Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alpha olefin Lubricant with Nano Additives under Reciprocating Motion

By

Muhammad Anas Nasir

(Registration No: 00000328042)

Department of Mechanical Engineering

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2023)

Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alpha olefin Lubricant with Nano Additives under Reciprocating Motion

By

Muhammad Anas Nasir

(Registration No: 00000328042)

A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in

Mechanical Engineering

Supervisor: Dr. Muhammad Usman Bhutta

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2023)

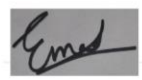
THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Regn No. 00000328042 Muhammad anas Nasir** of **School of Mechanical & Manufacturing Engineering (SMME)** has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis titled. **Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alphaolefins Lubricant with Nano Additives under Reciprocating Motion**

Signature: 

Name (Supervisor): Muhammad Usman Bhutta

Date: 14 - Feb - 2024

Signature (HOD): 

Date: 14 - Feb - 2024

Signature (DEAN): 

Date: 14 - Feb - 2024

Form TH-4

National University of Sciences & Technology (NUST)

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Muhammad anas Nasir (00000328042) Titled: Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alphaolefins Lubricant with Nano Additives under Reciprocating Motion be accepted in partial fulfillment of the requirements for the award of MS in Mechanical Engineering degree.

Examination Committee Members

1. Name: Riaz Ahmed Mufti Signature:

2. Name: Rehan Zahid Signature:

Supervisor: Muhammad Usman Bhutta Signature: -

Date: 30 - Jan - 2024

30 - Jan - 2024

Head of Department Date

COUNTERSINGED

30 - Jan - 2024

Date Dean/Principal

CERTIFICATE OF APPROVAL

This is to certify that the research work presented in this thesis, entitled "Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alpha olefin Lubricant with Nano Additives under Reciprocating Motion" was conducted by Mr. Muhammad Anas Nasir under the supervision of Dr. Muhammad Usman Bhutta.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the School of Mechanical and Manufacturing Engineering in partial fulfillment of the requirements for the degree of Master of Science in Field of Mechanical Engineering

Department of Mechanical Engineering, National University of Sciences and Technology, Islamabad.

Student Name: Muhammad Anas Nasir Signature: ________________

Examination Committee:

a) External Examiner 1: Signature: ________________

(Designation & Office Address)

………………………………..

b) External Examiner 2: Signature: ________________

(Designation & Office Address)

…………………………………

Dr. M. Usman Bhutta: Signature: ________________

(HOD) Dr. Mian Ashfaq: Signature: ________________

AUTHOR'S DECLARATION

I Muhammad Anas Nasir hereby state that my MS thesis titled "Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alpha olefin Lubricant with Nano Additives under Reciprocating Motion" is my own work and has not been submitted previously by me for taking any degree from National University of Sciences and Technology, Islamabad or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

Name of Student: Muhammad Anas Nasir

Date: 14-02-2024

PLAGIARISM UNDERTAKING

I solemnly declare that research work presented in the thesis titled "Tribological Performance Analysis of Grey Cast-Iron against 52100 Steel Ball Bearing with Poly-alpha olefin Lubricant with Nano Additives under Reciprocating Motion" is solely my research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero-tolerance policy of the HEC and National University of Sciences and Technology (NUST), Islamabad towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the University reserves the rights to withdraw/revoke my MS degree and that HEC and NUST, Islamabad has the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized thesis.

Student Signature:

Name: Muhammad Anas Nasir

DEDICATION

I dedicate this work to my Parents

Nasir Mehmood and Humaira Shaheen

my Sisters

Arfa Nasir, Alina Nasir and Mydah Nasir

and my beloved wife

Iqra Moazzam

ACKNOWLEDGEMENTS

Praise be to ALLAH as nothing would have been possible without His will. I am grateful to Allah Almighty for guiding me at every single stage during this research. And I am thankful to everyone who by His will, helped me during this work.

I am extremely thankful to my beloved parents for nurturing and upbringing and my sisters who always stood with me at enduring times.

I would sincerely like to appreciate my supervisor Dr. Usman Bhutta for his supervision that helped me to all the time during this research and his and valuable suggestions that led me shape this thesis in this final form.

I would like to thank Dr. Riaz Ahmad Mufti and Dr Sami-ur-Rehman Shah for being amazing teachers and helped me further expand my knowledge in field for tribology and IC engines. I would like to thank my committee members Dr. Rehan Zahid and Dr. Jawad Aslam for their invaluable assistance.

I would also like to thank Akbar Khanzada for helping me out hands on during the experimental stage of my work and helping me out in preparing samples conducting lab work.

At last I would thank my dear friends Abdul Haseeb and Umar Safir for always standing beside me throughout the period of my master's degree.

TABLE OF CONTENTS

LIST OF TABLES

Page No.

LIST OF FIGURES

Page No.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

CoF	Coefficient of Friction
PAO	Poly Alpha-Olefins
λ	Lambda ratio (Ratio of fluid film thickness and surface roughness)
η	Dynamic Viscosity
E	Elastic Modulus
H_{min}	Minimum Film Thickness
Ra	Surface Roughness

ABSTRACT

This study is based on nano-particle based lubricants and their role in enhancement of tribological performance of base oil. CuO, ZnO and MoS2 nanoparticles are added to PAO-10 in 1wt% concentration along with 2wt.% oleic acid as a dispersant, these three mixtures are then set up for testing with a tribo-pair of ASTM-52100 steel ball and SAE-J431 (G-3000) gray cast iron. The tests are carried out on a computer controlled reciprocating tribometer and all the lubricants are subjected to 10N, 20N and 30N loading conditions. Test duration is 7200 seconds, at 50 rpm and ambient temperature. Under these conditions and a sliding point contact the test rig is designed to test lubricant performance under boundary lubrication regime. To study the wear scar, a digital optical microscope was used and dimensions for each wear scar were recorded along with the surface roughness before and after the testing.

The reciprocating tribometer tests were also conducted on SAE-40 and SAE-0W20 fully formulated oils to compare the results with nano-particle based lubricants. The results from the tribometer tests suggest that ZnO nanoparticles showed positive results by slightly improving CoF values and showed a significant reduction in wear volume. CuO nanoparticles showed improvement in CoF values for lower loading conditions but could not improve performance for higher loading conditions. The MoS2 nanoparticles were observed to be most effective in reducing the CoF and wear scar volume when added to PAO-10. The lowest CoF value was observed with PAO+MoS2 at 20N load, which is a 93% improvement as compared to PAO-10. The lowest value for wear scar volume was observed for PAO+MoS2 at 10N load which was 92% improvement as compared with PAO-10 only.

This study further discusses the mechanism that physically changes the sliding conditions and play part in reducing the CoF and wear due to presence of nanoparticles and tries to relate them with the results of this study.

Keywords: PAO, Polyalphaolefins, nanoparticles, CuO, ZnO, MoS_2, Reciprocating Tribometer, Tribology, sliding friction, point contact, wear volume, coefficient of friction, nano-lubricants, Gray cast-iron, SAE-J431 G-3000, 52100 steel ball

CHAPTER 1: INTRODUCTION

The efficiency of any system is input vs output in basic terms. The reduction in output means lower efficiency and a large portion of this is the losses. Any type of energy losses is like parasites in a system that reduce the output of any mechanical system. Hence one effective way to increase output of a system is to minimize these losses which is generally a reliable method to increase system response without altering the principle design of the system.

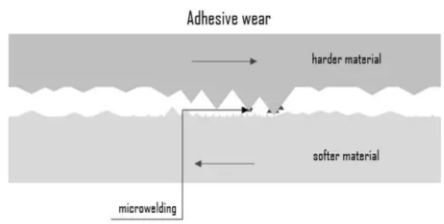
One such effective way to increase output is to reduce the frictional losses. In typical applications, the friction cannot be eliminated but reduced to some level where energy loss is minimal. So, this leaves us with a need for a lubrication system that is efficient and performs well under multiple conditions.

Nowadays most of our lubrication needs are fulfilled by hydrocarbon based lubricating oils. A typical engine lubricating oil contains 90% hydrocarbons and the rest are the additives like friction modifiers, viscosity modifiers detergents and corrosion inhibitors, which play an essential role in the lubricant performance and making them safe for the materials they are interacting with.

In order to understand the lubrication, it is necessary to discuss the mechanisms of friction and how they are dealt with in the presence of a liquid or a solid lubricant. There are several wear mechanisms found commonly in wear related literature named as:

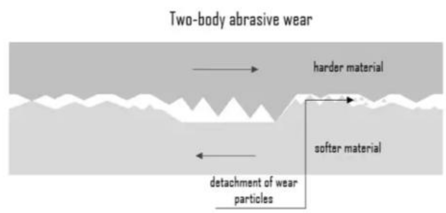
Adhesive Wear

Adhesive wear occurs when surface asperities or microscopic high points (surface roughness) between two sliding materials start bonding during the contact. In simpler words when a peak from one surface comes into contact with a peak from the other surface the friction generates heat and instantaneous micro-welding takes place. This results in detachment or material transfer from one surface to the other. Adhesive wear occurs under high frictional forces, while the surfaces must be in intimate contact in order for it to take place.



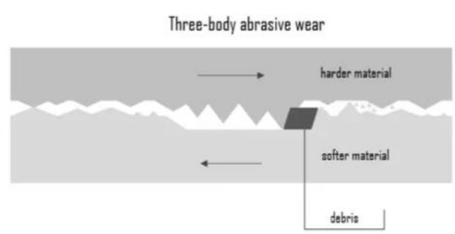
Two Body Abrasive Wear

Two-body wear occurs when the grits or surface peaks from a harder surface remove material from the opposite softer surface. The common analogy is that cutting or plowing operations happen on the surface level and these mechanisms are responsible for material loss.



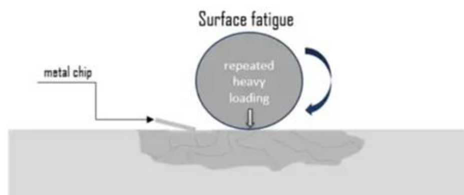
Three Body Abrasive Wear

Three-body abrasive wear occurs when the particles separated from material or any external particles enter between the two sliding surfaces. These particles actively move around causing impact damage on surface or cause plowing action to remove material during the motion.



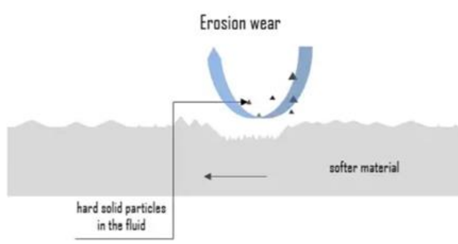
Surface Fatigue

Surface fatigue, also known as fatigue wear, is the result of subsequent cracking and pitting of surfaces that are subjected to cyclic stresses during rolling contact or the stresses caused by the combined action of rolling and sliding. This fatigue wear is produced when microcracks start growing on the surface subjected to loading. Eventually, after a critical number of cycles these cracks can propagate and lead to material separation that will introduce the fragments to the wear model.



Erosion Wear

Erosion wear is a process of progressive material removal from a target surface due to repeated impacts of solid particles. The particles suspended in the flow of solid-liquid mixture erodes the surface of the material, limiting the service life of the equipment. Each particle cuts or fractures a tiny amount of material (known as *wear chips*) from the surface. If repeated over elongated service periods this can result in significant metal loss.



Other wear mechanism also includes impact wear, fretting wear, cavitation wear, corrosive wear and diffusive wear, these are not discussed here due to lack of relevance to this study

Up until recent times the Organic phosphorus and sulfide compounds have played positive roles as friction modifiers and wear resisters [1]. However, a lot of studies have emerged recently exploring the performance of nano-lubricants. Nano-lubricants are a homogenous mixture of base oil, nanoparticles and other additives.

