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Tribology investigation of high speed steel onto aluminium alloy AL319 applying nano-coolant

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KEYWORDS

Wear rate
Coefficient of friction
Worn surface
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Nano-coolant
Tribology

ABSTRACT

In this study, SiO2/Gear oil nano-coolant with varying volume concentrations was employed in the tribological process using a tribometer for machining aluminium AL319 using the smeared technique. The primary objective was to determine the wear rate and coefficient of friction of high-speed steel onto aluminium alloy AL319 by applying SiO2/gear oil nano EDM dielectric. Load, duration, and nano concentration are varied, while spindle speed is kept constant. The stability of the hybrid nano-coolant was confirmed through factorial and response surface methods, showing stability for up to 21 days. The performance of SiO2/Gear oil nano-coolant with the smeared technique succeeded. The optimal inclusion level was determined through the RSM outcome, with 0.10% of SiO2/Gear oil nano-coolant exhibiting the best performance in terms of wear rate and coefficient of friction. The lowest wear rate is 1.6842×10^{-8} m^3/Nm with 400 grams of load, 30 minutes of duration, and 0.10% of nano concentration whereas the highest wear rate value is 6.13296842×10^{-8} m^3/Nm with 1200 gram of load, 90 minutes of duration and 0% of nano concentration. The same parameter goes with the lowest and highest coefficient of friction values which is 0.9241 and 0.9661.

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1.0 INTRODUCTION

The main focus of this project is on the coefficient of friction and wear rate of the aluminium alloy AL319 by dry condition and when applying chosen lubricant. The traditional use of specimen and pin, attached and embedded on the surface of the disc resulted in low accuracy of reading in coefficient of friction and wear rate. The needs for innovative approaches to reduce the wear and friction in the tribology process. Traditional methods have limitations in achieving greater wear, friction, and lubrication. This project was to ensure more accuracy and better reading in friction force and wear rate when using mini pin on disc tribology machine that is in vertical position. The novelty of this work focuses on the role of lubricant addition in enhancing the wear performance aluminium composites to replace the conventional materials. The proposal of this project is to study the involvement of nano coolant if it is applied to aluminium alloy 319 while we evaluate the interaction between these two surfaces. In order to achieve that, weight of load, fixed time, and speed used should be included to collect data.

The project aimed to assess the influence of nano-coolant utilization within the research field. The objective of this project is to enhance the comparison results of the coefficient of friction and wear rate under both dry conditions and controlled sliding conditions. This will be achieved by utilizing a mini pin-on-disc setup with high-speed steel pins against aluminum alloy 319 specimens, while applying nano coolant.. The application of nano-coolant in the tribological investigation of high-speed steel onto aluminium alloy Al319 has shown potential benefits in terms of cutting temperature, surface roughness, drilling performance, and reduced wear and friction. The result produced is by evaluating the physical interaction of two surfaces which is pin and specimen disc according to specified time. It is based on the speed of rotation of the disc controlled by a controller (that control the speed of the motor). In determining the friction force between the pin (high-speed steel) against the circular aluminium alloy AL319, a load sensor device will be used. Whereas, a tachometer will be used to measure the rotational speed of the disc. The chosen nano-coolant are silicon dioxide (SiO_2) and the base fluid is used gear oil. The project conducted at the laboratory will resulted in more accurate reading to determine the coefficient of friction and wear rate of specimen applying chosen lubricant.

Aluminium alloy 319 is a type of aluminium casting alloy with a specific composition designed for excellent cast ability and good mechanical properties. It falls under the category of aluminium-silicon alloys, which are commonly used for various casting applications due to their favorable combination of properties. Aluminium alloy Al319 has good hardness, fatigue strength, ductility and machinability. Aluminium alloy 319 has become preferred material because of its lightweight and good mechanical properties for automotive components that is widely used such as cylinder head component. J. Nanavati and A. J. Makadia, (2013) has state that is count on its excellent casting characteristic and mechanical properties. Supported by V. Kryzhanivskyy et al, (2015) that stated the material also used in automotive parts such as wheel spacer.

