INVESTIGATION OF CONTAMINATION IN BALL BEARING OPERATED UNDER HEXAGONAL BORON NITRIDE (hBN) NANOPARTICLE ADDITIVES MIXED WITH ENGINE OIL

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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 (Plant and Maintenance).

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DECLARATION

I declare that this project report entitled “Investigation of Contamination in Ball Bearing Operated under Hexagonal Boron Nitride (hBN) Nanoparticle Additives Mixed with Engine Oil” is the result of my own work except as cited in the references

Signature : ……………………………………..

Name : ……………………………….........

Date : ……………………………………..

DEDICATION

To my beloved mother and father

ABSTRACT

Rolling element bearings are widely used as mechanical structures which support the shafts, axles, wheels or any rotating components on the machines. As the machines continuously operating under a long period of time, a high speed and a heavy load, consequentially cause early fatigue failure to the bearings. The presence of contaminants inside the lubricant is probably one of the main reasons for this phenomenon. Considering to this problem, the potential use of hexagonal boron nitride (hBN) as additive in SAE 15W40 diesel engine oil was studied. An experimental work was conducted on a test rig in order to identify the contaminant characteristics and the effect of different percentages concentration volume of hBN mixed with diesel engine oil in producing contaminations and wears on several conditions of rolling element bearings. Oil View Analyser indicates that the contamination index and wear rate are reduced significantly by increasing the percentage of hBN concentration volumes. The contamination and wear rate are lowest at 0.5 % concentration volume of hBN. Besides that, microscopic examination result shows the presence of contaminants and wears are typically in the form of fibers and ferrous metals respectively. Therefore, performance of hBN nanoparticles as contaminant, wear and friction reducing agent is clearly relevant.

ABSTRAK

Elemen galas berputar digunakan secara meluas sebagai struktur mekanikal yang menyokong aci, gandar, roda, atau mana-mana komponen berputar pada mesin. Mesin yang beroperasi dalam tempoh masa yang panjang, pada kelajuan yang tinggi dan beban yang berat secara tidak langsung meyumbang kepada kerosakkan peringkat awal galas. Kehadiran bahan cemar di dalam minyak pelincir merupakan salah satu faktor dominan yang menyumbang kepada fenomena tersebut. Oleh hal yang demikian, potensi penggunaan heksagon boron nitrida (hBN) sebagai bahan tambahan dalam SAE 15W40 minyak enjin diesel telah dikaji secara terperinci. Eksperimen telah dijalankan ke atas mesin ujikaji untuk mengenal pasti ciri-ciri bahan cemar dan kesan peratusan jumlah kepekatan hBN berbeza yang telah dicampurkan dalam minyak enjin diesel untuk mengurangkan bahan cemar dan bahan haus berdasarkan beberapa jenis kondisi galas berbola. Mesin analisa minyak menunjukkan bahawa kadar pencemaran dan kadar kehausan makin berkurang dengan penambahan peratusan jumlah kepekatan hBN yang dimasukkan. Berdasarkan analisa minyak yang dilakukan, penggunaan hBN 0.5 % menunjukkan kadar kehausan dan kadar pencemaran yang paling rendah Selain itu, hasil pemeriksaan mikroskopik menunjukkan kehadiran bahan cemar dan bahan haus adalah dalam bentuk gentian dan logam ferus. Justeru itu, penggunaan partikel nano hBN sebagai agen pengurang bahan cemar, kehausan dan geseran adalah relevan.

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LIST OF ABBREVIATIONS

hBN	Hexagonal Boron Nitride
COF	Coefficient Of Friction
RCW	Rolling Contact Wear
MACs	Multialkylated Cyclopentanes
MWNTs	Multi-Walled Carbon Nanotubes
NCB	Nano-Calcium Borate
LDLS	Laser Dynamic Light Scattering
CAD	Computer Aided-Drawing
WDA	Wear Debris Analysis

LIST OF SYMBOLS

ρ	Density
m	Mass
v	Volume

CHAPTER I

INTRODUCTION

1.1 Background

Figure 1.1: Various type of bearings

(Source from www.weiku.com)

Nowadays, there are many types of bearings as shown in Figure 1.1 that have been used and required in various industrial sectors or everyday objects in order to operate such as washing machines, food processors and tumble driers. Besides, rolling element bearings are also widely used as mechanical structures which support the shafts, axle, wheel or any rotating component on the machines. As the machine continuously operating at a long period of time, under a high speed and a heavy load, indirectly will cause a critical damage or early fatigue failure to the bearing. This phenomenon might be occurred due to the huge friction and presence of contaminants on the bearing itself. The unbalance and misalignment of existing components on the machines might be also one of the several reasons that lead to a high vibration on the machine component and cause machinery breakdown. As a result, the performance of the machine to operate decrease and could be dangerous to the users while running the machine. Moreover, the maintenance cost would be high if there is a critical damage or broken part on the machine component.

Figure 1.2: Lubricant Oil

(Source from autoworld.com.my)

Figure 1.3: Grease

(Source from www.techtransfer.com)

As a solution to this problem, lubricant is required to lubricate the machine component in order to reduce the friction, corrosion and seizure on the bearings. The existence of lubricant on the bearing, increase the performance of the machine while operating. Today, lubricant oil and grease are basic types of lubricants that commonly used in rotating machinery. Lubricant oil as shown in Figure 1.2 is a liquid lubricant which is combination of base oil and additives. It has low viscosity that provides great versatility and low friction which is really suitable for lubricating parts that rotate at high speed. Meanwhile, grease as in Figure 1.3 is semisolid lubricant which is made up of dispersed thickener and liquid lubricant. It is less expose to aging and usually recommended for long-life products. These type of lubricants are still accepted, used and practiced until now.

Figure 1.4: Hexagonal Boron Nitride Powder

(Source from www.supervacoils.com)

Recently, several researches on nanoparticles lubricant have been studied due to its efficiency to low friction and wear. The performance of this nanoparticles lubricant have been reviewed in tribology field. Therefore in this case, Hexagonal Boron Nitride (hBN) powder as shown in Figure 1.4 is used as lubricant additive. It can be dispersed in oil lubricant, grease, solvent and water. Due to its characteristics of strong thermal resistance, good thermal conductor and good insulator, therefore it is really suitable being an additive for a high temperature lubrication and on a high friction of contact surfaces (Gao Y *et. al*., 2011). In addition to that, detail experimentation and testing must be carried out from time to time in order to optimize the performance of hBN as lubricant additive.

1.2 Problem Statement

Friction or early fatigue failure on the bearing of rotating machinery is a critical problem that could lead to total damage to the machine components and dangerous to users while running the machines. Besides, as the rotating machine continuously operating for a long time under a high speed and heavy load, it will cause the bearing to wear out and reduce the performance of the machines. The solid contaminants in lubricants of the bearings are also one of factors that lead to bearing failure. As a result, the lifespan of the bearings will be shorten and the maintenance cost would be expensive if there is serious damage on the machine components.

There are few studies that have been conducted by several researchers regarding the performance of hBN nanoparticles as lubricant additives in reducing the wear rate and coefficient of friction (COF) of machine components. They found that the performance of hBN nanoparticle was influenced by the percentage of volume concentration of hBN powder that mixed with base oil. Muhammad Ilman Hakimi Chua Abdullah *et al.* (2013) stated that the contribution of 0.5 vol. % of hBN can be used as an ideal additive composition in conventional diesel engine oil to achieve a lower COF. Therefore, a detail experimentation and testing are carried out to propose an effective percentage of hBN volume concentration as wear reducing agent and in order to achieve the objectives of this study.

1.3 Objectives

1. To investigate the effects of certain contaminant characteristics on bearing and hBN performance.
2. To study the effects of concentration of hBN mixed with diesel oil in producing contamination on rolling bearings.

1.4 Scope of Project

The scope of this project are:

1. Do an experimental work in order to identify the performance of hBN nanoparticles mixed lubricants on new and defected rolling bearings at different concentrations value operating for long time under high speed and heavy load.
2. Obtain the contaminants inside the tested lubricant sample by using debris machine.
3. Conduct vibration test to obtain the trends in the amounts of vibration affected by different contamination in the hBN mixed lubricant.
4. Perform gravimetry and ferrography test to obtain the roughness measurements and microscopic observation.

1.5 Gantt Chart

Table 1.6 Gantt chart for PSM 1

Weeks / Activities	PSM 1													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Problem Statement & Objectives														
Literature review														
Design of project														
Fabrication of project														
Sample preparation of experiment														
Experimental work														
Preliminary data collection														
Preliminary data analysis														
Draft of report writing														
Report writing submission														
Seminar 1 presentation														

Table 1.7 Gantt chart for PSM 2

Weeks / Activities	PSM 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Introduction to PSM 2														
Literature review														
Materials finding														
Test rig modification and fabrication														
Experimental work														
Progress report submission														
Final data collection														
Final data evaluation														
Writing draft of final report														
Submission of final draft report														
Seminar 2 presentation														

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Doing a careful and thorough literature review is essential when writing a research at any level. Therefore, this chapter briefly explains the related published researches and paper works as well as the studies that have been investigated regarding this project. This chapter also defines, summarizes, evaluates and clears up the findings that have been discovered from various references. These references obtained from internet sources and libraries were in the form of thesis, articles, journals and books. All relevant information and ideas gathered from different materials were then implemented to study this project in more detail.

2.2 Types of Rolling Bearings

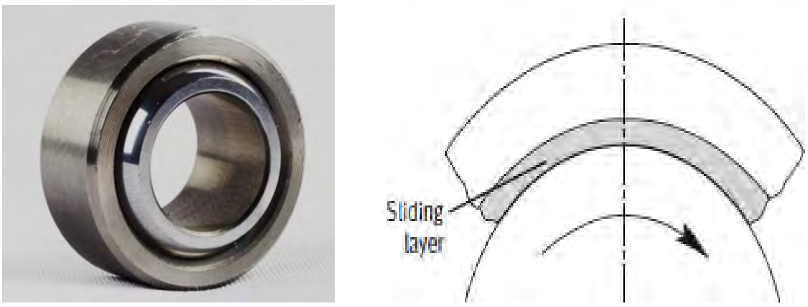


Figure 2.1 Plain bearing

(Source from www.mcgillmotorsport.com)

Over the years, bearings have received overwhelming response from industrial sectors and consumers all around the world. Bearing manufacturing has increased due to growing needs in various industries that rely on machinery. Basically, the function of bearings is principally to reduce mechanical friction. When the friction is reduced, the machinery will operate more efficiently. Besides, there will be less frictional wear, as a result the operating life of the machinery will be longer. Bearings also contribute to lower energy consumption by decreasing friction and enabling the efficient transmission of power. This is just one way in which bearings are environmentally friendly. Instead of minimizing friction, bearings are specially designed to connect machine components. Bearings transfer motions and forces. They are usually located on axles or shafts and installed in housings. There are two types of bearing which are plain bearing and rolling bearing. Plain bearings as shown in Figure 2.1 are components that have sliding layer between two parts. The sliding layer is in the form of solid layer which is fixed to the bearing such as plastic or bronze layers. Besides, plain bearings are specially designed for heavy loads.

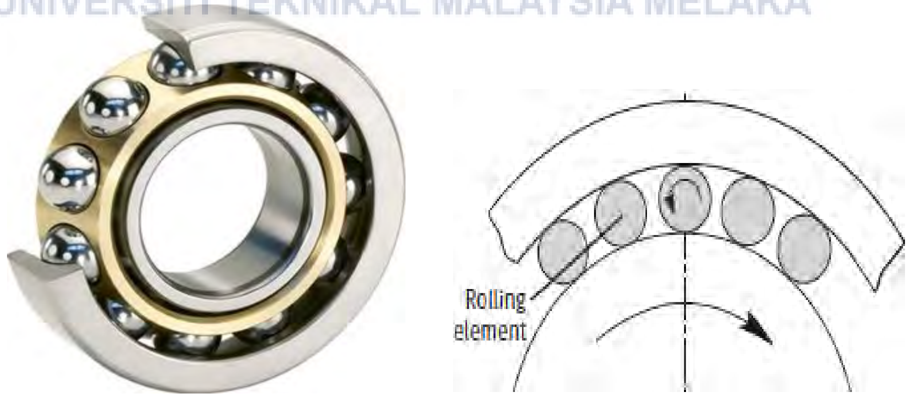


Figure 2.2 Rolling bearing

(Source from www.directindustry.com)

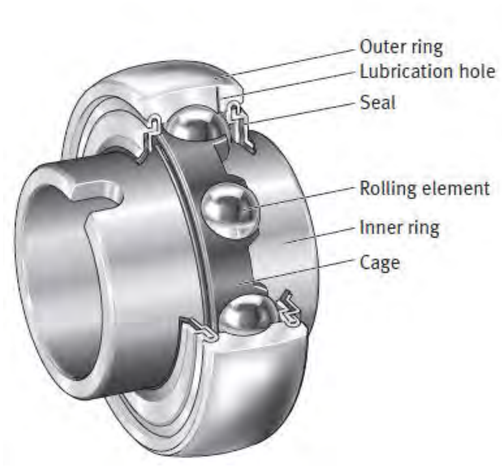


Figure 2.3 Outer ring and inner ring

(Source from www.directindustry.com)

However, rolling bearings as shown in Figure 2.2 are bearings that have two parts and move in opposite directions. There are inner and outer ring as shown in Figure 2.3 that separated by rolling elements. The rolling elements roll between the two rings during operation. This happens on hardened steel surfaces called raceways. The friction produced on this part is lower compared to plain bearings. Apart from that, rolling bearings are divided into two types which are ball bearings and roller bearings. Example of ball bearings are deep groove ball bearings, angular contact ball bearings, four point contact ball bearings and self-aligning ball bearings. For roller bearings, they are consist of cylindrical roller bearings, needle roller bearings, tapered roller bearings and spherical roller bearing. Selecting the best type of bearing is important to minimize the wear and friction that producing contaminants inside the lubricants. One of the suitable type of bearing to be used is ball bearing due to its attractive characteristics. The separation of the races by the balls reduces the friction that exist between the shaft and housing.

2.3 Type of Lubricants

Failure on machine components is most probably due to the high frictional force that occurred between two contacted surfaces or might be due to the operating under a high speed for a long period of time. The high friction on the surfaces produced abrasive wears and contaminants. Shizu and Ping (2012) stated that components that usually influenced by abrasive wear are piston/cylinders, journal bearings, gears, swash plates, cams and rolling element bearings. Watson *et* al. (1995) supporting that wear in engine usually happens in pistons rings, cylinders, bearings and cam lobes. However, wear occurs frequently in pistons rings of an engine. The performance of piston ring/engine cylinder bore system in an internal combustion engine will affect the efficiency and durability of engines (Simon and Huang, 2004). Contaminations seem to be another factor that affects engine bearings, cams valve train, piston rings and cylinder liners. Contaminations were abrasive according to observed scars and debris generated between metallic test surfaces (Enzhu *et* al., 2013).Therefore, lubrication is very essential in the industrial sectors where it is widely used in automotive industry and all rotating machinery. Lubricant is mainly used to reduce the friction between two contacting metal surfaces. It also can increase the performance of machine, engine or rotating parts as well as protects them to prevent wear and corrosion indirectly prolongs their life. Lubricants are available in the form of oil and grease.

Based on the research study, plant oils are quite famous in industrial applications due to its properties as a good lubricant. S. Syahrullail *et* al. (2013) stated that vegetable oil has a high viscosity index, high lubricity, low vitality, low toxicity and high biodegradability. Therefore, addition of vegetable oil with existing mineral oil can maximize the performance of both lubricants in terms of the coefficient of friction and wear performance. Balamurugan *et* al. (2010) supported this statement by addressing that palm oil methyl ester enhances wear resistance and oxidation stability. Besides that, Masjuki *et* al. (1999) carried out a comparative study of wear, friction and exhaust emissions with palm oil and mineral based lubricating oil. The results showed that palm oil based lubricating oil exhibited better performance in wear properties meanwhile the mineral based lubricating oil revealed better performance in terms of friction. However, the palm based lubricants also were more effective in reducing emission levels. Wan Nik *et* al. (2007) performed a research on coconut oil in machining applications for metal cutting. Its performance was excellent with respect to cutting speed, depth of cut, and feed rate. Also, the surface roughness of the specimen was smooth compared to mineral oil. For application in the milling process, palm oil was proven to produce smoother surfaces than mineral oil, and it also extended tool life. The results were the same for sunflower oil when it was tested in drilling machines.

The other type of lubricant is grease. Grease is commonly used to lubricate moving parts in order to reduce friction, wear and corrosion that operated under a high temperature and a long period of time. Hamnelid L (2000) and Baart P *et* al. (2011) claimed that grease can absorb a huge amount of contaminants, such as particles and water without decrement in its lubricating properties hence acting as efficient seals. Besides that, wear is probably due to loss of material that affects the lifetime of several mechanical components such as gears and rolling-element bearings. Rolling contact wear (RCW) is a certain type of wear that results from the continuous of mechanical stressing on the surface of a loaded body rolling against another. To enhance RCW life, lubrication is often applied. The contacting surfaces are separated by a lubricant film in order to keep them apart. One of the famous types used lubricants are greases, which contribute low friction and have a long lubricating time at a low price (Stachowiak GW *et* al, 2001). Therefore, the properties of grease as lubricant has been effectively proven.

2.4 Nano-Additives

Additives are synthetic chemical substances that can enhance lots of different properties of lubricants. They can improve existing properties, against undesirable properties and propose new properties in the base fluids. Nanoparticle additives are categorized into few main groups, which are metal, metal oxide, nano-carbon materials and boron-based nanoparticles (Sheida Shahnazar *et* al, 2015)

2.4.1 Metal

Metal nanoparticles are commonly used in many different applications, such as semiconductors, magnetics, catalysts, and photonic fields. Recently, tribological properties of metal nanoparticles have been of attention to researchers. Zhang *et* al. (2011) mentioned the consequence of Cu nanoparticles on the tribological behaviour of diesel oil with serpentine powder as its nanoparticle was studied. When the concentration of Cu nanoparticles was 7.5 wt%, maximum friction and wear reduction property was detected. Zhang *et* al. (2013) studied the effect of Sn and Fe nanoparticles, which they were mixed with multialkylated cyclopentanes (MACs). MACs have been used as lubricants in the space industry. These nanoparticles decreased friction, wear, and heat in MACs oil. Because of better solubility of Fe in steel bass surfaces, its nanoparticles show better anti-wear ability.