According to some studies the nanoparticles within the nano lubricant act as friction modifiers but they also act as heat dispersing agents [2] that positively impact the thermal requirements. The lubrication mechanisms in the nano-lubricants are due to physical and chemical interactions between the nanoparticles, lubricant and surfaces. According to studies the four mechanisms are most commonly agreed upon in research [3].

Rolling Effect

The first of these mechanisms is the rolling effect. In this mechanism the spherical nanoparticles act as the micro/nano sized balls in between the sliding surfaces, which changes the sliding action into the rolling action resulting in the reduction of COF [1],[3].

Protective Tribo-film

The second mechanism commonly found in studies is the adhesion of nanoparticles on the sliding surfaces that forms a protective layer or a tribo-film over the mating surface and hence protects the surfaces against wear [1],[3].

Mending Effect

Third mechanism is the mending effect, in this mechanism the nanoparticles fill in the asperities, and friction cracks result in a smoother surface, resulting in lower CoF and sliding friction [3] [4].

Polishing Effect

The fourth mechanism is the polishing effect, this happens when nanoparticles act in abrasive manner and polish out the surface roughness resulting in smoother surface and reduced CoF and sliding friction [3].

The figure below shows the illustrated representation of these four mechanisms and how nanoparticles affect the interaction of two contacting bodies during a sliding motion:

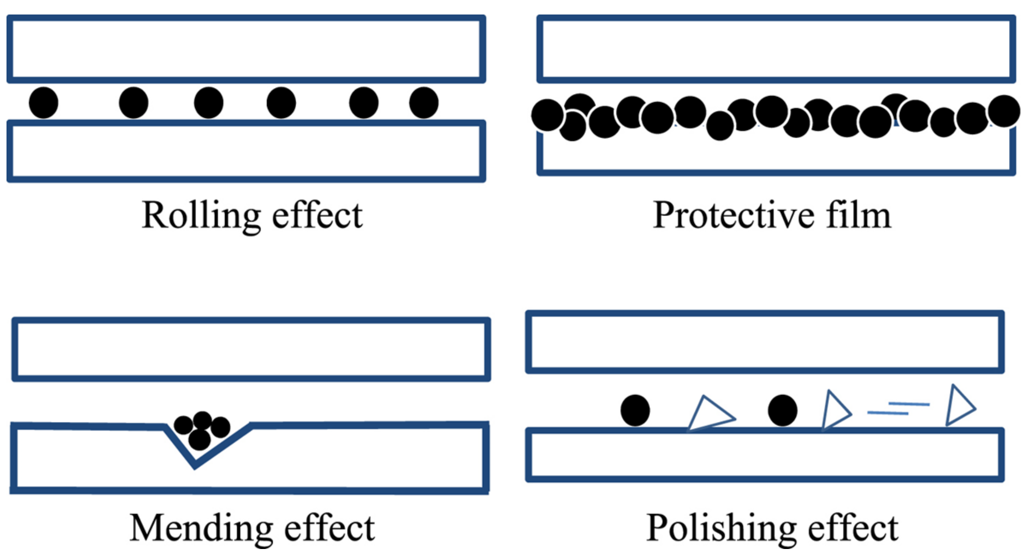


Figure 1: Four mechanisms of friction modification in presence of nanoparticles

While conducting the literature review of numerous publications for this study, it is observed that every study had its unique testing conditions, such as base oil, nanomaterials, nanoparticle concentration, the testing setup, temperature range, load, workpiece material, test parameters, lubrication regime, and many others. However, in most of the publications the parameters used to measure the tribological performance improvement were the minimum value of COF, the max% reduction in COF, and the max % reduction in wear. Since these three parameters are staple in nano lubricant research, they have become the basic parameters for comparison. Apart from that some studies also state the reduction in frictional force and a few were stating the wear scar diameter for 4-ball tribo-test.

The study of above-mentioned parameters does not give the full picture regarding the performance of nanoparticles in lubricants. Comparison of all three parameters at the same time is required to judge the improvements for each nanoparticle [3].

The motivation behind this study is to find the optimum performing nano-lubricants at startup conditions. The cold starting conditions in engines or other low temperature startup procedures for mechanical setups can be the point of high wear during a product's life cycle, due to the system not being at the optimum temperature at that point. In addition, due to lack of ability to flow under a high viscosity state many lubricants will be unable to form a mixed or hydrodynamic lubrication regime between sliding surfaces, at this instance we need a lubricant that forms an effective film even under boundary lubrication regime. Some other reciprocating tribometer studies conducted on PAO + nanoparticles have carried out testing for viscosity of fluids at ambient temperature [9][10][14][17].

The nanoparticles have multiple mechanisms such as mending, forming a tribo-layer, inducing rolling friction effect and working as a matrix to hold oil film against shearing. These mechanisms can help improve the wear and losses faced by a mechanical system when functioning in ambient or cold temperatures, usually right after the starting procedure.

Keeping these conditions in view, the test conditions that are set here are designed to test the performance of lubricants at the ambient temperature and boundary lubrication regime.

As discussed, the base lubricant used in this study is PAO-10, the PAOs are used in fully synthetic lubricating oils, the purpose of using these is due to their superior properties like better viscosity index, better shear stability and above all they have better oxidation stability. The higher oxidation stability of PAO's against refined mineral based oils is that they are long chain saturated hydrocarbon molecules with active sites on two ends only. This gives them stability against degradation and oxidation. However, this property also makes it difficult to bind performance enhancement additives to the PAO.

Nanoparticles when used with dispersive agents can enhance the performance of the PAOs without the need for binding additives.

In order to test the three nanoparticles for their performance, it was decided to add these nanoparticles in a similar concentration. Since each of the selected nanoparticles have a different shape and size and hence are expected to show their respective tribological properties

This study aims to explore the potential of some of the nanoparticles for improving tribological properties of PAO. The nanoparticles used in this study are CuO, ZnO and MoS_2 are tested and results are discussed comprehensively in this study.

2.1 Research Objectives

The goal and objective of this study is to investigate and compare the tribological performance of a base lubricant against the nanoparticles when added to the base lubricant. This will be done by testing the lubricants and for tribological performance under a certain set of conditions. These same conditions will be applied to some commercial based lubricants as well to establish the reliability of the results obtained. The results of this study can help contribute to the ongoing research on using nanoparticles to enhance the performance of different base oils.
To achieve our goals this study will be conducted in accordance with the following research objectives:

1.1.1 Baseline Characterization of PAO-10:

First one is to conduct tribological tests on PAO-10 using a computer controlled reciprocating tribometer under varying loads of 10N, 20N, and 30N at ambient temperature for two hours. Get the results for coefficient of friction (CoF), sliding friction, wear volume and surface roughness values to establish a baseline performance for the base lubricant.

1.1.2 Effect of Nanoparticles on Tribological Performance:

Major part of this study is to introduce copper oxide (CuO), zinc oxide (ZnO), and molybdenum disulfide (MoS_2) nanoparticles into PAO-10 at a concentration of 1 wt.%. This makes our nanoparticle-based lubricants that will be tested for wear, friction and CoF values. We will perform reciprocating tribometer tests under the same load conditions as et for base PAO-10 to assess the influence of each nanoparticle on the tribological behavior of the lubricant.

1.1.3 Comparative Analysis of Lubricant Performance:

Based on the results of the tests performed on the nanoparticle-based lubricants and base lubricant, this study will show a comparative analysis of all the lubricants and then determine the optimal nanoparticle formulation for PAO-10 in terms of minimizing friction, enhancing sliding properties, and reducing wear. This comparison will also include the comparison with commercially available lubricants like SAE-40 and SAE 0W20.

1.1.4 Establish Optimal Nanoparticle Formulation:

Based on the comparative analysis, determine the optimal nanoparticle-based oil made with PAO-10. The optimum solution from this study will be established based on minimizing friction, enhancing sliding properties, and reducing wear.

1.1.5 Correlation of Results with Nanoparticle Properties:

This study links the observed tribological outcomes with the inherent properties of each nanoparticle, such as size and morphology. This research will also try to understand the mechanisms underlying the enhanced lubrication provided by specific nanoparticles, providing an understanding and reasoning behind the performance of those nanoparticles.

Through these research objectives, this study aims to increase understanding of the relation between PAO and nanoparticles, and hence provide us with valuable insights for the formulation of high-performance lubricants. The outcomes of this research will contribute to the optimization of lubricants and additives, it will hopefully help recover the energy losses in mechanical systems thereby enhancing the efficiency, durability, and longevity of mechanical systems.

1.2 Deliverables

1.2.1 Experimental Testing of Tribo-pairs:

This study will test the ASTM-52100 steel ball against SAE-J431 G3000 gray cast iron in the presence of prepared lubricants. The tribo-pair will be tested on a reciprocating tribometer where the 52100-steel ball will be attached to the reciprocating head and it will form a wear scar on stationary gray cast iron plate. The test will be done on three loads, 10N, 20N and 30N. This test will give us essential data like the trend of sliding friction and CoF and their average values over a duration of 2 hours. This data will be used to conclude results of this study.

1.2.2 Tribological Performance Analysis:

This study will collect tribological performance data of the tribo-pair with base oil PAO-10, then three nanoparticle-based lubricants PAO+CuO, PAO+ZnO and PAO+MoS2 and the two commercially available lubricants SAE-40 and SAE-0W20. This data will be combined and then analyzed for any performance increase or decrease. Average sliding frictional force (N), and Average CoF will be used to compare the performance of nanoparticle based lubricant vs base lubricant. (The tests done on SAE-40 and SAE 0W20 are to make sure that the results we are getting with nanoparticle-based lubricants are comparable to lubricants available in market)

1.2.3 Wear Scar Analysis:

Wear scar analysis of the samples will be done on the digital optical microscope. This analysis will give us results in form of the dimensions of the wear scar and condition of the surface. The wear scar length and width will be recorded under microscope for all the tests conducted and the side section (side profile view) will be used to analyse the depth of the wear scar. All these readings will help us calculate the Wear volume. The digital microscope’s line roughness tool will be used to compare surface roughness before and after the test conducted.

1.2.4 Picking the Most Effective Nanoparticle Based Lubricant:

The values recorded in tribological test results and wear scar analysis will be placed for comparison. After comparing the results, the performance will be discussed with strong and weak areas of each mixture and we will find the overall most effective lubricant and nanoparticle mixture.

1.3 Areas of Application:

1.3.1 Protection Against Wear:

The research conducted in this study holds significant relevance to the field of tribology i.e. study of friction, wear and lubricating mechanisms between two sliding surfaces. The purpose here is to enhance the layer of protection between two bodies that are sliding against each other. Lubricants with nanoparticles added in optimized quantity can increase service life of powertrains, gearboxes and differentials of automobiles and heavy machinery that is used in transport, construction, mining, oil and gas and marine applications. These nanoparticle-based lubricants can also be used in the drive mechanisms of industrial equipment and tooling machinery.

1.3.2 Mechanical Efficiency:

Not only are these nanoparticle-based lubrication systems effective in protecting contacting surfaces against wear, but they also have potential to reduce CoF and sliding friction. The friction causes loss of energy in form of heat and reduces the mechanical efficiency of an engine or a machinery. Reduction in friction will reduce the energy losses in turn will increase the efficiency of an engine or machinery.

1.3.3 Lubricant Manufacturing:

Nano lubricants when used as performance enhancers are actually replacing additives that are used to improve physicochemical properties like shear stability. The problem with many additives is that they degrade with time and lose their functions. Nano additives on the other hand will provide better shelf life to the products and will be able to perform their function for an extended period of time. PAO is a basic ingredient in fully synthetic motor oils, however their application is currently quite limited as many manufacturers are selling synthetic oils made from mineral bases (advertised as semi-synthetic or synthetic). One limitation of PAO is that they are large molecules with very few active sites. Lack of active sites make them very stable against oxidation unlike mineral oils. However, this lack of active sites makes binding of additives a bit challenging. Using nano-particles as additives solves the problem of using performance enhancing additives in PAO based oils.

