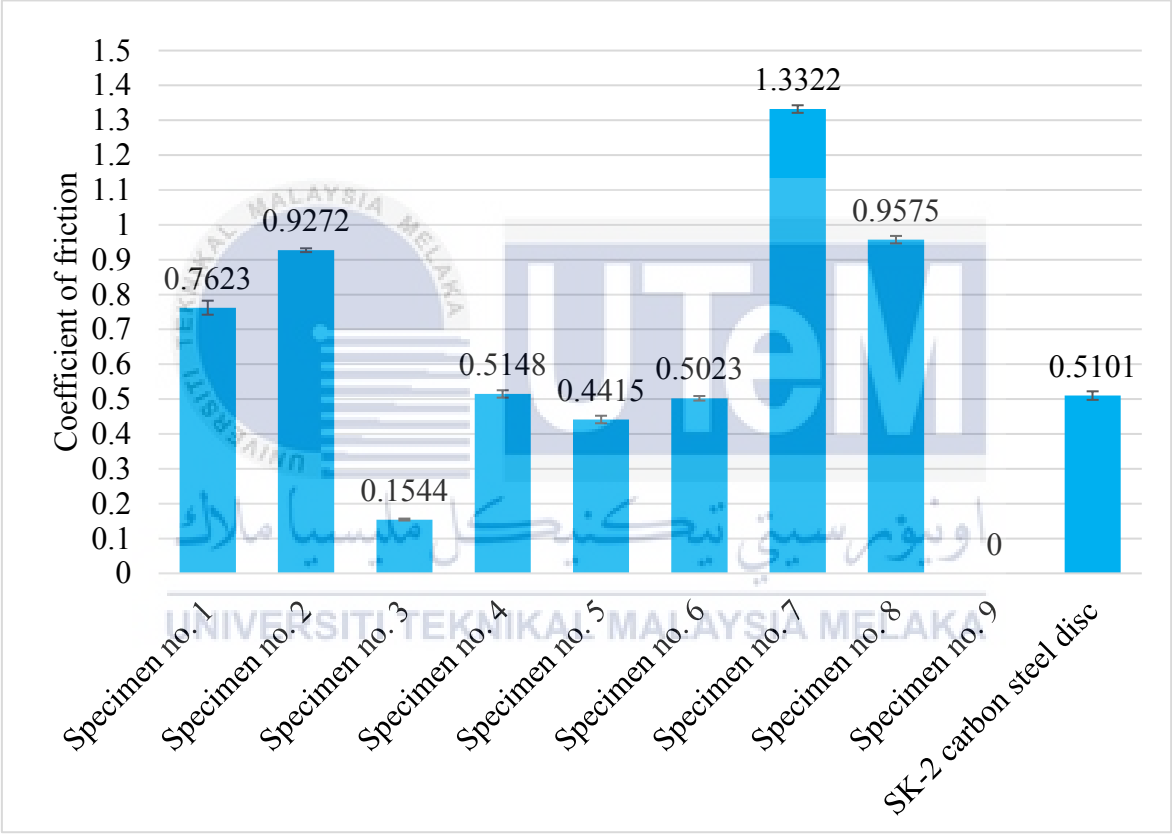


Figure 4.4: Bar chart of coefficient of friction versus type of specimen

4.5 Specific Wear Rate

The specific wear rate is an important data which can indicate the tribological performance of specimens under specific condition such as dry sliding condition with long distance and optimal sliding speed. The calculation of specific wear rate is performed

manually and required the parameters which obtain from previous testing. The result of specific wear rate for all specimen is shown in Table 4.8. The wear of a material or composite is a system response where the wear rate of a material can be varied from 10^{-3} to 10^{-10} mm^3/Nm depending on sliding contact condition in tribological testing. (Kato, 1997) Hence, the comparison of specific wear rate of all specimens is made and shown in Figure 4.5.

Based on the findings, the SK-2 carbon steel disc which represents conventional composite has the lowest specific wear rate which is 0.110×10^{-3} mm^3/Nm while the specimen no. 5 (60 wt.% of palm oil fibers and 40 wt.% of epoxy) has the highest specific wear rate which is 2.785×10^{-3} mm^3/Nm. Besides, the specimen no. 6 (60 wt.% of alumina powder and 40 wt.% of epoxy) and no. 7 (35 wt.% of palm oil fibers, 35 wt.% of alumina powder and 30 wt.% of epoxy) have the identical specific wear rate value which is 0.994×10^{-3} mm^3/Nm.

In the category of 50 wt.% of composite and 50 wt.% of epoxy, the specimen no. 1 (25 wt.% of palm oil fibers, 25 wt.% of alumina powder and 50 wt.% of epoxy) has the higher specific wear rate while specimen no. 3 (50 wt.% of alumina powder and 50 wt.% of epoxy) has the lower specific wear rate. The low wear rate of specimen no. 3 can be related to the physical properties of specimen where the hardness value of specimen no. 3 is the highest among the hybrid composite. Hence, the relationship shows that the higher the hardness value, the lower the specific wear rate of specimen. Furthermore, the specific wear rate of specimen no. 1 is greater than others because it is a hybrid composite with the mixture of alumina powder and palm oil fibers with 50 wt.% of epoxy. Besides, the specific wear rate is affected by the different in particle size of alumina and palm oil fibres which is used in specimen preparation where the particle size of alumina is less than 100nm while the palm oil fibres are cut into 2-3mm (Chauhan, 2013). By comparing the specific wear rate in Figure 4.14, result shows that the specific wear rate of SK-2 carbon steel disc is lower than the specimens with composition of 50 wt.% of composite and 50 wt.% of epoxy.

In the category of 60 wt.% of composite and 40 wt.% of epoxy, specimen no. 5 has the highest specific wear rate among three specimens. However, the specimen no. 4 (30 wt.% of palm oil fibers, 30 wt.% of alumina powder and 40 wt.% of epoxy) and no. 6 (60 wt.% of alumina and 40 wt.% of epoxy) have obtained the specific wear rate which is 1.070×10^{-3} mm^3/Nm and 0.994×10^{-3} mm^3/Nm respectively with small deviation from each other. The highest specific wear rate is occurred on specimen no. 5 because of the specimen composition where it is a pure palm oil fibres with 40 wt.% of epoxy. The adhesive effect in between palm oil fibres is not effective while it can be caused the higher wear loss and specific wear rate in tribological testing. The spectacular size of composite material is required the suitable amount of epoxy to provide the effective adhesive effect in composite (Petrie, 2005). Besides, the specific wear rate of specimen no. 4, no. 5 and no. 6 is higher than SK-2 carbon steel disc with the significant difference as shown in Figure 4.5.

The comparison in between specimen with 70 wt.% of composite and 30 wt.% of epoxy shows that the specific wear rate of specimen no. 8 (70 wt.% of palm oil fibers and 30 wt.% of epoxy) is higher than specimen no. 7 (35 wt.% of palm oil fibers, 35 wt.% of alumina powder and 30 wt.% of epoxy). This situation can be explained in term of poor adhesive effect in composite which is caused the palm oil fibres can be easily worn in tribological testing. However, the specimen no. 7 is a hybrid composite where the mixture of alumina powder and palm oil fibres can resist the wear and obtain the lower specific wear rate which is 0.994×10^{-3} mm^3/Nm. However, both specimen no. 7 and no. 8 are having higher specific wear rate compared to SK-2 carbon steel disc.

Based on the comparison result, the specimen no. 3 (50 wt.% of alumina powder and 50 wt.% of epoxy) has the lowest specific wear which is 0.877×10^{-3} mm^3/Nm among all specimens and can be selected as optimal composition ratio but the coefficient of friction value is lower than other hybrid composite. However, the specimen no. 7 (35 wt.% of palm

oil fibers, 35 wt.% of alumina powder and 30 wt.% of epoxy) with specific wear rate, 0.994 $\times 10^{-3}$ mm^3/Nm in hybrid composite category is selected as the optimal composition ratio because it has the lower specific wear rate and higher coefficient of friction value compared with other hybrid composites which are specimen no. 1 and no. 4. The selection is conducted based on the objectives stated in this project where the priority is given to determine the optimal composition ratio of hybrid composite with lower specific wear rate and high coefficient of friction. It is because the lower specific wear rate of hybrid composite is allowed the extension of wear mechanism as an industry product.