2.4.2 Metal oxide

Metal oxides are usually dispersed in lubricant base fluids as additives, and used for anti-friction and anti-wear agents. Nano-TiO_2 is responsible as an effective heterogeneous catalyst for ring-opening of epoxides. It was proven that even after several cycle of reactions, the catalyst remained unweakened. Nano-TiO_2, as additives in API-SF engine oil and mineral oil, showed acceptable friction reduction and anti-wear behaviors. Wu *et* al. (2007) analyzed TiO_2 and also CuO behaviors as nano-additives to lubricant oil. It was shown that the addition of two different nanoparticles to oil reduces its friction (CuO performed better than TiO_2). Moreover, both produced uniform dispersion and distribution in base oil . Previously, the effects of various nanoparticles as anti-wear additives for exclusively mineral and synthetic-based lubricants were comprehensively described. Nevertheless, in 2013, Arumugam and Sriram studied the influence of nano and microscale particles on the tribological behavior of chemically-modified vegetable oil. They chemically modified raw rapeseed oil by epoxidation, hydroxylation, and esterification to increase oxidation stability and cold flow behavior. They stated that the addition of TiO_2 nanoparticles enhance the lubricating properties (15.2% reduction in friction coefficient) of rapeseed oil better than metal oxide micro particles (6.9% reduction in friction coefficient). It showed that spherical TiO_2 particles have a smaller aspect ratio. Furthermore, the 0.65 mm diameter wear scar for the chemically modified rapeseed oil was reduced by 11 and 6.1% for nano and micro scale TiO_2, respectively. Moreover, the solubility of TiO_2 nanoparticle in rapeseed oil appeared to be acceptable, and it was detected that the particles did not settle even after 80 h.

2.4.3 Nano-carbon materials

2.4.3.1 Zero-dimensional carbon nanomaterials

Lee *et* al. (2007) studied the effect of various volume concentration of fullerene nanoparticle in mineral oil. A disk-on disk testing facility was used in the experiments to get the friction surface temperature and friction coefficient. These two parameters were assessed for raw mineral oils and oils, comprising nanoparticles, by exchanging the variables such as the volume fraction of additive fullerene and normal forces. The frictional surfaces wear and the coefficient of the fraction is measured through the volume concentration of the fullerene nanoparticles in oil. Additionally, the reduction of contact surfaces of moving parts is achievable through the adding of nanoparticles to the lubricants.

2.4.3.2 One-dimension carbon nanomaterials

Nanotubes, nanowires, and nanorods, which are considered as one-dimensional nanomaterials, have a varied range of uses (Lu X *et.* al, 2011). Carbon nanotubes (CNTs) have been of attention to numerous uses over the past decade. However, due to the chemical dullness of CNTs, their dispersion in solvents remains pretty tough. Consequently, in the perspective of lubricative additives, the topic that must be talked first is its stability in the base oil. Chen *et* al. (2005) started revising multi-walled carbon nanotubes (MWNTs) as an oil additive. They improved MWNTs by performing treatments using sulfuric and nitric acids, and refluxing with stearic acid (SA) to improve the tribological properties. They demonstrated that the ability of nano-lubricant for wear and friction reduction subjected not only on the tribological behavior of the nanoparticles, but also on the diffusion pattern of particles in oil. They said that modified MWNTs are steady in oil for more than six months, while for unmodified particles, it is only two months.

2.4.3.3 Two-dimensional carbon nanomaterials

Graphene is a two-dimensional material settled in honeycomb lattice, proposing significant anti-wear and friction properties. It also has appropriate thermal, electrical, mechanical, and optical properties, and is a good idea for lubricating machineries (Joly-Pottuz L *et.* al., 2008).

However, until now, only a few numbers are keen to the evaluation of the tribological properties of graphene.

2.4.3.4 Three-dimensional carbon nanomaterials

Although the micro scale particles of diamond are being broadly used in the industry as a polishing material, it has been verified that nano-sized particles of diamond could perform as ball bearings between sliding parts of a machine (Hirata A *et*. al., 2004). Figure 2.4 reviews some of these studies. Graphite has also been applied both as a powder lubricant and additive.

Author	Nanoparticle	Effect
Xu et al. [123].	Diamond nanoparticle	Anti-wear, Anti-friction, excellent load-carrying capacity. (caused by surface polishing and increase in rubbing surface hardness effects of diamond nanoparticles)
Shen et al. [124].	Diamond nanoparticle	Viscosity increasing effect, Friction coefficient decrease
Chou and Lee [125]	Diamond nanoparticle	Increasing the friction and wear
Chu et al. [126]	Diamond nanoparticle	Improvement of anti-scuffing performance Significant reduction in friction

Figure 2.4 Summary of studies conducted on lubricating properties of diamond nanoparticles

(Source from: Hwang *et*. al. (2011))

2.4.4 Boron-based nanoparticles

Recently, boron-based nanoparticles have been under examination because of its load carrying and anti-wear behaviors. It is too environmental friendly and thermally stable, making them a reliable applicant for use as a lubricant oil additive. In 2014, Zhao *et* al. discovered nano-calcium borate (NCB) for anti-wear and load-carrying abilities for usage as lithium grease additive. They also observe the nanoadditive performance in greases. The ethanol supercritical fluid drying technique was used for nanoscale synthesis of calcium borate. The tribological performance of calcium borate as grease additive for lubricating steel-steel contacts was assessed using an oscillating reciprocating friction and wear tester (SRV). Using an SEM, the microstructure of calcium borate particles was found, while the sizes of the nanoparticles were characterized using laser dynamic light scattering (LDLS). It was expected that the coefficient of friction is dependent on the concentration of nanoparticles. Addition of NCB to lithium grease at a concentration range of 1.5e6% (with optimal concentration of 6%) reduce the friction coefficient and wear, which enables them possible for usage of nanoparticles as friction-reducing agent (friction modifier). In the same year and in another work by Zhao *et* al. (2014), the performance of zinc borate was studied as an additive to sunflower oil additive. Utilizing pin-on-disc and four-ball tribotesters, the anti-wear and friction reduction behavior of sunflower oil, including zinc borate as additive, were reviewed. With particle sizes of 500e800 nm, ZBUP was confirmed to be outstanding in terms of friction reduction and anti-wear properties. The results from this study have confirmed the advantages of using ZBUP in bio-based lubricant in order to produce an environmentally friendly lubricant.

2.5 Wear Debris Analysis

2.5.1 Wear Debris Generation

Wear debris is produced when machine components such as bearings and gears experience a rubbing, sliding or rolling action among their solid surfaces, which cover roughness areas that are disseminated above the surface. Under a microscope, the actual contact area of the two surfaces is spreads depends on several microscopic sharpness contact zones or junctions, considerably dissimilar from the contact area observed with the naked eye (Yuan *et.* al., 2003). Therefore, the actual area of contact is actually the addition of sharpness contact zones proportional to the external load. When load rises, new contact zones are formed and due to the continuous load, contact zones bend plastically and indicate the deterioration of the surface (wear), potentially causing to material loss (Hunt, 1992). There are several possible wear production trends in the life of machinery, and all machinery will typically experience wear processes in three different periods, which are the running-in, useful working life, and a failure zone periods. Figure 2.5 displays the trend lines for dissimilar types of wear particle production over time.

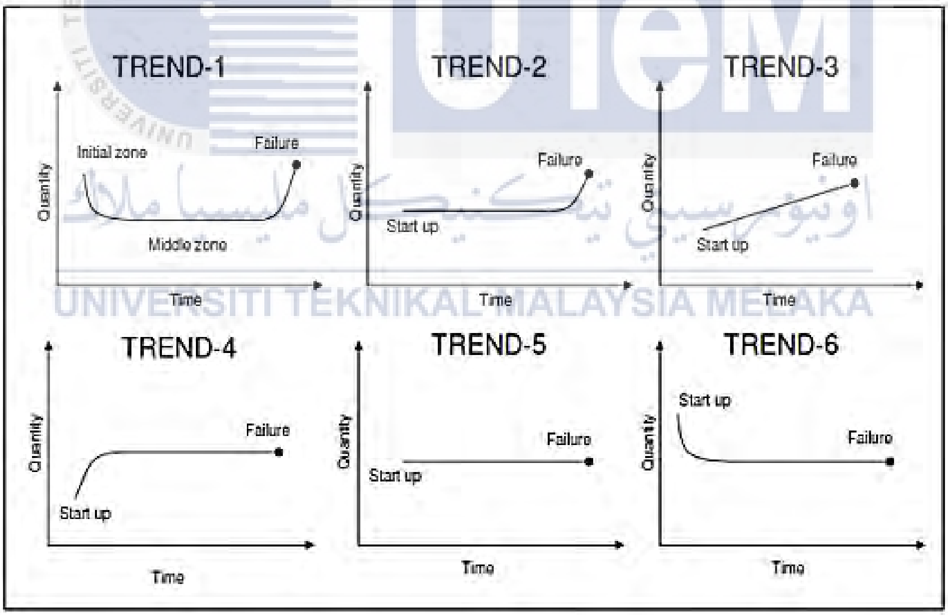


Figure 2.5 Potential quantity features trend in machine component operation

(Source from: Yuan (2003) and Hunt (1992))

Trend-1 is called a 'bath tub' trend, whereby at the starting of the operation the machinery will be having a running-in process where all of the severities in the case of gears will be knocked down. At the beginning stage of graph trend-1, the line express a downward trend, representing a decrease in the wear rate over time, but then slowly deviates to a useful working life zone which is the longest period, where a horizontal, straight line indicates that the wear rate is constant. Lastly, at the end of this zone, the line started to grow, representing an 'onset of failure'; in the failure zone, the wear rate is greater and bigger particles are produced. This trend is a perfect trend, but in real life wear development of a gear mesh very difficult follows this trend. Moubray (1997) stated that only 4 % of failures follow this type of trend. Experiments conducted in this research are actually, none of the trends formed follow this trend except during the running in period.

Trend-2 in Fig 1 displays that the production of wear particle is constant from the starting of the machine's life. At this trend, it is hard to discriminate among the period of running-in and the useful working life zone, since the wear rate in both zones is equivalent. However, when the failure activates and the condition of the machine fails, an upward trend in the graph displays more wear 23 particles in terms of quantity and also sizes are produced. Moubray guesses that only 2% of failure trends will follow this shape.

Trend-3 proposes that wear generation steadily growths over time and 5% of equipment failure look like this trend. Trend-4 shows a bigger rate in wear generation during the running-in time, but the wear rate remains the same all over the remaining life. Moubray recommends that about 7% of equipment failure follows trend 4. Trend- 5 proposes the wear generation is at a constant rate from the starting until the end of life and Moubray recommends about 14% of equipment failure rates follow this pattern.

Finally, in Trend-6, the wear particle generation is decreased during the running-in time but then remains at a constant rate until failure. The most mutual trend in wear particle generation is Trend-6. It exhibited about 68% of failure rates follow this shape. It is hard to fix the starting of failure if the trends stay continuous towards the end of the gear's life.

2.5.2 Types of wear debris particles

Lately, many researchers have a tendency to focus on six main types of wear debris particles and offer diagnostics in terms of the existence of the types of the particles as stated below [28; 29; 30; 31]:

• Rubbing – Random outlines of shape boundary images. Originally from the broken parts of a shear mix layer and considered as a normal wear particle, increment in quantity forecasts approaching disaster. The particles are obtain in most lubricants in the form of platelets.

• Severe Sliding – Renowned by a surface having scratches as parallel grooves, indicating the breakdown of lubricating films and causing unhealthy machine condition. Severe mode reached when the concentration of the particles growths, and scratches and striation marks become more noticeable.

• Cutting wear – Long curved particles, which are produced when one surface enters another, and the existence of large numbers of cutting particles shows the cutting wear process is ongoing.

• Spherical – Like a small ball, these are generally obtained in bearing fatigue cracks from rolling bearing fatigue, cavitation, erosion, welding, or grinding processes with high temperatures.

• Chunk – Chunky particles will usually have one flat or worked surface, though the other three perpendicular dimensions are irregular and unequal with a jagged boundary profile. They are typically produced from rolling fatigue, combined rolling and sliding. The existence of chunk particles shows a high load or extreme rotational speed of gear. Figure 2.6 displays images of different types of wear particles.

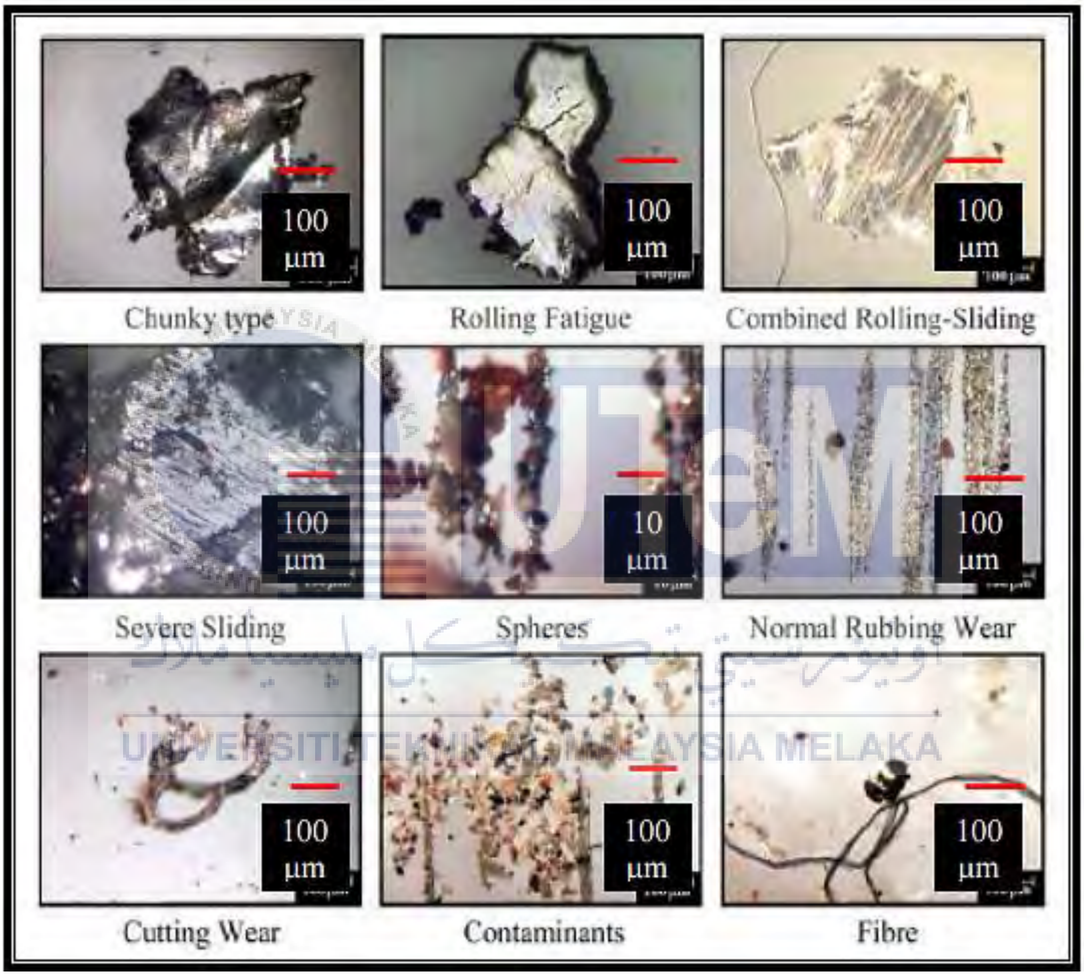


Figure 2.6 Types of wear debris particles

(Source from: Radnui (2005))

2.5.3 Techniques of wear debris analysis technology

There are numerous techniques applied in wear debris analysis. The following are the most typical techniques used [27; 33]:

• Dielectric Constant - A dielectric is an insulator and a dielectric constant is the ratio of electric flux density formed in a material to the value in the vacuum delivered by the similar electric field strength. The sensor detects any change of dielectric constant caused by contaminants such as oxidation, water, mixed fluids, acids, and wear debris.

• Magnetic Flux - Estimation of the concentration of ferromagnetic particles is completed through means of a fixed magnetic field. The field detects the particles and is consequently modified by the presence of the particles. The change in flux can then be translated into the ferromagnetic particle concentration through an algorithm. 100 µm 100 µm 10 µm 100 µm 100 µm 100 µm 100 µm 100 µm 100 µm 43

• Magnetic Collection Switch/Grid - Opposing electrodes by means of an electric grid or plates attract ferromagnetic particles and the existence and general quantity of conductive magnetic particles are detected by current flowing between the electrodes. This technique estimates particle size and concentration by means of the gap between the grid/plates and a time-sequence.

• Induction Sensors - When a particle enters the magnetic field generated by the sensor, the magnetic flux is modified. Induction techniques use this idea to detect the presence of the particles. A fluid sample containing the wear debris particles is introduced into a container or tube with an inductive coil attached around it to create the magnetic field. The sensor is capable of differentiating between ferrous and non-ferrous debris and electronic circuitry has the ability to ignore signals from air bubbles.

• X-ray Fluorescence (XRF) Spectroscopy - In identifying and quantifying the chemical element of wear debris particles, the sample is irradiated with X-rays, energizing electrons to higher levels. As electrons return to their initial state, they release X-rays at an energy level, which contains the signature of a particular element. The magnitude of the energy level is directly related to the concentration of the element. The element and its concentration can then be identified and measured.

• Laser imaging - A laser imaging optical flow cell is used to examine equipment fluids such as hydraulic oil, lubricants and fuels. It captures images of the fluid which contains wear debris particles as it passes through a flow cell, and is able to measure the size and classify the type of the particles.

• Dielectric Loss Factor - Water, glycol and oxidation product contamination all increase the dielectric loss factor or Tan delta. Similarly, metallic wear, debris, and soot, which are electrically conductive, also increase Tan delta.

• Electrostatic sensor -This technique, originally invented to detect debris in the gas path of a jet engine, monitors the electrostatic charge and any changes associated with debris. An advantage of the electrostatic technique is that it can directly measure debris concentration and hence can be used to provide an early warning for component degradation.

2.6 Oil Analysis Condition Monitoring

Machine condition monitoring or predictive maintenance is the preparation of evaluating a machine's condition by periodically gathering data on key machine-health indicators to identify when to schedule maintenance. One of the keys to ensure machinery operating at optimal performance includes monitoring and analyzing lubricant oils for characteristics such as contamination, chemical content and viscosity. Money spent annually replacing machinery components that have worn out due to the incapability of the lubricants to accomplish the required task. Knowing how to understand changing lubricant properties can increase both the uptime and the life of mission critical capital equipment. The presence or amount of debris and particles from wearing parts, erosion and contamination deliver perceptions about the issues affecting performance and reliability. Lubricant, fuel and other key fluid analyses offer critical early warning information indicative of machine failure. Analyzing and trending the data means can schedule maintenance before a serious failure happens.

2.6.1 TriVector Minilab

A Trivector™ Minilab was designed to encounter the needs of industrial reliability engineers to monitor oil conditions of rotating equipment such as gearboxes, compressors, and turbines. It is the most cost effective method for a comprehensive on-site oil analysis test lab. It offers oil parameters indicative of machine wear, contamination and degradation (chemistry) and plots the information on an innovative and straightforward Trivector™ chart. Apart from that, the oil condition data can then be combined into other predictive maintenance techniques such as vibration and thermal imaging which deliver a comprehensive overview of machine condition. The comprehensive Minilab involves tests such as dielectric (oil degradation), water contamination, ferrous particles, particle count, viscosity and wear debris analysis. It is easy to practice and the entire test suite can be accomplished in less than 10 minutes.

