Analyzing the Impact of Fly Ash Additive Ratio on Lubricant Properties

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ABSTRACT

Preventing surface damage is crucial for optimal machine performance, with lubricants and additives playing a vital role in achieving this objective. This study specifically focuses on evaluating the influence of fly-ash additives on the wear resistance of machine components when incorporated into lubricant oil. The experiments were conducted following ASTM standard operating conditions, utilizing the four-ball wear test to measure the scratch width and weight loss of balls using different lubricant oil formulations, including 0, 0.1%, 0.5%, 0.75%, and 1% additive. The findings demonstrate that the inclusion of 0.5% fly ash additive in the lubricant oil results in a significant reduction in both scratch width and weight loss of the balls. However, it should be noted that higher additive ratios may lead to increased scratch width and weight loss due to the agglomeration of the fly ash particles on the sliding surfaces. To achieve optimal effectiveness in reducing friction and wear, it is recommended to carefully control the content of fly ash within an appropriate range. Furthermore, this study highlights the width of scratches on balls as a reliable indicator for assessing the anti-wear properties of oils. The insights gained from this research offer valuable guidance to manufacturers in the selection of suitable anti-wear oils for specific applications. Further investigations could explore the impact of different lubricants and additive ratios to identify the most appropriate lubrication parameters. Overall, this study contributes to a better understanding of the effects of fly ash additives on the performance of lubricant oil and provides practical guidance for optimizing lubrication strategies in diverse industrial contexts.

Keywords-fly ash additive; lubricant; wear resistance; scratch width; scratch diameter

I. INTRODUCTION

Industrial lubricants are in high demand and typically require an appropriate additive in a specified ratio. Among the most critical quality criteria for lubricants is the viscosity index which measures their thermal stability. In order to enhance the load-carrying capacity and other lubrication properties, lubricant manufacturers have proposed a variety of additive packages. The lubricating properties of lubricants when using nano Al_2O_3 particles as additives were studied in [1, 2]. The addition of additives to lubricants may improve their rheological properties. Moreover, nano Al_2O_3 can also improve the heat resistance by reducing the viscosity at high temperatures. The dynamic viscosity and rheological properties of the oil-nano Al_2O_3 mixture have been examined at various additive ratios and temperatures. In addition, there have been various studies on the influence of particulate additives on lubricating oil quality. Some researchers have conducted studies on the effect of different ratios of metal oxides, such as CuO, Fe_2O_3, NiO, and Al_2O_3, in lubricants, and the influence of temperature on oil viscosity. Authors in [3] studied the influence of CuO, Fe_2O_3, and NiO nano-particles and temperature on oil viscosity. Various ratios of nano metal oxides at different temperatures were considered. The findings demonstrated that the viscosity of the oil mixture was influenced by these factors, depending on the ratio of the additives. Authors in [4] reported that the viscosity of heavy oil mixtures can decrease by 20-93% depending on the proportion of emulsion solution blended into the lubricating oil. Authors in [5] reported that the viscosity reduction relies on the size and density of the metal particles. Authors in [6] found that SiO_2 nanoparticles can reduce friction by acting as rolling elements at the friction interface. Authors in [7] developed a special oil with improved lubricity by adding SiO_2 nanoparticles, resulting in improved thermo-physical properties and tribological performance. Authors in [8] investigated the use of composite nanoparticles synthesized by chemical deposition as new additives in grease, which reduce the friction coefficient and wear scratch diameter significantly when added at a 1 wt% concentration and form a solid-liquid phase composite lubricating film. Authors in [9] conducted a comparison of the tribological properties between chemically modified rapeseed oil and two distinct anti-wear nano additives, TiO_2 and Al_2O_3, using a pin-on-disc tribometer, and found that TiO_2 shows better friction properties than the oil with fibrous nano Al_2O_3 wire [9]. Authors in [10] investigated the effect of adding ZnO to rapeseed oil at different concentrations on a four-ball machine and observed a reduction of the wear rate with an addition of 1%wt ZnO, although the friction coefficient remained unchanged. Authors in [11] studied the impact of $CaCO_3$ and SiO_2 particles on the properties of lithium-based grease, and found that the additives improved the properties of the original grease. Authors in [12] reported that the use of CuO and TiO_2 nanoparticles to a metal-working polymeric lubricant resulted in a significant improvement in anti-wear properties, with 0.01 wt.% TiO_2 and 0.05 wt.% CuO showing the highest improvement of 77% and 33%, respectively, proving the potential of nano lubricants in enhancing mechanical component efficiency. Authors in [13] investigated the properties of CuO particles in lubricant and observed a 60.83% decrease of wear rate and 33.1% reduction in friction coefficient with 0.75 wt.% additive used. Other studies that have also reported the effect of metal oxide nano additives on the lubricating properties and the decrease in viscosity of certain types of industrial oil due to the presence of these nanoparticles are [14-20]. Research on the rheological properties of multigrade oil mixture mixed with water in the form of vapor or paraffin in solid state has also been published. Accordingly, the viscosity of the oil mixture increases with the addition of paraffin and decreases in the case of an oil-steam mixture [21]. In mechanical machining, the coolant mixture is also supplemented with metal oxide particles to improve the cooling and lubrication performance in cutting and machining processes [22, 23]. Although previous studies have presented that those additives can enhance the lubricating properties of lubricants and extend the operational lifespan of machine components, however, specific investigation regarding the impact of these additives on the load-carrying capacity of the oil has not been conducted. Therefore, investigating the lubrication properties of oil with additives could be a solution to change the viscosity or stabilize the working conditions of machines.