Table 4.8: Result of specific wear rate and coefficient of friction for all specimen

Specimen No.	Parameters					
	Volume of specimen, V ($\times 10^3$ mm^3)	Density of specimen, ρ ($\times 10^{-3}$ g/mm^3)	Total mass loss of specimen, M_{loss} (g)	Total volume loss of specimen, V_{loss} (mm^3)	Specific wear rate, k ($\times 10^{-3}$ mm^3/Nm)	Coefficient of friction (COF)
1	15.052	1.081	0.380	351.526	**2.389**	**0.7623**
2	30.105	0.954	0.220	230.607	**1.567**	**0.9272**
3	19.354	1.550	0.200	129.032	**0.877**	**0.1544**
4	21.504	1.207	0.190	157.448	**1.070**	**0.5148**
5	30.925	0.903	0.370	409.745	**2.785**	**0.4415**
6	21.504	1.778	0.260	146.210	**0.994**	**0.5023**
7	24.298	1.435	0.210	146.289	**0.994**	**1.3322**
8	32.256	1.001	0.260	259.887	**1.766**	**0.9575**
SK-2 carbon steel disc	17.671	7.441	0.120	16.127	**0.110**	**0.5101**

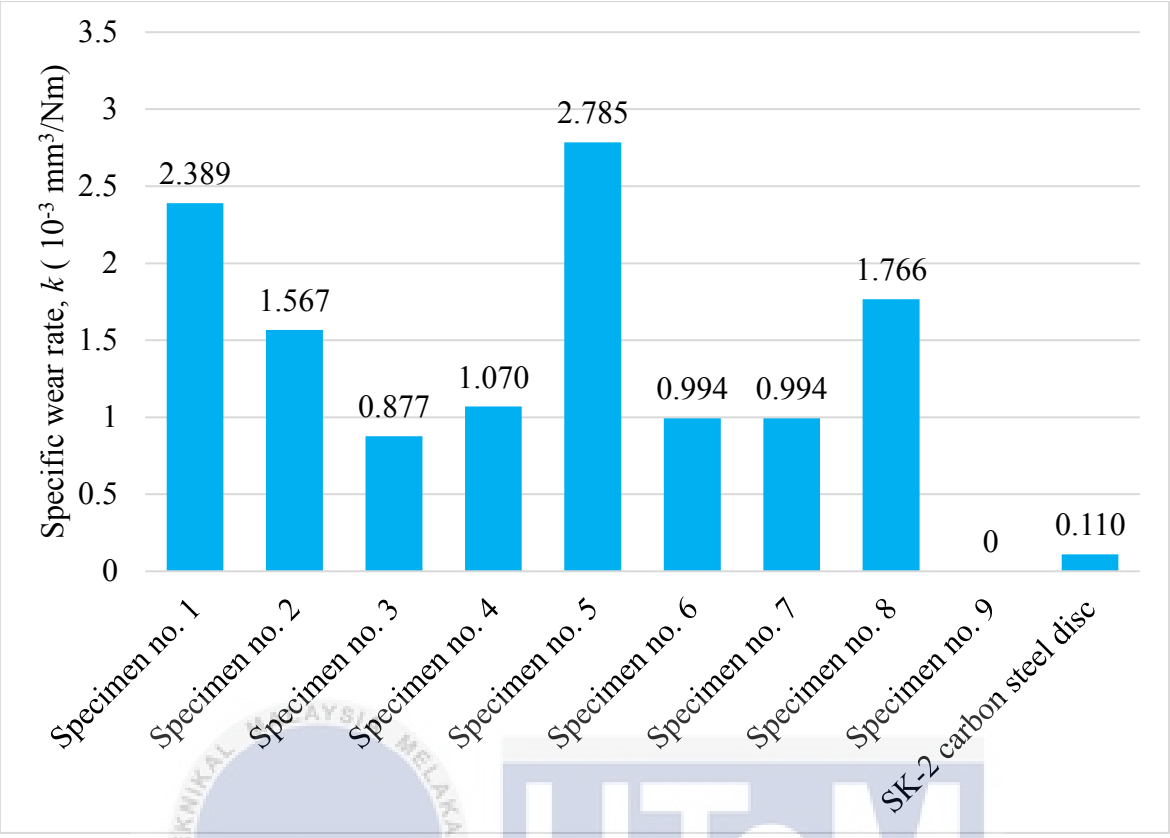


Figure 4.5: Bar chart of specific wear rate versus type of specimen

4.6 Wear Morphology

The wear morphology of specimen is carried out using 3D Non-contact Profilometer to observe the worn surface of specimens and the optical micrographs are captured using 15μm lens for further discussion in wear mechanism. Thus, the optical micrographs of specimen and SKF stainless-steel ball worn surface are presented in Table 4.9. The morphology of wear and observation of wear track are useful and able to provide the information for researcher to study the wear mechanism on worn surface (Tyagi, 2014). Furthermore, examination of result in wear morphology is allowed the researcher to study and recognise the transfers of wear debris between composite and stainless-steel ball surface in tribology (Jianbin Luo, 2008). Therefore, the wear can be occurred because of adhesion, surface fatigue, tribo-chemical reaction and abrasion (Gahr, 1987). The specimen with pure palm oil fibres reinforced with epoxy is more difficult to identify the wear mechanism on

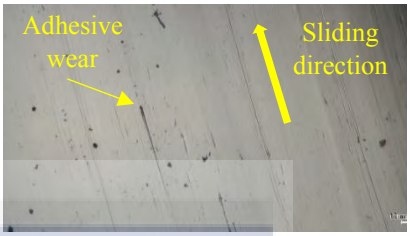
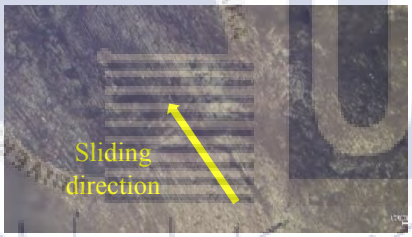
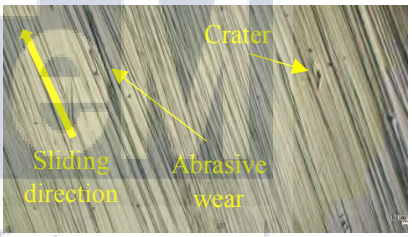
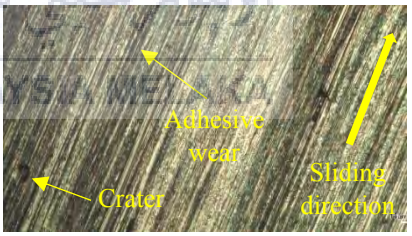
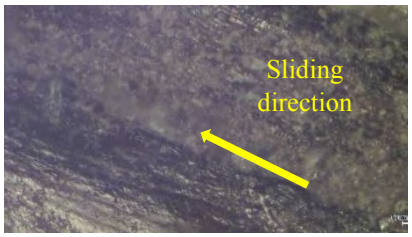
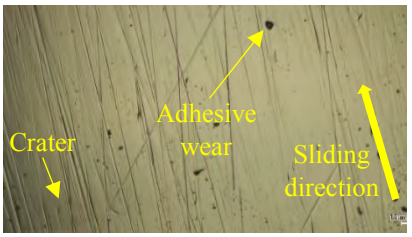
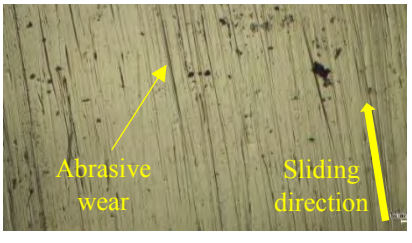
the worn surface. However, the specimen with pure alumina reinforced with epoxy is easier to identify the wear occurred on the worn surface.

Throughout the observation in Table 4.9, the wear mechanism with abrasive wear and adhesive wear is identified on the worn surface of SKF stainless-steel ball. Abrasive wear is the most frequently encountered wear mechanism in industry. The mechanism of abrasive wear is similar to the grinding in manufacturing process. The hard asperities are penetrated into the softer surface under the normal contact pressure (Stachowiak, 2005). Meanwhile, the adhesive wear is occurred at the asperity contacts at the interface, and these contacts are sheared by sliding during tribological testing which mat result in detachment of a fragment from one surface and attachment to another surface (Bharat, Principles and Applications of Tribology, 1999). The abrasive wear mechanism is found in optical micrographs of SKF stainless-steel ball worn surface for specimen with pure palm oil fibres and hybrid composite reinforced with epoxy, it is because the palm oil fibres have the hard particle in physical properties which is caused the removal of material surface on SKF stainless-steel ball during tribological testing (Chattopadhyay, 2001). However, the adhesive wear is occurred on the SKF stainless-steel ball worn surface for specimen with pure alumina powder, it is because the small particle size of alumina powder is allowed to be transferred from specimen to SKF stainless-steel ball during tribological testing.

Figure 4.6 shows the images of wear track of all specimen included SK-2 carbon steel disk and the width of wear track is measured. Based on the observation, the specimen no. 3 (50 wt.% of alumina powder and 50 wt.% of epoxy) has the highest value of wear track width which is 5mm when the radius of wear track is set on 15mm while SK-2 carbon steel disk has the lowest value of wear track width which is 2mm. By comparing the width of wear track, specimen no. 3 and no. 6 which are made up of pure alumina composite obtain the greater value because the particle size of alumina used in specimen preparation. The

smaller size particle in alumina is easier to be worn in tribological testing, thus the wider the wear track on specimen. However, the specimens with palm oil fibres as composite material are obtain the smaller wear track width value which is caused by the stronger bonding effect and high wear resistance of palm oil fibres in composite.

Table 4.9: Optical micrographs of worn surface

Specimen No	Optical micrographs of specimen worn surface	Optical micrographs of SKF stainless-steel ball worn surface
1		
2		
3		
4		
5		

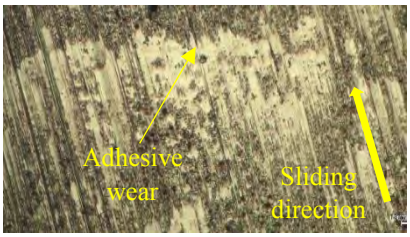
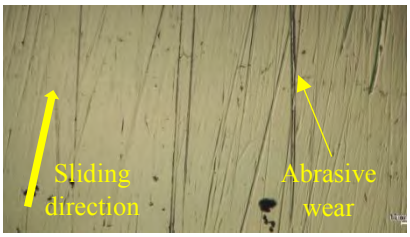
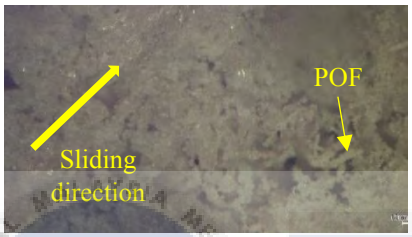
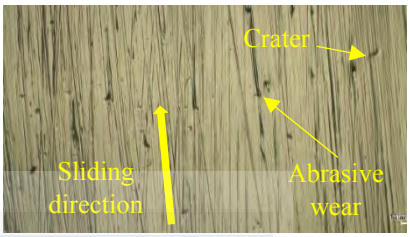
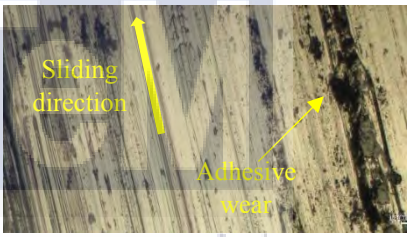
6		
7		
8		
SK-2 carbon steel disc		