2.6.2 ISO 4406 Cleanliness Codes

The International Organization for Standardization formed the cleanliness code 4406:1999 as shown in Figure 2.7 to compute particulate contamination levels per milliliter of fluid at three sizes: 4μ[c], 6μ[c], and 14μ[c]. This ISO code is stated in 3 numbers: 19/17/14. Each number represents a contaminant level code for the correlating particle size. The code contains all particles of the specified size and larger. It is important to note that each time a code rises the number range of particles doubles.

ISO 4406:1999 Code Chart

Range Code	Particles per milliliter More than	Up to / Including
24	80000	160000
23	40000	80000
22	20000	40000
21	10000	20000
20	5000	10000
19	2500	5000
18	1300	2500
17	640	1300
16	320	640
15	160	320
14	80	160
13	40	80
12	20	40
11	10	20
10	5	10
9	2.5	5
8	1.3	2.5
7	0.64	1.3
6	0.32	0.64

Figure 2.7 IS0 4406: 1999 Code Chart

2.6.3 NAS 1638 Cleanliness Code

The NAS system in Figure 2.8 was originally established in 1964 to state contamination classes for contamination confined in aircraft components. The application of this standard was extended to industrial hydraulic systems as nothing else occurred at the time. It is still referred to in some industries, although the ISO 4406 cleanliness codes are more generally found. The NAS 1638 coding system explains the maximum numbers permitted of 100mL volume at various size intervals (differential counts) compared to using cumulative counts as in ISO 4406. Even though there is no supervision given in the standard on how to quote the levels, most industrial users quote a single code which is the highest recorded in all sizes. This convention is employed with laser particle size analysers.

Class	Maximum Particles/100mL in Specified Size Range (μm)				
	5-15	15-25	25-50	50-100	>100
00	125	22	4	1	0
0	250	44	8	2	0
1	500	89	16	3	1
2	1,000	178	32	6	1
3	2,000	356	63	11	2
4	4,000	712	126	22	4
5	8,000	1,425	253	45	8
6	16,000	2,850	506	90	16
7	32,000	5,700	1,012	180	32
8	64,000	11,400	2,025	360	64
9	128,000	22,800	4,050	720	128
10	256,000	45,600	8,100	1,440	256
11	512,000	91,200	16,200	2,880	512
12	1,024,000	182,400	32,400	5,760	1,024

Figure 2.8 NAS 1638 Contamination Classification System

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this research, the methodology is constructed into five main phases. The initial phase shall discuss on the research and studies regarding the performance of hBN nanoparticles alternative additive and the effect of contaminants on ball bearing. The second phase is process of designing and fabrication of test rig for the experimental purpose. Next, the third phase is focusing on the process of oil sample preparation and the homogenization process. The fourth phase briefly explains on the experiment procedures and the analysis of the results gained. Finally, the fifth phase is the comparison of the data obtained at different concentrations of hBN nanoparticles used in the experiment.

3.2 Project Flow Chart

The process steps of project are based on the project flow chart constructed. Therefore, several steps are taken in order to achieve the objectives of the project. Literature review is carried out as the first step in this project. Next, a project draft and test rig is designed by using software. After the design process is finished, the test rig is then fabricated based on the design specifications. Later, the sample preparation is performed by dispersing hBN nanoparticles additive into diesel engine oil. The mixture is then undergoes homogenization process. Once the samples are prepared, the experiment can be performed by inserting different types of ball bearings onto the test rig and run it under several time intervals. After that, the tested oil samples are taken and the data are collected and compared. Besides, the analysis of the data gained is performed. Further analysis and review on the performance of the hBN nanoparticles is carried out based on the results. The methodology of this project is summarized in the project flow chart as shown in **Figure 3.1**.

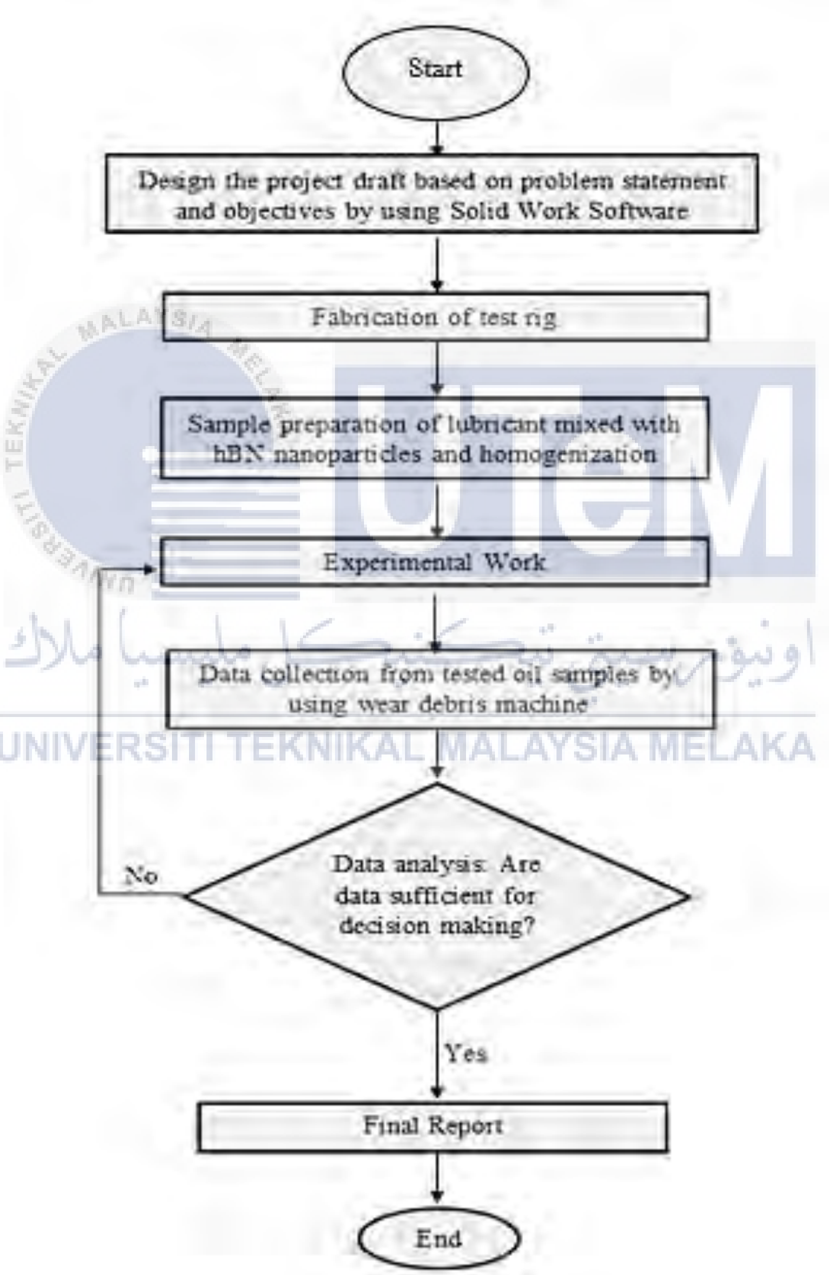


Figure 3.1 Project flow chart

3.3 Research and Studies

Research and studies are the efficient investigation of materials and sources to create facts and achieve new conclusions for a better understanding regarding the project. A literature review is carried out as the first step in this project. All the relevant information and ideas are obtained from the published articles, journals, books and other internet sources. The collected information will be then used to run the experiment and analyse the data gained. Having a discussion with the supervisor in charged is important in completing this project. Since that, supervisor can highlights and generates brilliant ideas and information based on the project research. Research and studies initiated with the scope of the project and designation of the experimental test rig. All specifications of the test rig to run the oil samples need to be precise and clear. The design specifications of the test rig are included main components and materials used as well as their dimensions. Drawing of the experimental test rig is assisted with a Computer-Aided Design (CAD) by using SolidWorks software.

3.4 Design of Test Rig

The design of experimental test rig is assisted with a computer-aided-design (CAD) by using SolidWorks software. By using CAD software, design of the experimental test rig will be more accurate, precise and easy to sketch with the aid of the programs before fabrication process. The design drawing is shown in Figure 3.2.

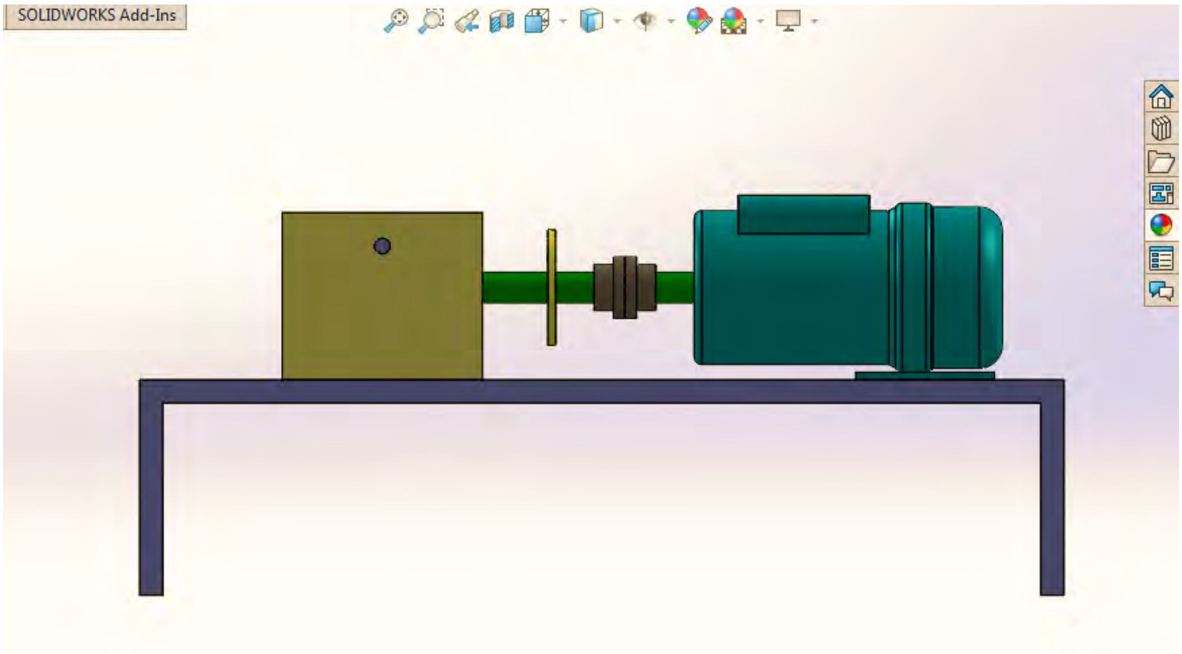


Figure 3.2 Test rig design drawing

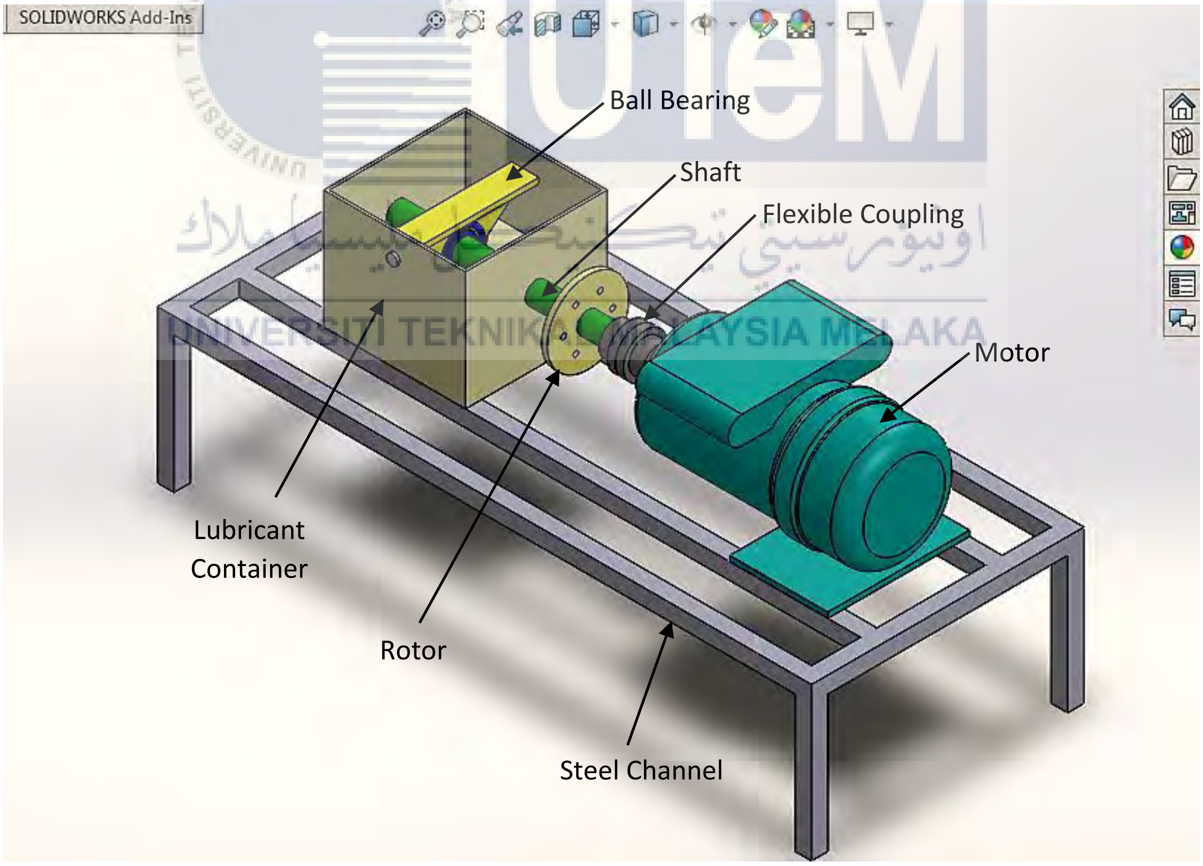


Figure 3.3 Main components of test rig

Main components of the experimental test rig such as motor, rotor, flexible coupling, ball bearing and lubricant container are shown in isometric drawing in Figure 3.3. The shaft is connected to the DC motor using flexible coupling. This shaft also attached with a rotor at middle part and deep groove ball bearing at the end of shaft. All the components are installed on steel channel which is welded together to reduce the vibration. A DC electric motor of 1 Horse Power (Volt-240V, Current-2.3 A) with operating speed of 1440 rpm is used in the experiment setup. Lubricant mixed with different concentration of hBN nanoparticles additive will be used and drain out through a hole on the lubricant container which is tapped with a block nut.

3.5 Fabrication of Test Rig

Figure 3.4 Fabrication Process

Once finished the designing process, fabrication process is started. The fabrication process including of cutting, joining and assembling procedure. All the procedures are conducted based on the design, materials and dimensions selected. In this process, the steel channel and shaft are undergone cutting process according to dimension designated. After that, all the components are assembled and installed by applying joining method. The joining technique comprising of arc-welding process and bolted connections of main components. The arc welding process as shown in Figure 3.4 is a process involves a consumable or a non-consumable electrode. An AC or DC power supply produces an arc between the tip of the electrode and the work piece to be welded. This is to ensure that the work pieces tightly fixed.

3.6 Oil Samples Preparation and Homogenization Process

Before run the experiment, the oil sampling must be completed. Oil sampling is the process of dispersing Hexagonal Boron Nitride (hBN) nanoparticles powder into SAE 15W40 diesel engine oil. The oil sampling is initiated with the preparation of materials and apparatus as shown in Figure 3.5, such as six bottles of 500 ml, hBN powder, SAE 15W40 diesel engine oil, spatula, 1L beaker, 10 ml cylindrical beaker, watch glass and digital analytical balance.

Figure 3.5 Materials and apparatus preparation

For this experiment, six bottles of 500 ml of oil are prepared with different hbN concentrations which are 0 %, 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 %. The formula to calculate the mass of hBN powder at different concentrations is:

$$m = \rho \times v \tag{3.1}$$

Where m is the mass of powder in gram, ρ is the density of hBN in g/cm^3 and v is the volume of oil in ml. The calculations for hBN concentrations are as follows:

Volume of diesel engine oil, v = 500 ml × percentage of concentration, %

Density of hBN powder, ρ = 2.3 g/cm^3

For 0.1 % concentration of hBN powder:

Volume, v = 500 ml × 0.1 % = 0.5 ml

Mass, g = 2.3 × 0.5 = 1.15 g

Therefore, the mass of hBN powder to be mixed with 500 ml engine oil is 1.15 g

For 0.2 % concentration of hBN powder:

Volume, v = 500 ml × 0.2 % = 1 ml

Mass, g = 2.3 × 1 = 2.3 g

Therefore, the mass of hBN powder to be mixed with 500 ml engine oil is 2.3 g

For 0.3 % concentration of hBN powder:

Volume, v = 500 ml × 0.3 % = 1.5 ml

Mass, g = 2.3 × 1.5 = 3.45 g

Therefore, the mass of hBN powder to be mixed with 500 ml engine oil is 3.45 g

For 0.4 % concentration of hBN powder:

Volume, v = 500 ml × 0.4 % = 2 ml

Mass, g = 2.3 × 2 = 4.6 g

Therefore, the mass of hBN powder to be mixed with 500 ml engine oil is 4.6 g

For 0.5 % concentration of hBN powder:

Volume, v = 500 ml × 0.5 % = 2.5 ml

Mass, g = 2.3 × 2.5 = 5.75 g

Therefore, the mass of hBN powder to be mixed with 500 ml engine oil is 5.75 g

After the calculations are made, the mass of hBN powder to be mixed with every 500 ml of engine oil are known. Firstly, the SAE 15W40 diesel engine oil of 500 ml is poured into a 1L beaker as shown in Figure 3.6.

Figure 3.6 Pour of 500 ml engine oil into a beaker

500 ml of engine oil is then poured into a bottle sample. Next, the hBN powders are taken out by using spatula and weighed on digital analytical balance as shown in Figure 3.7, based on the value of mass that have been calculated previously. The digital analytical balance is set to zero value before taking the measurement in order to avoid zero error.

Figure 3.7 Weighing of hBN powders

The weighed hBN powder are then slowly put on watch glass as shown in Figure 3.8 before mixed with the engine oil.

Figure 3.8 hBN powder on watch glass

Every oil samples are then pour with different concentrations of hBN nanoparticles powders as shown in Figure 3.9.

Figure 3.9 Pour of hBN powders into oil sample

Once the oil samples are ready, they are taken to tribology laboratory for homogenization process as shown in Figure 3.10. Basically, the homogenization process is any of certain methods used to mix two mutually non-soluble liquids completely blend. This is achieved by changing of hBN nanoparticles into a state containing of tiny particles dispersed uniformly throughout the diesel engine oil by using ultrasonic homogenizer. Therefore, the hBN nanoparticles are decreased in size and dispersed uniformly through the diesel engine oil. After the homogenization process is complete, the oil samples are ready to run on the test rig.

