ASSESSING THE TRIBOLOGICAL PERFORMANCE OF POLYALPHAOLEFIN UNDER ELECTRICAL CURRENT CONDITIONS

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ABSTRACT

Polyalphaolefin (PAO) lubricants have long been a staple in the aviation industry, prized for their exceptional friction-reduction properties in high-temperature environments. However, as the industry embraces electrification to decarbonise passenger planes, the demand for suitable lubricants to accommodate the extreme working conditions of electric motors has surged. Understanding how these lubricants perform under electrical conditions becomes crucial, particularly by delving into the frictional characteristics when exposed to electrical current. This study explores the frictional behaviour of PAO4, a specific type of PAO lubricant when subjected to electrical working conditions. It is to conclude that the frictional performance of PAO4 decreases subject to electrical current discharge, with the friction increasing around 30% with an additional temperature increment of 15%. Thus, the investigation aims to understand the interplay between friction and electrical current within the evolving aviation industry.

KEYWORDS

Polyalphaolefin; lubrication; aviation; electrification; electrical current

INTRODUCTION

Lubricants are critical in reducing friction within various industries, particularly mechanical parts involving continuous sliding, moving, and rotating components [1]. In addition, it has the ability to transfer forces, transporting foreign particles such as electrons and either heat or cool surfaces in contact [2]. An exceptional lubricant possesses characteristics such as a high boiling point and low freezing point (to remain liquid across a broad temperature range), robust thermal and hydraulic stability, high viscosity index (VI), and substantial corrosion and oxidation resistance [3, 4].

Technological innovation has advanced quickly, leading to the introduction of synthetic lubricants [5]. These lubricants are unique in that they can function well in a wide range of temperatures, exceeding the constraints imposed by traditional petroleum-based oils. Given these circumstances, polyalphaolefin (PAO) synthetic oil has become popular due to its many noteworthy qualities, including low corrosion rate, high viscosity, low volatility, and low toxicity [6]. Its strong thermal stability at extreme temperatures makes it particularly well-suited for demanding applications, and its versatility and adaptability allow it to be utilized over a wide spectrum of operating circumstances [7, 8]. The aviation industry has successfully used PAO-based lubricants to reduce wear and handle high-temperature situations [9].

Examining the situation from a wider environmental perspective, the automotive sector has been under fire for continuously harming the environment since it contributes significantly to global CO2 emissions—roughly one-third of all emissions globally [10], with a rising tendency. Concerns about air quality, global warming, and climate change have been raised by the environmental effects. Although land transport is responsible for 75–80% of the emissions [11], the aviation sector contributed only 2.4% [12] of the total emissions, although having a significant environmental impact. Despite this, there is an expectation of an annual growth rate of 5% [13], signalling a potential increase in its environmental impact. Recognizing the urgency of reducing greenhouse gas emissions and striving towards net-zero targets, concerted efforts have been initiated to minimize carbon footprints in the automotive and aviation industries. This involves a comprehensive approach that spans technological innovation, regulatory measures, and a shift towards more sustainable practices.

Despite the aviation sector's relatively small contribution of emissions compared to other sectors, proactive measures are deemed imperative. Thus, in the aviation sector, substantial strides are being made through the exploration of alternative jet fuels, with the ambitious goal set by industry experts to achieve a remarkable reduction of over 50% in CO2 emissions by 2050 [13]. Simultaneously, inland transportation, particularly with the widespread adoption of electric cars, has realized a noteworthy 25% reduction in global CO2 emissions as of 2022 [10, 14]. Although adopting electrification in the aviation industry may not seem viable due to battery technology limitations and capacity constraints [15], recent breakthroughs in electric aviation have challenged these assumptions. The successful development of passenger planes like "Alice", exclusively powered by batteries and employing electric motor systems akin to those found in electric vehicles [16], exemplifies the transformative potential of electric aviation.

In the shift to electric propulsion, electric motors function at increased rotational speeds [17], reaching up to 16,000 rpm, and endure continuous current flow and complex voltage conditions [18], resulting in intensified heat generation [19, 20]. Electrical erosion will also occur due to electrical currents' discharge [21]. The confluence of these complex conditions can potentially create high-friction environments [1, 20]. The extremes of these working conditions underscore significant challenges to the optimal performance of conventional lubricants, as they do not have proper thermal and electrical properties [22]. To address these issues, the lubricants used for electrical environments need to maintain their physical and chemical properties under extreme temperature conditions and have additional effective heat transfer capabilities to manage the heat produced by the electric current discharge effect [23]. Nonetheless, current research efforts are dedicated to developing lubricants that align with the requirements of electric motors [24].

The principal objective of this study is to conduct a comprehensive study and in-depth analysis of the frictional behaviour of PAO4, a widely used synthetic lubricant in the aviation industry, under the influence of electrical current conditions, with a keen emphasis on unravelling the intricate dynamics between the lubricant performance and the nuanced influence of electrical currents. Understanding the impact of electrical current discharge on lubricant performance holds great significance, as it has the capacity to alter the tribological properties of even the most efficient lubricants [17]. Ultimately, this research aims to advance mechanical efficiency and prolong the operational lifespan of systems operating under electric propulsion. Thus, this supports efforts to lessen environmental effects and encourage responsible resource use, supporting the larger sustainability goals of the aviation sector and beyond.