Silicon dioxide (SiO_2) plays a versatile role in tribology investigations, offering opportunities to study various aspects of friction, wear, and lubrication in different materials and systems. Syafiq, A. M., et al. (2021) has state that it improves the surface roughness quality and lowers the cutting temperature. Additionally, the higher the volume concentration of SiO_2 nano fluid, the better the surface roughness quality and the lower the cutting temperature. Sayuti, Mohd, et al. (2014) support that silicon dioxide reduces tool wear, surface roughness, and oil consumption. The use of SiO_2 solid nanoparticles in mineral oil can act as a combination of rolling and sliding bearings at the tool chip interface, which can reduce the coefficient of friction and improve machining performance significantly.

Furthermore, a pin-on-disc tribometer is a type of testing device or instrument used to evaluate the friction and wear properties of materials. It consists of two main components: a rotating disc and a stationary pin. The pin is brought into contact with the disc, and a controlled load is applied to create a sliding or rolling motion between the pin and the disc. The purpose of a pin-on-disc tribometer is to simulate and study the interactions that occur between two surfaces in relative motion, mimicking real-world conditions. The test can be conducted under various environmental conditions, such as different temperatures, humidity levels, or lubrication conditions, to assess the material's performance under specific operating conditions. During the test, the frictional forces between the pin and the disc are measured, along with the wear of the materials. These measurements can provide insights into the material's tribological properties, such as its coefficient of friction, wear resistance, and lubrication effectiveness. Pin-on-disc tribometers offer several advantages in tribological research and development. They allow for controlled and repeatable testing conditions, enabling comparative studies of different materials, coatings, or lubricants. The device can also be used to investigate the effects of variables like load, speed, and surface roughness on the friction and wear behaviour of materials. Applications of pin-on-disc tribometers include assessing the performance of various materials, coatings, and lubricants for industrial components like bearings, gears, brake pads, and sliding contacts. The data obtained from these tests can aid in material selection, optimization of surface treatments, and development of lubrication strategies to enhance the durability and efficiency of mechanical systems. Overall, a pin-on-disc tribometer is a valuable tool for studying the friction and wear characteristics of materials and evaluating their performance in practical applications.

The tribology investigation of high-speed steel onto aluminium alloy AL319 with the application of nano-coolant represents a significant exploration into the friction, wear, and lubrication characteristics of these materials in machining or industrial applications. This study likely involves the examination of the interactions between high-speed steel and aluminium alloy AL319 under various operating conditions, with a particular focus on the influence of nano-coolant on the tribological properties. The use of nano-coolant, which likely contains nanoscale particles designed to enhance heat dissipation and reduce friction, introduces an innovative aspect to the investigation. The research probably aims to assess how nano-coolant affects the wear resistance, frictional behavior, and overall tribological performance of the high-speed steel and aluminium alloy AL319 interface. The outcome of this tribology investigation could provide valuable insights for industries that utilize high-speed steel and aluminium alloy AL319 alloy in machining processes. Understanding the tribological behavior under different conditions, especially with the introduction of nano-coolant, may lead to improved efficiency, durability, and performance of materials in high-speed applications, ultimately contributing to advancements in the field of metalworking and materials engineering

2.0 EXPERIMENTAL PROCEDURE

Machine used in this experiment testing is Mini Pin on Disc Tribology Machine in Figure 2.1. The different between this machine is the position of the pin and the disc. Most of the pin on disc tribometer is in horizontal position but this mini pin on disc is in vertical position where the debris that resulting from the process will fall down so the result taken will be more accurate compare to standard pin on disc tribometer.