Figure 3.10 Homogenization process

3.7 Experimental Work

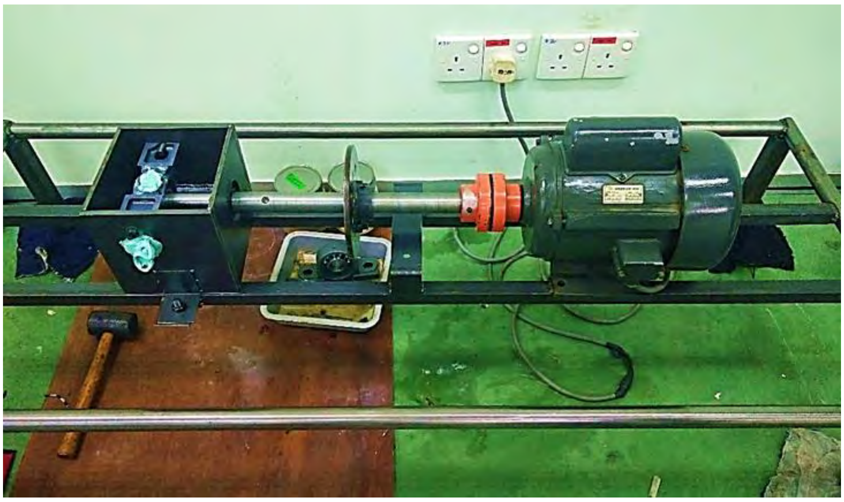


Figure 3.11 Experimental set up

After the homogenization process, the oil samples are then ready to run on the test rig as shown in Figure 3.11. At the beginning of the experiment, the ball bearing must be attached to end of shaft inside the lubricant container. The ball bearing is then tighten up to the left and right surfaces of lubricant container by using bolt nuts. This is to ensure the ball bearing in fixed position and to prevent it from rotating altogether while the shaft is rotating. Next, a bolt nut is attached to the rotor. The bolt nut is act as a load to create unbalance while the shaft is rotating. When the shaft becomes unbalance, it will create a greater vibrations due to the unbalance condition. Therefore, the unbalance that occurred will cause the surface contact of between shaft and the ball bearing is higher. Due to that the frictional force between the two contacted surfaces become larger.

After that, the lubricant oil that mixed with 0 % of hbn nanoparticles is then poured into the lubricant container. The level of the oil is not necessarily full and the ball bearing is not fully submerged inside the lubricant oil. The motor is then switched on and operated for 30 to 40 minutes. The procedures are repeated for different value concentrations of 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % with different physical conditions of ball bearing: healthy bearing, outer defected bearing and inner defected bearing.

Once the experiment completed, the operated oil samples are then taken from lubricant container for data collection and analysis. For the data collection, the oil samples are tested by using wear and debris machine as shown in Figure 3.12, called Spectro 5200 Trivector Oil Analyzer. Invisible contaminants, corrosion, inappropriate lubrication and machine wear are the factors that affect the performance of machinery. Due to that, Spectro 5200 Trivector Oil Analyzer is a multi-function tool that discovers most lubricant-related complications and allows on-site analysis of machinery oils and lubricants. It offers full hints of metal wear, contamination and lubricant chemistry. Besides, the Spectro 5200 is specially designed to measure the value of dielectric, magnetic differentiation of wear particles, water content, viscosity, laser particle counting and microscopic examination. Moreover, it can measures, logs and trends the lubrication condition of rotating machinery and identifies contamination and machine wear.

Figure 3.12 Spectro 5200 Trivector Oil Analyzer

3.7.1 Oil Analysis Test

In this case, there are four tests carried out to obtain the value of contaminants in the oil samples. The first test is chemistry test. The chemistry test is performed in order to accurately measure the dielectric of the "neat," undiluted oil sample, and identify the chemical index. The second test is wear and contamination test. Wear and contamination test is to identify water and metal debris that settle out of the oil by using sensor. Third test is particle count test. Particle count test is to calculate particles and identify particle size spreading in eight different size ranges. The last test is ferrography test. Ferrography test is to observe the size, shape and texture of different types of contaminants and wears inside the oil sample.

3.7.1.1 Chemistry Test

The oil sample is taken from the lubricant container after run for 30 to 40 minutes. After that, syringe is filled up with 10 ml of neat oil or undiluted oil from the sample bottle as shown in Figure 3.13. Valve is turned into correct position.

Figure 3.13 10 ml of undiluted oil taken from sample bottle

The tip of syringe is then placed into the hole at the bottom of the Test 1 chamber and injected into hole at bottom as shown in **Figure 3.14**

Figure 3.14 Insertion of syringe into Test 1 chamber

Button 1 is pressed as shown in Figure 3.15 and the chemistry test is completed. The chemistry test result is shown at analysis data system which is transferred to the computer.

Figure 3.15 Button 1 of chemistry test

3.7.1.2 Wear and Contamination Test

The empty sample bottle is weighed by using analytical digital balance as shown in Figure 3.16. Once the value is appeared on the computer, the scale button is pressed.

Figure 3.16 Weighed of empty sample bottle

After that, the empty sample bottle is filled with neat oil and placed on the scale as shown in Figure 3.17. The button is pressed to weight the sample.

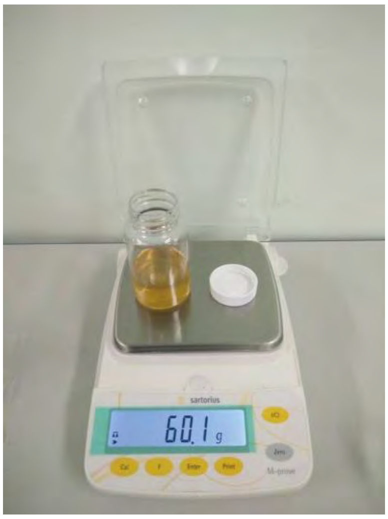


Figure 3.17 Weighed of neat oil sample bottle

Next, the sample bottle is filled up with a diluent solution which is two times of neat oil mass as shown in Figure 3.18. Paraffin oil is used as the diluent. Diluent is used for heavy oil sample in order to filter the solvent used for dilution otherwise it can contributes error to particle count itself later. Dilution reduces the viscosity of oil sample that having a high viscosity range to a very low range of viscosity. This enables the particles to settle during the test time. Dilution also makes cleaning easy and cross-contamination unlikely. Therefore, it has to be balance. The scale button is pressed.

Figure 3.18 Addition of diluent

The bottle containing the mixture of diluent and neat oil is then shake vigorously about 30 seconds. After that, the diluted oil is poured into Test 2 chamber about 20 ml as shown in Figure 3.19. The sensor is automatically detect the fluid, start the test immediately and the LED light will stop flashing.

Figure 3.19 Pour of diluted oil into Test 2 chamber

Large syringe is filled up with 30 ml of diluted oil. Then, the tip of syringe is inserted to the top chamber as shown in Figure 3.20. The pump is switched on approximately 30 seconds in order to remove the air bubbles inside the oil.

Figure 3.20 Insertion of large syringe to the top chamber

The syringe is then removed from the chamber and the guarding kit is taken out. Finally, the tip of syringe is attached to the bottom chamber on the right as shown in Figure 3.21. After the test is completed, the pump is switched on in order to clean all the chambers.

Figure 3.21 Attachment of syringe to bottom chamber

3.7.1.3 Particle Count Test

A syringe is filled up with 30 ml of diluted oil. Guarding kid is installed to the syringe to compression of syringe while the test is running. Finally, the syringe is put at degasing chamber as shown in Figure 3.22 and vacuum pump is switched on about 30 seconds to eliminate the bubbles inside the oil

Figure 3.22 Syringe attached to degasing chamber

3.7.1.4 Ferrography Test

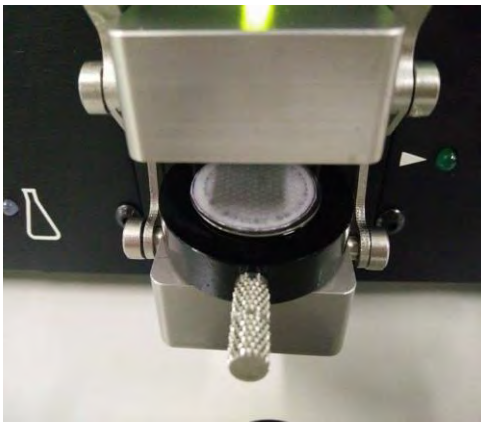


Figure 3.23 Patch port

The main purpose of ferrography test is to observe the particle shapes, sizes and textures as well as identify elements of different type of wear or contaminant produced inside the oil sample. Patch filter is placed on the patch port as shown in Figure 3.23. The wear debris filter patch maker is connected between the Test 2 chamber and the drain. Therefore, as the diluted oil sample is drained from the Test 2 chamber, it passes through the filter patch maker. The filter patch must be taken out before the cleaning process. The filter patch is taken out by using forceps. The filter patch that containing the oil sample is then put on the specimen. The specimen is then placed on the specimen stage as shown in Figure 3.24. The specimen is ensured to locate below the objective lens in order to have a clear image. The focus knob on the microscope can be adjusted for better size of image.

Figure 3.24 Placement of specimen on specimen stage

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discuss on the results obtained from the OilView Analyzer. OilView Analyzer software provides useful and fast results to solve lubricant related problems as well as monitoring the condition of oil. In this case study, oil samples are taken for healthy, inner and outer defected bearings which are then run on a test rig for about an hour. Besides, the oil samples (SAE 15W40) are dispersed with different percentage concentration volumes of Hexagonal Boron Nitride (hBN) which are 0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5%.

In this section, the TriVector plot data obtained combines multiple test results into one graph in order to represent the condition of oil samples based on their category. Apart from that, the trending of contamination index against the hBN concentration is observed to identify the correlation between both variables. Moreover, the relation between wear rate and hBN concentration is discovered as well. Finally, the Wear Debris Analysis (WDA) tab is used to support in analysis and documentation of visual microscopic observations of wear debris and contamination extracted from operated oil samples.

4.2 Results

4.2.1 Healthy ball bearing

Table 4.1 Results for Healthy Ball Bearing

Reference Oil	**Shell – Rotella T – 15W40**					
Sample of hBN concentration (%)	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Wear Rate	0	0	0	0	0	0
Ferrous Index	0	0	0.6	0.6	0	0
Chemistry	0	0	0	0	0	0
Contamination Index	71	51	51	41	21	12
ISO >4 – n/a	22	22	23	23	23	20
ISO >6 –n/a	22	22	23	23	21	13
ISO >14 – n/a	21	21	15	19	13	8
NAS 1638	17	15	15	14	13	4

For clean or fresh oils, all Oil View Analyzer index should be at or approximately zero. Increasing index values indicates increasing levels of degradation or contamination. In this experimental study, oil will be contaminated in two main ways. One will be through debris that comes in through the air intake into the lubricant container. The second source of contamination will be metal shavings in between two contacted surfaces of the ball bearing and the shaft itself. The lesser the quality of the oil, the higher percentage of these shavings because there will be more metal to metal contact inside the bearing component. Due to this condition, the oil is not suitable to be used for a long period of time as the contaminated oil will decrease the oil performance and bearing life. In addition, machine with imbalance or misalignment will have increased loads, thus reducing the life of bearing (Graney, 2008).

In Table 4.1, the particle counting indicates highest contamination index at hBN concentration of 0 % which is 71. Meanwhile, the lowest contamination index is 12 at 0.3% of hBN concentration. The rests are 51, 51, 41 and 21 at 0.1%, 0.2%, 0.3% and 0.5% of hBN concentration respectively. Besides that, the value of wear rate, chemistry and ferrous index are approximately zero. Thus, it shows a good condition of oil sample and good lube chemistry as well as healthy ball bearing even though has a high contamination. Hence, the oil is suitable for continued use. However, the dispersion of hBN into the oil sample gradually decrease the contamination production. In terms of particle count, it shows a decrement amount of particles existence at different sizes. For 4 micron size, the highest value would be 23 at 0.2%, 0.3% and 0.4% but then decreased to 20 at 0.5%. Meanwhile, for 6 micron size, the particle amount increase initially and after some time decrease gradually same as 14 micron size. Overall, the smaller particles size (4 micron) will be much greater compared to bigger particles size (6 micron and 14 micron). The production of small and fine particles which are less than 5 micron indicate the normal wear condition. This is probably because of fatigue wear production through the sliding friction between the shaft and bearing. Meanwhile, abnormal wear condition tend to proceed gradually with many fine wear particles together with coarse or large wear particles. Anyhow in this circumstance, the larger particles probably generated from large particles of contamination (dust, fibers and etc.) not the wear itself since the wear rate are zeroes. According to NAS 1638, the class range also decreasing gradually from 17 to 4 by means the oil cleanliness level is improved with increasing of hBN percentage volume.

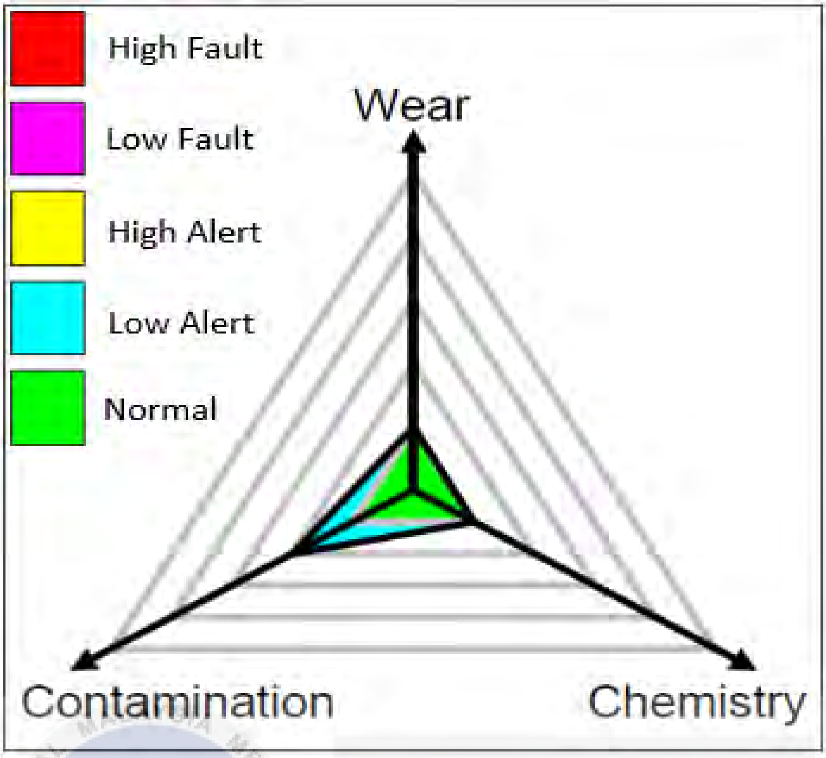


Figure 4.1 TriVector Plot for Healthy Ball Bearing

The TriVector plot merges several test results into one graph. It involves of three equally perpendicular axis extending from a mutual origin. The results of an oil test are characterized to fit into one of three evaluation areas: wear, contamination, or chemistry. Each axis represents one of these categories. The plot reports oil condition in each category in a range from "Normal" to "Alert" to "High Alert" to "Fault" to "Extreme." A sample with a normal wear and lube chemistry otherwise a low alert contamination is appeared on Figure 4.1. It indicates a low contamination in oil sample but a healthy and normal oil and bearing condition. Therefore, the oil still can be used for the machine operational.

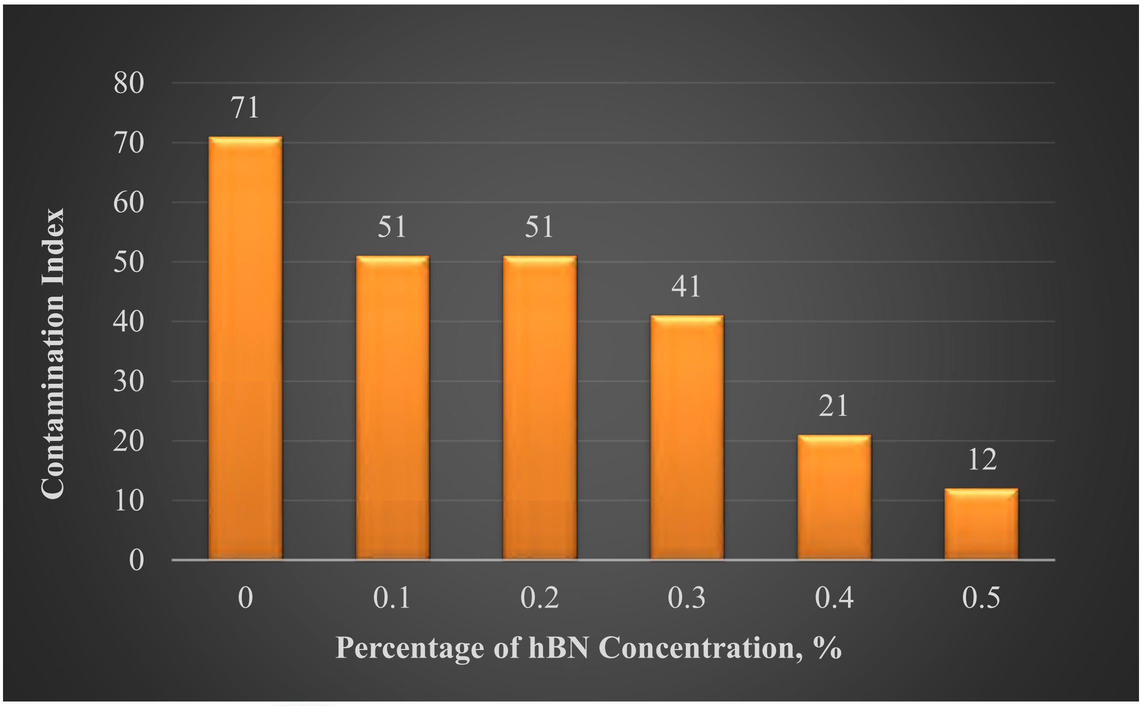


Figure 4.2 Graph of Contamination Index against Percentage of hBN Concentration, % for Healthy Ball Bearing