1.3.4 Engine oil additives:

There are multiple off the shelf engine oil additives that serve the purpose improving compression and stopping leakages on old engines that are close to wearing out. Nanoparticles are not only capable of reducing the rolling/sliding friction or CoF, it also fills out the crevices and helps sealing the gaps in piston rings. These additives have a successful use in the market and they help improve cylinder compression, improve tribological performance and stop leaks.

1.3.5 Materials and Surface Science:

The results of these studies and wear scar analysis can be very useful for the ongoing nanoparticle related research in the field of materials and surface sciences. These results will be offering valuable data for materials scientists and engineers. This can help in development of coatings and studying the influence of lubricant and nanoparticles on different materials, their surface interaction and reactions.

1.4 Relevance to National Needs:

1.4.1 Local Development of Nano-based Lubricants:

Research in this field will play a part in the progress on integrating nanoparticles as performance enhancing additives. This can give local manufacturers an edge over competition. Potentially leading to the creation of locally produced, high-performance lubrication solutions.

1.4.2 Relevance to Local Industrial Sector:

The research on tribological performance and the development of advanced lubricants aligns with the needs and caters the problems of the local industrial sector. High performance lubricants can potentially improve the efficiency, longevity, and reliability of machinery, thereby positively impacting the industrial sector of our country.

CHAPTER 2: MATERIALS AND METHODS:

2.1 Preparation of tribo-pair:

The tribo-pair used in our test consists of a 10mm steel ball that is fixed to the reciprocating head and a gray cast iron plate that is secured to the sump.

2.1.1 52100 steel ball:

The steel ball used in the reciprocating head of the friction and wear testing machine is a standard stainless-steel ball used in ball bearings. The material grade is ASTM-52100 and size of the ball is 10mm as it fits in the test rig we are working on. This ball is supposed to be secured tightly inside the head of the reciprocating tribometer as it should be stationary and should not move or change contacting faces during the duration of the test. This ball was sourced from a tool store and is easily available in the markets.

2.1.2 Gray Cast-iron flat plate:

The flat-plate used in the test is made out of ASTM-A159 grey cast-iron. This material is also known as SAE-J431 G3000 steel. The SAE-G3000 is a material with many applications in the automotive industry.

The reason to select this material for the testing was its use in multiple powertrain related / moving and sliding automotive parts. Some of its applications include:

1) Gasoline and diesel engine cylinder blocks
2) Cylinder heads
3) Transmission and differential casings
4) Flywheel and sprockets
5) Clutch disc
6) Brake discs

The mechanical properties of SAE-J431 (grade G3000) gray cast iron and its metallurgical composition is given in the table below:

Mechanical Properties	
Brinell Hardness	187-241
Vickers Hardness	225
Elastic Modulus	180 GPa
Poisson's Ratio	0.29
Tensile Strength	150 MPa
Ultimate Tensile Strength	220 MPa
Material composition	
Carbon, C	3.1% - 3.4%
Iron, Fe	94%
Manganese, Mn	0.6% - 0.9%
Phosphorus, P	0.1%
Silicon, Si	0.19% - 2.3%
Sulfur, S	0.15%

Table 1: Mechanical properties and Composition of SAE-J431(G3000)

The samples were sourced from an OEM single plate rear brake-disc of a 4-seater family car. The steps for preparation of these plates for experiment are as follows:

1. An SAE-J431 G3000 brake disc was purchased from an automobile parts store and then machined to reduce the thickness down to 4mm.

2. The faced and machined disc was then cut into small plates. The dimensions of the plate were 30mm X 60mm X 4mm.

3. Since the gray cast iron was proving brittle for the lathe tool used for facing the surface. Some hand sanding was required to smoothen out the surface finish. This sanding was done with 240 grit sandpaper.

4. After sanding the samples were taken to a metallography setup, where 400, 600, 800, 1000 and 1200 grit cutting papers were used to achieve approximate surface roughness of (0.250 Ra).

5. Not all flat plate test samples were at 0.250 Ra, some were a bit lower than this value. However, this study mentions the exact Ra values of separate test plates in the wear scar analysis, and the percentage increase or decrease in Ra value was also calculated using exact Ra values.

These test plates were kept in sealed plastic bags to prevent any corrosion.

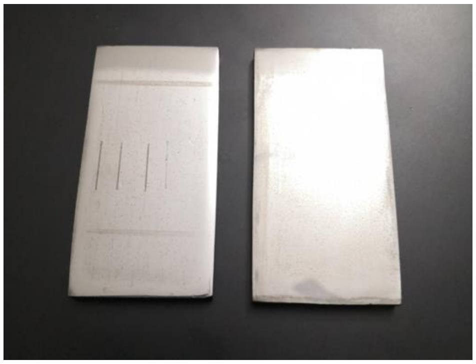


Figure 2: Polished Grey Cast-Iron Plate

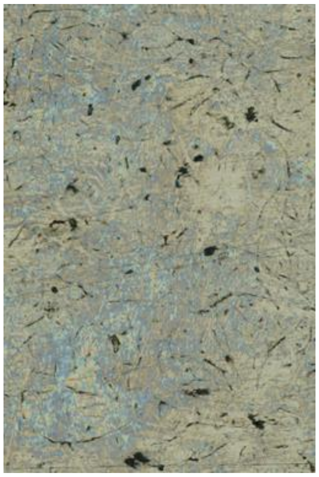


Figure 3: Finished Surface at 300x Magnification

2.2 Lubricants Used:

The test conditions we selected for this study were applied on multiple lubricants:

1) PAO-10
2) PAO-10 + 1wt% CuO nanoparticles
3) PAO-10 + 1wt% ZnO nanoparticles
4) PAO-10 + 1wt% MoS2 nanoparticles
5) SAE 0W20 (API-SN)
6) SAE-40 (Monograde)

The base oil used in this study is PAO-10, this lubricant was sourced from the market manufactured by INEOS Oligomers USA, similar for the two commercial oils in the mix SAE-0W20 (Shell) and SAE-40 (Castrol).

The PAO-10 is used as the baseline for this study as this lubricant is to be mixed with nanoparticles. The mixtures created with PAO and 1wt% nanoparticles were checked for performance improvements against the PAO-10 [10].

The two commercially present fully formulated lubricants were added in this study to compare the results with the ones prepared in the lab. The purpose is to make sure that the performance we are getting is comparable or acceptable against fully formulated products.

2.2.1 Preparation of nanoparticle-based lubricant:

The nanoparticles used in this study are all manufactured by Sigma-Aldrich. According to the information provided by the manufacturer the particle size for CuO is 50 nm, the approximate particle size for MoS_2 nanoparticles is 90 nm and for the ZnO nanoparticles a range of <100 nm was given by the product data sheet. All of the nanoparticles used in this study are spherical in shape [18] [19].

The preparation of a lubricant with PAO-10 and nanoparticles at a 1 wt.% concentration involves a systematic approach to ensure proper dispersion and stability of the nanoparticles in the base lubricant:

1. Start by measuring the required quantity of the base oil that will be used for testing.

2. Weight the quantity of oil using a precision electronic balance.

3. Measure the required quantity of CuO / ZnO / MoS_2 nanoparticles. Since you want a 1 wt.% concentration, calculate the weight of nanoparticles needed based on the weight of the PAO-10.

4. Add surfactants to the blend by 2wt% to enhance the dispersion stability.

5. Use a magnetic stirrer and probe ultrasonicator to disperse the nanoparticles in the PAO-10. Stirring or ultrasonication helps break down agglomerates and ensures uniform distribution of the nanoparticles in the base oil. Stir or sonicate the mixture for a sufficient period until a stable dispersion is achieved. Since the time required can vary for different nanoparticles.

6. It is recommended to handle nanoparticles with care to avoid exposure with moisture and contamination. Use PPE i.e. gloves and mask when dealing with dry nanoparticles and work in a well-ventilated area.

For this study the nanoparticle-based lubricants are prepared in 200g of base oil. Before the addition of nanoparticles, 2wt% oleic acid was added to the base oil to achieve better dispersion stability. Oleic acid was chosen as a surfactant for nano-lubricants in this study since it is an unsaturated fatty acid that helps to prevent nanoparticle agglomeration. Furthermore, it leads to a significant improvement in the lubricant's tribological properties. [18],[19].

The CuO, ZnO and MoS_2 nanoparticles are then added in 1wt% concentration respectively. The exact quantities of the nanoparticles added are listed in the table below. The concentration of 1 wt.% was selected after comparing multiple studies that used varying concentrations and their optimum results. It was observed that the majority of the studies claim 1wt% concentration as optimum for enhancement of tribological properties as shown in the table (below). Hence making it a good starting point for preparing nano lubricants.

	Base Oil	**nanoparticles**	**Optimum concentration**	**CoF (% reduction)**	**Ref.**
1	PAO-6	F-GR Fluorinated graphene	1wt%	84%	[9]
2	PAO-4	Al_2O_3	1wt%	20.86%	[10]
3	PAO	Diamond NPs	0.4wt%	57%	[12]
4	5W30	CuO	0.1wt%	32%	[7]
5	PAO-4 + PAO-40	IF-MoS_2	1wt%	62%	[14]
6	PAO-10	MoS_2	1wt%	53%	[15]
7	PAO-4	WS_2	1wt%	55.8%	[20]
8	PAO8	CuO & Al_2O_3	2wt%	16.3	[21]
9	Hydraulic oil	Graphene NPs	1wt%	28	[22]
10	Hydraulic oil	MoS_2	1wt%	50	[22]

Table 2: Optimum Nanoparticle Concentration and Reduction in CoF Achieved

	Surfactant **Oleic Acid**		**CuO** nanoparticles		**ZnO** nanoparticles		**MoS_2** Nanoparticles		**PAO-10**
	wt.%	grams	wt.%	grams	wt.%	grams	wt.%	grams	grams
1	2%	5.0	1%	2.5	-	-	-	-	242.5
2	2%	5.0	-	-	1%	2.5	-	-	242.5
3	2%	5.0	-	-	-	-	1%	2.5	242.5

Table 3: Composition and Quantities in Nanoparticle based lubricants

CHAPTER 3: PHYSICOCHEMICAL PROPERTIES OF LUBRICANTS

3.1 Density:

The density in liquids is defined as mass per unit volume and it is a crucial physical property of a lubricating oil that is calculated using the basic formula $\rho = Mass\,/\,Volume$.

From the applications point of view the density of the lubricant affects its pumpability and circulation within the engine. Knowing the density helps in designing lubrication systems that can efficiently pump and circulate the lubricant to critical engine components. Other than that, the density of the lubricant can affect its fuel efficiency. Lighter lubricants with lower density may contribute to reduced friction and improved fuel economy in engines.

The density of the PAO+CuO, PAO+ZnO and PAO+MoS_2 is measured on density bottle equipment according to the ASTM D1480 standard. This measurement procedure is valid for liquids within the temperature range of 20 and 100 degree Celsius. The volume of the bottle used for measurement is already known. The liquid is then filled to the said volume, the temperature is recorded and then the amount is weighed.

The formula $\rho = Mass\,/\,Volume$. Is then used to calculate the density for nanoparticle-based lubricant. The values of density for PAO-10 were taken from the technical data sheets of the product provided by the manufacturer.