Fly ash is composed of some metal oxides, ranging from nano to micro in size, and is sourced from thermal power plant dust as a byproduct of coal-fired furnaces. Fly ash can be utilized in various fields to enhance the properties of the used mixture [24, 25]. Besides, in the field of lubricating industry, the investigation will focus on determining the optimal concentration of the additive to enhance the lubrication properties of the lubricant, minimize oil residue emissions, and promote sustainable development. Previous studies have demonstrated the potential of additives to enhance the lubricating properties of lubricants and prolong the operational lifespan of machine components. However, a specific investigation into the impact of fly ash additives on the load-carrying capacity of the oil has not yet been published. Therefore, further research is necessary in order to assess the influence of fly ash additives on the load-carrying capacity and anti-wear properties of lubricants. It is essential to determine the optimal concentration of fly ash that can effectively improve the lubrication performance while minimizing the emission of oil residues. By conducting this optimization process, sustainable development can be promoted while mitigating the adverse effects associated with oil refining and the disposal of lubricant waste. One of the aims of this research is to protect the environment by addressing the negative consequences linked to oil refining and the disposal of lubricant waste. To evaluate the load-carrying capacity, thermal stability, and other pertinent characteristics of oils, the scientific community relies on the ASTM D-4172 test standard, which is specifically designed for assessing lubricant anti-wear properties. This standard entails measuring the wear scar diameter of the balls in a four-ball machine, under controlled conditions of temperature, load, and duration of ball contact, reaching a point where the viscosity of the oil can no longer effectively separate the friction surfaces. Adopting this standardized evaluation methodology can provide reliable insights into the performance of lubricants containing fly ash, facilitating comparisons with existing lubricants in the field.

II. MATERIALS AND METHODS

In order to evaluate the specific lubricating properties in accordance with the ASTM D4172 standard, thorough preparation and planning were undertaken for the experimental equipment and test parameters. The stability of the equipment is meticulously verified, and the parameters were subsequently adjusted as outlined below:

- The temperature was kept constant at 75°C ± 2°C.
- The speed of the upper ball was set to about 1200 rpm ± 60 rpm.
- The experiment time was 60 min ± 1 min.
- The load applied on the upper ball was 392 N ± 2 N.

Figure 1 shows the principal diagram of the four-ball friction testing machine. The predetermined plan is followed to prepare the lubricating oil, utilizing a commonly employed industrial lubricant to assess specific lubrication properties. Furthermore, fly ash was introduced into the oil mixture at concentrations of 0.5%, 0.75%, and 1% to facilitate a comparative analysis of the lubrication properties.