METHODOLOGY

Material and Sample Preparation

This investigation used PAO4 (Durasyn 164X PAO) as the preferred lubricant. Steel balls (6 mm diameter) and stainless-steel discs (304 B2 finishing, 50 mm diameter, 1 mm thickness) were used for the friction testing setup. A fresh set of balls and discs was utilised for every test setup to ensure uniform circumstances. The stainless-steel discs were spun-coated to get them ready for friction testing. The disc surface was uniformly coated with precisely 0.5 mL of PAO4, administered after 30 seconds of 3500 rpm spinning. This procedure made sure the coating was even and under control.

The stainless-steel wear discs and balls were thoroughly cleaned before coating. This involved rinsing with water and ultrasonically sonicating in acetone to remove any remaining cutting or machining fluids. To guarantee full ethanol evaporation, the wear discs were submerged in ethanol and allowed to air dry for half an hour. According to reference [25], this strict cleaning schedule was carefully created to maintain the stainless-steel surfaces' wettability, enhance the performance of later coating procedures, and guarantee consistent results. The wear discs were cleaned and coated, then gently rinsed with distilled water, dried in an oven, and allowed to come to room temperature naturally. The steel balls were stored in an air-tight bag containing silicone gel to prevent rust formation.

Electrical Resistance and Contact Temperature Measurement

Following applying a PAO4 layer through spin-coating on each disk, the resistance is measured using a simple complete circuit. A static voltage of 4.5 V was set, and as the current transversed the circuit, the ensuing voltage drop was recorded. Subsequently, the resistance was calculated employing Ohm's Law. The temperature measurement near the contact point of the steel balls and discs was conducted using a laser pointer temperature gun. An initial temperature of 27℃ was taken and served as a baseline. The temperature readings were taken for each configuration before adding the next load.

Friction Testing

The friction test was conducted utilizing a custom-designed ball-on-disc tribometer, as illustrated in Figure 1. The tribometer was equipped with a grounded current flow path traversed through the point of contact between the ball and the disc, similar to reference [26]. A series of friction tests were systematically carried out, maintaining a constant rotational speed of 500 rpm. These tests encompassed a range of applied loads, starting at 80 g and incrementally increasing by 20 g with each iteration, spanning from 80 g to 160 g. Each test was designed to cover a distance of 200 m, around 255 s of running time. Each disc had an initial run-in trial before the start of each friction test to ensure the stability of the system. During this initial run-in, the disc was rotated at 1000 rpm for 60 seconds while bearing a 60 g load.

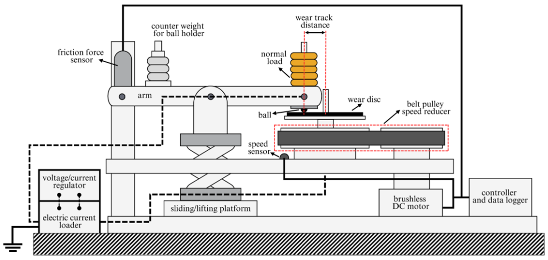

Figure 1: Purpose-built Tribometer

Three different situations were used for the friction tests: no current, 1 A, and 2 A, all with the same setups. Every test was conducted thrice, producing results with an error margin of less than 5% for repeatability. A dry disc friction test was also conducted without oil to evaluate the lubricant's performance. After the friction tests were finished, the diameter of the wear scar on the steel ball and the width of the wear track on the stainless-steel disc were measured using an optical microscope.

RESULTS AND DISCUSSION

Frictional Performance

The friction force measurement of PAO4 over a range of current settings is shown in Figure 2, with a normal load of 100 g applied for 255 seconds. The data's trend indicates a stable friction measurement with few vibrations. This implies that the experiment's tribometer is steady and well-balanced during the testing phase. Notably, higher vibrations are expected in dry contact— when there is no lubricant, reflected in the wider range of friction force shown in the related figure. The difference in lubricated and dry situations highlights how important adequate lubrication is to reduce vibrations and guarantee steady friction behaviour. All things considered, the data is considered satisfactory, with an error rate of less than 10%. This observation confirms the tribometer's efficacy in generating consistent friction force measurements under various configurations.