Figure 4: Density bottle/ Pycnometer on a precision electronic scale

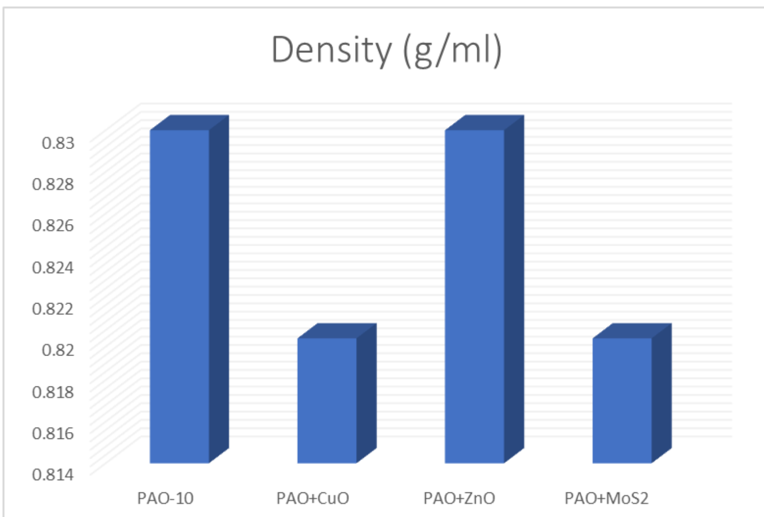


Figure 5: Density of Lubricants

3.2 Pour Point:

The pour point is the lowest temperature at which a liquid's movement ceases due to its increasing viscosity. It gives an indication of the ability of the oil to flow at low temperatures, which is important for its performance in cold weather conditions. The standard test method which was used here was ASTM D97 developed by the American

Society for Testing and Materials (ASTM) used to determine the pour point of petroleum products, including lubricating oils.

The pour point of an engine lubricant is a critical property that has significant implications for the performance and functionality of the lubricant. The pour point directly affects the pumpability and circulation of the lubricant inside the engine at low temperatures. The engine oil pump relies on the lubricant's ability to flow easily and to ensure proper lubrication. A high pour point will lead to honey-like or waxy consistency of oil at cold temperatures leading to inadequate lubricant circulation, resulting in increased wear during cold starts.

Pour point of nanoparticle-based lubricants was measured on a Kohler’s cloud and pour point tester, as shown in the figure below.

To move to a new chapter, you must tell Word that you are moving on to a new page. You do this by inserting a page break. A page break forces the next line of text to appear at the top of a fresh page.

Figure 6: Kohler’s cloud and pour point tester

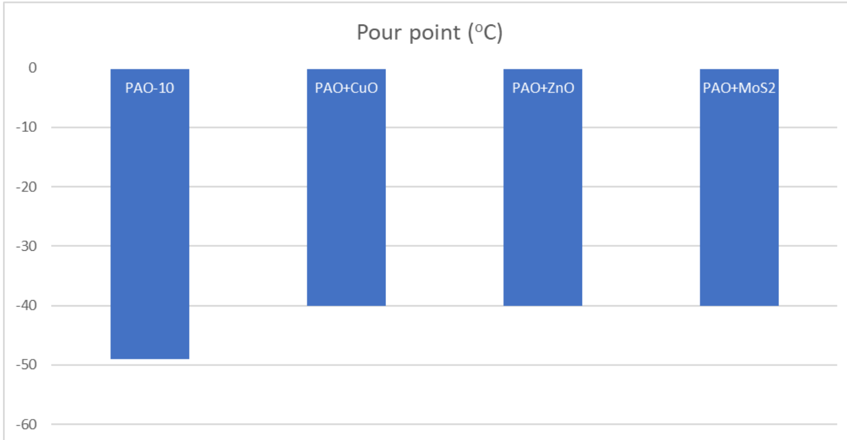


Figure 7: Pour Point of Lubricants

3.3 Flash Point:

Flash point of the test lubricants is tested according to ASTM D92 standard with the help of flash point testing apparatus. The equipment used to test this was a Seta-flash Series 3 Open Cup Flash Point Tester) as shown in Figure. The flash point determination of flammable liquids is done using a manual Cleveland open cup apparatus where a test cup is filled with 5 mL of specimen. The temperature of the test specimen is varied quickly in order to bring it closer to actual flash point, once liquid reaches that temperature it is then varied at a slower consistent rate. During this time a test flame is passed over the cup at predetermined intervals. The flash point is noted at the lowest temperature at which the fumes of the test specimen catch the flame and burn.

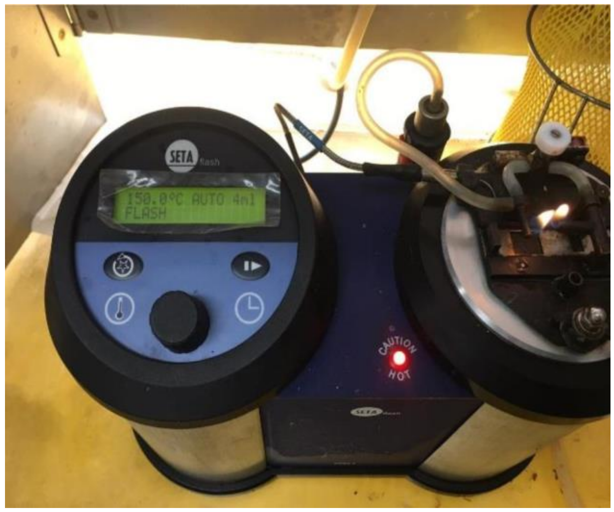


Figure 8: Flash point testing apparatus

3.4 Kinematic Viscosity:

Kinematic viscosity is a crucial property of engine lubricants that plays a significant role in determining their performance and effectiveness in various operating conditions. Kinematic viscosity is a measure of a fluid's resistance to flow under the influence of gravity and is expressed in units of square millimeters per second (mm^2/s) or centistokes (cSt). The standard used to test fluids for kinematic viscosity is ASTM-D445.

A certain kinematic viscosity is crucial for providing a protective lubricating film that minimizes wear on engine components. This is essential for preserving the life of critical parts such as bearings, cams, pistons and cylinder liners.

The Kinematic viscosity values at 40^oC and 100^oC for the lubricants used in this study are shown in the chart below. The measurement of these values was carried out on the Ostwald viscometer (as shown in the figure). This test determines the viscosity by measuring the time it takes for the test liquid to follow under gravity inside a glass capillary tube.

To conduct the test, fill up the U-shaped tube with the test liquid and fill the tube till the bottom of the bulb. After filling use a pipette to suck the the liquid in the smaller diameter tube raising it to the top marking on the tube. Remove the suction pipette to release pressure and start the timer. Note the time taken by the liquid to flow from top mark to the bottom mark.

The time taken by the test liquid to flow is compared by the time taken by a liquid with known viscosity and the viscosity is determined.

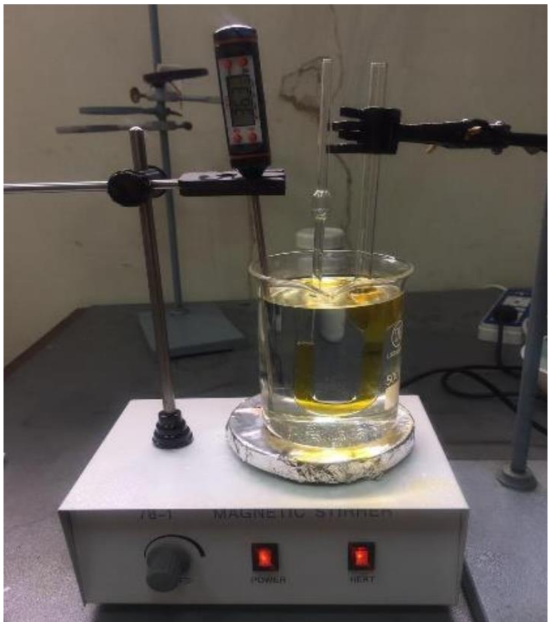


Figure 9: Ostwald Viscometer setup

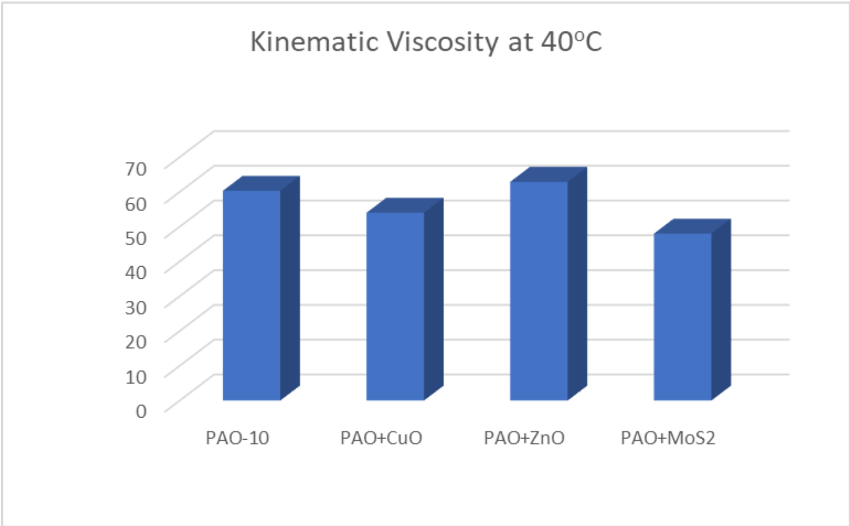


Figure 10: Viscosity of lubricants at 40°C

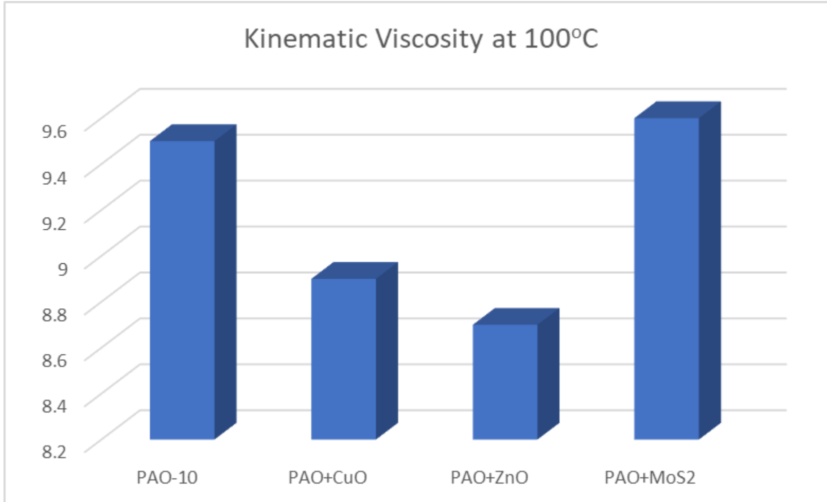


Figure 11: Viscosity of lubricants at 100ºC

3.5 Viscosity Index:

Kinematic viscosity is highly temperature-sensitive. As temperatures increase, viscosity tends to decrease, and as temperatures decrease, viscosity tends to increase. Viscosity index (VI) is a parameter used to characterize this temperature sensitive behavior of lubricants. A high viscosity index is beneficial for cold start performance. In cold conditions, the oil needs to flow easily to provide lubrication to critical engine components. A high Viscosity index value ensures that the oil maintains sufficient fluidity at low temperatures. ASTM D2270 is a standard test method used to determine the Viscosity Index (VI) of lubricating oils. The viscosity index values for lubricants used in this study are shown in the figure below.