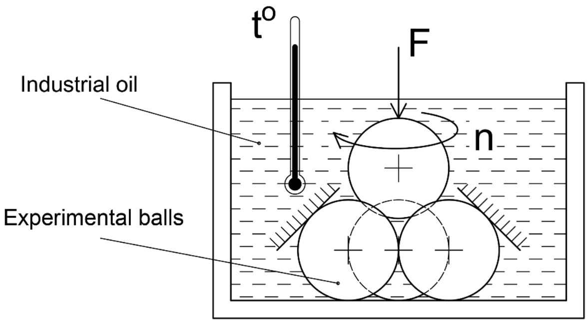


Fig. 1. Principal operation of a four-ball machine.

The experimental procedure involves using four steel balls with a diameter of 12.7 mm. Three of these balls were positioned in contact with each other and were kept fixed, while the fourth ball was placed on top, contacting the three lower balls. The arrangement was submerged in the test oil, and the temperature was carefully controlled and monitored. The applied force F on the upper ball results in pressure being exerted on the lower balls, leading to the generation of a rotational motion perpendicular to the plane formed by the lower balls. The time of the test was set at 60 min, and once the test was completed, the balls were cleaned and the scratches were measured for further analysis.

The experimental procedure includes the following steps: (1) Clean the balls and prepare the oil cup for each experiment. After cleaning, all parts should be handled with new wiping cloths. There should be no residue of the solvent when the test oil is replenished, and the apparatus is assembled. (2) Put one of the clean balls onto the spindle of the machine and verify its tightness. (3) Assemble three of the other cleaned balls into the test oil cup and tighten the holding mechanism for the lower balls. (4) Pour the oil or oil mixture under evaluation into the test oil cup. (5) Install the oil cup onto the machine and avoid shock loading by gradually applying the test load. (6) Control the temperature of the oil or the oil mixture at the required value. (7) Once the desired temperature is reached, turn on the power to transfer the motion for the upper ball. (8) After the experiment is completed, remove the oil cup and clean the balls. (9) Measure the scratch dimensions on the balls using a highly accurate measuring device after they are cleaned.

A. *Experimental Balls*

The experimental balls were meticulously prepared to ensure the experiment's accuracy. A suitable quantity of balls was carefully cleaned and examined for diameter and surface hardness prior to their installation in the machine. Following each experiment, the balls underwent thorough cleaning, were marked for identification, and were categorized.

B. *Experimental Oil*

The main technical specifications of the experimental oil are listed in Table I.

TABLE I. MAIN TECHNICAL SPECIFICATIONS OF THE EXPERIMENTAL OIL

Specification	Test method	Unit	Value
Specific gravity at 15°C	ASTM D4052	g/ml	0.868
Kinematic viscosity at 100°C	ASTM D445	mm²/s	14.6
Kinematic viscosity at 40°C	ASTM D445	mm²/s	126
Viscosity index	ASTM D2270	-	117
Cleveland flash point	ASTM D92	°C	205
Sulfated Ash	ASTM D874	%	0.88

The viscosity of the lubricating oil significantly impacts its lubrication quality, as indicated by the scratch test conducted in accordance with the ASTM D4172 standard. However, relying solely on the viscosity index for evaluating the lubrication characteristics may be misleading since the properties of the oil additives also play a significant role. In low-temperature environments, the viscosity of the oil increases, causing difficulties in the starting equipment due to the direct frictional surface. To address this issue, special additive compounds were added to the lubricating oil to reduce its viscosity dependence on environment temperature, resulting in multi-grade oil. This oil provides lubrication while enabling the engine to start smoothly in low temperatures. However, the viscosity index is not the only parameter affecting the quality of lubrication, as the properties of oil additives also play a significant role, as indicated in the specifications provided by the supplier.

C. *Fly Ash Additive*

The use of fly ash in this study as an additive for lubricant was explored due to components such as metal oxide particles of SiO_2, Al_2O_3, K_2O, Fe_2O_3, among others. These components have a spherical structure and a micrometer-sized particle, making them a suitable friction modifier to increase viscosity and thermal conductivity of lubricant oil mixtures, while also extending their service life and reducing sludge deposition. For this study, fly ash from a thermal power plant was chosen as an inert additive at 0.5%, 0.75%, and 1% ratios to the selected oil. The determined optimal concentration enhanced wear resistance, reduced sludge emissions, promoting environmentally sustainable development and minimizing the environmental impacts of oil refining. The main components of fly ash used in the current study are shown in Table II.