Figure 4.6: Wear track of specimens

(From left: Specimen no. 1, no.2, no. 3, no. 4, no. 5, no. 6, no. 7, no. 8 and SK-2 carbon steel disc)

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study of wear performance is important to identify the wear properties of hybrid composite. Hence, the tribological testing is carried out for different composition ratio composite which is included the hybrid composite and SK-2 carbon steel disc to determine the wear properties in terms of coefficient of friction and specific wear rate. From the result and discussion, the study of wear performance for hybrid composites based on palm oil fibres and alumina powder blend can be summarized as below:

i. Specimen no. 7 has the optimal composition ratio which is 35 wt.% of palm oil fibres, 35 wt.% of alumina powder blended and 30 wt.% of epoxy because it can provide high friction with coefficient of friction value, 1.3322 and low wear rate which is 0.994×10^{-3} mm^3/Nm

ii. Tribological properties of hybrid composites in terms of coefficient of friction and specific wear rate are investigated

iii. Comparison of tribological performance shows that SK-2 carbon steel disc has the lower value in coefficient of friction and specific wear rate than the hybrid composites

5.2 Recommendation for Future Works

The experiment of study the wear performance of hybrid composites can be expanded to various type of material in tribological testing to identify the optimal composition ratio in

hybrid composition. Thus, the following recommendations are suggested for future works which could lead the improvements in the study of wear performance for hybrid composite:

i. Reduction of palm oil fibres size in composite preparation using grinding machine into shorter length which is able to combine with other type of materials in powder form as well.

ii. Replace the alumina powder blend with other mineral material to investigate the wear performance of new formation of hybrid composite.

iii. Replace the palm oil fibres with other type of natural fibres to identify the suitable type of fibres which can provide higher friction in wear performance

iv. Expand the range of composition ratio (70 wt.% of composite and 30 wt.% of epoxy) in specimen preparation to investigate the precise optimal value in hybrid composite

v. Conduct the wear morphology using the Scanning Electron Microscope (SEM) to obtain more information about topography of worn surface.

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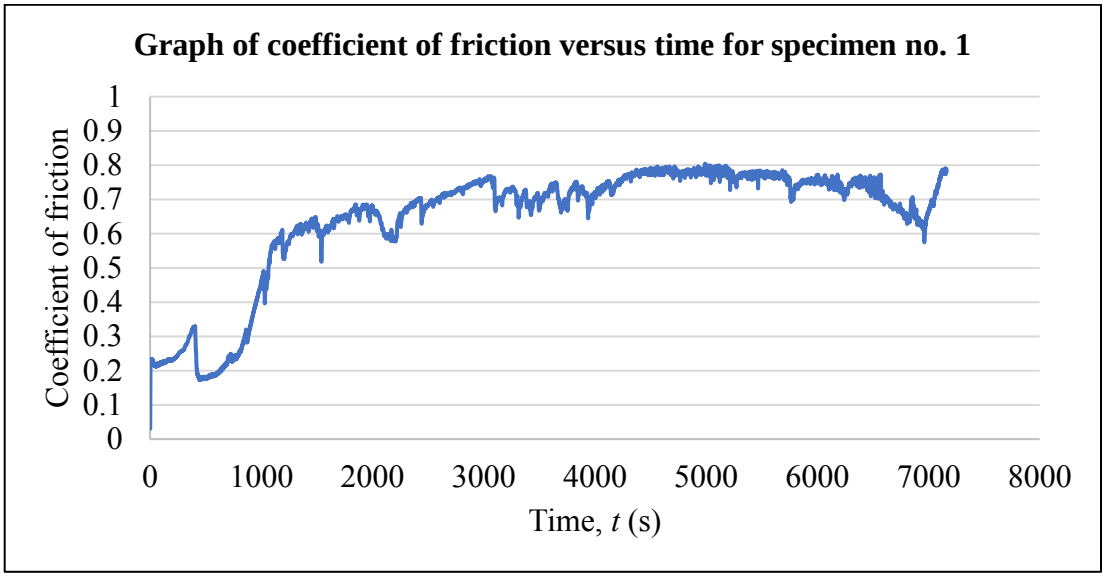
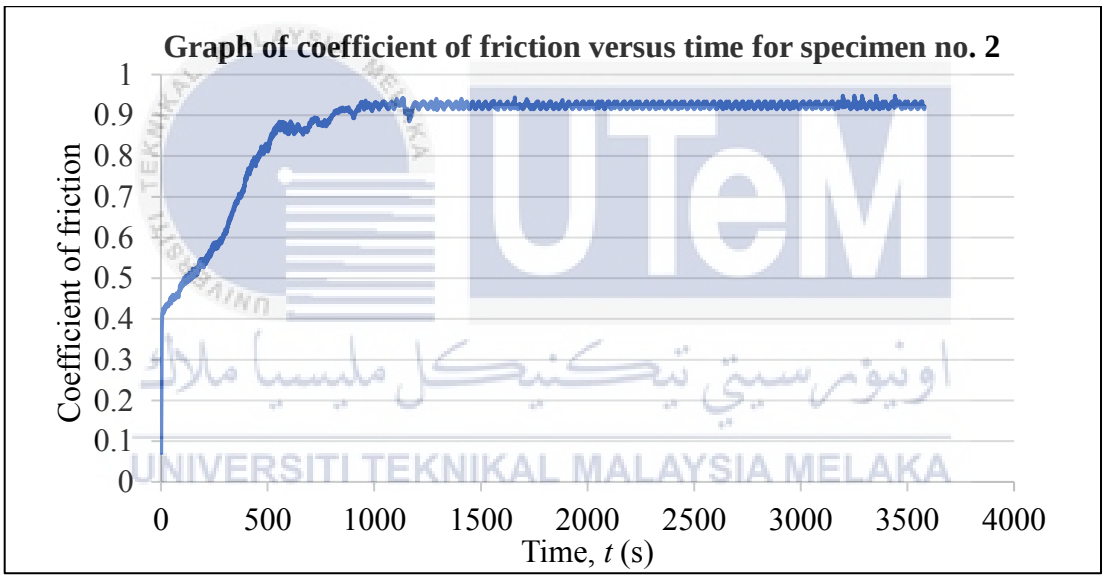
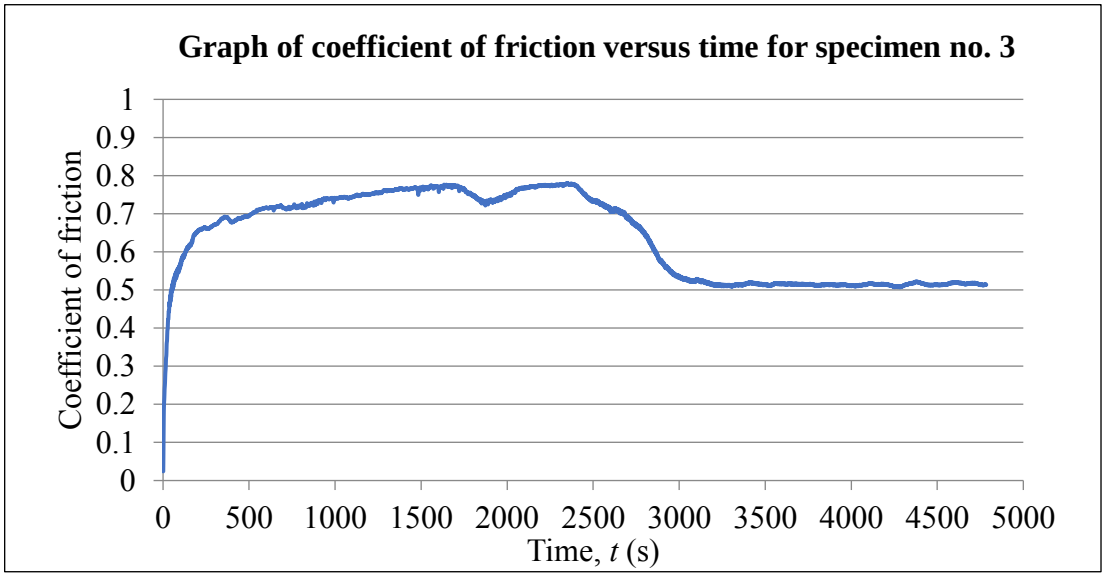
APPENDIX