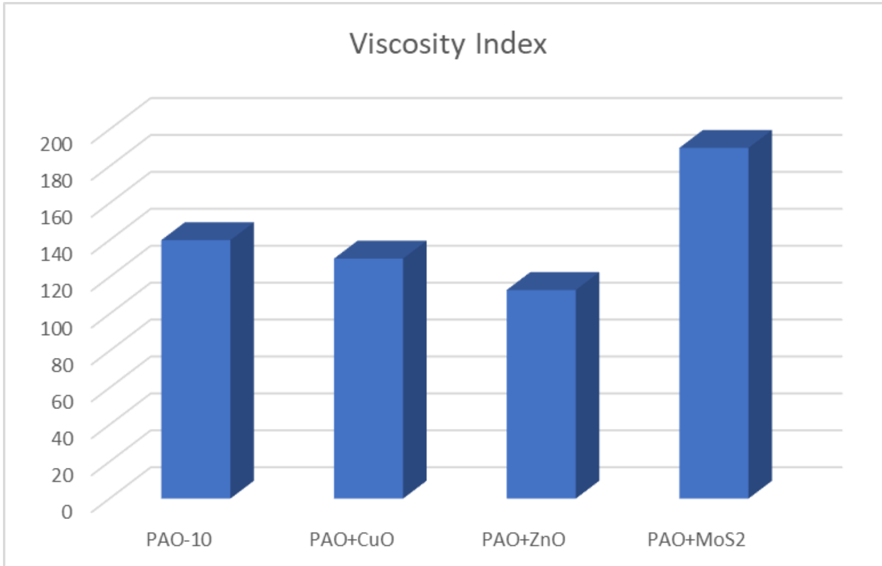


Figure 12: Viscosity index of lubricants

property	units	standard	PAO-10	PAO+CuO	PAO+ZnO	PAO+MoS$_2$
Density at 20ºC	g/ml	ASTM D1480	0.83	0.82	0.83	0.82
Pour Point	ºC	ASTM D97	-49	-40	-40	-40
Flash Point	ºC	ASTM D92	271	227	225	>235
Viscosity at 40ºC	cSt	ASTM D445	60.3	54	62.9	48
Viscosity at 100ºC	cSt	ASTM D445	9.5	8.9	8.7	9.6
Viscosity Index	-	ASTM D2270	140	130	113	190

Table 4: Physicochemical properties of nano lubricants and base oil

CHAPTER 4: EXPERIMENT SETUP AND TESTING:

4.1 Experimental Setup:

The tribological testing of the tribo-pair under the prepared lubricants is carried out on a computer-controlled friction and wear testing machine (Reciprocating tribometer). This setup is capable of recording and sending the real time data to a PC that is part of the experimental setup.

Figure 13: Test bed of Computer Controlled Friction and Wear Testing Machine

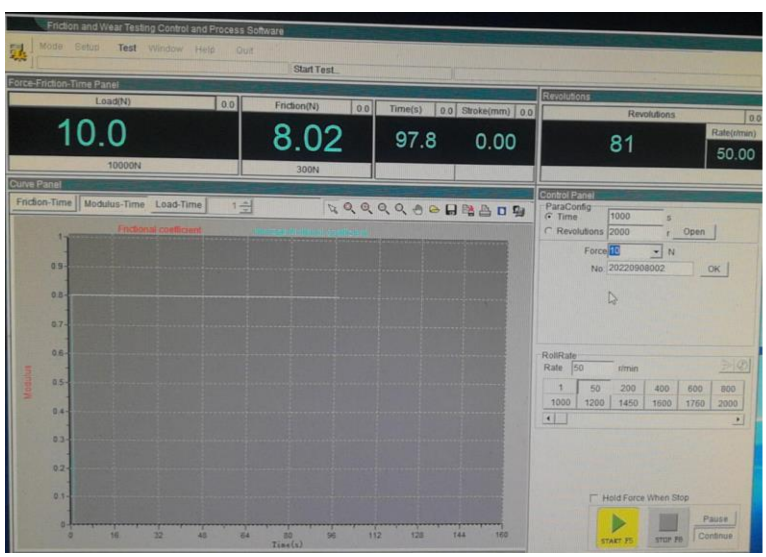


Figure 14: Interface of Computer Controlled Friction and Wear Testing Machine

The conditions and setup for the testing machine before running the experiment are as listed:

- **Load:** 10N, 20N and 30N
- **Speed:** 50 Rpm
- **Run Time:** 7200 seconds (2 hours)
- **Reading interval:** 300 milliseconds (records data at every 300 milliseconds)
- **Plot:** Average CoF and Average Friction Force (N)
- **File Type:** Export data points in form of excel sheet or text file

4.2 Testing Procedure:

1) Clean the gray cast iron test plate and steel ball with the acetone before mounting on the tribometer sump. This is done to remove any impurities and dust particles and prevent them from affecting the results and performance of nanoparticles.
2) Mount the test plate on the tribometer carefully and make sure that all the screws are properly secured. So that during testing the sample remains fixed and values do not get compromised due to play and movement in the test plate.
3) Now add the approximately 90 ml lubricant with the help of a graduated syringe into the oil sump, where the test plate is fixed. Make sure that the test plate is submerged in the lubricant.
4) Now fix the ball in the load unit head and secure the load weights of 10N, 20N or 30N as required by the testing procedure.
5) Leave both test samples for the soaking time of 1 hour. This is done to homogenize the temperature of lubricant and the samples with the ambient temperature.
6) Cover the machine with the Dust cover. So that during soaking and testing dust, moisture or contaminants do not interfere with the setup.
7) To start the test, turn on the computer, open the software and set the testing conditions. As given above the testing procedure.

8) After setting all the testing conditions, click on the start button and let the test run for 2 hours till the test is complete. During this time, it is advised to observe the values and real time graphs for any abnormal behavior. It is also recommended to save the data every 20 minutes, so that you don't lose data in case of power outage.
9) After the test is complete, remove the loading unit, and remove the steel ball. Then open all the screws and remove the test plate.
10) Carefully, then clean that specimen with a soft paper towel to remove unnecessary oil and place the test plate sample in a sealed plastic bag with silica gel, so that moisture does not interact with the wear scar.
11) It is recommended to always wear latex gloves from the start of the experimental test to avoid possible irritation on skin. And make sure not to touch the wear scar as it can spoil the sample for microscopy stage.

4.3 Wear Scar Analysis:

The wear scar analysis was done on the test plates to look for the dimensions of the wear scar, these dimensions and the depth of the wear scar, these readings were then used to calculate the wear scar volume. The equipment used for this was a digital optical microscope (Olympus DSX10-UZH), with PC based real time display and analysis tool/software (DSX-1000). This software was used to capture and stitch together the magnified images of the wear scar and save it as a file that could be opened and analyzed anytime later.

This software was used to measure wear scar dimensions, surface roughness of test plates and surface roughness of the scar after testing.

4.3.1 Surface Roughness:

By using the DSX-1000 analysis tool, line roughness (Ra) values were calculated for every individual test plate before the tests were conducted. For every test plate, multiple values were recorded and then average was taken to establish the overall surface roughness of the test plate.

After completing the tribology testing on samples, the line roughness tool was then used to calculate the roughness of the wear scar. In case of wider scars, two or sometimes three values were recorded and then averaged out.

Both of these values recorded before and after the test, were then compared for and the percentage difference (which could be percentage increase or percentage decrease in Ra value) is then presented in this study.

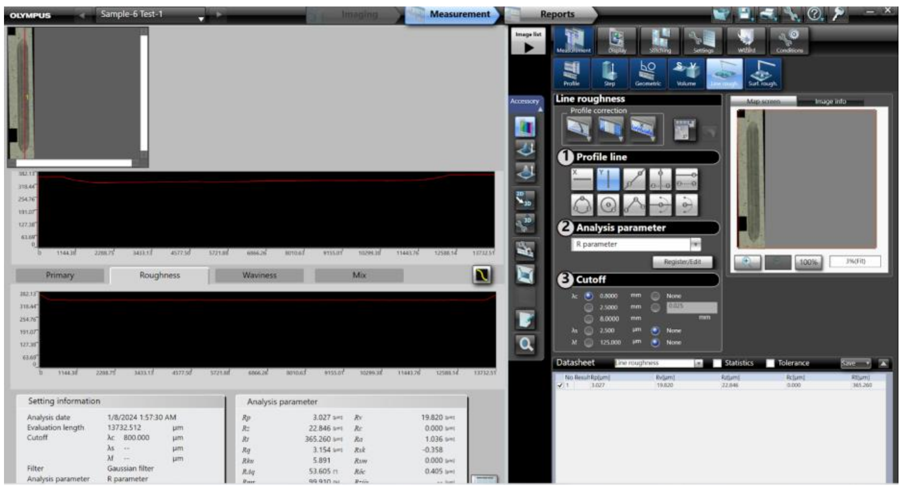


Figure 15: DSX-1000 Interface for Roughness (Ra) value measurement.

Figure 16: Olympus DSX10-UZH Digital Optical Microscope

Test	Roughness (Ra) of Test Plate	Roughness (Ra) of wear scar
0W20 10N	0.258	0.225
0W20 20N	0.241	0.217
0W20 30N	0.249	0.210
SAE-40 10N	0.241	0.204
SAE-40 20N	0.249	0.265
SAE-40 30N	0.236	0.223
PAO 10N	0.236	0.211
PAO 20N	0.236	0.222
PAO 30N	0.236	0.217
PAO+CuO 10N	0.245	0.203
PAO+CuO 20N	0.245	0.212
PAO+CuO 30N	0.212	1.161
PAO+ZnO 10N	0.212	0.261
PAO+ZnO 20N	0.212	0.216
PAO+ZnO 30N	0.212	0.205
PAO+MoS2 10N	0.171	0.149
PAO+MoS2 20N	0.171	0.199
PAO+MoS2 30N	0.171	0.222

Table 5: Values for surface roughness

4.3.2 Wear Scar Volume:

The procedure for wear scar volume calculation starts with taking dimensions of the wear scar and calculating the depth of the scar. For this activity we will use the Profile tool in DSX-1000 and then select the horizontal profile line to check the width of the wear scar.

This tool shows the top view of the wear scar along with the side section of the surface. Side section is helpful in determining the depth of the wear scar and will show the section of cup formed by the reciprocating 52100 steel ball.

The Profile line is then laid over the wear scar and value for width is recorded, since the wear scar width can vary along the stroke length. 11 values were recorded along the stroke length at every 1mm spacing, since the stroke length for our tribo-tests is 11.5mm or 11,500µm.

For every value of wear scar width, a value for maximum depth at that point is also recorded. These values are then averaged out to get a single number for both parameters each. For the length of the wear scar, the vertical line profile tool was used.

After obtaining the dimensions (length, width and depth) the overall wear volume was calculated manually and values were recorded and compared for further analysis.

Below are some magnified images of the wear scar of the tests conducted:

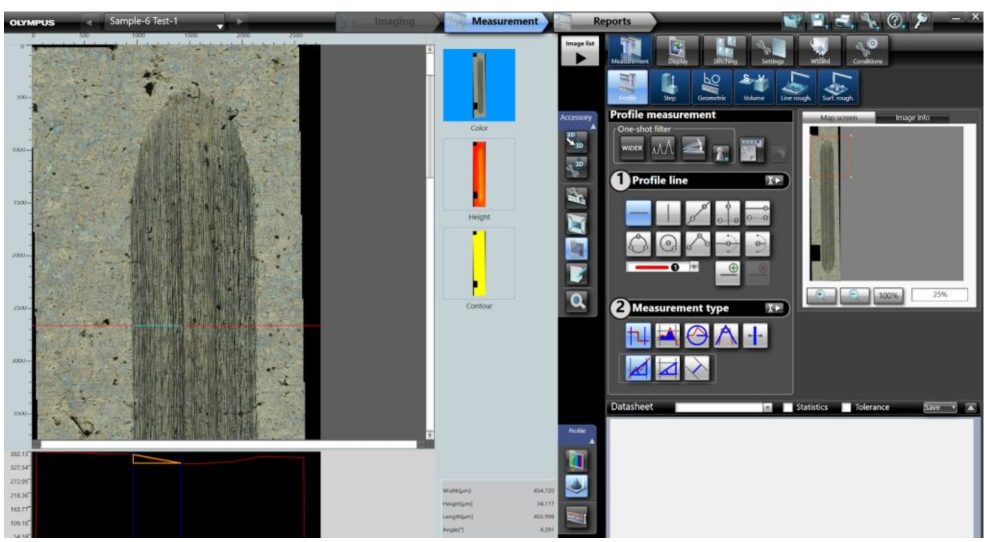


Figure 17: DSX-1000 Interface for wear scar measurements.