TABLE II. COMPONENTS OF FLY-ASH ADDITIVE

Component	Percentage
SiO_2	57.02%
Al_2O_3	23.82%
K_2O	6.56%
Fe_2O_3	4.69%

III. RESULTS AND DISCUSSION

To evaluate the influence of fly ash content percentage on the lubricating properties of industrial oil, especially the anti-wear ability of the oil blend, the weight of the balls before and after the experiments was carefully measured. Additionally, a microscope measuring device was used to measure the scratch sizes on the balls during the experiments. In each experiment, the scratch diameter of the ball was measured and processed for further analysis. The parameters of the balls before and after the experiment are the average values of these parameters for each experiment.

Experiments were carried out with oil and three different ratios of additives, and the scratches on the upper and lower balls with and without additives were observed. Figures 2-5 show the images of the scratches on the upper and lower balls for these experiments. The wear resistance of the material with and without the additive was assessed by measuring the width of the scratch on the upper ball and the diameter of the scratch on the lower ball, compared to the case without the additive. For the upper ball, a long scratch resulting from the friction between the upper and lower balls was observed, as illustrated in Figure 2(a), Figure 3(a), Figure 4(a), and Figure 5(a) corresponding to additive contents of 0%, 0.5%, 0.75%, and 1%, respectively. For the lower ball, the wear mark had a circular shape that could be easily observed and measured with the scratch diameter, as illustrated in Figure 2(b), Figure 3(b), Figure 4(b), and Figure 5(b) correspond to additive contents of 0%, 0.5%, 0.75%, and 1%, respectively. Additionally, the mass of the balls before and after the experiment was measured for further analysis and evaluation.

(a)

(b)

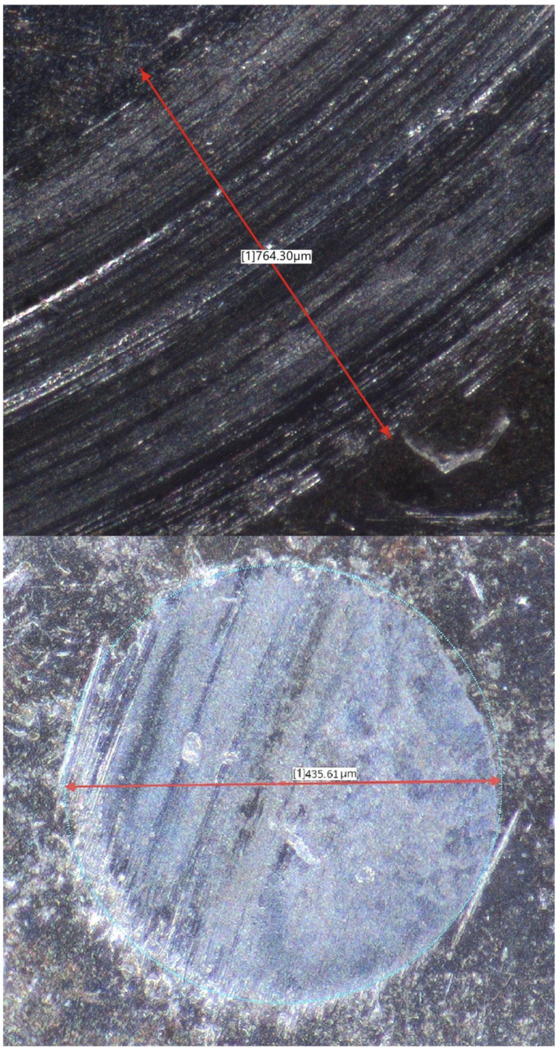


Fig. 2. Surface of balls experimented with oil without additive. (a) Upper ball, (b) lower ball.