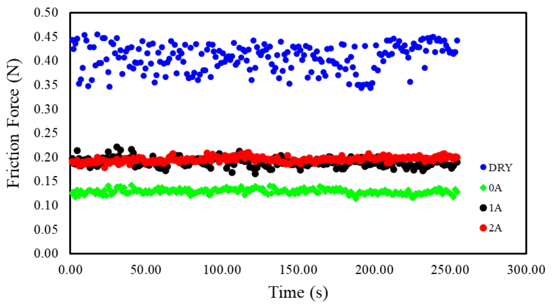

Figure 2: Friction Force against Time for 0.1 N Loading

Figure 3 illustrates the frictional characteristics of PAO4 across a spectrum of normal loads and sliding speeds under three distinct current conditions: no current, 1 A, and 2 A. A discernible pattern emerges, indicating a direct linear correlation between the applied loads and the resultant frictional forces. The reliability of this linear association is substantiated by the coefficient of determination, R^2, which consistently yields values within the range of 0.98 to 0.99, affirming the robustness of this linear relationship. Notably, for all experimental conditions, the coefficient of friction, derived from the slope of the frictional force plotted against the applied load, consistently intersects the origin. Detailed values for both the friction coefficient and R^2 can be found in Table 1, further elucidating the observed trends and reinforcing the reliability of the findings.

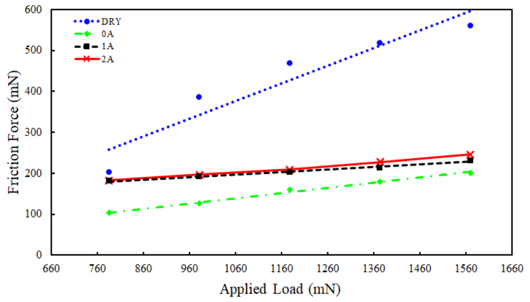

Figure 3: Friction Force against Applied Load

Table 1: Coefficient of friction and R^2 values

Sample	Coefficient of Friction	R^2
DRY	0.366	0.99
0 A	0.131	0.98
1 A	0.168	0.98
2 A	0.175	0.99

As depicted in Figure 3, the absence of lubrication (dry contact) leads to a notably elevated friction force on the disc, underscoring the essential role of lubricants in mitigating friction between two contacting surfaces within a mechanical system. Applying a PAO4 layer to the disc yields a substantial 64.2% reduction in friction, thus confirming the commendable friction-reduction capabilities attributed to PAO4, as substantiated by prior research. However, when 1 A and 2 A currents are discharged through the lubricated contact, an interesting trend emerges: the coefficient of friction experiences a respective increase of 28.4% and 33.6%, respectively, compared to the one without current discharge. This observed pattern underscores the correlation between increasing electrical current and heightened friction forces, highlighting the influence of current magnitude on the frictional behaviour within this mechanical system.

Resistivity and Temperature Effect

The resistance measurements, along with the corresponding temperature variations in the vicinity of the lubricant contact, as summarized in Table 2, yield pivotal insights within the scope of this study. Without any electrical current, the anticipated heat generation arises primarily from frictional interactions at the contact points, commonly called shear heating. In contrast, applying a PAO4 coating to the disc, as evidenced by the recorded resistance value of 1.79 Ω in Table 2, leads to a notable increase in resistance. This elevated resistance aligns with a concurrent rise in the measured temperature in the contact vicinity, reaching up to 31.1 °C at the highest load under the 2 A current condition.

Table 2: Electrical resistance and temperature in the lubricated contact vicinity

Sample	Electrical Resistance (Ω)	Final Temperature (°C)
DRY	1.01	37.2
0 A	-	27.6
1 A	1.26	28.2
2 A	1.79	31.1

It is important to note that in this case, the temperature increase that is noticed is a direct result of the electric current passing through the contacts. It is crucial to understand that an imbalance in the lubricant film's resistivity might obstruct the efficient passage of electricity through the ball, which can lead to increased heat production in the system.

The approach to temperature and resistance measurements provides important information about how the system behaves thermally under various loads and configurations. It also highlights the importance of electrical conductivity controlling the system's thermal characteristics and reveals the complex interaction dynamics between the lubricant and the mechanical parts. This detailed knowledge gives a better picture of the thermal responses inside the setup under study.

CONCLUSION

This study highlights the need to extend research into lubricants designed for electrical working conditions. PAO4, a lubricant with excellent contact friction, showed friction reduction capabilities of 64.2%. Nevertheless, their performance is much different considering the electrical current discharging through the lubricated contact. The coefficient of friction noticeably increases even with a slight 1 A current present, increasing by 28.4% in the same lubricated configurations.

In the absence of current, the final temperature of the contact is relatively low. In contrast, applying 1 A current increases the resistance by around 25%, subsequently increasing the contact vicinity's temperature by almost 15%. This is due to improper resistivity that does not allow proper current flow through the contact, which increases the temperature. Ultimately, lubricants with improper resistivity prevent smooth electrical current flow within the contacts, causing a build-up of temperature within the system. Consequently, this increases friction, adding to the friction from the high-speed moving machinery inside the electric motor.

This study contributes significantly, shedding light on the performance of synthetic lubricants, specifically PAO4, within the realm of electrical working conditions. It offers valuable insights that have the potential to drive innovation within the lubrication industry, stimulating the development of a new generation of lubricants engineered to address the challenges posed by electrical current discharge effectively. Such advancements promise to enhance the efficiency and longevity of mechanical systems operating under electric propulsion, aligning with broader sustainability goals.

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