4.3.3 Wear scar images for SAE-0W20

Figure 18: SAE-0W20 10N

Figure 19: SAE-0W20 20N

Figure 20: SAE-0W20 30N

4.3.4 Wear scar images for SAE-40

Figure 21: SAE-40 10N

Figure 22: SAE-40 20N

Figure 23: SAE-40 30N

4.3.5 Wear scar images for PAO-10

Figure 24: PAO-10 10N

Figure 25: PAO-10 20N

Figure 26: PAO-10 30N

4.3.6 Wear scar images for PAO+CuO

Figure 27: PAO+CuO 10N

Figure 28: PAO+CuO 20N

Figure 29: PAO+CuO 30N

4.3.7 Wear scar images for PAO+ZnO

Figure 30: PAO+ZnO 10N

Figure 31: PAO+ZnO 20N

Figure 32: PAO+ZnO 30N

4.3.8 Wear scar images for PAO+MoS_2

Figure 33: PAO+MoS_2 10N

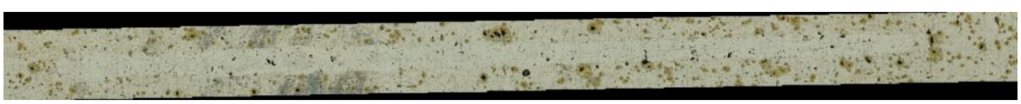


Figure 34: PAO+MoS_2 20N

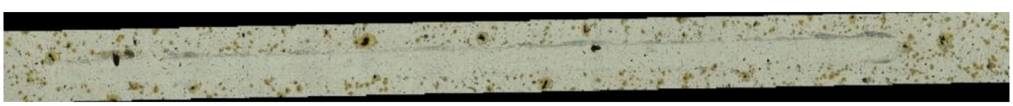


Figure 35: PAO+MoS_2 30N

Lubrication Regime:

To identify the lubrication regime present under the sliding contact conditions we need to know the Lambda ratio (λ). The lambda ratio is the ratio of the fluid film present between two sliding surfaces and the surface roughness, if this ratio is λ<1 this means that the fluid film thickness is lower than the surface roughness and hence we have a boundary lubrication regime. For λ=1 or λ>1 we will have a separation between sliding surfaces with possible occasional contact, these numbers will indicate a mixed regime. For λ values more than 3 to 5 we can confidently say that the fluid film is separating the two sliding bodies effectively and we have an elasto-hydrodynamic or hydrodynamic regime.

The surface roughness values were recorded during the wear scar analysis and can be used to calculate lambda ratio. In order to calculate the fluid film thickness equations, form a famous study done by Hamrock and Dawson (1978) can be useful. The equation used to calculate the film thickness for this study is the iso-viscous elastic regime equation found in Hamrock and Dawson (1978). The below equation is taken from that study and is applied to a ball on flat plate sliding contact [12].

$$H\mathrm{min} = 7.43\mathrm{R}(1 - 0.85e^{-0.31K}).\left(\frac{\eta \upsilon}{ER}\right).\left(\frac{L}{ER}\right)^{-0.21} \quad (1.1)$$

H_{min} = Minimum film thickness
η = Dynamic Viscosity
R = Contact Radius
U = Sliding speed
L = Normal Load
E = Elasticity Modulus

The lambda ratio is calculated using the relation shown below; where (H) is film thickness and Ra is value of surface roughness.

$$\lambda = \frac{\mathrm{H}}{Ra} \quad (1.2)$$

$$\eta = \nu\rho \tag{1.3}$$

Dynamic viscosity is obtained by product of Kinematic viscosity (***ν***) and density (***ρ***) of the fluid.

The contact radius value is taken from the wear scar track width. For the calculation of fluid film thickness, maximum velocity is used. As at the ends of the stroke length, the speed is zero and hence the fluid film thickness drops to the minimum value that is in the boundary lubrication regime. To further verify the lubrication regime, we can use Hersey's number and its position on the Stribeck curve along with the CoF value to determine the region where our test conditions exist on the curve.

The Srtibeck's curve is a graphical representation of the relationship between friction coefficient and Hersey's number. Hersey's number is a dimensionless value found on the horizontal axis of the Stribeck curve and it is based on the factors like lubrication regime, and the operating conditions in a sliding contact or tribological system. The Stribeck curve helps illustrate how different lubrication regimes transition from boundary lubrication to mixed lubrication to hydrodynamic lubrication.

After obtaining required results such as CoF, Viscosity, Normal load and wear scar width, we can now calculate Hersey's number for each of our tests. The Hersey's number is given by the following formula:

$$H = \eta \frac{U}{P} \tag{1.4}$$

η= Dynamic Viscosity
U= Sliding Speed (m/s)
P= Load per unit length (N/m)

For calculation of ***P*** (normal load divided by contact length), we will use the **normal load** (***L***) applied during the test (10N, 20N or 30N) and for contact length we will use the **wear scar width** (***W***) value for the respective test.

$$P = \frac{L}{W} \tag{1.5}$$

For calculation of sliding speed of the steel ball the following formula is used:

$$U = 2\frac{S.N}{60} \tag{1.6}$$

***S*=** Stroke Length
***N*=** Rpm

Using the above equations for dynamic viscosity, load per unit length and sliding speed the Hersey's number is calculated and used to approximate the lubrication regime present under the test conditions.

CHAPTER 5: RESULTS AND DISCUSSIONS:

5.1 Results:

After testing all of the Prepared oils and commercially available oils used in this study, the results are presented in a graphical form. The results include:

1) Average Coefficient of Friction
2) Average Frictional Force
3) Wear Scar Volume
4) Surface roughness

5.1.1 Chart for Average Coefficient of Friction of the Tests Conducted

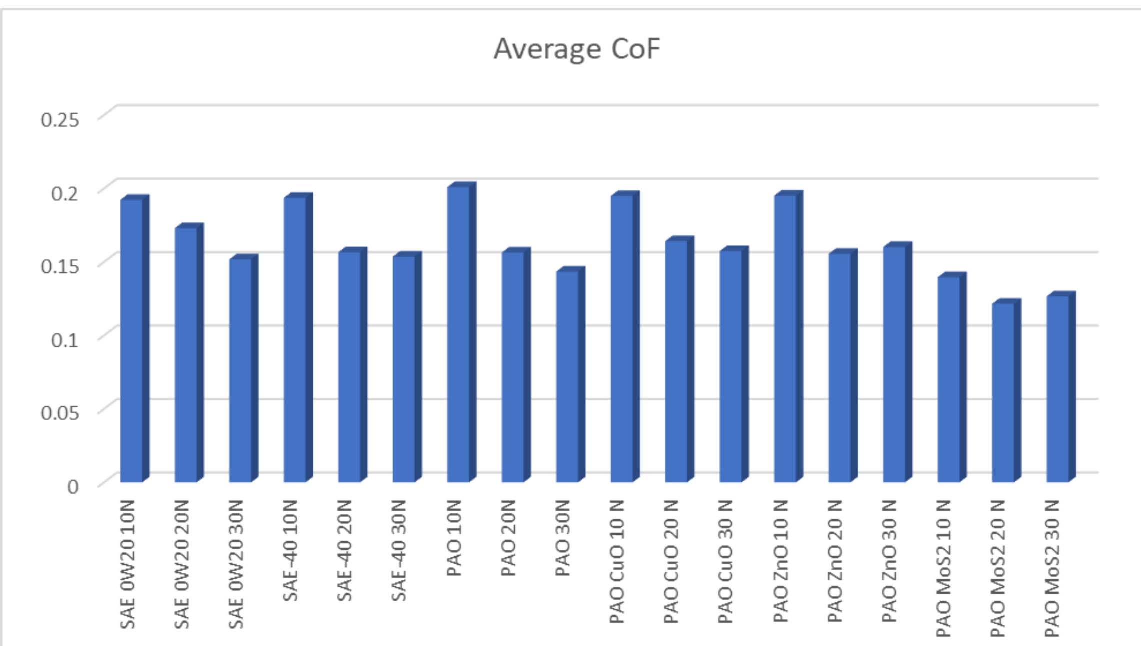


Figure 36: Average Coefficient of Friction

5.1.2 *Chart for Average Friction Force of the Tests Conducted*

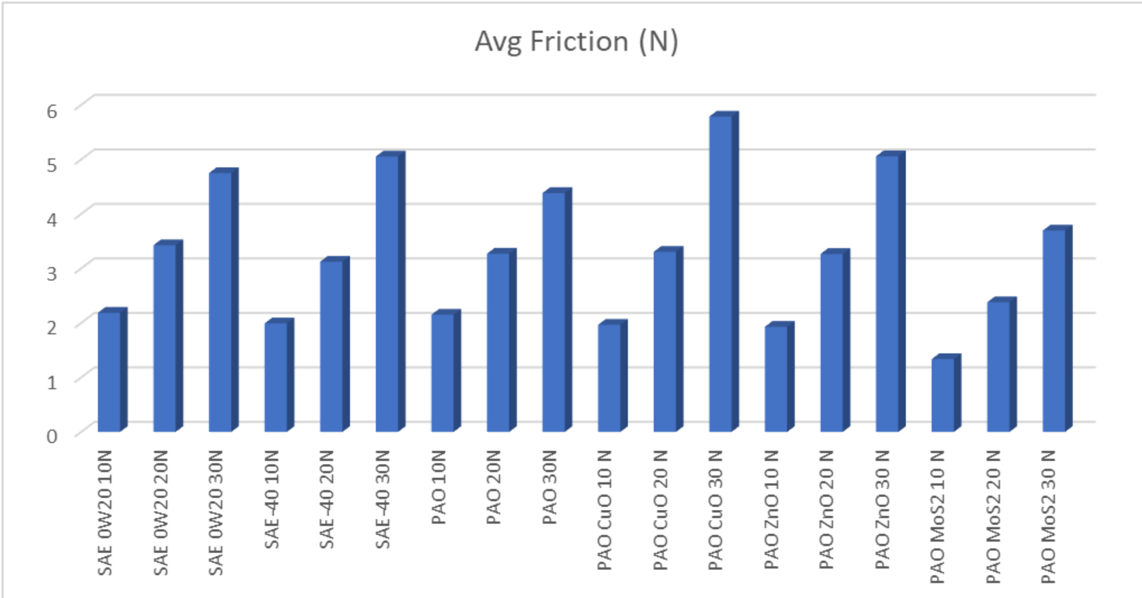


Figure 37: Average Frictional Force (N)