(a)

(b)

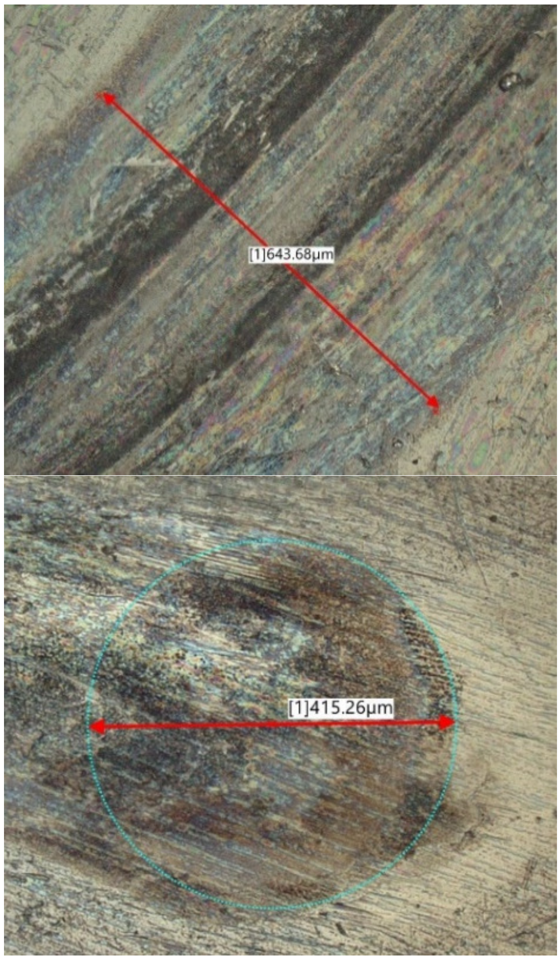


Fig. 3. Surface captured of balls experimented with oil and 0.5% additive. (a) Upper ball, (b) lower ball.

(a)

(b)

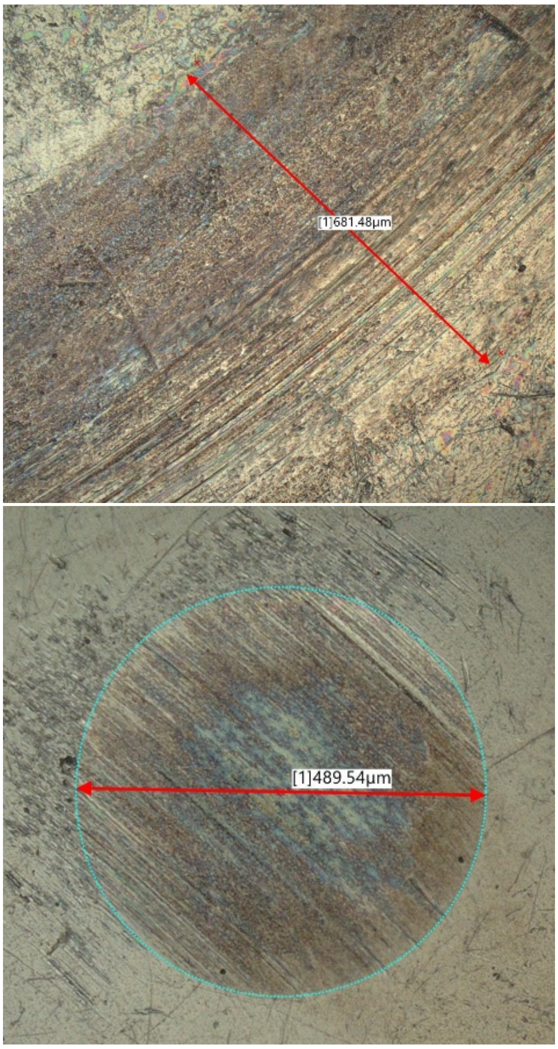
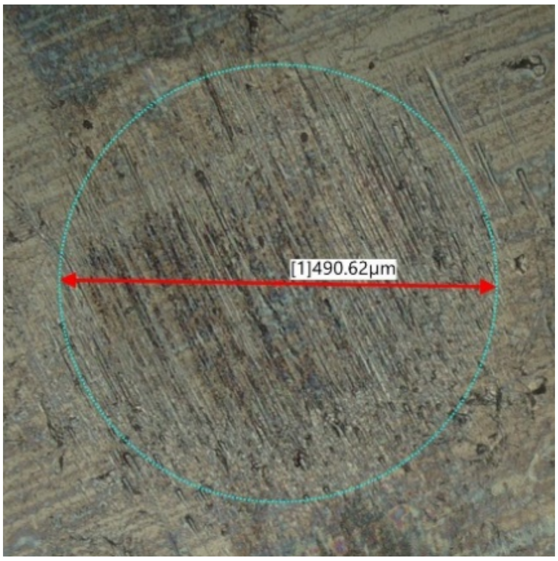