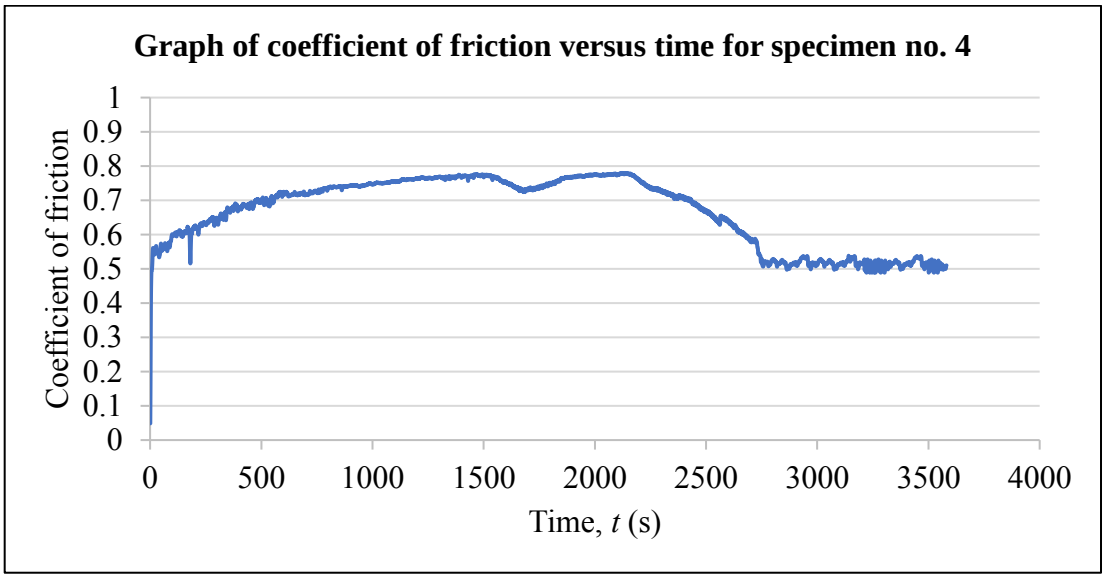
A

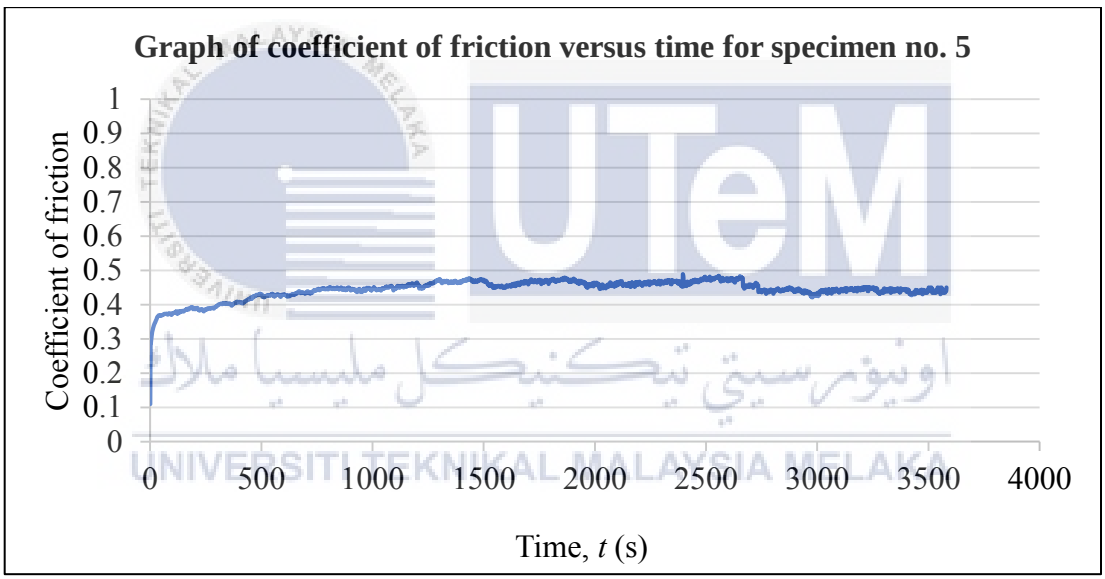
Graph of Coefficient of Friction versus Time