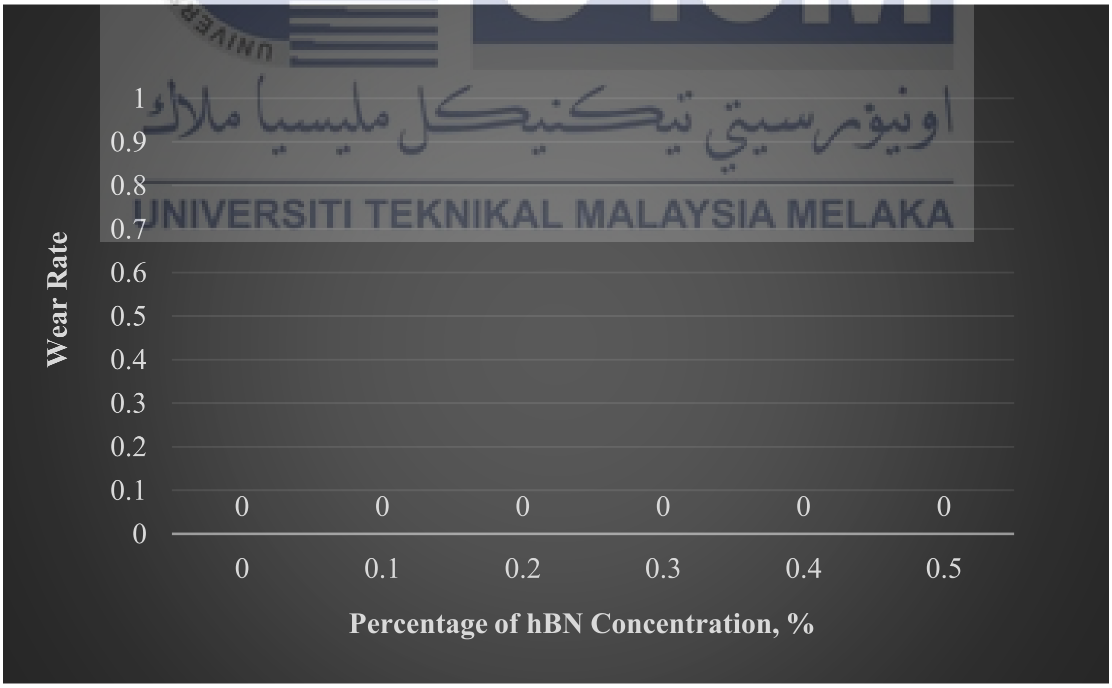


Figure 4.3 Graph of Wear Rate against Percentage of hBN Concentration, % for Healthy Ball Bearing

Based on Figure 4.2, the contamination index is decreasing with the percentage of hBN concentration. With no addition of hBN (0% concentration), the contamination shows a high index value which is 71. However, after the oil sample mixed with hBN nanoparticles, it displays a positive change where contamination value decreased steadily. Due to tiny size (70 nm) and spherical shape of nanoparticles, so it embedded in wear debris easily and coat the surface of contaminants. As a result, the coefficient of friction between two contacted surfaces will be reduced and production of contaminant will be decreased as well. In addition to that, there is no significant wear produced by the healthy ball bearing as shown in Figure 4.3 whereby the Oil Analyzer indicates zero wear index at all hBN concentration. This is might be due to a short operational time of the test rig as well as no defect on the surface of inner and outer race of ball bearing. Since the nanoparticles completely covered the asperities, so it leads to mending effect on the inner and outer race of the bearing and they exhibited the lowest wear rate (Celik *et*.al. 2013). The existence of adequate nano hBN additives in engine oil avoids direct contact and allows friction and wear reduction. Moreover, addition of boron additive decrease the wear rate and alter the sliding effect to the rolling effect that leads to reduction of friction at the two metal surfaces (Ilman *et* al., 2013).

4.2.2 Inner defected ball bearing

Table 4.2 Results for Inner Defected Ball bearing

Reference Oil	**Shell – Rotella T – 15W40**					
Sample of hBN concentration (%)	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Wear Rate	71	76	72	60	45	7
Ferrous Index	24.4	56.4	27.2	17.8	11.8	3.9
Chemistry	0	0	0	0	0	0
Contamination Index	71	51	41	30	21	21
ISO >4 – n/a	22	23	23	23	23	23
ISO >6 –n/a	22	23	23	22	21	21
ISO >14 – n/a	20	16	16	15	13	14
NAS 1638	17	15	14	14	13	13

For inner defected ball bearing, the values of contamination index for outer defected bearing are also decreasing with percentage of hBN. The contamination index decrease from 71 to 21. However, the wear rate indicates higher than the healthy ball bearing. As shown in Table 4.2, the wear rate at 0%, 0.1%, 0.2%, 0.3%, 0.4 and 0.5% are 71, 76, 72, 60, 45 and 7 respectively. Even though, the wear rate is lower initially at 0% compared to 0.1%, still the wear rate reducing steadily after that. . Besides, the ferrous index is highest at 0.1% which is 56.4 but then decrease to 3.9 at 0.5%.Thus, the formulation of ferrous metal inside the oil is decrease by dispersing of hBN. The chemistry lube is zero, therefore shows a good oil condition even tough has high wear rate and contamination. In terms of particle count, the 4 micron size shows an increment from 22 to 23. Meanwhile, 6 micron size of particles increased initially from 22 to 23 and decreased back to 21. For 14 micron size, the values are reduced from 21 to 14. Rationally, inner race part produces a greater value of wear rate and contamination due to the direct contact between shaft and bearing itself. Moreover, a large vibration and misalignment give a huge impact by producing a large sliding friction between two contacted surfaces as there is severity and defected on the inner race part. Existence of load on the rotor and a small cracked on the inner race part also contribute to unbalance condition thereby increase the stress formation on the contacted surfaces indirectly cause a massive wear to the bearing.

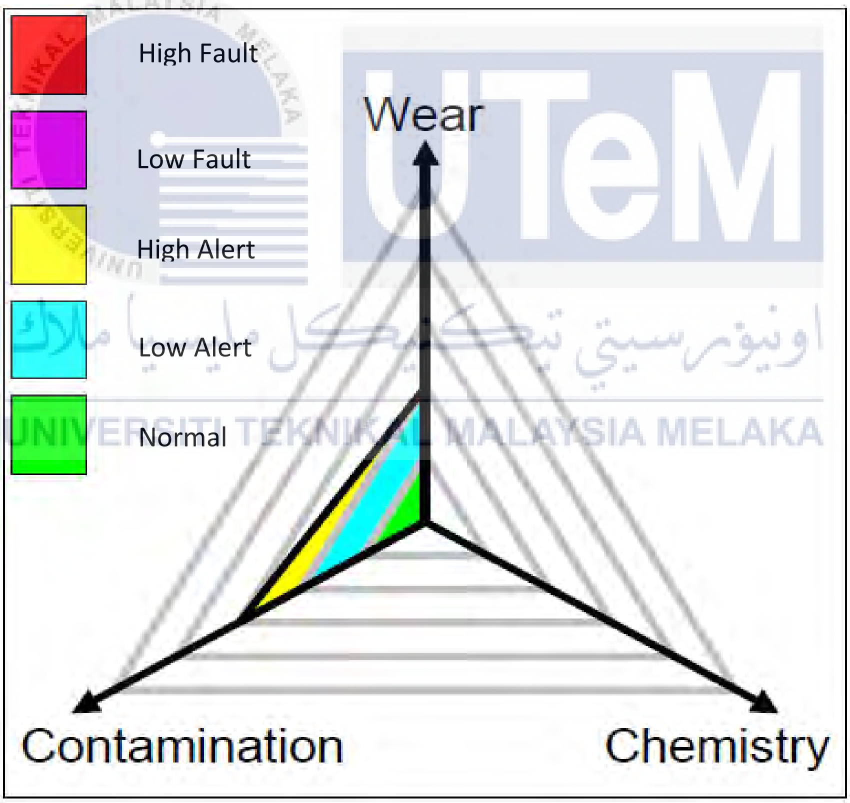


Figure 4.4 TriVector Plot for Inner Defected Bearing

According to TriVector Plot in Figure 4.4 above, the oil sample indicates a good condition of chemistry lube but with a high alert of wear rate and contamination. However, TriVector shows that bearing is not in critical condition even there is a little defects on the inner race part. Consequently, if the bearing is kept or operated for a long period of time, it can minimize the bearing life despite of decreasing the oil performance. Therefore, the oil condition should be monitor periodically to avoid any major malfunction or failure to other parts of the bearing and machine.

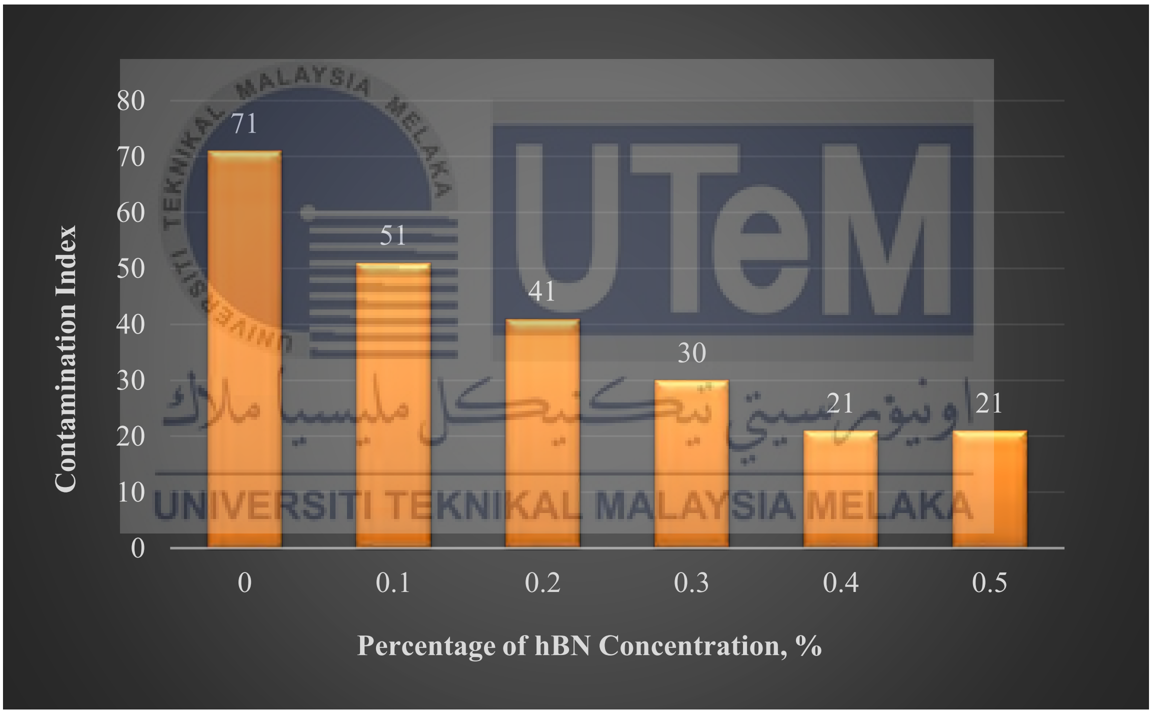


Figure 4.5 Graph of Contamination Index against Percentage of hBN Concentration, % for Inner Defected Ball Bearing

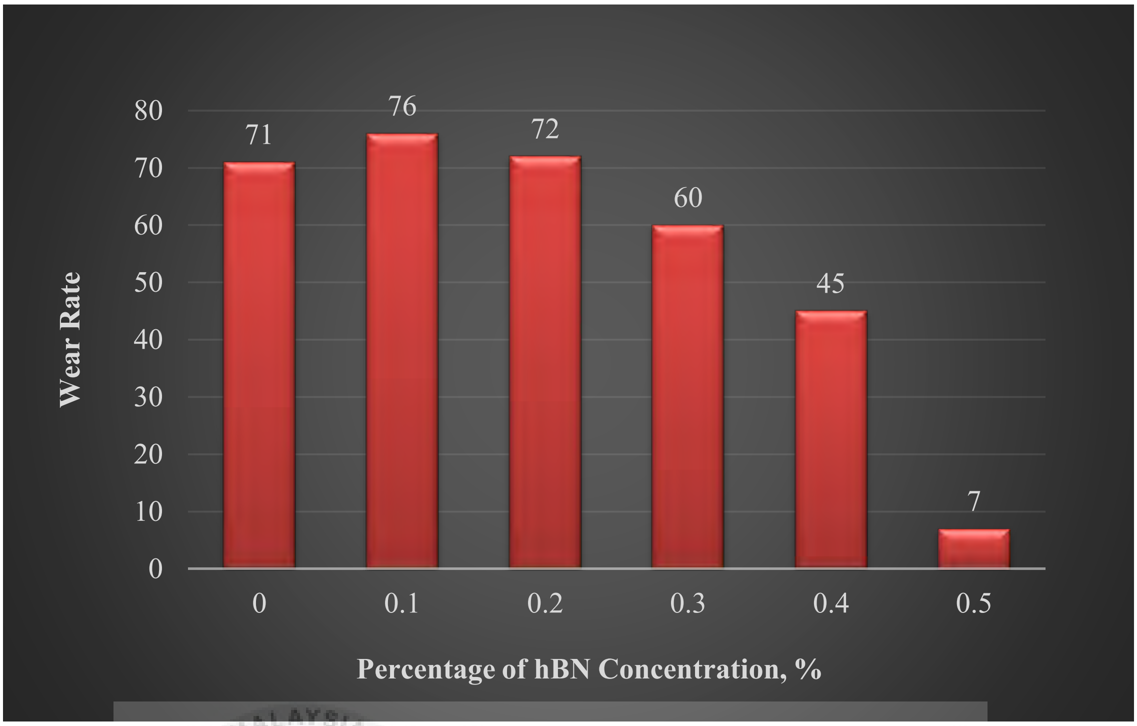


Figure 4.6 Graph of Wear Rate against Percentage of hBN Concentration, % for Inner Defected Ball Bearing

Based on Figure 4.5, the contamination index are decreasing gradually from 71 to 21 with increasing of hBN concentrations. Overall, the wear rate is highest for inner defected bearing compared to healthy bearing and outer defected bearing. However, the wear rate is increase initially but then reduce significantly as shown in Figure 4.6. With additional increase in load and speed, frictional heating may occur due to the interaction of the severities of two contact surfaces and in this case the wear process may consist of creation and elimination of oxide on the surface thereby resulting in decrease of wear rate (Mohd Fadzli Abdollah *et* al., 2014)

4.2.3 Outer Defected Ball Bearing

Table 4.3 Results for Outer Defected Ball Bearing

Reference Oil	**Shell – Rotella T – 15W40**					
Sample of hBN concentration (%)	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Wear Rate	77	72	66	52	44	3
Ferrous Index	60.3	26.1	20.5	14.5	11.2	3.3
Chemistry	0	0	0	0	0	0
Contamination Index	71	51	51	41	71	21
ISO >4 – n/a	22	22	22	23	23	24
ISO >6 –n/a	22	22	22	23	22	21
ISO >14 – n/a	21	21	21	17	20	12
NAS 1638	17	15	15	14	17	13

Based on the Table 4.3, shows the highest wear index at 0% which is 77 and lowest wear index at 0.5% which is equivalent to 3. Besides, the wear rate is decreasing as the concentration value of hBN increasing. The ferrous index also indicates a significant decrement by dispersing the hBN nanoparticles indirectly reduce the sliding friction and formulation of ferrous wear. On the other hand, the chemistry index is equivalent to zero for entire concentration volumes. Thus, it still indicates a good lubes chemistry otherwise the wear rate and contamination are high. In term of contamination, the values are decreasing gradually from 71 to 21 with increasing of hBN concentration values. The contamination is high due to existence of dirt, dust and debris during the operational of test rig. However, the presence of hBN reduce the friction of defected surface contacts indirectly produce smaller debris (ferrous). In term of particle counts, the 4 micron size particle shows a highest value compared to larger size of particle (6 micron and 14 micron). However, the amount is decrease significantly at the end. The NAS 1638 shows that class range is decrease from 17 to 13 as well.

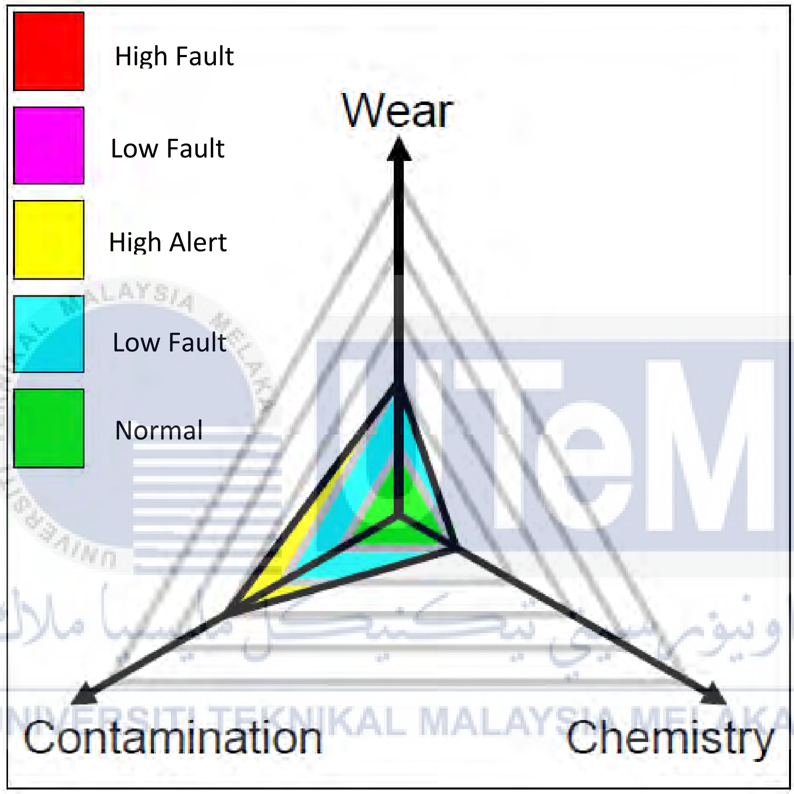


Figure 4.7 TriVector Plot for Outer Defected Ball Bearing

Based on Figure 4.7, the TriVector Plot shows a good lube chemistry but with high contamination and wear rate. However, the wear rate is lower compared to inner defected bearing but higher than healthy bearing. Since the outer race and inner race are separated with balls of the bearing, therefore the sliding friction will be lesser.