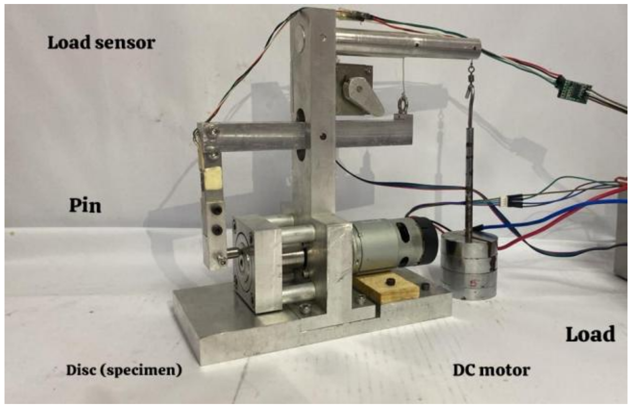


Figure 2.1 Mini pin on disc tribology machine

The first step is to prepare the specimen using Lathe machine and prepare the nano-coolant. The specimen needs to be prepared to 20 pieces and the nano-coolant od SiO_2/Gear oil with 0%, 0.05%, and 0.10% nano concentration. The preparation of nano-coolant includes stability test with sedimentation and UV-Vis spectrophotometer. The sedimentation process going through 21 days. Next, set up the mini pin on disc tribology machine by inserting the specimen. Third step is experiment process, firstly under dry condition of aluminium alloy AL319 and then repeat the step by applying nano-coolant which is SiO_2/Gear oil. After 20 runs of experiment, data of the wear rate and coefficient of friction of the specimen will be inserted in the table. Proceed with the optimization of the input parameter to decide what value of parameter will get better result of wear rate and coefficient of friction. If the result is as expected, continue with analysis but if not, repeat the experiment process starting at experiment setup. After the analysis process, continue with comparing the dry condition result and applied nano-coolant condition result. Lastly, continue with report writing for the project.

The experiment was conducted to determine the coefficient of friction and wear rate of the specimen (Al319) alloy in dry and applying nano-coolant condition. The parameters for the experiment test are listed in Table 2.1:

Table 2.1 Parameter and Description

Parameter	Description
Time (s)	The duration for the experiment consists of 30 minutes, 60 minutes, and 90 minutes.
Weight of load (g)	The weight consists of 400g, 800g, and 1200g.
Speed (rpm)	The spindle speed is fixed to 1000rev/min.
Nano-coolant	SiO2/Gear oil

Nano-coolant fluid was prepared by using a two-step method in which the particles are in powder appearance. The fluid was prepared in various concentration from 0% to 0.10% by mixing into used gear oil. The base fluid that is use are gear oil that was mixed with nano particles using a stirring method of 30 minutes to ensure the solution was mixed properly. Then, place it in an ultra-sonication for about 90 minutes to ascertain that it dissolved completely. The two-step method was used to produce nano-coolant fluid according to the specific amount and concentrations required for the testing process. Visual sedimentation and UV-Vis spectrophotometer are the test conducted for nano-coolant stability test.

Limitation of using the new horizontal pin on disc tribometer are because it is smaller and easier to carry anywhere but it also barely had any space left to apply the nano-coolant at the surface of the specimen. So, this experiment conducted with applying nano-coolant by smearing the nano-coolant at the surface using tissues. This method also conducted by Godfrey, Douglas.

(1995) and Łępicka, Magdalena, et al. (2019). Godfrey, Douglas. (1995) stated "the grease and oils were smeared uniformly over the face of the disc with laboratory tissues.".

The wear rate equation is a mathematical relationship used to describe the rate at which a material wears away or loses mass due to friction, abrasion, or erosion. Using this method is easier because it provides a straightforward and practical way to quantify the amount of material loss due to wear. By calculating wear rate by weight, it directly quantifies the amount of material that has been worn away, which is a crucial factor in understanding and predicting the service life of components. The mass loss of the test specimens was measured by weighing the test samples before and after the test using an analytical balance. The specific wear rate for each specimen could then be determined as

$$k=\frac{\Delta m}{\rho . \Delta s . F_N} \tag{2.1}$$

Where Δm is the mass loss of the specimen, ρ is the density of the specimen, Δs is the sliding distance during the test, and FN is the normal load applied to the pin. Wahlström, Jens, et al. (2017) developed a method that allows for the calculation of the specific wear rate for both the pin and disc components and this calculation are used in this project.