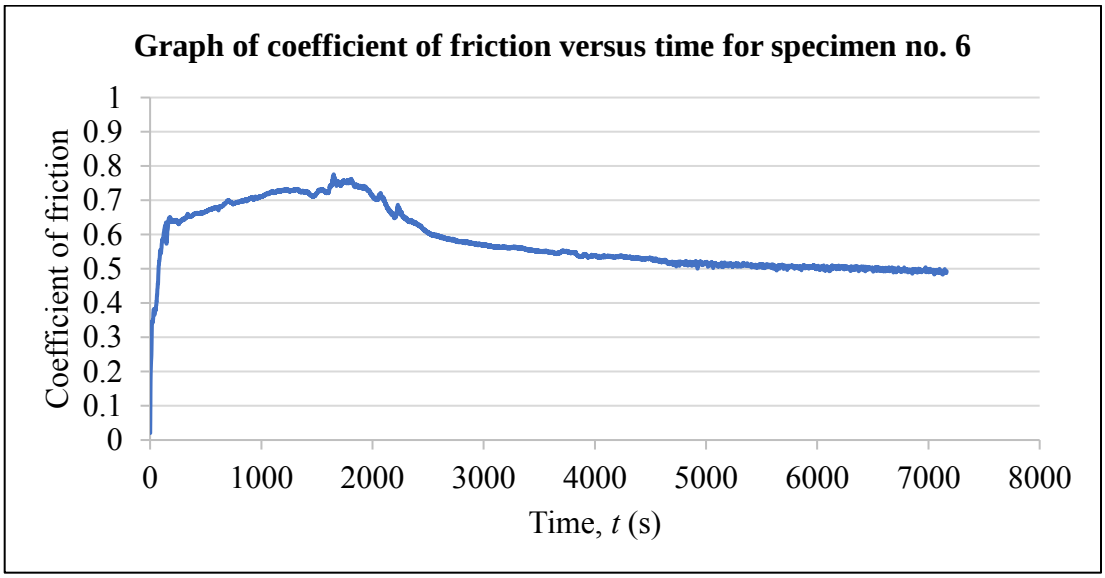


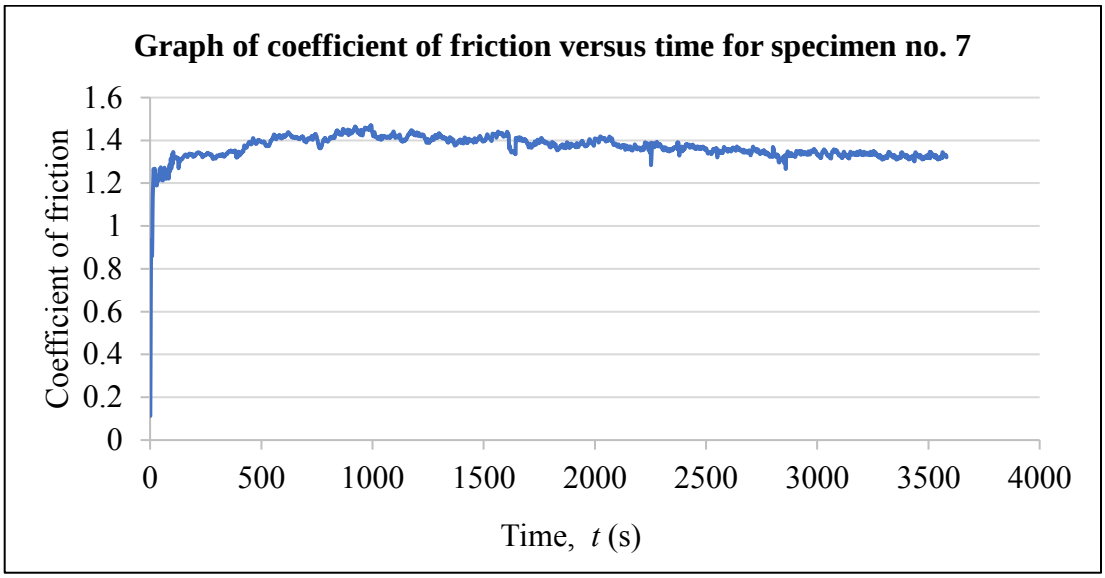


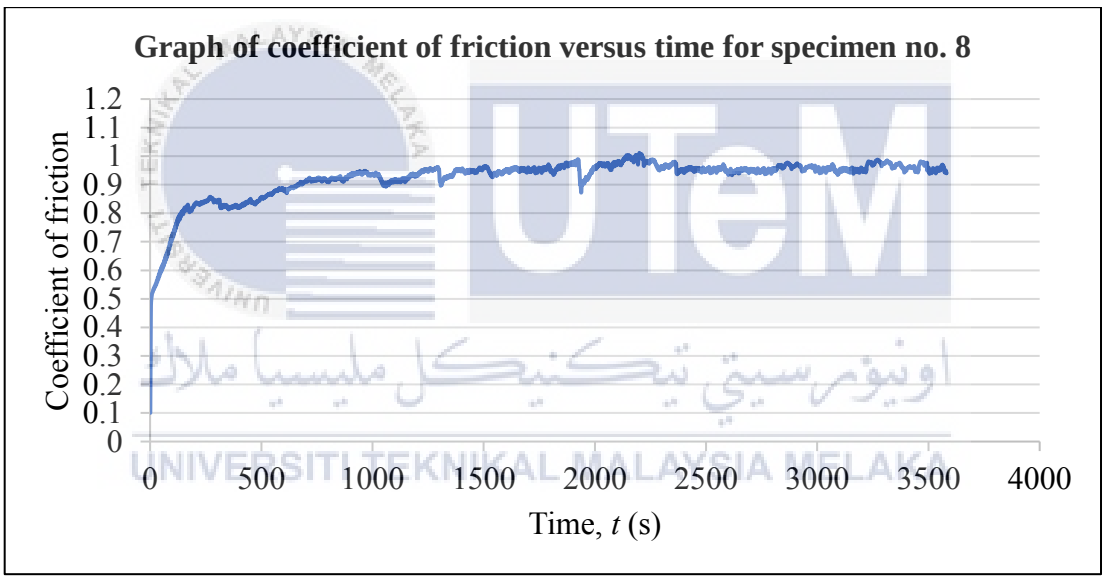


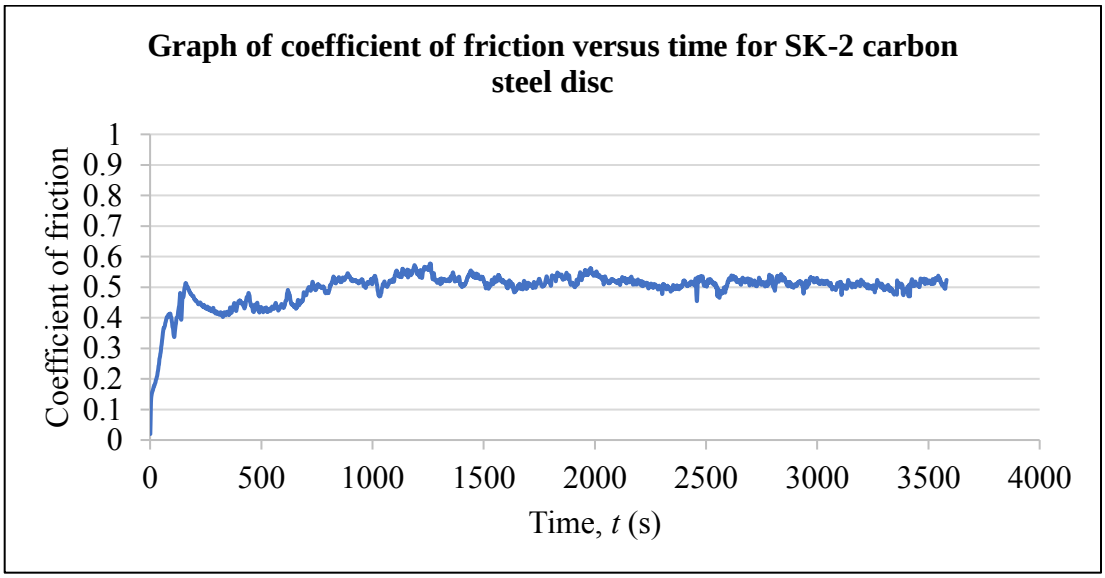












APPENDIX

B

Calculation Steps

Specific Wear Rate of Specimen no. 1:

Volume of specimen: $V = \pi(37)^2(3.5) = 15.052 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{16.270}{15.052 \times 10^3} = 1.081 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 16.270 - 15.890 = 0.380 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.380}{1.081 \times 10^{-3}} = 351.526 \text{ mm}^3$

Specific wear rate of specimen: $\text{k} = \frac{351.526}{(49.05)(3000)} = 2.389 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 2:

Volume of specimen: $V = \pi(37)^2(7.0) = 30.105 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{28.710}{30.105 \times 10^3} = 0.954 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 28.710 - 28.490 = 0.220 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.220}{0.954 \times 10^{-3}} = 230.607 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{230.607}{(49.05)(3000)} = 1.567 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 3:

Volume of specimen: $V = \pi(37)^2(4.5) = 19.354 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{29.990}{19.354 \times 10^3} = 1.550 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 29.990 - 29.790 = 0.200 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.200}{1.550 \times 10^{-3}} = 129.032 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{129.032}{(49.05)(3000)} = 0.877 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 4:

Volume of specimen: $V = \pi(37)^2(5.0) = 21.504 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{25.950}{21.504 \times 10^3} = 1.207 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 25.950 - 25.760 = 0.190 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.190}{1.207 \times 10^{-3}} = 157.448 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{157.448}{(49.05)(3000)} = 1.070 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 5:

Volume of specimen: $V = \pi(37.5)^2(7.0) = 30.925 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{27.910}{30.925 \times 10^3} = 0.903 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 27.910 - 27.540 = 0.370 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.370}{0.903 \times 10^{-3}} = 409.745 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{409.745}{(49.05)(3000)} = 2.785 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 6:

Volume of specimen: $V = \pi(37)^2(5.0) = 21.504 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{38.240}{21.504 \times 10^3} = 1.778 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 38.240 - 37.980 = 0.260 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.260}{1.778 \times 10^{-3}} = 146.210 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{146.210}{(49.05)(3000)} = 0.994 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 7:

Volume of specimen: $V = \pi(37.5)^2(5.5) = 24.298 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{34.880}{24.298 \times 10^3} = 1.435 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 34.880 - 34.670 = 0.210 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.210}{1.435 \times 10^{-3}} = 146.289 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{146.289}{(49.05)(3000)} = 0.994 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen no. 8:

Volume of specimen: $V = \pi(37)^2(7.5) = 32.256 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{32.270}{32.256 \times 10^3} = 1.001 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 32.270 - 32.010 = 0.260 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.260}{1.001 \times 10^{-3}} = 259.887 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{259.887}{(49.05)(3000)} = 1.766 \times 10^{-3} \text{ mm}^3/\text{Nm}$

Specific Wear Rate of Specimen SK-2 carbon steel disk:

Volume of specimen: $V = \pi(37.5)^2(4.0) = 17.671 \times 10^3 \text{ mm}^3$

Density of specimen: $\rho = \frac{131.500}{17.671 \times 10^3} = 7.441 \times 10^{-3} \text{ g/mm}^3$

Total mass loss of specimen: $M_{loss} = 131.500 - 131.380 = 0.120 \text{ g}$

Total volume loss of specimen: $V_{loss} = \frac{0.120}{7.441 \times 10^{-3}} = 16.127 \text{ mm}^3$

Specific wear rate of specimen: $k = \frac{16.127}{(49.05)(3000)} = 0.110 \times 10^{-3} \text{ mm}^3/\text{Nm}$

APPENDIX C

Properties of Aluminium Oxide / Alumina

Properties	Conditions	Units	values
Bulk Density	20°C	g/cm^3	3.96
Tensile Strength	20°C	Mpa	220
Flexural (Bending) Strength	20°C	> Mpa	410
Elastic Modulus	20°C	Gpa	375
Hardness	20°C	kg/mm^2	14
Fracture Toughness	20°C	$Mpa{\cdot}m^{1/2}$	4-5
Porosity	20°C	%	0

Mechanical properties of Alumina

Max. working temp	-	°C	1700
Coef. Thermal Expansion	25-300°C	10^{-6}/°C	7.8
Coef. Thermal Expansion	25-1000°C	10^{-6}/°C	8.1
Thermal Conductivity	20°C	W/m°K	28

Thermal properties of Alumina

Dielectric Strength	2.5mm tk	ac-kv/mm	10
Dielectric Constant	1 MHz	-	9.7
Volume Resistivity	20°C	Ohm-cm	$>10^{14}$
Volume Resistivity	300°C	Ohm-cm	10^{10}
Volume Resistivity	1000°C	Ohm-cm	10^{6}
Loss Factor	1 MHz	-	0.009
Dissipation Factor	1 MHz	-	0.0001

Electrical properties of Alumina

APPENDIX D

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HARDNESS CONVERSION TABLE
PRIMERJALNA TABELA TRDOT

Date/datum: 08.2015

Vickers (HV)	Rockwell (HRc)	Scleroscope Hardnes No. (Shore HSc, HSd)	Scleroscope hardness (Shore HFRSc)	Shore HS (HSC/HSD)	Leeb	
					(HLd)	(HLe)
ASTM E 140			*ASTM A 427*	*JIS B 7731*	*Eqoutip - Proceq*	
940	68	97,3	-	98	890	855
926	67,6	96,8	105	97,2	886	850
913	67,3	95,9	104	96,4	882	846
900	67	95	103	95,6	879	843
888	66,7	94,4	102	94,8	876	840
875	66,3	93,8	101	94,0	872	836
862	65,9	92,4	100	93,2	868	832
850	65,6	91,6	99	92,4	865	829
837	65,2	90,6	98	91,5	861	825
825	64,8	90,1	97	90,7	858	821
812	64,4	89,8	96	89,9	854	817
800	64	88,5	95	89,0	850	814
787	63,7	87,6	94	88,1	847	811
774	63,1	86,7	93	87,2	841	805
761	62,4	85,7	92	86,3	834	798
748	62,1	84,7	91	85,4	831	795
735	61,6	83,9	90	84,4	826	791
723	61,1	82,9	89	83,5	822	786
710	60,6	81,8	88	82,5	817	781
698	60	80,9	87	81,6	811	776
685	59,5	80,3	86	80,6	797	771
672	58,9	78,8	85	79,6	796	765
660	58,3	78,2	84	78,6	795	760
647	57,7	76,6	83	77,6	790	754
635	57,2	75,8	82	76,6	785	750
622	56,5	74,7	81	75,5	769	744
610	55,7	73,6	80	74,5	767	736
597	55,1	72,6	79	73,4	766	731
584	54,5	71,8	78	72,3	761	725
571	53,7	70,2	77	71,2	753	718
558	52,9	69,2	76	70,0	746	711
545	52	67,9	75	68,8	739	703
533	51,5	67,1	74	67,8	734	699
520	50,7	65,7	73	66,6	727	692
508	49,6	64,5	72	65,4	718	682
495	48,8	63,3	71	64,2	711	676
482	47,9	62,1	70	63,0	704	669
470	47	61	69	61,8	696	662
457	46	59,7	68	60,5	688	653
445	45	58,4	67	59,3	680	646
432	43,9	57	66	58,0	672	637
420	42,8	55,9	65	56,7	663	628
412	42	54,9	-	55,9	658	622
402	41	53,7	-	54,9	650	615
392	40	52,6	-	53,8	642	608
382	39	51,5	-	52,7	634	601
372	38	50,4	-	51,6	628	594
363	37	49,3	-	50,6	620	587
354	36	48,2	-	49,6	612	580
345	35	47,1	-	48,6	606	573
336	34	46,1	-	47,6	598	567
327	33	45,1	-	46,6	592	561
318	32	44,1	-	45,5	584	554
310	31	43,1	-	44,6	578	548
302	30	42,2	-	43,6	572	542
294	29	41,3	-	42,7	566	536
286	28	40,4	-	41,7	560	531
279	27	39,5	-	40,9	552	525
272	26	38,7	-	40,0	546	519
266	25	37,8	-	39,3	540	514
260	24	37	-	38,5	534	508
254	23	36,3	-	37,7	528	503
248	22	35,5	-	37,0	522	-
243	21	34,8	-	36,4	516	-
238	20	34,2	-	35,7	510	-

APPENDIX E

SHORE DUROMETERS

The durometer hardness scale was defined by Albert F. Shore, who developed a measurement device called a durometer in the 1920s. The term durometer is often used to refer to the measurement, as well as the instrument itself. Durometer is typically used as a measure of hardness in polymers, elastomers, plastics and rubbers.