Fig. 4. Surface captured of balls experimented with oil and 0.75% additive. (a) Upper ball, (b) lower ball.

(a)



(b)

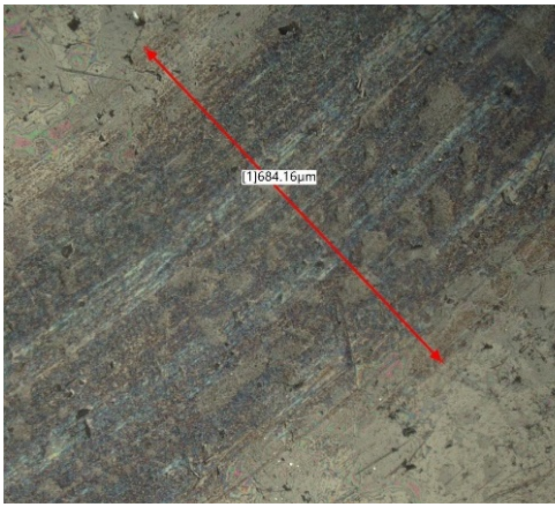


Fig. 5. Surface captured of balls experimented with oil and 175% additive. (a) Upper ball, (b) lower ball.

TABLE III. AVERAGE BALL WEIGHT

Fly-ash additive	Before the experiments (g)	Standard deviation	After the experiments (g)	Standard deviation
0%	8.328	0.0021	8.327	0.0019
0.5%	8.336	0.0014	8.335	0.0014
0.75%	8.350	0.0015	8.348	0.0014
1%	8.345	0.0012	8.343	0.0005

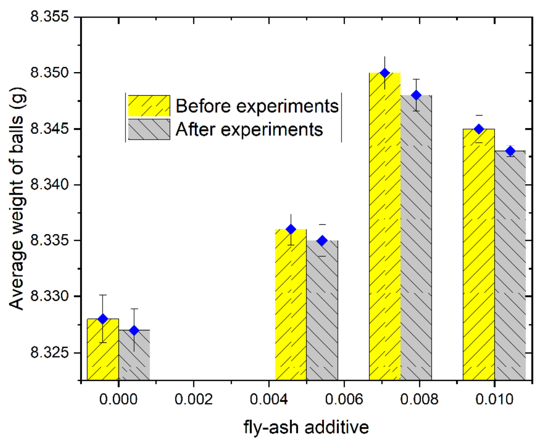


Fig. 6. Average ball weight.

TABLE IV. AVERAGE BALL SCRATCH DIAMETER

Fly-ash additive	Average ball scratch diameter (mm)	Standard deviation
0%	0.426	0.017
0.5%	0.417	0.004
0.75%	0.495	0.007
1%	0.503	0.012