The coefficient of friction is a dimensionless quantity that represents the ratio of the force of friction between two surfaces (pin and disc) to the normal force pressing them together. It is denoted by the symbol "μ" (mu) and is often used to characterize the frictional behaviour between two materials in contact. The coefficient of friction helps in understanding how much force is required to overcome the resistance between two contacting surfaces. It provides insights into the frictional behavior, which is essential for designing efficient and reliable mechanical systems. The coefficient of friction equation is given by equation 2.2:

$$\mu = \frac{F}{N} \tag{2.2}$$

Where F is the friction force and N is the normal force. Both F and N are measured in unit of force (Newton). The value is not the same as static friction or kinetic friction

For the DOE, three (3) parameters were selected which are load, duration, and nano concentration. Based on parameter, RSM come out with 20 running for the process. The responses study mainly wear rate and coefficient of friction. The DOE type is Response Surface Method (RSM). The experiment design was generated by Design Expert software. The design was used by various researchers such as Jamil et al. (2019), Ariffin et al. (2018), Thakur et al. (2020) and Kumar Sharma et al. (2020). The running of the experiment will be based on the combination with run number 1 until number 20.

Each of the specimen surface conditions will be measured and taken using a portable LCD digital microscope in Figure 2.2. Specimen surface conditions for the initial surface and final surface will be taken and recorded.

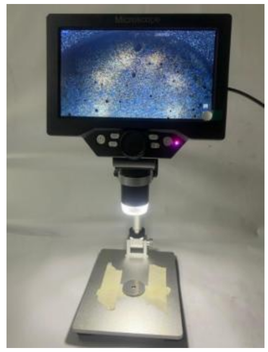


Figure 2.2 Portable LCD Digital Microscope.

3.0 RESULTS AND DISCUSSION

Analysis of wear rate involves the assessment of the amount of material loss or degradation over a specified period, often due to friction, abrasion, or other mechanical actions. Wear rate analysis is crucial in understanding the performance and durability of materials, especially in engineering and tribology. Wear rate is calculate using formula at Equation 2.1. The basic wear value was recorded and measured by determining weight loss before and after the experiment process as in Table 3.1.

Table 3.1 ANOVA for response surface linear model wear rate

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	Remarks
Model	2.560E-015	9	2.844E-016	45.96	< 0.0001	Significant
A-load	6.090E-017	1	6.090E-017	9.84	0.0106	
B-duration	3.342E-016	1	3.342E-016	53.99	< 0.0001	
C-nano concentration	2.068E-015	1	2.068E-015	334.09	< 0.0001	
Residual	6.189E-017	10	6.189E-018			
Lack of Fit	*2.854E-017*	*5*	*5.708E-018*	*0.86*	*0.5659*	
Pure Error	*3.336E-017*	*5*	*6.671E-018*			Not significant
Cor Total	2.622E-015	19				

The coefficient of determination R-Squared for wear rate was found to be 0.9764 as shown in Table 3.2. Furthermore, the predicted R-Squared value is 0.8844, which is in reasonable agreement with the adjusted R-Squared value of 0.9551. Moreover, the adequate precision value for wear rate is 25.729 which is greater than 4.0.