Durometer scales

There are several scales of durometer hardness, used for materials with different properties. The two most common scales, using slightly different measurement systems, are the type A and type D scales. The A scale is for softer plastics, while the D scale is for harder ones. There are 12 scales, depending on the intended use; types A, B, C, D, DO, E, M, O, OO, OOO, OOO-S, and R. Each scale results in a value between 0 and 100, with higher values indicating a harder material.

Method of measurement

Durometer, like many other hardness tests, measures the depth of an indentation in the material created by a given force on a standardized presser foot. This depth depends on the hardness of the material, its viscoelastic properties, the shape of the presser foot, and the duration of the test. The durometers allows for measurements of the initial hardness, or the indentation hardness after a given period of time. The basic test requires applying the force in a consistent manner, without shock measuring the hardness.

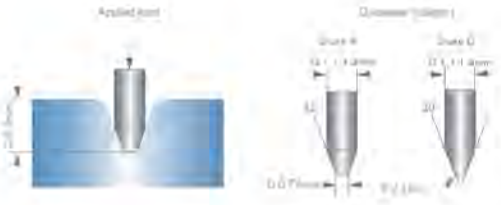
Depth of the indentation

If a timed hardness is desired, force is applied for the required time and then read. The material under test should be a minimum of 6.4mm.

The final value of the hardness depends on the depth of the indentor after it has been applied for 15sec on the material. If the indentor penetrates 2.5mm or more into the material, the durometer is 0 for that scale. If it does not penetrate at all, then the durometer is 100 for that scale. It is for this reason that multiple scales exist. Durometer is a dimensionless quantity, and there is no simple relationship between a material's durometer in one scale, and its durometer in any other scale, or by any other hardness test.

Durometer hardness of various common materials

Material	Durometer Scale
Bicycle gel seat	15-30 OO
Chewing gum	20 OO
Sorbothane	40 OO
Sorbothane	0 A
Rubber band	25 A
Door seal	55 A
Automotive tire tread	70 A
Soft skateboard wheel	75 A
Hydraulic O-rings	70-90 A
Hard skateboard wheel	98 A
Ebonite rubber	100 A
Solid truck tires	50 D



INNOVATEST®

SHORE DUROMETERS DSAS001/DSDS001

DSAS001
SHORE "A" TESTER

DSDS001
SHORE "D" TESTER

FEATURES

- Testing rubber, plastic, leather and all other soft materials
- Fast and easy to read
- Large digital display, digits 8mm high
- Supplied as standard with UKAS certificate of calibration
- Portable
- Use by hand or mounted on a stand
- Available in Shore A or Shore D
- Supplied with a reference block
- Data output for SPC
- Power on/off automatic
- Electronic module protection to IP65, even with data output
- According to DIN 53505, ASTM D2240, ISO R/868
- Can be used in conjunction with Shore bench stand

TECHNICAL SPECIFICATIONS

Scale	Shore A or Shore D
Resolution	0.1 unit
Standards	Conforms to DIN 53505, ASTM D2240 and ISO R/868
Measuring range	0-100
Pressure foot	ø18mm
Penetrator	A scale blunt taper 35° D scale sharp point 35°
Indentor	ø1.25mm
Battery	Lithium 3V, CR2032
Data output	RS-232 combined with external power supply

STANDARD DELIVERY

- Instrument
- Button battery
- Reference block
- Blunt taper 35° penetrator (A scale)
- Sharp point 35° penetrator (D scale)
- UKAS certificate of calibration
- Carrying case
- Manual

OPTIONAL ACCESSORIES

- Bench stand
- Communication cable
- Reference block
- Software

SHA0003

DSAS PENETRATOR

DSDS PENETRATOR

ORDER DETAILS

DSAS001 Handheld digital durometer for Shore A hardness testing
DSDS001 Handheld digital durometer for Shore D hardness testing
SHA0003 Bench stand

APPENDIX

F

Designation: G 99 – 95a (Reapproved 2000)ε1

Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus[1]

This standard is issued under the fixed designation G 99; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε1 NOTE—Editorial corrections were made throughout in May 2000.

1. Scope

1.1 This test method describes a laboratory procedure for determining the wear of materials during sliding using a pin-on-disk apparatus. Materials are tested in pairs under nominally non-abrasive conditions. The principal areas of experimental attention in using this type of apparatus to measure wear are described. The coefficient of friction may also be determined.

1.2 The values stated in SI units are to be regarded as standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[2]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[2]

E 178 Practice for Dealing with Outlying Observations[2]

G 40 Terminology Relating to Wear and Erosion[3]

2.2 *Other Standard:*[4]

DIN-50324 Testing of Friction and Wear

3. Summary of Test Method

3.1 For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk center. In either case, the sliding path is a circle on the disk surface. The plane of the disk may be oriented either horizontally or vertically.

NOTE 1—Wear results may differ for different orientations.

3.1.1 The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. Other loading methods have been used, such as, hydraulic or pneumatic.

NOTE 2—Wear results may differ for different loading methods.

3.2 Wear results are reported as volume loss in cubic millimetres for the pin and the disk separately. When two different materials are tested, it is recommended that each material be tested in both the pin and disk positions.

3.3 The amount of wear is determined by measuring appropriate linear dimensions of both specimens before and after the test, or by weighing both specimens before and after the test. If linear measures of wear are used, the length change or shape change of the pin, and the depth or shape change of the disk wear track (in millimetres) are determined by any suitable metrological technique, such as electronic distance gaging or stylus profiling. Linear measures of wear are converted to wear volume (in cubic millimetres) by using appropriate geometric relations. Linear measures of wear are used frequently in practice since mass loss is often too small to measure precisely. If loss of mass is measured, the mass loss value is converted to volume loss (in cubic millimetres) using an appropriate value for the specimen density.

3.4 Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed. One set of test conditions that was used in an interlaboratory measurement series is given in Table 1 and Table 2 as a guide. Other test conditions may be selected depending on the purpose of the test.

3.5 Wear results may in some cases be reported as plots of wear volume versus sliding distance using different specimens for different distances. Such plots may display non-linear relationships between wear volume and distance over certain portions of the total sliding distance, and linear relationships over other portions. Causes for such differing relationships include initial "break-in" processes, transitions between regions of different dominant wear mechanisms, etc. The extent of such non-linear periods depends on the details of the test system, materials, and test conditions.

3.6 It is not recommended that continuous wear depth data

[1] This test method is under the jurisdiction of ASTM Committee G02 on Wear and Erosion and is the direct responsibility of Subcommittee G02.40 on Non-Abrasive Wear.

Current edition approved Nov. 10, 1995. Published January 1996. Originally published as G 99–90. Last previous edition G 99 – 95.

[2] *Annual Book of ASTM Standards*, Vol 14.02.

[3] *Annual Book of ASTM Standards*, Vol 03.02.

[4] Available from Beuth Verlag GmbH, Burggrafenstrasse 6, 1000 Berlin 30, Germany.

TABLE 1 Characteristics of the Interlaboratory Wear Test Specimens

NOTE 1—See Note 4 in 10.4 for information.

	Composition (weight%)	Microstructure	Hardness (HV 10)	Roughness[A]	
				R_z(mean) (μm)	R_a(mean) (μm)
Steel ball (100 Cr6) (AISI 52 100)[B] Diameter 10 mm	1.35 to 1.65 Cr ← 0.95 to 1.10 C 0.15 to 0.35 Si 0.25 to 0.45 Mn	martensitic with minor carbides and austenite	838 ± 21	0.100	0.010
Steel disc (100 Cr6) (AISI 52 100)[C] Diameter 40 mm	← <0.030 P <0.030 S	martensitic with minor carbides and austenite	852 ± 14	0.952	0.113
Alumina ball, diameter = 10 mm[D]	← 95 % Al_2O_3 (with additives of TiO_2,	equi-granular alpha alumina with very minor secondary phases	1610 ± 101 (HV 0.2)	1.369	0.123
Alumina disc, diameter = 40.6 mm[D]	← MgO and ZnO)		1599 ± 144 (HV 0.2)	0.968	0.041

[A] Measured by stylus profilometry. R_z is maximum peak-to-valley roughness. R_a is arithmetic average roughness.
[B] Standard ball-bearing balls (SKF).
[C] Standard spacers for thrust bearings (INA).
[D] Manufactured by Compagnie Industrielle des Ceramiques Electroniques, France.

TABLE 2 Results of the Interlaboratory Tests[A]

NOTE 1— See Note 4 in 10.4.
NOTE 2—Numbers in parentheses refer to all data received in the tests. In accordance with Practice E 178, outlier data values were identified in some cases and discarded, resulting in the numbers without parentheses. The differences are seen to be small.
NOTE 3—Values preceded by ± are one standard deviation.
NOTE 4—Between eleven and twenty laboratories provided these data.
NOTE 5—Calculated quantities (for example, wear volume) are given as mean values only.
NOTE 6—Values labeled "NM" were found to be smaller than the reproducible limit of measurement.
NOTE 7—A similar compilation of test data is given in DIN-50324.