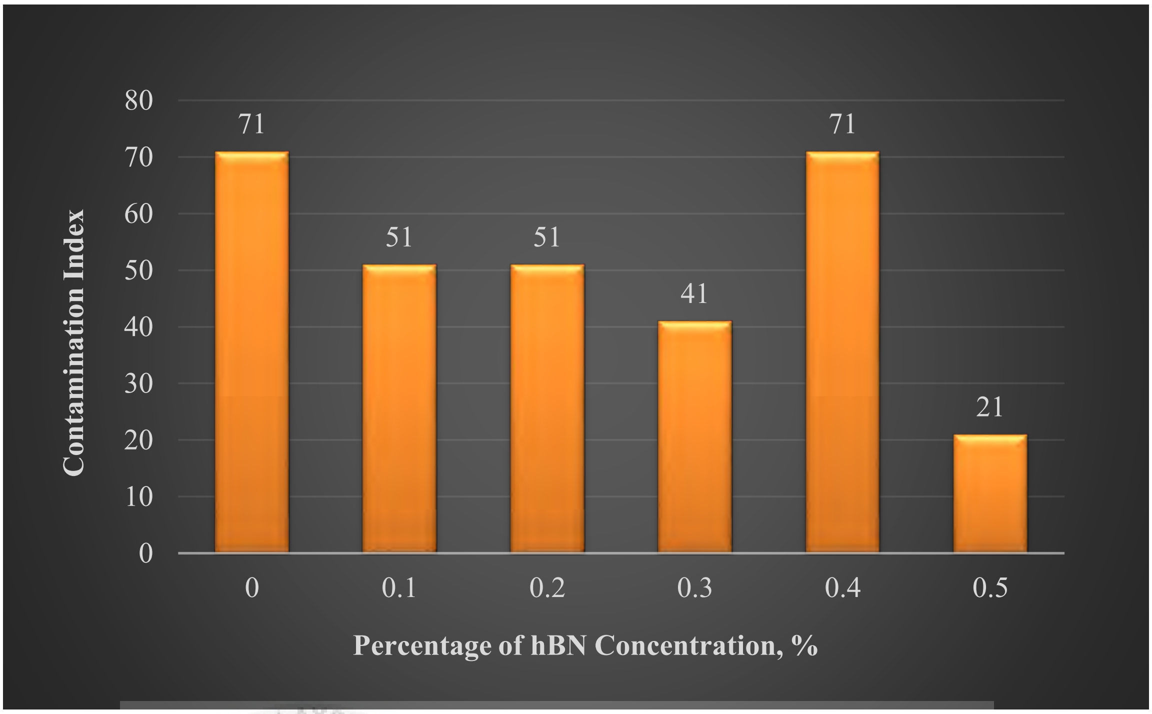


Figure 4.8 Graph of Contamination Index against Percentage of hBN Concentration, % for Outer Defected Ball Bearing

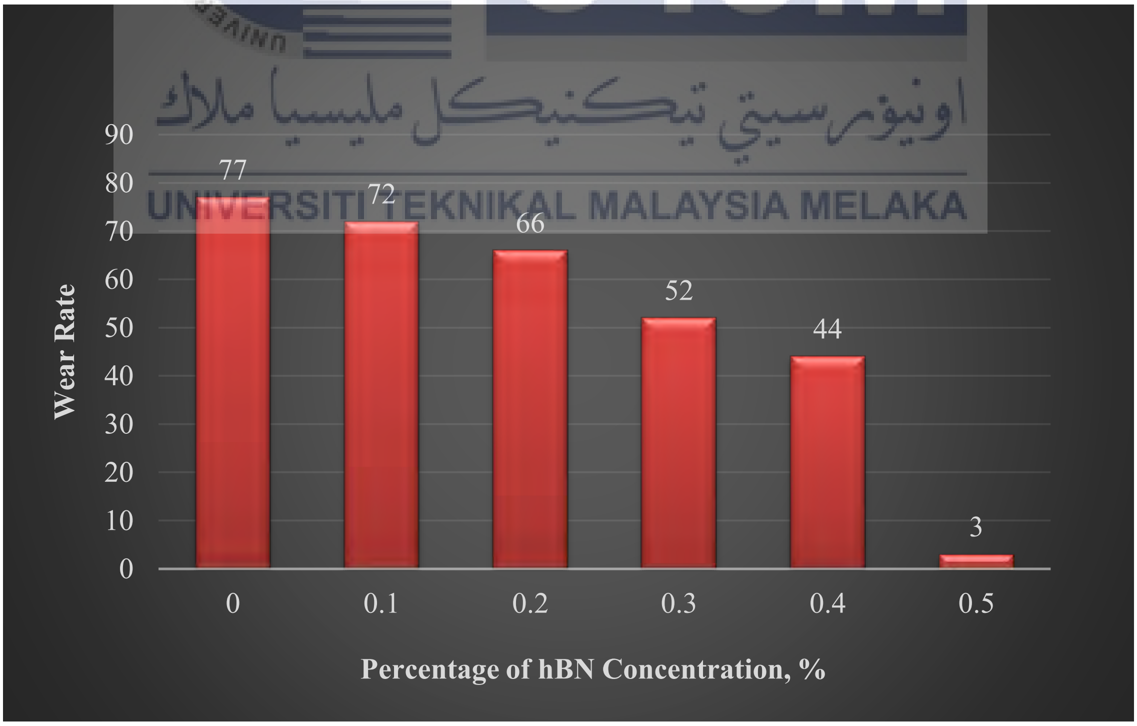


Figure 4.9 Graph of Wear Rate against Percentage of hBN Concentration, % for Outer Defected Ball Bearing

Based on Figure 4.8, the contamination is decrease with increasing of hBN concentration value as well. The highest value of contamination would be at 0% which is 71 while the lowest would be at 0.5% which is 21. However, it shows an insignificant value at 0.4% whereby the contamination value is increase suddenly to 71. This might be due to some external contaminants (dust, fibers and etc.) during the operational of the experiment. Based on Figure 4.9, the wear rate is decrease from 77 to 3.

4.2.4 Particle Count ISO Plot

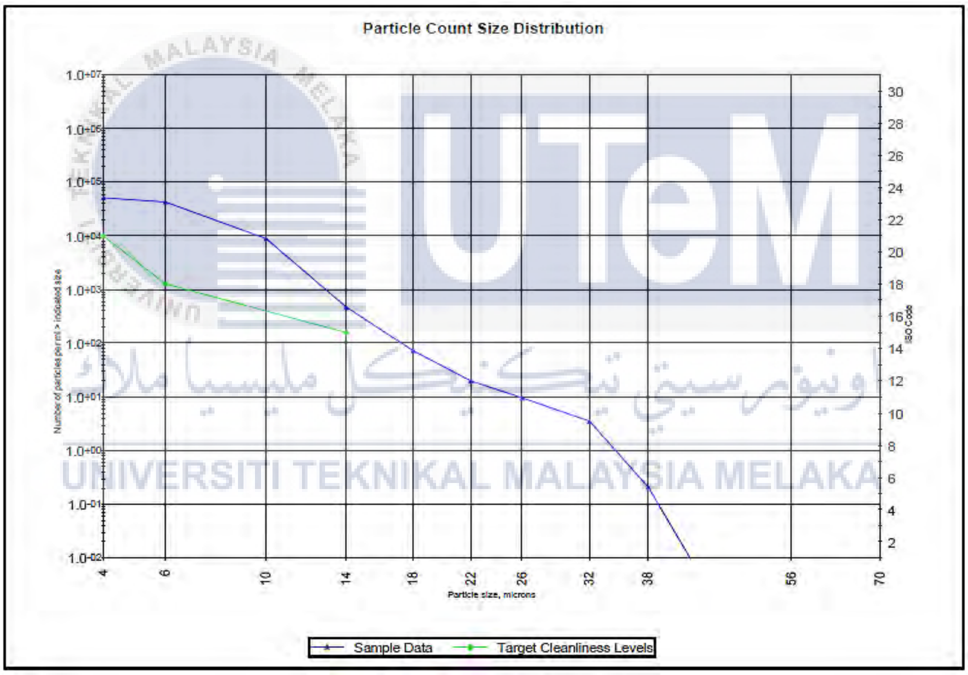


Figure 4.10 ISO plot for outer defected ball bearing at 0.1 % of hBN concentration volume

The ISO 4406 plot represents the size distribution and concentration for particles in tested oil sample. Besides, particle counts are subject to a wide range of variability due to sample preparation, oil formulations, contamination of the sample container, location and method of sampling. Every graph has two lines. First line on behalf of the sample data and second line represents the target cleanliness level. Each percentage concentration volume, % of hBN that mixed with engine diesel oil has different ISO plot. Figure 4.10 illustrates the ISO plot for outer defected ball bearing at 0.1 % of hBN concentration volume. It shows that the sample data line (blue line) is above the target cleanliness levels (green line) which means the oil sample is contaminated with different size particles at different particle counts as shown in Table 4.4.

Table 4.4 Contamination results for outer defected ball bearing at 0.1 % of hBN concentration volume.

Contamination results:	
NIST Size, um(c):	Counts/ml
>4	51, 683
>6	43, 223
>10	8, 981
>14	476
>18	73.6
>22	20.0
>26	9.8
>32	3.6
>38	0.2
>56	n/a
>70	0.0
ISO Code 4/6/14	**23/23/16**

According to the Table 4.4, there is 51, 683 (ISO Code = 23) particles per ml greater than 4 microns in size, 43, 223 (ISO Code = 23) particles per ml greater or equal to 6 microns in size and 476 (ISO Code = 14) particles per ml greater than 14 microns in size. ISO plot for other concentration volumes can refers to appendix section of this report.

4.2.5 Wear Debris Analysis

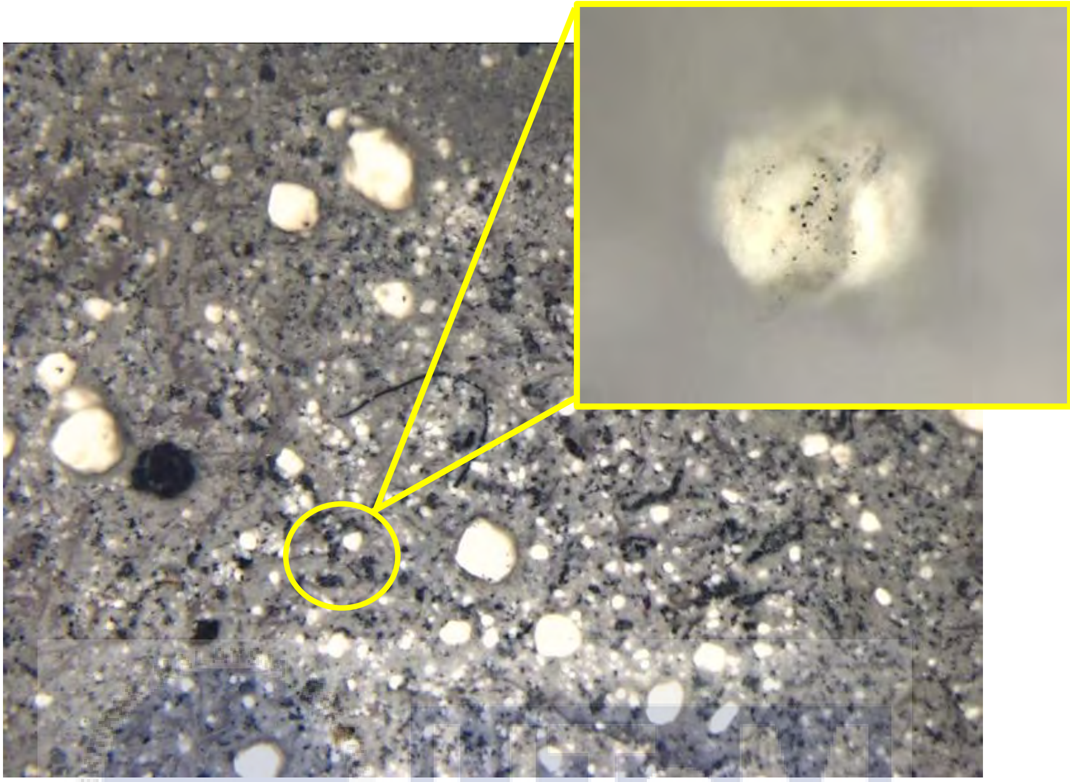


Figure 4.11 Visual microscopic observation of hBN nanoparticles agglomeration

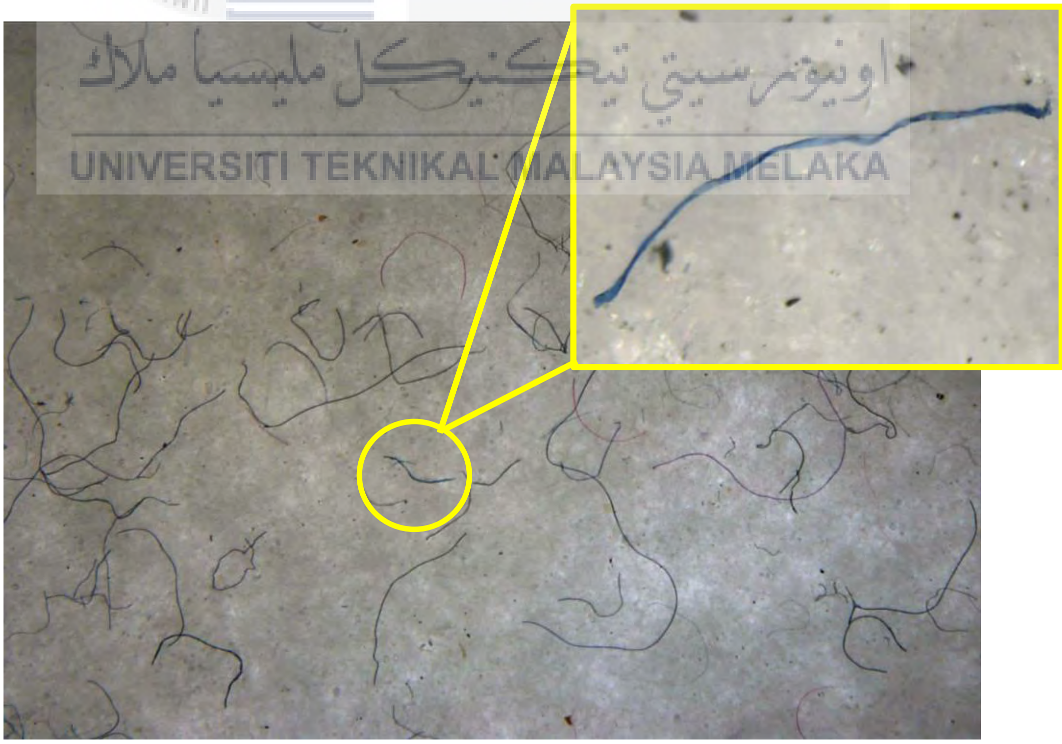


Figure 4.12 Visual microscopic observation of fibers extracted from oil sample

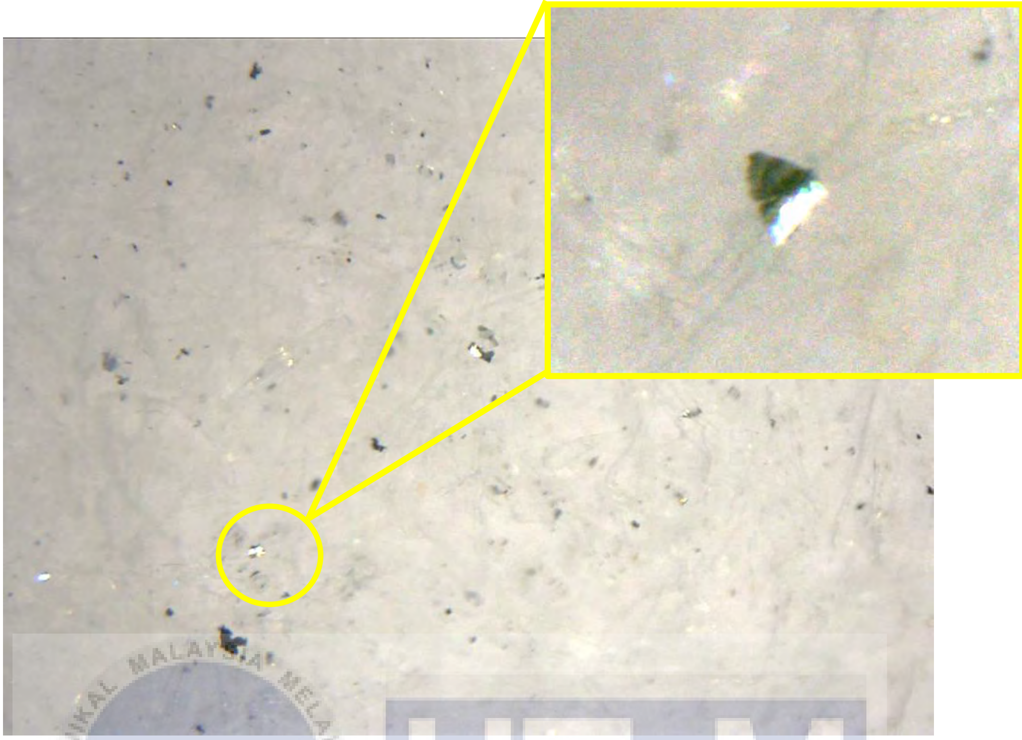


Figure 4.13 Visual microscopic observation of ferrous metals extracted from oil sample

Ferrography test is performed based upon the systematic collection of oil samples from an oil lubricated machine. This technique detects, separates and categorizes wear particles from machine parts. A magnetic field is used to classify the wear particles in the oil lubricant samples. The microscopic observation obtained from the oil samples displays agglomeration of nano particles in Figure 4.11. Agglomeration of nanoparticles occur in various geometrical forms such as spherical, cuboidal or rod-like geometry. In this case, the shape of nanoparticles is spherical shape. Dirk Walter 2013) mentioned that, these nanoparticles are then agglomerate to larger units by adhesion (weak physical interactions) and combine together at the corners or edges of the particles. As a result, agglomerates are not rigid units but could change their size and shape. Changing conditions (temperature, pressure, pH-value, viscosity, etc.) of the surrounding leads to varied agglomerates. Larger agglomerates may also divided into smaller agglomerates or, vice versa, smaller agglomerates may again form larger agglomerates. Qingming Wan et.al. (2015), also told that huge agglomeration particles at high concentration will not only to fill in the valleys on the worn surface but also form new asperities made of these large agglomeration. Different from base oil, these new asperities are same as solid lubricant, which could reduce the friction. Reeves C J *et*. al. (2013), however specified that these new asperities are badly to the roughness of the worn surface, which could cause greater friction and rougher worn surface compared to the small particles with a little agglomeration.

Figure 4.12 displays contaminants (dust, fibers and etc) that observed under microscope. This contaminants most probably come from external surrounding during the experimental work. Besides, common cause of internal debris contamination include wear from machinery components. For example, in real life situation, the wear are usually obtained from gears, seals, splines, clutches, joints, brakes and failed or spalled components. These hard particles travel within the lubrication, over the bearing, and finally scratch (dents) the internal surfaces. The dents create shoulders that act as surface-stress risers which then lead to premature surface damage and decrease bearing life. This condition occurs on defected ball bearing whereby the ferrous fragments generated from the defected bearing itself worsen the friction between the crack surfaces and indirectly produce adhesive, abrasive and fatigue wears. Figure 4.13 shows the tiny and flat particle shape of wear extracted from oil sample and observed under microscope. This kind of particle shape typically due to the surface fatigue of two continuous contacted surfaces which is having bright, shiny and smooth surface texture with approximately 1 to 5 microns size. It is considered as onset of early surface pitting in the form of small and plate-like particles.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research study, the performance of hexagonal boron nitride (hBN) nanoparticles mixed with SAE 15W40 diesel engine oil was investigated to identify the effects of certain contaminant characteristics on healthy and defected ball bearings. Besides that, the effect of different percentage volume of hBN concentration mixed with diesel engine oil was determined in producing contamination on rolling bearings. An oil analysis testing was conducted by using Spectro 5200 Trivector Oil Analyzer and interpreted by using OilView software to identify the contamination and wear rate of nano-lubricants. Based on the overall results, the following conclusions can be drawn from this study;

- White powder of hexagonal boron nitride (hBN) was mixed with diesel engine oil (SAE 15W40) by using ultrasonic homogenizer for 15 minutes in order for tiny particles of the additive dispersed uniformly throughout the diesel engine oil. The oil samples were prepared at different percentage of hBN concentration volumes which 0 %, 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 %.
- An experimental work was carried out on 6206-deep groove ball bearing with three different conditions which are healthy ball bearing, inner defected ball bearing and outer defected ball bearing. These bearings were then partially submerged in nano-lubricant and operated for about an hour.