Table 3.2 Coefficient of determination

Source	Model Summary	Remarks
R-Squared	0.9764	Close to 1.0
Adjusted R-Squared	0.9551	Close to Predicted R-Squared
Predicted R-Squared	0.8844	Close to Adjusted R-Squared
Adequate Precision	25.726	More than 4.0

Figure 3.1 and Figure 3.2 demonstrate the interaction effect of duration and load on wear rate. As can be observed in both figures below, the wear rate has the minimum value of 30 minutes of time with 400 grams of load. Hence, it proves that the wear rate decreases as duration and load value decreases while increasing the use of SiO_2/Gear Oil concentration.

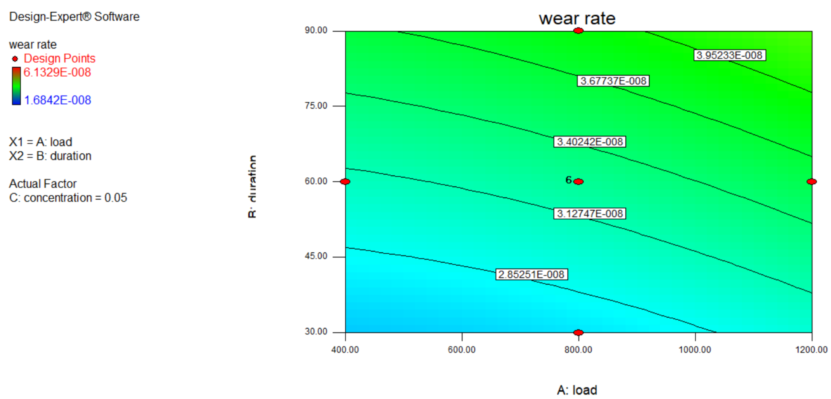


Figure 3.1 The contour view of the interaction effect between duration and load on wear rate.

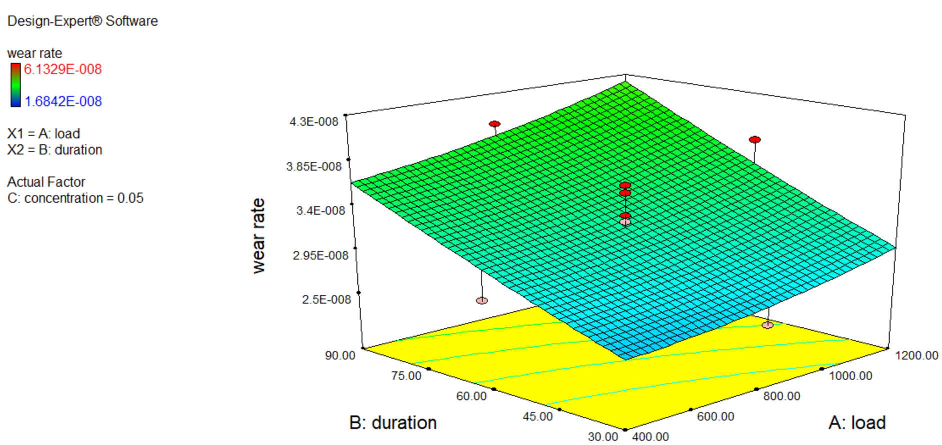


Figure 3.2 3D view contour graph of an interaction effect between duration and load on wear rate.

Table 3.3 shows the detailed output of the wear rate. It indicates that the lowest wear rate result was at 1.6842 x10^{-8} m^3/Nm with a 0.1% volume concentration of nano-coolant, 400 gram of load, and 30 minutes of duration. Followed by the highest wear rate was at 6.1329 x10^{-8} m^3/Nm with 0% hybrid nano-coolant, 1200gram load, and 90 minutes of duration. The higher the concentration of nano, the lower the load and time value. Additionally, the time causes lower wear rate.

Table 3.3 Detailed output of wear rate

Data Collected	Nano Concentration (%)	Load (gram)	Time (minutes)	Wear rate ($x10^{-8}$ m^3/Nm)
Lowest	0.1	400	30	1.6842
Highest	0	1200	90	6.1329

The coefficient of friction (COF) is a dimensionless value that represents the ratio of the force of friction between two bodies to the force pressing them together. It is a crucial parameter in understanding and analyzing the frictional behavior of materials in contact. Coefficient of friction measured using formula Equation 2.2. COF is calculated using two main point which is the load used and normal force as illustrated in Table 3.4.