5.1.3 *Chart for wear volume of the tests conducted*

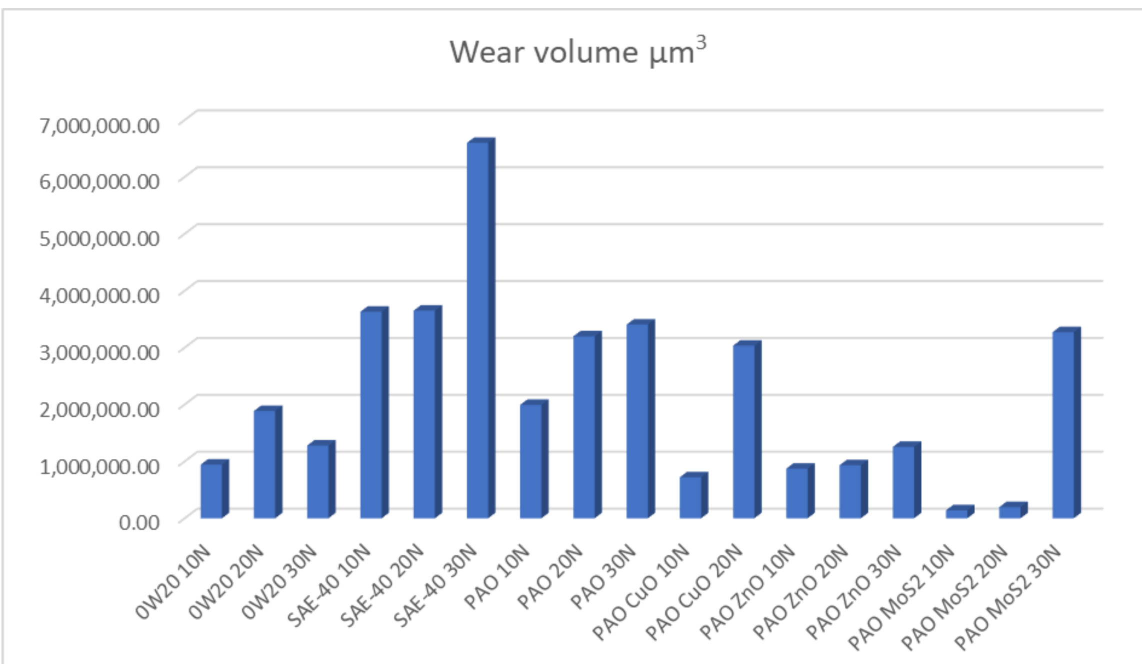


Figure 38: Wear scar volume

5.2 Results of PAO+CuO

CuO nanoparticles are spherical nanoparticles of about 50 nm in size. These nanoparticles were prepared in 1wt% concentration with PAO-10 along with 2wt.% oleic acid. When compared with only PAO, the CuO nanoparticles displayed a behavior pattern that stood out from other tests. Even the tests done for repeatability were not close in case of PAO+CuO blend. However, the average of two tests are used for comparison with base PAO.

At 10N load the CoF was observed to have a slight decrease of 3%. The frictional force (N) was also reduced after addition of nanoparticles by 8.6%. However, a significant difference was observed in wear volume that reduced by 63.8%. A significant change in wear scar width was also observed, changing from 347.5m to 283.5m after adding CuO nanoparticles. The CuO nanoparticles manage to reduce wear by deposition of nanoparticle film on the surface that forms a physical tribo-film that prevents mass loss [8].

For 20N and 30N load, the values for CoF were increased by 5% and 9.8% when compared with PAO-10, frictional force also increased by 1.1% and 32% for 20N and 30N tests respectively. For 20N load the wear volume was reduced by 5%. However, the wear volume for the 30N test was the highest recorded of all experiments in this study and it has increased multiple folds from 3.404x10^6 m3 to 221.3x10^6 m3.

The lambda ratio for all the loading conditions is less than zero with film thickness of 0.005µm for 30N load. The Hersey's number for 10N test conditions is 2.74x10^-7, since this number is very much close to zero and CoF is higher than 0.1, we can confidently say that these values lie in the boundary lubrication region of a Stribeck curve. Similarly, for 30N test conditions Hersey's number obtained was 3.9x10^-7. Since all three tests lie in the upper left region of the Stribeck curve. The boundary lubrication regime was in action during these tests.

PAO+CuO at 30N load was the highest outlier among all experiments performed. This test showed highest frictional force, largest wear volume, widest wear scar and roughest wear scar surface of all the tests conducted. The values and condition of the wear scar clearly shows signs of abrasive wear caused by three body wear mechanisms, which indicates that CuO nanoparticles are not suited well to perform with PAO-10 and Oleic acid. The long chain molecules like PAO have strong polarity and will result in aggregation with CuO nanoparticles, resulting in three body abrasions under higher concentrations [16]. Some recent studies claim much larger reductions in CoF with 0.1wt% concentration of CuO nanoparticles; these articles state 32% [16] and 16.1% [5] reduction in CuO. The observations in [16] discuss that. The studies show that the 1wt% concentration used in this study could be far from the optimum results [5][16].

5.2.1 *Comparison of PAO+CuO Nano-Lubricant with other Lubricants*

	CoF		Fric. Force (N)		Wear scar width µm		Wear volume µm³		Wear scar roughness	
	PAO	PAO+CuO	PAO	PAO+CuO	PAO	PAO+CuO	PAO	PAO+CuO	PAO	PAO+CuO
10N	0.201	0.195	2.151	1.966	347.1	283.45	1.993x10^6	0.721x10^6	6.7% dec	16.91% dec
20N	0.156	0.164	3.271	3.306	401.35	368.73	3.198x10^6	3.034x10^6	6.13% dec	13.4% dec
30N	0.143	0.157	4.384	5.787	394.7	1215.7	3.404x10^6	221.3x10^6	8.77% dec	440% inc

Table 6: Comparison of PAO+CuO vs PAO

	CoF		Fric. Force (N)		Wear scar width µm		Wear volume µm³		Wear scar roughness	
	0W-20	PAO+CuO	0W-20	PAO+CuO	0W-20	PAO+CuO	0W-20	PAO+CuO	0W-20	PAO+CuO
10N	0.192	0.195	2.186	1.966	301.33	283.45	0.943x10^6	0.721x10^6	6.4% dec	16.91% dec
20N	0.173	0.164	3.427	3.306	309.76	368.73	1.88x10^6	3.034x10^6	10.1% dec	13.4% dec
30N	0.304	0.157	4.751	5.787	279.94	1215.7	1.278x10^6	221.3x10^6	15.5% dec	440% inc

Table 7: Comparison of PAO+CuO vs 0W-20

	CoF		Fric. Force (N)		Wear scar width µm		Wear volume µm³		Wear scar roughness	
	SAE-40	PAO+CuO	SAE-40	PAO+CuO	SAE-40	PAO+CuO	SAE-40	PAO+CuO	SAE-40	PAO+CuO
10N	0.194	0.195	1.99	1.966	400.2	283.45	3.629x10^6	0.721x10^6	14.3% dec	16.91% dec
20N	0.156	0.164	3.12	3.306	404.2	368.73	3.649x10^6	3.034x10^6	5.7% dec	13.4% dec
30N	0.155	0.157	5.053	5.787	421.7	1215.7	6.59x10^6	221.3x10^6	5.45% dec	440% inc

Table 8: Comparison of PAO+CuO vs SAE-40

5.3 Results of PAO+ZnO

ZnO nanoparticles are spherical nanoparticles with size ranges of <100 nm. These nanoparticles were prepared in 1wt% concentration with PAO-10 and 2wt% concentration of oleic acid was added. The combination of PAO+ZnO showed positive results with the tribo-pair under all loading conditions. The average CoF for PAO+ZnO was reduced by 3% for the 10N load, for 20N load the CoF remained the same as PAO-10. Meanwhile for 30N load the average CoF value saw an increase of 11%.

A similar pattern was observed for average friction, for 10N load a reduction of 10.3% in friction was observed, the friction for 20N load decreased very slightly by 0.2%, under 30N loading conditions friction increased by 15.9%.

However, the presence of ZnO nanoparticles in PAO showed an overall decrease in wear volume across all three loading conditions. For 10N load test PAO+ZnO showed 55% reduction in wear volume, for 20N load 68% reduction in wear was observed and for 30N load wear was reduced by 63%.

These results show that ZnO nanoparticles under this concentration were not fully effective in reducing CoF by significant margins. However, minor improvements in CoF can be observed. When wear scar was observed under the microscope it showed a relatively thick layer of nanoparticles deposited on the wear track as compared to CuO and MoS2 nanoparticles. This formation of this protective tribo-film can explain the huge reduction in wear volume achieved by PAO+ZnO as compared to only PAO. This similar behavior was also reported in other studies. Where physical deposition of nanoparticles resulted in strong tribo-film and caused reduction in wear [18], and adhesion of ZnO nanoparticles was observed on steel balls in four ball tests [23]. It was also claimed that this adhesive property results in agglomeration and three body wear when ZnO is used in higher concentrations [23].

When compared with the results obtained from SAE-0W20 multi-grade, non-synthetic fully formulated oil tested under the same conditions. PAO+ZnO gave very similar CoF values for 10N load and showed 9.8% and 45% lower CoF under 20N and 30N load conditions respectively. Across the three tests wear volume values for PAO+ZnO were lower than that given by SAE-0W20 by 7.5%, 47% and 2% for 10N, 20N and 30N respectively.

Compared with SAE-40 monograde oil under the same testing conditions. PAO+ZnO has very similar CoF values to that of SAE-40. Meanwhile the wear scar volume for PAO+ZnO being 75%, 72% and 80% lower than that of SAE-40.

The lambda ratio for all the loading conditions is less than zero with film thickness of 0.005µm for 30N load. The Hersey's number values for 10N, 20N and 30N are between 0 and 1. CoF values are between 0.1 and 0.2, which suggests that the model lies in the boundary lubrication regime of the Stribeck curve.

5.3.1 Comparison of PAO+ZnO Nano-Lubricant with other Lubricants

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	PAO	PAO+ZnO	PAO	PAO+ZnO	PAO	PAO+ZnO	PAO	PAO+ZnO	PAO	PAO+ZnO
10N	0.201	0.195	2.151	1.930	347.1	279.45	1.993x10^6	0.873x10^6	6.7% dec	22.9% inc
20N	0.156	0.156	3.271	3.266	401.35	369.84	3.198x10^6	0.993x10^6	6.1% dec	1.9% inc
30N	0.143	0.160	4.384	5.058	394.7	435.86	3.404x10^6	1.254x10^6	8.8% dec	3.9% dec

Table 9: Comparison of PAO+ZnO vs PAO

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	0W-20	PAO+ZnO	0W-20	PAO+ZnO	0W-20	PAO+ZnO	0W-20	PAO+ZnO	0W-20	PAO+ZnO
10N	0.192	0.195	2.17	1.930	301.33	279.45	0.943x10^6	0.873x10^6	6.4% dec	22.9% inc
20N	0.173	0.156	3.42	3.266	309.76	369.84	1.88x10^6	0.993x10^6	10.1% dec	1.92% inc
30N	0.152	0.160	4.75	5.058	279.94	435.86	1.278x10^6	1.254x10^6	15.5% dec	3.9% dec

Table 10: Comparison of PAO+ZnO vs 0W20

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	SAE-40	PAO+ZnO	SAE-40	PAO+ZnO	SAE-40	PAO+ZnO	SAE-40	PAO+ZnO	SAE-40	PAO+ZnO
10N	0.194	0.195	1.99	1.930	400.2	279.45	3.629x10^6	0.873x10^6	14.3% dec	22.9% inc
20N	0.156	0.156	3.12	3.266	404.2	369.84	3.649x10^6	0.993x10^6	5.7% dec	1.92% inc
30N	0.155	0.160	5.053	5.058	421.7	435.86	6.59x10^6	1.254x10^6	5.45% dec	3.9% dec

Table 11: Comparison of PAO+ZnO vs SAE-40

5.4 Results of PAO+MoS2

MoS2 nanoparticles are relatively larger in size, approximately at 90 nm diameter. These nanoparticles are mixed with PAO-10 alongside oleic acid to make a blend of PAO+MoS2 with 1wt% concentration of MoS2 nanoparticles and 2wt% concentration of oleic acid. This blend turned out to be the most effective of all three nanoparticles tested in this study. Not only did it show a reduction in wear volume but it also showed a significant decrease in CoF and frictional force.

The MoS2 and PAO blend reduced the CoF by 30.4%, 21.7% and 11.2% for the 10N, 20N and 30N load conditions respectively. The values for average friction were also reduced by 38.9%, 30.5% and 22.2% for 10N, 20N and 30N respectively.