- Oil samples were extracted from lubricant container on the test rig to perform an oil analysis test. Oil analysis test was involved of chemistry test, wear and contamination test, particle count test and ferrography test.
- It was found that a contribution of 0.5 vol.% of hBN as a surfactant can be used as an optimal additive composition in conventional diesel engine oil, to obtain a lower wear rate and contamination for healthy, inner defected and outer defected ball bearing.
- According to wear and contamination test, it was found that the wear rate and contamination are highest for inner defected ball bearing compared to outer defected and healthy ball bearing. This may be due to a high sliding and coefficient of friction at inner race surface of the bearing as well as due to direct contact between inner race surface and shaft itself.
- The ISO plot illustrated that the line of sample data (blue line) was above of target cleanliness level line (green line) which indicates the presence of contaminants and wears instead of large number of particle counts.
- The NAS Codes indicate significant decrement by dispersing of hBN additive and showed the lowest NAS class range at 0.5 % of hBN concentration volume for healthy inner defected and outer defected ball bearing.
- Particle count test indicates an increment of number for smaller size of particles (>4 microns size) but decrement of number for larger size of particles (>6 microns and >14 microns).
- Ferrography test showed the presence of contaminants and wears in the form of fibers and ferrous metals. The wears found to be in tiny plate-like particles with shiny, birght and smooth surface texture.

5.2 Recommendation

There are several suggestions and recommendations offered for future studies to improve the methods that applied in current research:

- Agglomeration of nanoparticles is the main cause of sedimentation process. Due to the particles bonding of small particles that forming a larger particles indirectly leads the large particles to accumulate at the bottom part of oil samples. Therefore, oleic acid should be added as well to slow down the sedimentation process.
- Instead of using hexagonal boron nitride (hBN) as additive, other type of additives should be reviewed such as Copper (Cu), Nickel (Ni) and Alumina (Al_2O_3). Each type of nanoparticle has their own properties that should be investigated in order to know their capability of improving the performance of current diesel engine oil.
- Lubrication is important to protect the engine against wear by reducing the friction between moving parts. Other functions involving cooling lubricated surfaces, protecting against corrosion and rust, stopping the formation of deposits, eliminating contaminates and neutralising acidic degradation as well to provide lubrication over a varied range of temperatures. Therefore, instead of using base oil, the performance of bio-lubricant and aqueous lubricant should be reviewed in reducing the coefficient of friction (COF).
- Infrared thermography also can be performed in order to prove the significant of hBN additive as a good heat resistance. Infrared thermography will detects infrared energy emitted from object then converts it to temperature, and displays image of temperature distribution on the machine component. By using this method, the critical level of temperature rise on the bearing can be observed and to tell if the hBN additive is really compatible reducing the heat emitted on the contacted surfaces while operating.

REFERENCES

Gao, Y., Gu, A., Jiao, Y., Yang, Y., Liang, G., Hu, J., . . . Yuan, L. (2011). High-performance hexagonal boron nitride/bismaleimide composites with high thermal conductivity, low coefficient of thermal expansion, and low dielectric loss. *Polymers for Advanced Technologies, 23*(5), 919-928.

Abdullah, M. I., Abdollah, M. F., Amiruddin, H., Tamaldin, N., & Nuri, N. R. (2013). Optimization of Tribological Performance of hBN/AL2O3Nanoparticles as Engine Oil Additives. *Procedia Engineering, 68*, 313-319.

Shizhu, W. and Ping, H., 2012. Principles of Tribology. Singapore: John Wiley & Sons (Asia) Pte Ltd.

Watson, C.E., Hanly, F.J., and Burchell, R.W., 1955. Abrasive wear of piston rings. SAE Transactions, 63, 717-728.

Simon, C.T. and Huang, Y., 2004. Modeling of abrasive wear in a piston ring and engine cylinder bore system. Tribology Transactions, 47, 17-22.

Enzhu, H., Xianguo, H., Tianxia, L., Ling, F., Karl, D.D. and Hongming, X., 2013. The role of soot particles in the tribological behavior of engine lubricating oils. Wear, 304, 152-161.

Syahrullail, S., Hariz, M., Hamid, M. A., & Bakar, A. A. (2013). Friction Characteristic of Mineral Oil Containing Palm Fatty Acid Distillate Using Four Ball Tribo-tester. Procedia Engineering, 68, 166-171.

Balamurugan K, Kanagasabapathy N, MayilsamyK. Studies on soya bean oil based lubricant for diesel engines. J Sci Ind Res 2010;69:794–7.

Masjuki HH, Maleque MA, Kubo A, Nonaka T. Palm oil and mineral oil based lubricants their tribological and emission performance.Tribol Int 1999;32 (6):305–14.

Wan Nik, W.B., Maleque, M.A., Ani, F.N., Masjuki, H.H., 2007. Experimental Investigation on System Performance using Palm Oil as Hydraulic Fluid, Industrial Lubrication and Tribology, 59,5, pp.200-208.

Hamnelid L. Introduction to rheology of lubricating greases. In: Balan C, editor. Rheology of lubricating greases. Amsterdam: ELGI; 2000. p. 1–20.

Baart P, Lugt PM, Prakash B. Contaminant migration in the vicinity of a grease lubricated bearing seal contact. J. Tribol. 2011;133:041801

Stachowiak GW, Batchelor AW. Engineering tribology. 2nd ed. Woburn: Butterworth-Heinemann; 2001.

Shahnazar, S., Bagheri, S., & Abd Hamid, S. B. (2016). Enhancing lubricant properties by nanoparticle additives. International Journal of Hydrogen Energy, 41(4), 3153–3170.

Zhang BS, Xu BS, Xu Y, Gao F, Shi PJ, Wu YX. CU nanoparticles effect on the tribological properties of hydrosilicate powders as lubricant additive for steel contacts. Tribol Int 2011;44(7e8):878e86

Zhang S, Hu L, Feng D, Wang H. Anti-wear and friction reduction mechanism of Sn and Fe nanoparticles as additives of multialkylated cyclopentanes under vacuum condition. Vacuum 2013;87(0):75e80.

Wu YY, Tsui WC, Liu TC. Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. Wear 2007;262(7e8):819e25.

Lee J, Cho S, Hwang Y, Lee C, Kim SH. Enhancement of lubrication properties of nano-oil by controlling the amount of fullerene nanoparticle additives. Tribol Lett 2007;28(2):203e8.

Lu X, et al. One-dimensional conducting polymer nanocomposites: synthesis, properties and applications. Prog Polym Sci 2011;36(5):671e712.

Chen CS, et al. Modification of multi-walled carbon nanotubes with fatty acid and their tribological properties as lubricant additive. Carbon 2005;43(8):1660e6.

Joly-Pottuz L, et al. Anti-wear and friction reducing mechanisms of carbon nano-onions as lubricant additives. Tribol Lett 2008;30(1):69e80.

Hirata A, Igarashi M, Kaito T. Study on solid lubricant properties of carbon onions produced by heat treatment of diamond clusters or particles. Tribol Int 2004;37(11e12):899e905.

Hwang Y, Lee C, Choi Y, Cheong S, Kim D, Lee K, et al. Effect of the size and morphology of particles dispersed in nano oil on friction performance between rotating discs. J Mech Sci Technol 2011;25(11):2853e7.

Zhao G, Zhao Q, Li W, Wang X, Liu W. Tribological properties of nano-calcium borate as lithium grease additive. Lubr Sci 2014;26(1):43e53.

Zhao C, Jiao Y, Chen YK, Ren G. The tribological properties of zinc borate ultrafine powder as a lubricant additive in sunflower oil. Tribol Trans 2014;57(3):425e34.

Yuan, C. Q.; Peng, Z.; Chou, X.C.; Yan, X.P. (2003). "The characterization of wear transitions in sliding wear process contaminated with silica and iron powder.", Tribology International 38 (2005) 129–143.

Hunt, T. M. (1992). “Handbook of wear debris analysis and particle detection in liquids”, Elsevier Science Publisher.

Khan, M.A.; Starr, A.G. (2006). “Basic principles of wear phenomena, mechanisms and lubrication – a review”. Lubmat, Preston UK.

Anderson, D.P. (1982). ”Wear Particle Atlas”, Naval Air Engineering Centre.

Roylance, B.J.; Hunt, M. T.(1999).”Wear Debris Analysis: Machine & systems condition monitoring series”, Coxmoor publishing company

Laghari, M.S.(2002),“Surface feature recognition of wear debris”, Artificial Intelligence , pp 627-637.

Raadnui, S. (2005). "Wear particle analysis – utilization of quantitative computer image analysis: A review." Tribology International 38: 871-878.

Gebarin S., Noria Corporation, "On-line and In-line Wear Debris Detectors: What's Out There?". Practicing Oil Analysis Magazine. September 2003

Moubray, J. (1997),"Reliability Centered Maintenance", Industrial Press Inc

Graney, B.P., "A Guideline for Overall and Narrow Band Alaraming", *Reliability Web,* Predictive Maintenance Technology Conference, 15-16 September 2008,Omaha, Nebraska.

Çelik O. N., Ay N., Göncü Y., Effect of nano hexagonal boron nitride lubricant additives on the friction and wear properties of AISI 4140 steel, Particulate Science and Technology, 31, 501–506, 2013.

Abdullah, M. I., Abdollah, M. F., Amiruddin, H., Tamaldin, N., & Nuri, N. R. (2013). Optimization of Tribological Performance of hBN/AL2O3Nanoparticles as Engine Oil Additives. *Procedia Engineering,68*, 313-319.

Abdollah, M. F., Mazlan, M. A., Amiruddin, H., & Tamaldin, N. (2014). Experimental Study on Friction and Wear Behaviors of Ball Bearings under Gas Lubricated Conditions. *Jurnal Teknologi,* 66(3).

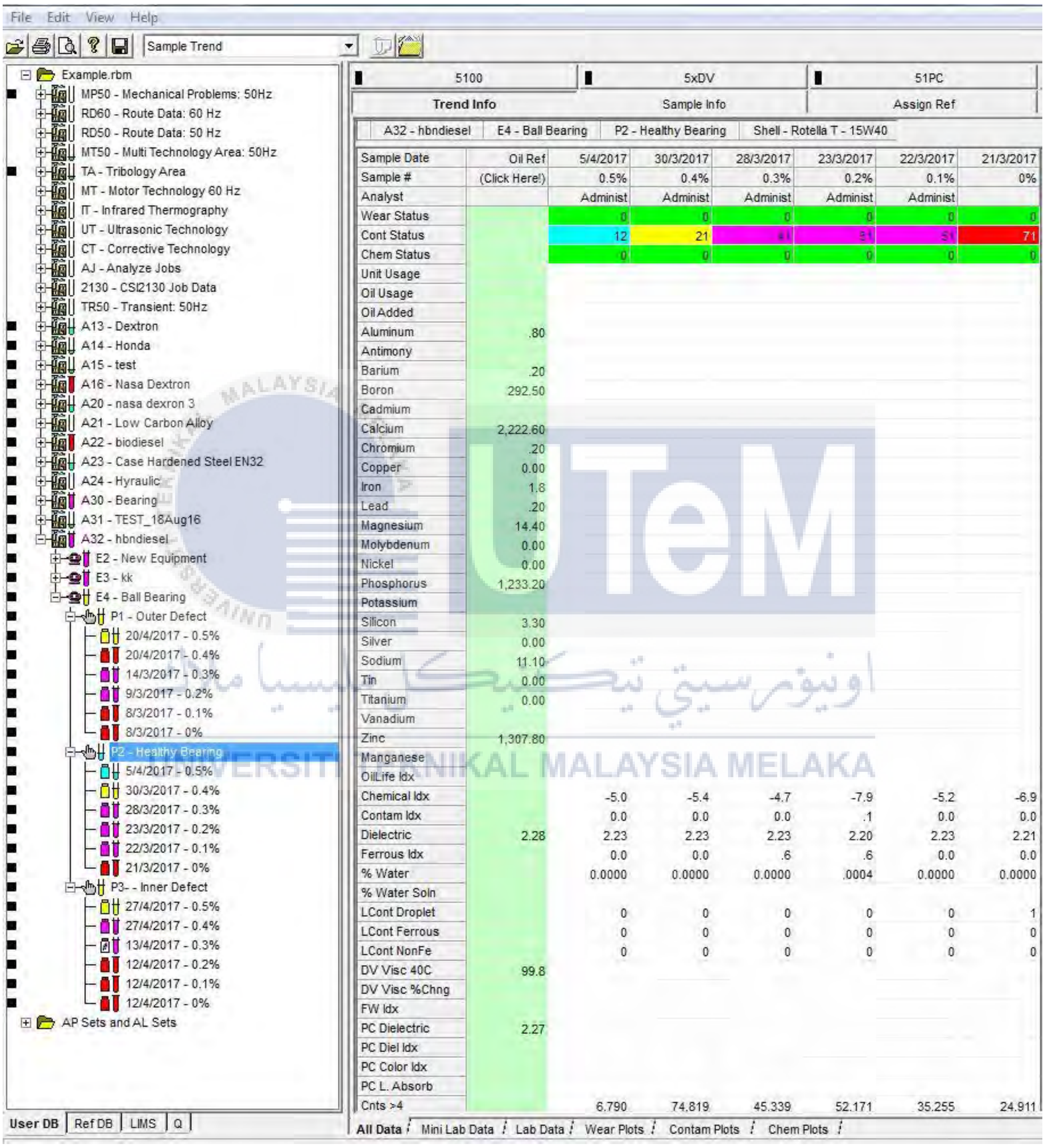
Walter, D. (2013). Primary Particles - Agglomerates - Aggregates. Nanomaterials, 9-24.

Wan, Q., Jin, Y., Sun, P., & Ding, Y. (2015). Tribological Behaviour of a Lubricant Oil Containing Boron Nitride Nanoparticles. *Procedia Engineering, 102*, 1038-1045.

Reeves C J, Menezes P L, Lovell M R, Jen T-C. The Size Effect of Boron Nitride Particles on the Tribological Performance of Biolubricants for Energy Conservation and Sustainability. Tribology Letters, 2013, 51(3): 437-452