Table 3.4 ANOVA for response surface surface model coefficient of friction

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	Remarks
Model	1.423E-003	9	1.581E-004	21.47	< 0.0001	Significa
A-load	8.585E-005	1	8.585E-005	11.66	0.0106	nt
B-duration	2.228E-004	1	2.228E-004	30.26	< 0.0001	
C-nano concentratio	9.584E-004	1	9.584E-004	130.17	< 0.0001	
n	7.363E-005	10	7.363E-006			
Residual	*7.313E-005*	*5*	*1.463E-005*	*146.26*	*< 0.0001*	
Lack of Fit	*5.000E-007*	*5*	*1.000E-007*			significa
Pure Error	1.497E-003	19				nt
Cor Total						

The coefficient of determination R-Squared for coefficient of friction was found to be 0.9920 as shown in Table 3.5. Furthermore, the predicted R-Squared value is 0.9455, which is in reasonable agreement with the adjusted R-Squared value of 0.9848. Moreover, the adequate precision value for coefficient of friction is 43.194 which is greater than 4.0.

Table 3.5 Coefficient of determination

Source	Model Summary	Remarks
R-Squared	0.9920	Close to 1.0
Adjusted R-Squared	0.9848	Close to Predicted R-Squared
Predicted R-Squared	0.9455	Close to Adjusted R-Squared
Adequate Precision	43.194	More than 4.0

Figure 3.3 and Figure 3.4 demonstrate the interaction effect of duration and load on coefficient of friction. As can be observed in both figures below, the coefficient of friction has the minimum value of 30 minutes of time with 400 grams of load. Hence, it proves that the coefficient

of friction decreases as duration and load value decreases while increasing the use of SiO_2/Gear Oil concentration.

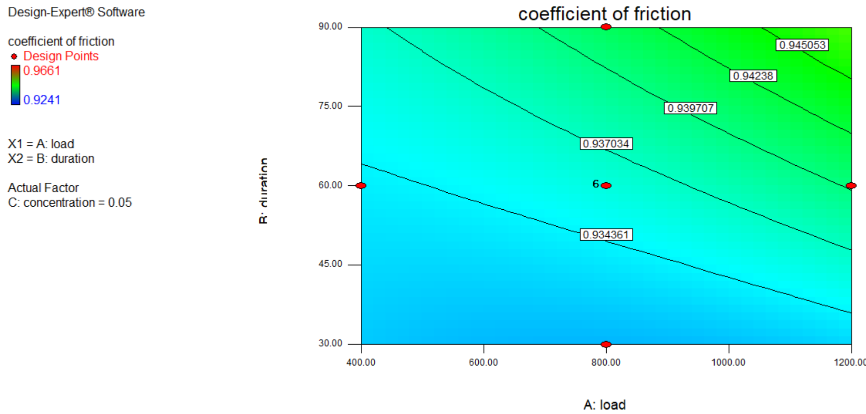


Figure 3.3 The contour view of the interaction effect between duration and load on coefficient of friction.