Table III presents the average of ball's mass and their standard deviation before and after the experiment. Figure 6 provides a visual representation of the wear resistance of the lubricating oil or lubricating oil mixtures with 0.5%, 0.75%, and 1% fly ash additive. After a certain working time, the balls experience corrosion, reflected by a decrease in mass. It can be seen that both cases with or without additive using in the oil, resulted in a weight loss of approximately 0.001-0.002 g. In the majority of the experiments, the observed average mass reduction was 0.001 g, except when involving 0.75% and 1% fly ash additives, where each ball experienced an average mass decrease of 0.002 g. This finding suggests that the inclusion of fly ash positively influences the wear resistance of lubricating oils. However, it is crucial to limit the ratio of the additive in the oil to 0.5%. This limitation could be ascribed to the additive's function of converting wet into wet-rolling friction by incorporating metal oxide particles between the machine component surfaces. Additionally, it could contribute to a more even corrosion of the friction surfaces. If the additive ratio is higher, the metal oxide particles, even in small sizes, may affect the friction performance by falling into the abrasive wear area. These observations provide insight into the potential applications of fly ash as an additive in lubricating oils. Furthermore, the scratch diameter of the balls was measured, and the resulting mean value and standard deviation are indicated in Table IV. These measurements are also visualized in Figure 7. Similarly, for the upper balls, the scratch width was determined, and the mean value and standard deviation were computed and are listed in Table V, and illustrated in Figure 8.

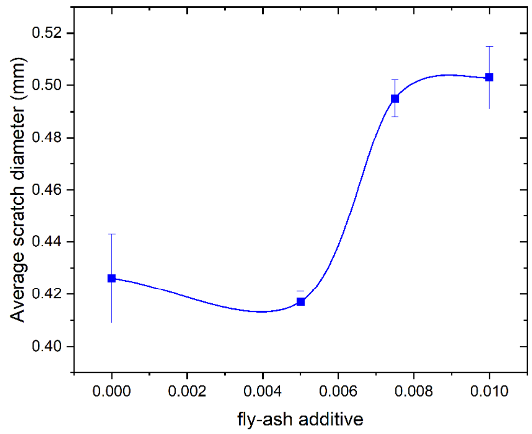


Fig. 7. Average diameter of ball scratch denpending on additive content.

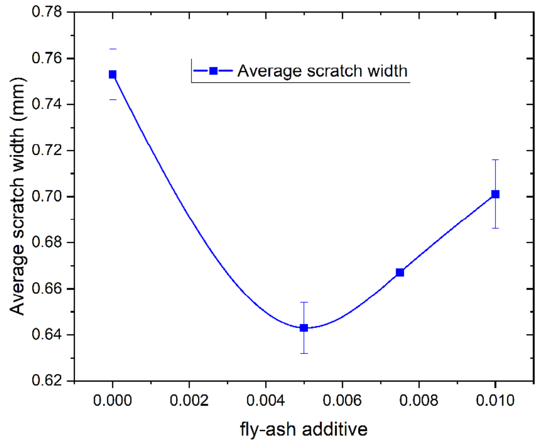


Fig. 8. Average width of ball scratch depending on additive content.

TABLE V. AVERAGE BALL SCRATCH WIDTH

Fly-ash additive	Average ball scratch width (mm)	Standard deviation
0%	0.753	0.011
0.5%	0.643	0.011
0.75%	0.667	0.014
1%	0.701	0.015

The average diameter of ball scratch with different fly-ash additive contents is shown in Figure 7. The results indicate that the average scratch diameter decreases with the increase in the amount of the additive. The scratch diameters for balls without any additive and with 0.5% additive were 0.426 mm and 0.417 mm, respectively. However, the addition of 0.75% and 1% fly-ash resulted in an increase in the scratch diameter to 0.495 mm and 0.503 mm, respectively. The standard deviation values for all the cases were relatively small, ranging from 0.004 to 0.017, suggesting that the results are consistent and reliable. These findings suggest that the addition of an appropriate amount of fly-ash has the potential to enhance the wear resistance of the surface of machine components, as indicated by the decrease in scratch diameter. However, excessive amounts of the additive may lead to a reverse effect, as observed in the 0.75% and 1% cases. This may be due to the mechanism of action of the fly-ash additive and its impact on frictional properties. When the fly-ash additive is added to the lubricant, the metal oxide particles in the additive fill the gaps between the frictional surfaces and form a protective film, minimizing friction between the surfaces. Therefore, with the addition of the additive, the scratch on the ball surface is smaller compared to the case without the additive. However, when the amount of fly-ash is increased beyond a certain level, the metal oxide particles concentrate too much and cannot be uniformly dispersed on the frictional surface, resulting in wear and tear of the surface. Thus, the amount of additive needs to be precisely controlled to ensure maximum effectiveness in reducing friction and wear.