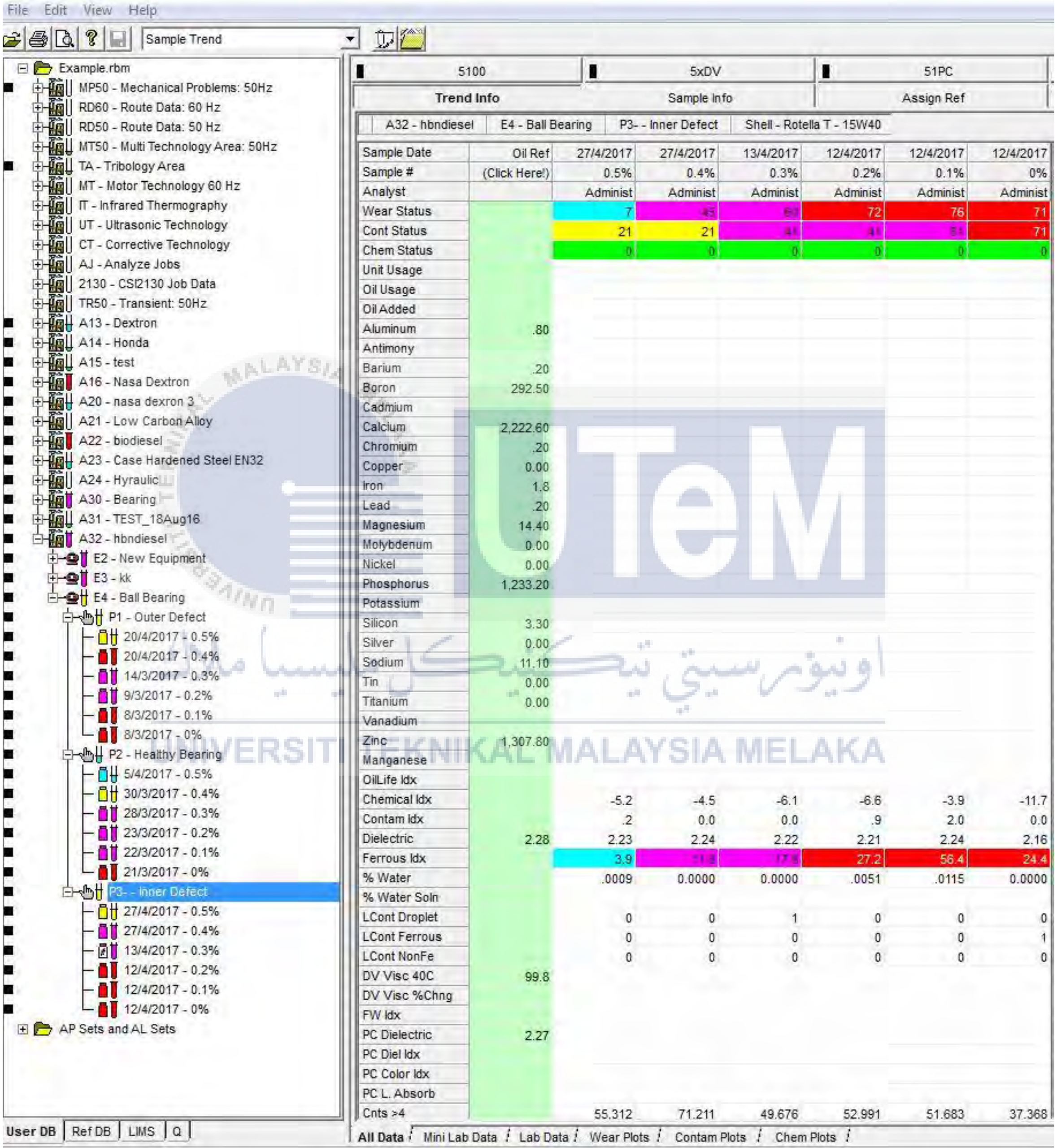
APPENDIX A1

Sample trend info for healthy ball bearing



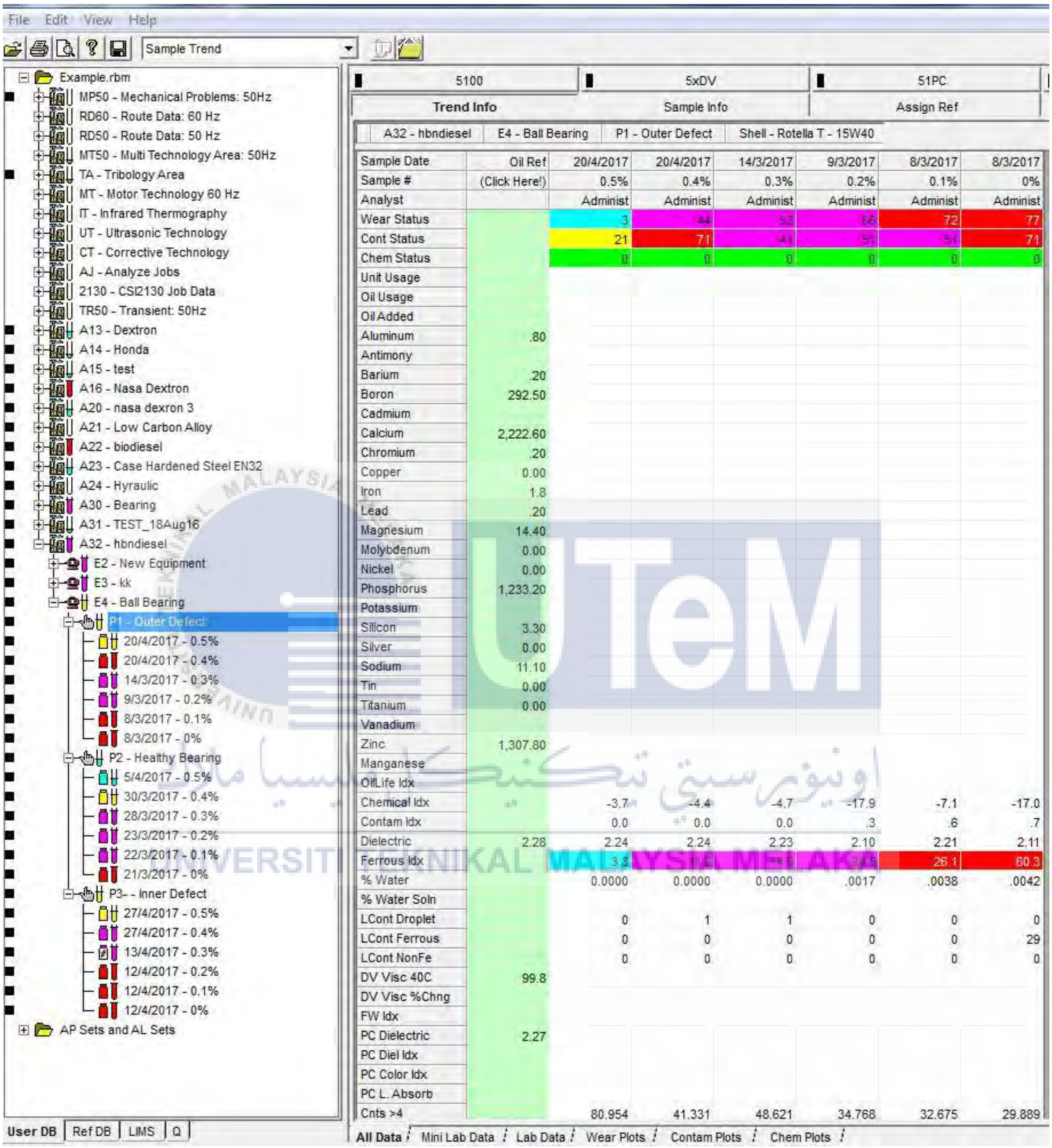
APPENDIX A2

Sample trend info for inner defected ball bearing



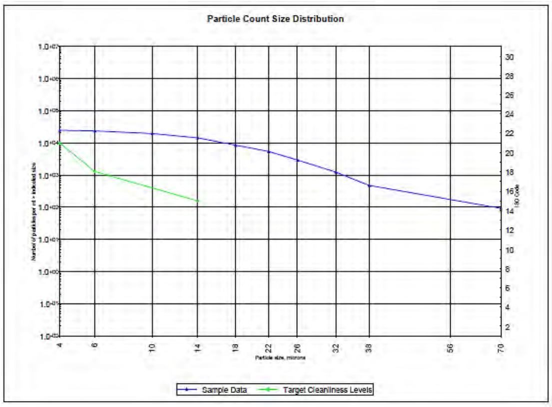
APPENDIX A3

Sample trend info for outer defected ball bearing



APPENDIX B1

ISO plot cleanliness codes for healthy ball bearing at different concentration volumes



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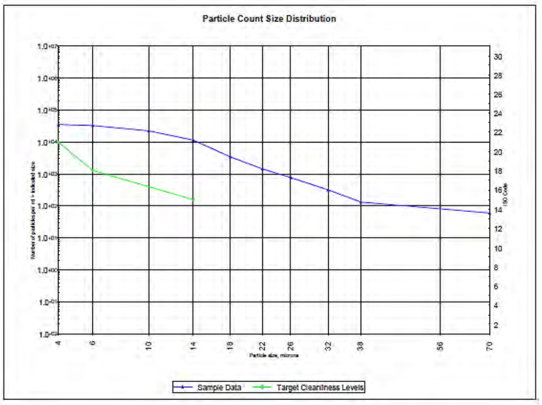

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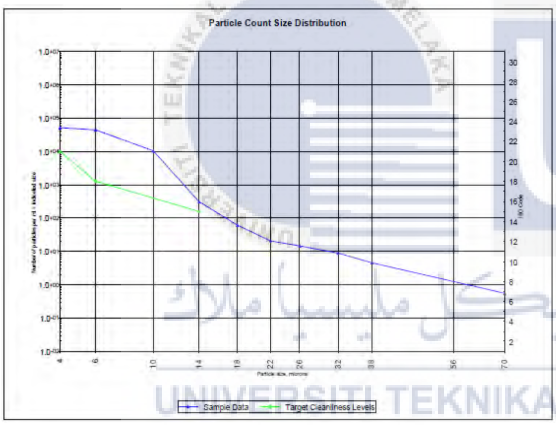

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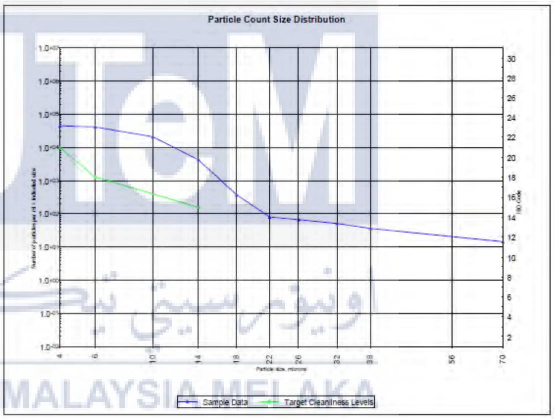

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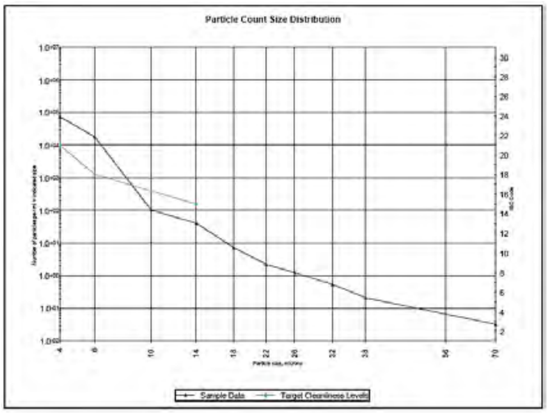

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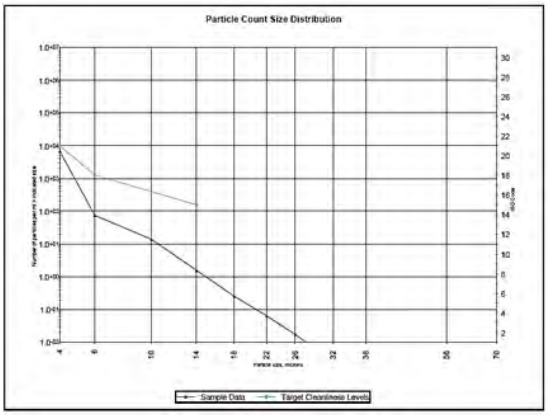

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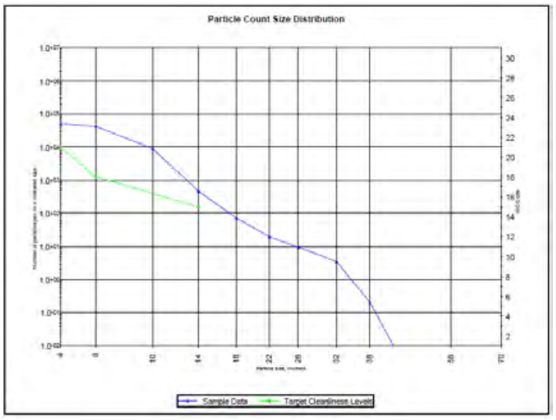
APPENDIX B2

ISO plot cleanliness codes for inner defected ball bearing at different concentration volumes



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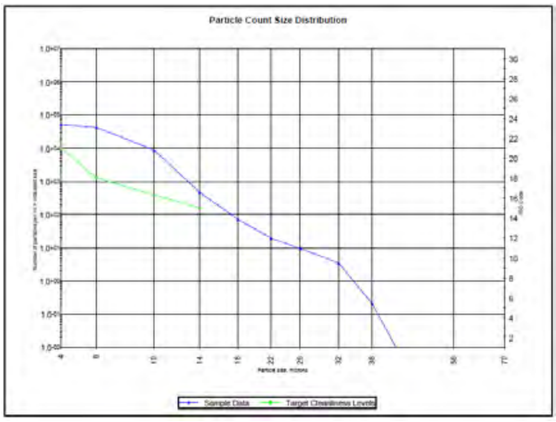

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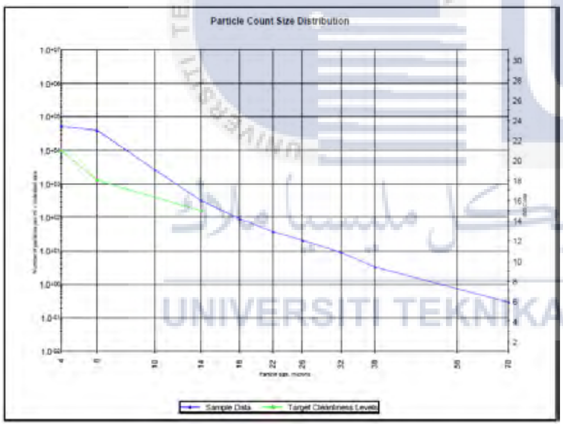

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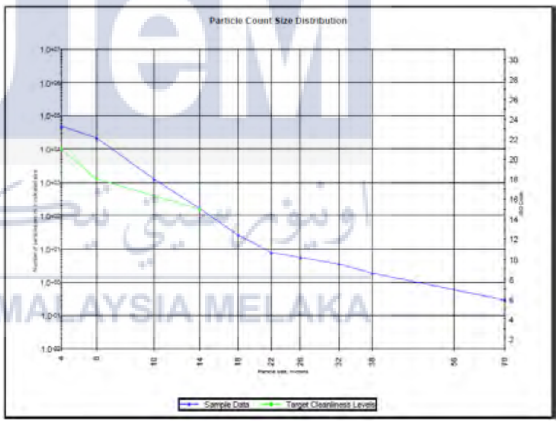

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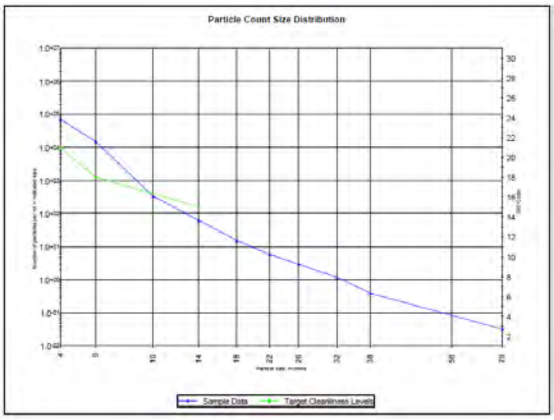

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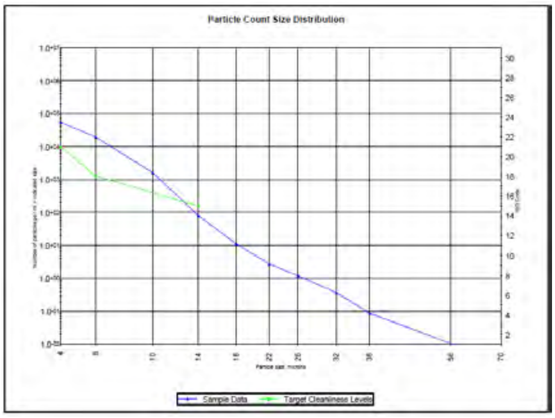

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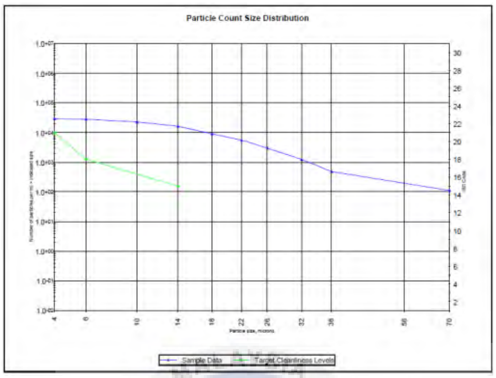
APPENDIX B3

ISO plot cleanliness codes for outer defected ball bearing at different concentration volumes



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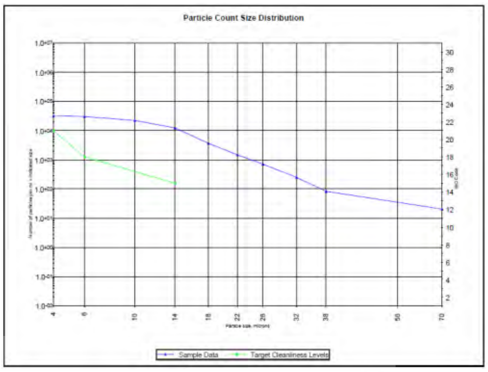

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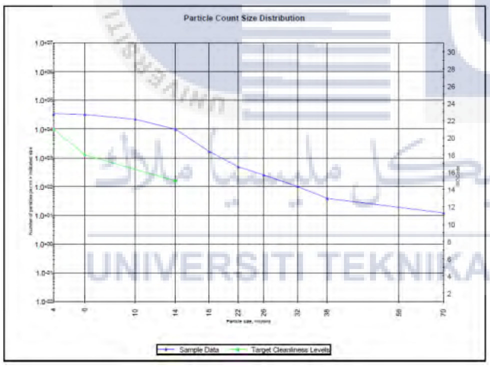

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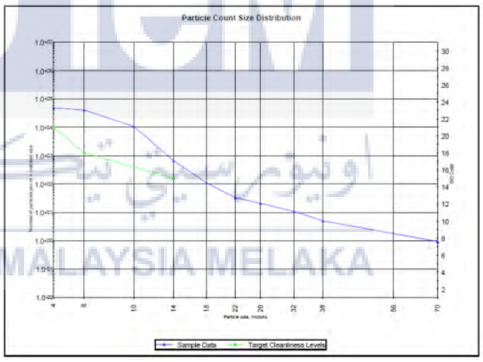

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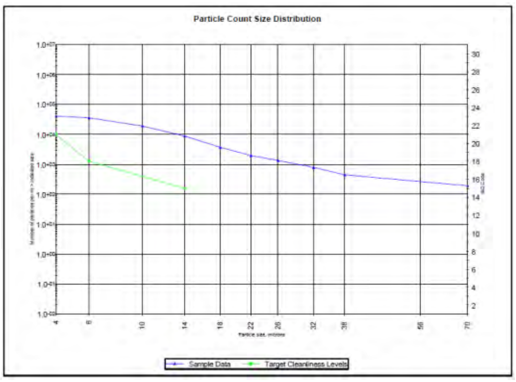

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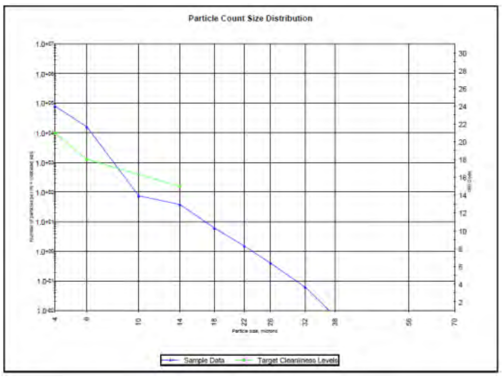

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APPENDIX C1

ISO 4406 codes table

UNDERSTANDING ISO CODES

The ISO cleanliness code is used to quantify particulate contamination levels per milliliter of fluid at 3 sizes 4μ[c], 6μ[c], and 14μ[c]. The ISO code is expressed in 3 numbers (ie 19/17/14). Each number represents a contaminant level code for the correlating particle size. The code includes all particles of the specified size and larger. It is important to note that each time a code increases the quantity range of particles is doubling.

ISO 4406 Chart

Range Code	Particles per milliliter More than	Particles per milliliter Up to/including
24	80000	160000
23	40000	80000
22	20000	40000
21	10000	20000
20	5000	10000
19	2500	5000
18	1300	2500
17	640	1300
16	320	640
15	160	320
14	80	160
13	40	80
12	20	40
11	10	20
10	5	10
9	2.5	5
8	1.3	2.5
7	0.64	1.3
6	0.32	0.64

Sample 1 (see photo 1)

Particle Size	Particles per ml*	ISO 4406 Code range	ISO Code
4μ[c]	151773	80000–160000	24
6μ[c]	38363	20000–40000	22
10μ[c]	6229		
14μ[c]	3339	2500–5000	19
21μ[c]	1048		
38μ[c]	112		

Sample 2 (see photo 2)

Particle Size	Particles per ml*	ISO 4406 Code range	ISO Code
4μ[c]	492	320 – 640	16
6μ[c]	149	80 – 160	14
10μ[c]	41		
14μ[c]	15	10 – 20	11
21μ[c]	5		
38μ[c]	1		

Photo 1

Photo 2

APPENDIX C2

NAS 1638 codes

Size range		5–15 µm	15–25 µm	25–50 µm	50–100 µm	>100 µm
NAS classes (based on maximum contamination limits, particles per 100ml)	00	125	22	4	1	0
	0	250	44	8	2	0
	1	500	89	16	3	1
	2	1,000	178	32	6	1
	3	2,000	356	63	11	2
	4	4,000	712	126	22	4
	5	8,000	1,425	253	45	8
	6	16,000	2,850	506	90	16
	7	32,000	5,700	1,012	180	32
	8	64,000	11,400	2,025	360	64
	9	128,000	22,800	4,050	720	128
	10	256,000	45,600	8,100	1,440	256
	11	512,000	91,000	16,200	2,880	512
	12	1,024,000	182,400	32,400	5,760	1,024