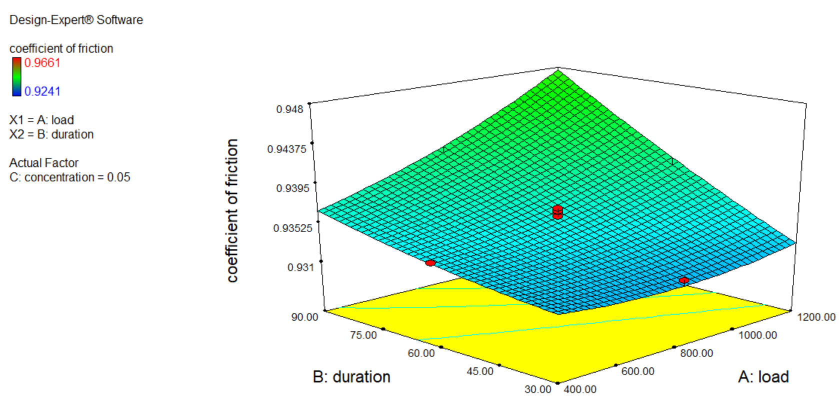


Figure 3.4 3D view contour graph of an interaction effect between duration and load on coefficient of friction.

Table 3.6 shows the detailed output of the coefficient of friction. It indicates that the lowest coefficient of friction was at 0.9241 with a 0.1% volume concentration of nano-coolant, 400 gram of load, and 30 minutes of duration. Followed by the highest coefficient of friction result was at 0.9661with 0% SiO_2/Gear oil nano-coolant, 1200gram load, and 90 minutes of duration. The higher the load and time value, the lower the concentration of nano. Additionally, the concentration causes lower coefficient of friction.

Table 3.6 Detailed Output of Coefficient of friction

Data Collected	Nano Concentration (%)	Load (gram)	Time (minute)	Coefficient of Friction
Lowest	0.1	400	30	0.9241
Highest	0	1200	90	0.9661

The optimization of the RSM experiment is crucial for identifying the optimal combination of machining parameter values and achieving the best output results for further investigation.

Numerous researchers have delved into studying the optimization of machining parameters to attain the most favorable combination and optimal output responses while minimizing deviation or error (Viswanathan et al., 2018; Najiha, Rahman, Kadirgama, et al., 2015). The experimental optimization encompassed a range of input parameter values, leading to a configuration characterized by a high nano concentration, low duration, and low load. Nonetheless, the anticipation was for minimal values in three responses, including wear rate and coefficient of friction, as illustrated in Table 3.7 Desirability Optimization. The selected optimization entailed a nano concentration of 0.1%, a load of 811.86 grams, and a duration of 30 minutes. Subsequently, the expected results from the experiment comprised a wear rate of 1.73366x10^{-8} m^3/Nm and a coefficient of friction of 0.9241.

The comparison of tribology performance conducted on the Al319 with dry specimen on pin on disc tribometer versus Al319 applying nano-coolant is elaborated below. It is the same technique performed. Furthermore, the experiments employed the same parameters. The result for 800 gram and 60 minute each of the specimen surface is in Table 3.7. On the other hand, the wear rate of dry condition increased as load and duration increase. The coefficient of friction of dry condition specimen also increases.

Table 3.7 Desirability optimization

No.	**Load (gram)**	**Dur (min)**	**N.C (%)**	**W.R (x10^{-8} m^3/Nm)**	**COF**	**Desirability**	
1	811.86	30.00	0.10	1.73366	0.9238	0.994	Selected
2	814.70	30.00	0.10	1.73650	0.9238	0.994	
3	820.09	30.00	0.10	1.74184	0.9241	0.993	
4	822.15	30.98	0.10	1.74563	0.9241	0.993	
5	825.33	30.00	0.10	1.74691	0.9241	0.993	
6	912.39	30.00	0.10	1.77887	0.9236	0.989	
7	859.13	33.68	0.10	1.78381	0.9241	0.989	
8	873.51	34.48	0.10	1.79719	0.9241	0.987	
9	768.08	36.37	0.10	1.76679	0.9247	0.984	
10	1097.14	30.00	0.10	1.88439	0.9231	0.977	
11	1107.33	30.00	0.10	1.89106	0.9231	0.976	
12	533.44	30.03	0.10	1.65344	0.9261	0.976	
13	414.80	39.39	0.10	1.70089	0.927038	0.963	
14	880.12	51.55	0.10	1.95334	0.925490	0.953	
15	538.31	30.00	0.09	1.84629	0.927445	0.942	
16	400.00	30.00	0.09	1.76293	0.928228	0.941	

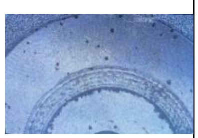
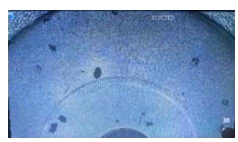
The results show that the actual wear rate value is slightly lower than expected as shown in Table 3.8. Coefficient of friction actual value also is lower. The deviation value of the three output performances is lower than 10% and is considered a good result.