The current literature lacks studies that investigate the influence of fly-ash additive ratios on the corrosion resistance properties of oil mixtures. In this study, the aim was to fill this research gap by investigating the scratch width of balls treated with various concentrations of fly-ash additive. The results shown in Table V indicate a decrease in scratch width as the fly-ash additive content increases up to 0.5%, followed by a slight increase at higher additive ratios. This observed trend can be attributed to the ability of fly-ash particles to fill the gaps between sliding surfaces, thereby creating a protective layer that effectively reduces friction and minimizes material removal during scratching, ultimately resulting in reduced scratch width. However, at higher fly-ash additive ratios, particle clustering and uneven dispersion on the sliding surface occurred. This phenomenon resulted in irregular wear patterns and an increase in scratch width. This observation is supported by the slightly higher scratch width values recorded at 0.75% and 1% additive content. The low standard deviation values indicate that the scratch width measurements are consistent and reproducible.

Based on the findings, we can conclude that an optimal fly-ash additive content of 0.5% is favorable for reducing scratch width and improving the frictional properties of the sliding surfaces. This optimal content level enables the formation of a protective layer, which effectively reduces friction and wear. However, it is crucial to control the fly-ash additive content within an appropriate range since exceeding this threshold may lead to particle agglomeration and the formation of abrasive regions, consequently increasing the wear rate. Thus, achieving maximum effectiveness in reducing friction and wear requires careful control of the fly-ash additive content. Additionally, it is important to note that the scratch width measurements and standard deviations for the ball bearing component vary depending on the additive content. This further emphasizes the need for comparative studies and examination of the effects of additive content on lubrication performance.

In summary, the addition of additives at an appropriate ratio has been shown to enhance oil viscosity, leading to the formation of a protective lubricant layer on the surface of machine parts. This layer effectively prevents wear and reduces oil consumption during machine operation. However, it should be noted that excessively high viscosity can have a negative impact on lubrication, resulting in decreased wear reduction. Furthermore, the incorporation of minute metal oxide particles in the additives facilitates the conversion of sliding friction to rolling friction between machine components, resulting in decreased friction and wear during operation.

However, it is essential to acknowledge the limitations of this study. There are additional known factors that can impact the overall performance of the lubricant, such as the friction coefficient, wear rate, and surface roughness. These factors could be further studied to conduct more comprehensive research. Furthermore, it is important to note that the current study was conducted under controlled laboratory conditions. The lubricating performance may be influenced differently under real-world operating conditions, where factors such as varying temperatures, different load conditions, and continuous usage come into play. Therefore, conducting experiments under more realistic conditions would provide a more accurate evaluation of the additive's effectiveness. Future studies will focus on examining various additive ratios for different lubricant types to determine optimal lubrication parameters. Moreover, a more comprehensive investigation of the rheological properties of the oil mixture with fly-ash additives will be conducted. These endeavors aim to further optimize the lubrication performance and provide valuable insights for industrial applications.

IV. CONCLUSION

The objective of the current study was to assess the impact of fly ash additive on lubricant oil in reducing friction and minimizing wear on machine components. The results demonstrated that the inclusion of a 0.5% concentration of fly ash additive in the lubricant oil resulted in the smallest scratch width and the lowest weight loss of the balls. However, at higher additive ratios, there was a slight increase in scratch width and weight loss due to the agglomeration of fly-ash particles on the sliding surfaces. It is recommended to maintain the appropriate range of fly-ash additive content for maximum effectiveness. Further research can explore different types of lubricants and additive ratios to identify the most suitable lubrication parameters. The study emphasizes the importance of choosing the right additive concentration to ensure the performance and service life of machine components. The addition of fly ash additive to the oil has been found to improve its anti-wear properties by converting wet into wet-rolling friction and introducing metal oxide particles between the surfaces of machine components. The study concludes that an optimal concentration of 0.5% fly ash enhances the anti-wear properties while preserving the essential physical and chemical properties of the oil. This information is valuable for manufacturers in making informed decisions regarding the selection and formulation of lubricating oils with improved anti-wear capabilities.

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