Results (ball) (disk)	Specimen Pairs			
	Steel-steel	Alumina-steel	Steel-alumina	Alumina-alumina
Ball wear scar diameter (mm)	2.11 ± 0.27 (2.11 ± 0.27)	NM	2.08 ± 0.35 (2.03 ± 0.41)	0.3± 0.06 (0.3 ± 0.06)
Ball wear volume (10^{-3} mm^3)	198 (198)	...	186 (169)	0.08 (0.08)
Number of values	102 (102)	...	60 (64)	56 (59)
Disk wear scar width (mm)	NM	0.64 ± 0.12 (0.64 ± 0.12)	NM	NM
Disk wear volume (10^{-3} mm^3)	...	480 (480)	...	...
Number of values	...	60 (60)	...	...
Friction coefficient	0.60 ± 0.11	0.76 ± 0.14	0.60 ± 0.12	0.41 ± 0.08
Number of values	109	75	64	76

[A] Test conditions: F = 10 N; v = 0.1 ms $^{-1}$; T = 23°C; relative humidity range 12 to 78 %; laboratory air; sliding distance 1000 m; wear track (nominal) diameter = 32 mm; materials: steel = AISI 52 100; and alumina = α-Al_2O_3.

obtained from position-sensing gages be used because of the complicated effects of wear debris and transfer films present in the contact gap, and interferences from thermal expansion or contraction.

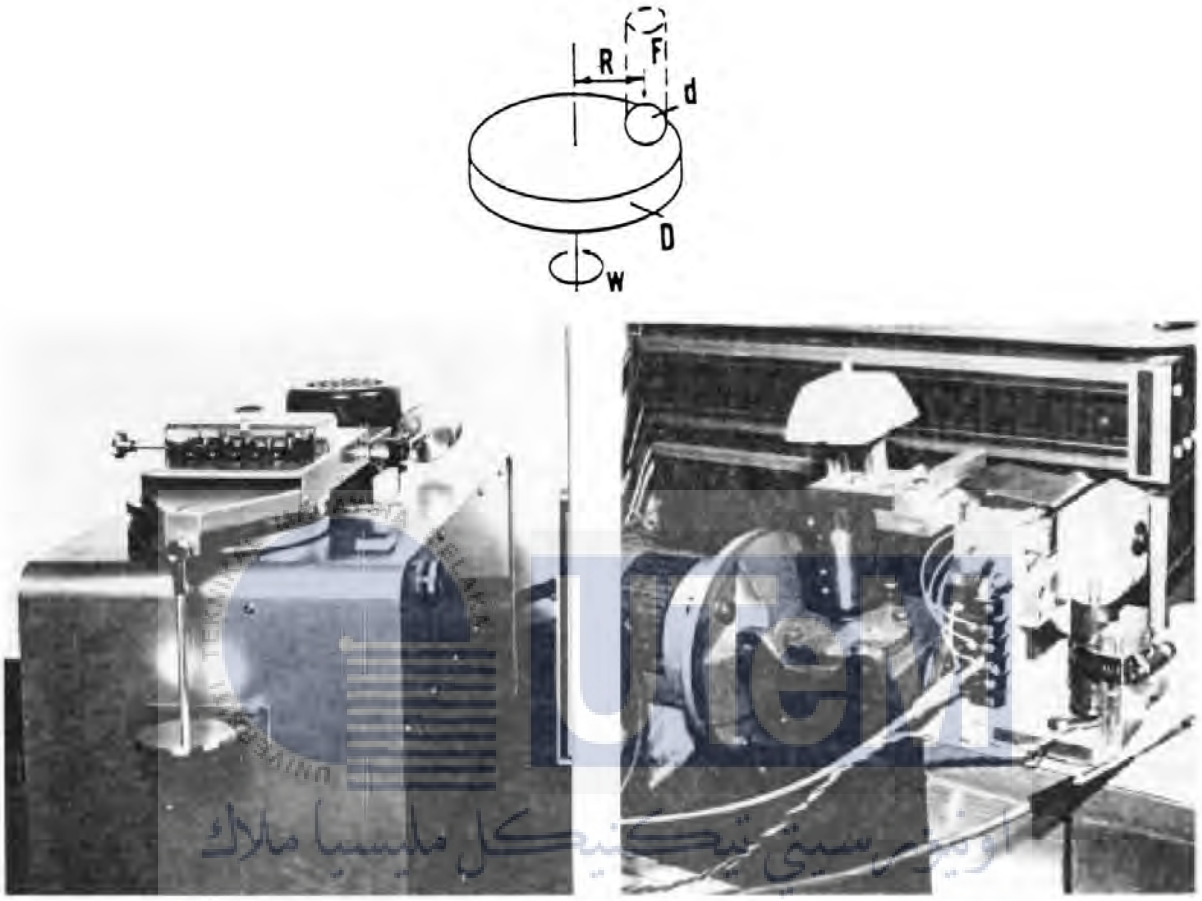
4. Significance and Use

4.1 The amount of wear in any system will, in general, depend upon the number of system factors such as the applied load, machine characteristics, sliding speed, sliding distance, the environment, and the material properties. The value of any wear test method lies in predicting the relative ranking of material combinations. Since the pin-on-disk test method does not attempt to duplicate all the conditions that may be experienced in service (for example; lubrication, load, pressure, contact geometry, removal of wear debris, and presence of corrosive environment), there is no ensurance that the test will predict the wear rate of a given material under conditions differing from those in the test.

5. Apparatus

5.1 *General Description*—Fig. 1 shows a schematic drawing of a typical pin-on-disk wear test system, and photographs of two differently designed apparatuses.[5] One type of typical system consists of a driven spindle and chuck for holding the revolving disk, a lever-arm device to hold the pin, and attachments to allow the pin specimen to be forced against the revolving disk specimen with a controlled load. Another type of system loads a pin revolving about the disk center against a stationary disk. In any case the wear track on the disk is a

[5] A number of other reported designs for pin-on-disk systems are given in "A Catalog of Friction and Wear Devices," American Society of Lubrication Engineers (1973). The sole source of supply of commercially built machines known to the committee at this time is Falex Corp., 1020 Airpark Dr., Sugar Grove, IL 60554. If you are aware of alternative suppliers, please provide this information to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, [1] which you may attend.



NOTE 1—*F* is the normal force on the pin, *d* is the pin or ball diameter, *D* is the disk diameter, *R* is the wear track radius, and *w* is the rotation velocity of the disk.

FIG. 1 (*a*) Schematic of pin-on-disk wear test system. (*b*) Photographs of two different designs.

circle, involving multiple wear passes on the same track. The system may have a friction force measuring system, for example, a load cell, that allows the coefficient of friction to be determined.

5.2 *Motor Drive*—A variable speed motor, capable of maintaining constant speed (±1 % of rated full load motor speed) under load is required. The motor should be mounted in such a manner that its vibration does not affect the test. Rotating speeds are typically in the range 0.3 to 3 rad/s (60 to 600 r/min).

5.3 *Revolution Counter*—The machine shall be equipped with a revolution counter or its equivalent that will record the number of disk revolutions, and preferably have the ability to shut off the machine after a pre-selected number of revolutions.

5.4 *Pin Specimen Holder and Lever Arm*— In one typical system, the stationary specimen holder is attached to a lever arm that has a pivot. Adding weights, as one option of loading, produces a test force proportional to the mass of the weights applied. Ideally, the pivot of the arm should be located in the plane of the wearing contact to avoid extraneous loading forces due to the sliding friction. The pin holder and arm must be of substantial construction to reduce vibrational motion during the test.

5.5 *Wear Measuring Systems*—Instruments to obtain linear measures of wear should have a sensitivity of 2.5 μm or better. Any balance used to measure the mass loss of the test specimen shall have a sensitivity of 0.1 mg or better; in low wear situations greater sensitivity may be needed.

6. Test Specimens and Sample Preparation

6.1 *Materials*—This test method may be applied to a variety of materials. The only requirement is that specimens having the specified dimensions can be prepared and that they will withstand the stresses imposed during the test without failure or excessive flexure. The materials being tested shall be described by dimensions, surface finish, material type, form, composition, microstructure, processing treatments, and indentation hardness (if appropriate).

6.2 *Test Specimens*—The typical pin specimen is cylindrical or spherical in shape. Typical cylindrical or spherical pin

specimen diameters range from 2 to 10 mm. The typical disk specimen diameters range from 30 to 100 mm and have a thickness in the range of 2 to 10 mm. Specimen dimensions used in an interlaboratory test with pin-on-disk systems are given in Table 1.

6.3 *Surface Finish*—A ground surface roughness of 0.8 μm (32 μin.) arithmetic average or less is usually recommended.

NOTE 3—Rough surfaces make wear scar measurement difficult.

6.3.1 Care must be taken in surface preparation to avoid subsurface damage that alters the material significantly. Special surface preparation may be appropriate for some test programs. State the type of surface and surface preparation in the report.

7. Test Parameters

7.1 *Load*—Values of the force in Newtons at the wearing contact.

7.2 *Speed*—The relative sliding speed between the contacting surfaces in metres per second.

7.3 *Distance*—The accumulated sliding distance in meters.

7.4 *Temperature*—The temperature of one or both specimens at locations close to the wearing contact.

7.5 *Atmosphere*—The atmosphere (laboratory air, relative humidity, argon, lubricant, etc.) surrounding the wearing contact.

8. Procedure

8.1 Immediately prior to testing, and prior to measuring or weighing, clean and dry the specimens. Take care to remove all dirt and foreign matter from the specimens. Use non-chlorinated, non-film-forming cleaning agents and solvents. Dry materials with open grains to remove all traces of the cleaning fluids that may be entrapped in the material. Steel (ferromagnetic) specimens having residual magnetism should be demagnetized. Report the methods used for cleaning.