Table 3.8: Performance optimization

Parameter	**Load (gram)**	**Time (min)**	**Nano concentration (%)**
Suggested parameter	811.86	30	0.1
Response	Wear Rate (m^3/Nm)		Coefficient of Friction
Expected Result	1.73366×10^{-8}		0.9238
Actual Result	1.5972×10^{-8}		0.9029
	Deviation		
Percentage Error (%)	8.54		2.31

The comparison of tribology performance conducted on the Al319 with dry specimen on pin on disc tribometer versus Al319 applying nano-coolant is elaborated below. It is the same technique performed. Furthermore, the experiments employed the same parameters. The result for 800 gram and 60 minute each of the specimen surface is in Table 3.9. On the other hand, the wear rate of dry condition increased as load and duration increase. The coefficient of friction of dry condition specimen also increase.

Table 3.9 Comparison of surface, wear rate, and coefficient of friction

Load (gram)	Time (min)	Dry condition	Nano concentration (%)		
			0	0.05	0.10
800	60				
Width (mm)		2.35	1.75	1.60	1.20
Depth (mm)		0.35	0.25	0.10	0
Wear rate ($\times 10^{-8}$ m^3/Nm)		4.9713	4.7978	2.9651	2.0013
Coefficient of friction		1.2194	0.9433	0.936	0.927

4.0 CONCLUSION

The primary aim of this research is to assess the wear rate and coefficient of friction between high-speed steel and aluminum alloy AL319 under the influence of SiO_2/gear oil nano-coolant. Furthermore, the study aims to optimize input parameters such as load, time, and nano concentration. Additionally, the research endeavors to draw a comparative analysis between the effectiveness of SiO_2/gear oil nano-coolant and dry conditions.. The outcome of wear rate and coefficient of friction, effectiveness, and comparison of the aluminium alloy AL319 applying nano-coolant with dry conditions were studied through a series of tests.

Overall, the objectives concluded as expected where determination of wear rate and coefficient of friction of high speed steel onto aluminium alloy AL319 applying SiO_2/Gear oil nano-coolant resulting to highest result of wear rate and coefficient of friction are 6.1329x$10^{-8}$$m^3$/Nm and 0.9661 with parameter of 1200gram load, 90 minutes of duration and 0% of nano concentration where lowest result of wear rate and coefficient of friction are 1.6842x10^{-8} m^3/Nm and 0.9241with parameter of 400gram load, 30 minutes of duration and 0.10% of nano-concentration. Optimization of the input parameter resulting to the actual result is lower than 10% of the actual result where result of actual wear rate and expected wear rate are 1.5972x10^{-8} m^3/Nm and 1.73366x10^{-8} m^3 /Nm. Comparison between the performance of SiO2/gear oil nano-coolant with dry condition resulting to reducing in term of wear rate and coefficient of friction starting from dry to 0.10% of nano-concentration wear dry condition wear rate is 2.7754x10^{-8} m^3/Nm goes to 1.6842x10^{-8} m^3/Nm for 0.1% nano concentration with lower parameter of 400 gram load and 30 minutes of duration.

Author Contribution

S. N. Masmera: Methodology, writing and editing. M.A.Joraimee,: data analysis. A.A.M.Redhwan: Methodology and supervision. O.W.Zulkarnain, and Kharudin Ali: Hardware development and troubleshooting.

Conflict Of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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