Width of the wear scar also decreased in all three tests. The wear volume decreased by 92%, 93% and 4% for 10N, 20N and 30N load conditions respectively.

When compared with SAE-0W20 multi-grade, non-synthetic fully formulated oil tested under the same conditions, PAO+MoS2 blend showed CoF values 27.1%, 29.5% and 58.2% lower than 0W20 for 10N, 20N and 30N loads. In comparison with 0W20, wear volume of PAO+MoS2 was 85% lower for 10N and 89% lower for 20N test. However, in the case of 30N test 0W20 showed a 60% lower value than PAO+MoS2.

In comparison with SAE-40 monograde, fully formulated oil, CoF values of PAO+MoS2 were observed to be lower by 27.8%, 21.8% and 18% for 10N, 20N and 20N respectively. Values of wear volume were also observed to be lower than that of SAE-40 by 96%, 94.6% and 50.3% for 10N, 20N and 30N loads respectively.

The lambda ratio for all the loading conditions is less than zero with film thickness of 0.005µm for 30N load. The Hersey's number for 10N test conditions is 2.6x10^-7 and for 30N test conditions it is 1.1x10^-7. The CoF for all of the PAO+MoS2 tests are between 0.10 and 0.15. These parameters suggest that our model lies in the Boundary lubrication region of the Stribeck curve.

5.4.1 Comparison of PAO+MoS_2 Nano-Lubricant with other Lubricants

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	PAO	PAO+MoS2	PAO	PAO+MoS2	PAO	PAO+MoS2	PAO	PAO+MoS2	PAO	PAO+MoS2
10N	0.201	0.140	2.151	1.336	347.1	266.9	1.993x10^6	0.141x10^6	6.7% dec	13.1% dec
20N	0.156	0.122	3.271	2.380	401.35	334.9	3.198x10^6	0.196x10^6	6.1% dec	16.3% inc
30N	0.143	0.127	4.384	3.696	394.7	330.6	3.404x10^6	3.270x10^6	8.8% dec	30% inc

Table 12: Comparison of PAO+MoS_2 vs PAO

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	0W-20	PAO+MoS_2	0W-20	PAO+MoS_2	0W-20	PAO+MoS_2	0W-20	PAO+MoS_2	0W-20	PAO+MoS_2
10N	0.192	0.140	2.186	1.336	301.33	266.9	0.943x10^6	0.141x10^6	6.4% dec	13.1% dec
20N	0.173	0.122	3.427	2.380	309.76	334.9	1.88x10^6	0.196x10^6	10.1% dec	16.3% inc
30N	0.304	0.127	4.751	3.696	279.94	330.6	1.278x10^6	3.270x10^6	15.5% dec	30% inc

Table 13: Comparison of PAO+MoS_2 vs 0W-20

	CoF		Fric Force (N)		Wear scar width µm		Wear volume µm^3		Wear scar roughness	
	SAE-40	PAO+MoS_2	SAE-40	PAO+MoS_2	SAE-40	PAO+MoS_2	SAE-40	PAO+MoS_2	SAE-40	PAO+MoS_2
10N	0.194	0.140	1.99	1.336	400.2	266.9	3.629x10^6	0.141x10^6	14.3% dec	13.1% dec
20N	0.156	0.122	3.12	2.380	404.2	334.9	3.649x10^6	0.196x10^6	5.7% dec	16.3% inc
30N	0.155	0.127	5.053	3.696	421.7	330.6	6.59x10^6	3.270x10^6	5.45% dec	30% inc

Table 14: Comparison of PAO+MoS_2 vs SAE-40

CONCLUSION:

While analyzing the results we observed that all of the tests conducted were in the boundary lubrication regime, which shows that this test setup was designed to test the shear stability of the lubricants at lower temperatures and their ability to sustain the lubricant film under high normal pressures and keep the sliding surfaces separate.

When nanoparticle-based lubricants were compared with commercially available SAE-40 and SAE-0W20 the results for coefficient of friction came out within 5% deviation of each other. This shows us that the combination of nanoparticles and additives were successful in yielding results that are comparable to fully formulated commercially available lubricants when tested under the conditions set in this study.

The best overall result was produced by the combination of PAO+MoS_2. The lowest value of CoF was obtained with PAO+MoS_2 at 20N load, the 2nd and 3rd lowest were also observed with PAO+MoS_2 under 30N and 10N respectively. The lowest recorded value for wear volume was also observed for PAO+MoS_2. This shows us that MoS_2 nanoparticles are most effective when it comes to separation of sliding layers.

Lack of deposition on the wear scar track of the tests carried out for MoS_2 nanoparticles means that they reduce the friction majorly by creating nano-ball bearing effect and create a nanolayer that changes friction model from sliding to rolling friction.

PAO+ZnO also showed significant improvement in terms of reducing wear volume. At 30N load, PAO+ZnO showed the lowest value for wear volume, with 61% lower value than PAO+MoS2. However, the reduction in CoF was not as significant as shown by MoS_2 nanoparticles. The large amount on nanoparticle deposits on wear scar track proves that ZnO nanoparticles are highly effective in forming protective tribo-film between the sliding surfaces. This film may not be as effective in reducing the CoF and Frictional force but has proved to be effective in protecting surfaces against material loss.

For the concentration used in this study CuO nanoparticles did not perform as well under higher loads. Although the 1wt.% concentration of all nanoparticles was selected based on optimum results in numerous studies done on PAO base oil under reciprocating motion, there are a number of studies that report lower optimum concentration for CuO nanoparticles. Performance of CuO nanoparticles can be further evaluated with varying concentration of dispersive agent and nanoparticles to establish optimum results.

After addition of nanoparticles the densities of lubricants remained almost same in all the cases. The pour point was observed to increase from -49^{o}C to -40^{o}C Celsius. Viscosity at 100^{o}C remained almost same however the viscosity oat 40^{o}C was decreased in case if CuO and MoS_2 and increased in case of ZnO nanoparticles. Drop in low temperature viscosity can be attributed to the addition of oleic acid, which is known to act as viscosity reducing agent. Among all nanoparticles-based lubricants PAO+MoS_2 showed highest viscosity index and PAO+ZnO showed lowest value of viscosity index.

Future suggestions:

As we can observe that All of the tests conducted with 1wt% concentration of nanoparticles had some well performing conditions and under the other conditions they were not giving promising results. This means that further optimization of lubricants based on concentration change is an option worth exploring, for future studies it is recommended to conduct tests on different concentrations trying to establish the optimized quantity required for these nanoparticles. Another point worth adding is to test these optimum concentrations to find maximum load that they can carry and deliver improved results.

Another area for exploration is the use of nanoparticles differing in size. The researchers use a fixed number of sizes in studies. Researchers can also focus on the size range. As we discussed earlier, small-sized nanoparticles can provide rectification effects, and large-sized nanoparticles can show rolling effects. So, the combination of different nanoparticles can improve performance and can be a good research subject.

For future studies the effect of these combinations under different temperature conditions is also recommended as there can be very different behavior of base oil and nanoparticle combinations at high temperatures. Since under a huge number of applications lubricants are expected to perform at higher temperatures, a heating setup with the reciprocating tribometer will give us the ability to test performance at those conditions.

REFERENCES

1. Tang Z and Li S (2014) A review of recent developments of friction modifiers for liquid lubricants (2007-present) Curr. Opin. Solid State Mater. Sci. 18 119–39

2. Dai W, Kheireddin B, Gao H and Liang H (2016) Roles of nanoparticles in oil lubrication *Tribol. Int.* 102 88–98

3. A P Singh, R K Dwivedi and A Suhane (2021) Influence of nano particles on the performance parameters of lube oil Mater. Res. Express 8 102001

4. T Luo, X Wei, X Huang, L Huang and F Yang (2014) Tribological properties of Al2O3 nanoparticles as lubricating oil additives Ceramics International 40 (5) 7143-7149

5. Alves S M, Mello V S, Faria E A and Camargo A P P (2016) Nanolubricants developed from tiny CuO nanoparticles Tribol. Int. 100 263–71

6. W Alghani (2020) Preparation characterization and tribological behavior of lube oil with nanoparticles additives Waleed Alghani PhD thesis Universiti Malaya.

7. Azam S, Park S S (2023) Sonochemical Synthesis of CuO Nanoplatelets and Their Tribological Properties as an Additive in Synthetic Oil Using Reciprocating Tribometer Lubricants 11(4) 185

8. Alves S M, Barros B S, Trajano M F, Ribeiro K S B and Moura E (2013) Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions, *Tribol. Int.* 65 28–36

9. Chen Y, Hu E, Zhong H, Wang J, Subedi A, Hu K, Hu X (2021) Characterization and Tribological Performances of Graphene and Fluorinated Graphene Particles in PAO. Nanomaterials 11(8) 2126.

10. Pranav D S, M S Charoo (2021) Tribological Behaviour PAO nano additive Based Lubricant for Eutectic Al-Si Alloy-Chromium Plated Chrome Steel Tribopair, Materials Today 44

11. Biresaw G (2018) Biobased Polyalphaolefin Base Oil: Chemical, Physical, and Tribological Properties. Tribol Lett 66-76

12. Ankush R and Ankush A (2018) Influence of surface roughness and nanoparticles concentration on the friction and wear characteristics of PAO base oil Mater. Res. Express 5 095018

13. Letícia R O, Túlio A R, Henara L C, Washington M S (2022) Scuffing resistance of polyalphaolefin (PAO)-based nanolubricants with oleic acid (OA) and iron oxide nanoparticles Materials Today Communications 31 103837

14. Pierre R, Fabrice D, Fabrice V, Moussa D, Béatrice D, Le-Mogne T, Michel B, Jérôme C (2014) An Investigation on the Reduced Ability of IF-MoS2 Nanoparticles to Reduce Friction and Wear in the Presence of Dispersants Tribo Lett 55 503-516

15. Xinhu W, Kuiliang G, Gaiqing Z, Wenjing L, Xiaobo W, and Weimin L (2018) Surface Modification of MoS2 Nanosheets as Effective Lubricant Additives for Reducing Friction and Wear in Poly-α-olefin Industrial & Engineering Chemistry Research 57 (23) 8105-8114

16. Gupta R N and Harsha A P (2018) Tribological study of castor oil with surface-modified CuO nanoparticles in boundary lubrication *Ind. Lubr. Tribol.* 70 700–10

17. Lahouij I, Vacher B, Martin J M and Dassenoy F (2012) IF-MoS2 based lubricants: Influence of size, shape and crystal structure, *Wear* 296 558–67

18. Hanif T M (2022) synthesis and tribological analysis of MoS2 and ZnO nanoparticles based bio-lubricants, *M Talha Hanif Ms Thesis, SMME, National University of Science and Technology*

19. Waqas M (2022) Synthesis and tribological analysis of CuO and TiO2 nanoparticles based bio-lubricants, *Muhammad Waqas Ms Thesis*, *SMME, National University of Science and Technology*

20. Sade H, Moshkovich A, Lellouche J-P and Rapoport L 2018 Testing of WS2 nanoparticles functionalized by a humin-like shell as lubricant additives *Lubricants* 6

21. Peña-Parás L *et al.* 2015 Effect of CuO and Al2O3 nanoparticle additives on the tribological behavior of fully formulated oils *Wear* 332–333 1256–61

22. Zhao J, He Y, Wang Y, Wang W, Yan L and Luo J 2016 An investigation on the tribological properties of multilayer graphene and MoS2 nanosheets as additives used in hydraulic applications, *Tribol. Int.* 97 14–20

23. Hernandez Battez A, Fernandez Rico J E, Navas Arias A, Viesca Rodriguez J L, Chou Rodriguez R and Diaz Fernandez J M 2006 The tribological behaviour of ZnO nanoparticles as an additive to PAO6 *Wear* 261 256–63