8.2 Measure appropriate specimen dimensions to the nearest 2.5 μm or weigh the specimens to the nearest 0.0001 g.

8.3 Insert the disk securely in the holding device so that the disk is fixed perpendicular (±1°) to the axis of the resolution.

8.4 Insert the pin specimen securely in its holder and, if necessary, adjust so that the specimen is perpendicular (±1°) to the disk surface when in contact, in order to maintain the necessary contact conditions.

8.5 Add the proper mass to the system lever or bale to develop the selected force pressing the pin against the disk.

8.6 Start the motor and adjust the speed to the desired value while holding the pin specimen out of contact with the disk. Stop the motor.

8.7 Set the revolution counter (or equivalent) to the desired number of revolutions.

8.8 Begin the test with the specimens in contact under load. The test is stopped when the desired number of revolutions is achieved. Tests should not be interrupted or restarted.

8.9 Remove the specimens and clean off any loose wear debris. Note the existence of features on or near the wear scar such as: protrusions, displaced metal, discoloration, microcracking, or spotting.

8.10 Remeasure the specimen dimensions to the nearest 2.5 μm or reweigh the specimens to the nearest 0.0001 g, as appropriate.

8.11 Repeat the test with additional specimens to obtain sufficient data for statistically significant results.

9. Calculation and Reporting

9.1 The wear measurements should be reported as the volume loss in cubic millimetres for the pin and disk, separately.

9.1.1 Use the following equations for calculating volume losses when the pin has initially a spherical end shape of radius R and the disk is initially flat, under the conditions that only one of the two members wears significantly:

$$\text{pin (spherical end) volume loss, mm}^3 = \frac{\pi\,(\text{wear scar diameter, mm})^4}{64\,(\text{sphere radius, mm})} \quad (1)$$

assuming that there is *no significant disk wear*. This is an approximate geometric relation that is correct to 1 % for (wear scar diameter/sphere radius) < 0.3, and is correct to 5 % for (wear scar diameter/sphere radius) < 0.7. The exact equation is given in Appendix X1.

$$\text{disk volume loss, mm}^3 = \frac{\pi\,(\text{wear track radius, mm})(\text{track width, mm})^3}{6\,(\text{sphere radius, mm})} \quad (2)$$

assuming that there is *no significant pin wear*. This is an approximate geometric relation that is correct to 1 % for (wear track width/sphere radius) < 0.3, and is correct to 5 % for (wear track width/sphere radius) < 0.8. The exact equation is given in Appendix X1.

9.1.2 Calculation of wear volumes for pin shapes of other geometries use the appropriate geometric relations, recognizing that assumptions regarding wear of each member may be required to justify the assumed final geometry.

9.1.3 Wear scar measurements should be done at least at two representative locations on the pin surfaces and disk surfaces, and the final results averaged.

9.1.4 In situations where both the pin and the disk wear significantly, it will be necessary to measure the wear depth profile on both members. A suitable method uses stylus profiling. Profiling is the only approach to determine the exact final shape of the wear surfaces and thereby to calculate the volume of material lost due to wear. In the case of disk wear, the average wear track profile can be integrated to obtain the track cross-section area, and multiplied by the average track length to obtain disk wear volume. In the case of pin wear, the wear scar profile can be measured in two orthogonal directions, the profile results averaged, and used in a figure-of-revolution calculated for pin wear volume.

9.1.5 While mass loss results may be used internally in laboratories to compare materials of equivalent densities, this test method reports wear as volume loss so that there is no confusion caused by variations in density. Take care to use and report the best available density value for the materials tested when calculating volume loss from measured mass loss.

9.1.6 Use the following equation for conversion of mass loss to volume loss.

$$\text{volume loss, mm}^3 = \frac{\text{mass loss, g}}{\text{density, g/cm}^3} \times 1000. \quad (3)$$

9.2 If the materials being tested exhibit considerable transfer between specimens without loss from the system, volume loss may not adequately reflect the actual amount or severity of wear. In these cases, this test method for reporting wear should not be used.

9.3 Friction coefficient (defined in Terminology G 40) should be reported when available. Describe the conditions associated with the friction measurements, for example, initial, steady-state, etc.

9.4 Adequate specification of the materials tested is important. As a minimum, the report should specify material type, form, processing treatments, surface finish, and specimen preparation procedures. If appropriate, indentation hardness should be reported.

10. Precision and Bias [6]

10.1 The precision and bias of the measurements obtained with this test method will depend upon the test parameters chosen.

10.2 The reproducibility of repeated tests on the same material will depend upon material homogeneity, machine and material interaction, and careful adherence to the specified procedure by the machine operator.

10.3 Normal variations in the procedure will tend to reduce the accuracy of the test method as compared to the accuracy of such material property tests as hardness, density, or thermal expansion rate. Properly conducted tests should, however, maintain a within-laboratory coefficient of variation of 20 % or less for wear loss values. Table 2 contains wear data obtained from interlaboratory tests (see Note 4). Standard deviation values are given for the measured quantities. Limits of 95 % repeatability can be obtained by multiplying those standard deviation values by the factor 2.8 ×. Reproducibility limits (between laboratories) are not available but are estimated to be twice as large as the repeatability limits.

10.4 No bias can be assigned to these results since there are no absolute accepted values for wear.

NOTE 4—The interlaboratory data given in Table 1 and Table 2 resulted through the cooperation of thirty one institutions in seven countries with the help of national representatives within the Versailles Advanced Materials and Standards (VAMAS) working party on wear test methods.[7]

10.5 In any test series, all data must be considered in the calculation, including outliers (data exceeding the obvious range); they are treated according to Practice E 178.

10.6 While two or more laboratories may develop test data that is within the acceptable coefficient of variation for their own individual test apparatus, the actual data of each laboratory may be relatively far apart. The selection of sample size and the test method for establishing the significance of the difference in averages shall be agreed upon between laboratories and shall be based on established statistical methods of Practice E 122, Practice E 177, and STP 15D.[8]

11. Keywords

11.1 ceramic wear; friction; metal wear; non-abrasive; pin-on-disk; wear

[6] Additional data are available at ASTM Headquarters.

[7] Czichos, H., Becker, S., and Lexow, J., *Wear*, Vol 114, 1987, pp 109–130 and *Wear*, Vol 118, 1987, pp 379–380.

[8] Manual on Quality Control of Materials, ASTM STP 15D, ASTM, 1951.

APPENDIX

(Nonmandatory Information)

X1. EQUATIONS

X1.1 Exact equations for determining wear volume loss are as follows for:

X1.1.1 A spherical ended pin:

$$\text{pin volume loss} = (\pi h/6)[3d^2/4 + h^2] \quad \text{(X1.1)}$$

where:

h = $r - [r^2 - d^2/4]^{1/2}$,
d = wear scar diameter, and
r = pin end radius.

Assuming no significant disk wear.

X1.1.2 A disk:

$$\text{disk volume loss} = 2\pi R\,[r^2 \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{1/2}] \quad \text{(X1.2)}$$

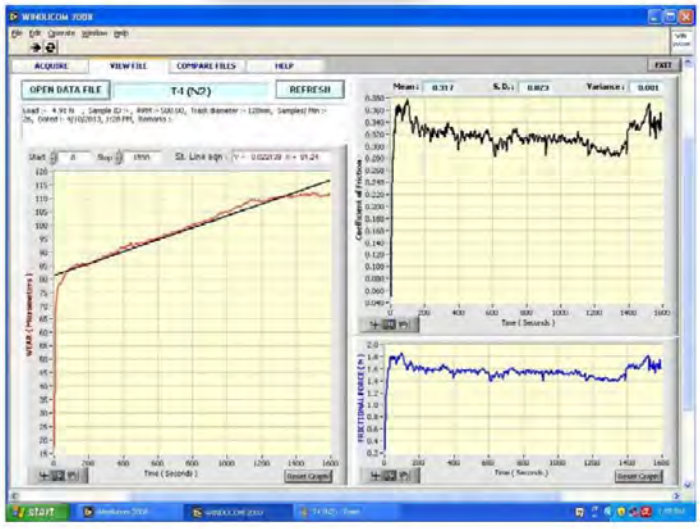
where:

R = wear track radius, and
d = wear track width.

Assuming no significant pin wear.

APPENDIX G

Pin/Ball-on-Disk Tribometer is a test instrument designed for accurate and repeatable tribological characterization of bulk materials, coatings and lubricants. Easily changeable holders allow users to quickly change the nature of tribological contact to something that is relevant to their application. A wide range of factory installed and field upgradable options make this system very scalable, ensuring years of unhindered research for various types of applications.



Faculty of Mechanical Engineering
Tribology Laboratory

1 FEATURES

- Friction and Compound Wear Sensing Module offered as standard supply
- Large number of options for extended testing capabilities
- Computer controlled operation with software license included

2 OPTIONS

- Automated Loading System
- Environment/Gas Chamber
- Lubricant Cup
- Lubrication Module
- Electrical Contact Resistance (ECR)
- Elevated Temperature Modules (various ranges)

3 TEST STANDARDS

- ASTM G 99
- ASTM G 133
- ASTM G 77
- ISO 20808
- DIN 50324 / DIN 51834-1

4 TECHNICAL SPECIFICATIONS

- Wear disc diamaeter : Ø 165 mm, 6 to 8 mm thick.
- Pin diameter, length : 4 to 12 mm diameter in steps of 2 mm, 20 to 30 mm long.
- Wear track diameter : Min. 50 mm & 100 mm.
- Disc speed : Min. 200 rpm, max. 2000 rpm.
- Normal load : Min. 10 N, Max. 200 N.
- Frictional force : Max. 200 N.
- Wear : ± 2000 micron
- Test duration : 99.59.59 hrs

5 CONTACT US

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