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The effects of oil treatment on tribological properties in used automatic transmission fluids (ATFs)

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ABSTRACT

Automatic Transmission Fluid (ATF) degrades over time, and its ability to reduce wear and friction declines, leading to poor transmission performance and shorter transmission lifespan. Oil treatments are capable of restoring the qualities of degraded automatic transmission fluid (ATF) by reducing wear and friction and ultimately improving transmission performance and longevity. This paper studies the effects of oil treatment on the tribological properties of used ATFs after 20,000km mileage. The samples were prepared by blending 4 vol.% of oil treatment to used ATFs. The samples were tested using spectrometer, viscometer and 4-ball tester for tribological testing according to ASTM standards D6595 (Elemental analysis), D2770 (Viscosity) and D4172 (WP). It was observed that the oil treatment enhanced the coefficient of friction (CoF) by up to 18% compared to the used ATF. These findings indicate that introducing oil treatment can significantly improve its tribological property of used ATFs, offering an effective solution to address friction and wear issues in transmissions.

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1.0 INTRODUCTION

Automatic transmission fluid (ATF) is a fluid that lubricates gears, operates the torque converter, and manages brake band friction. ATF is also used in some manual transmissions, transfer cases, and power steering systems. It acts as a hydraulic fluid, protects gears, controls heat, and ensures smooth shifts (Halley et al., 2020; Rizvi, 2003). The development of modern hydraulic components also aimed at increasing the transmitted power, reducing energy intensity, minimizing environmental pollution, and increasing technical life and machine reliability (Kosiba & Petrović, 2018). The ATF degrades over time, especially if the transmission overheats during towing or hauling, leading to oxidation and sludge formation (Hoque et al., 2020). This sludge can clog crevices and impede movement. The performance and longevity of ATF are crucial for maintaining stable friction properties and smooth torque transfer at the friction interface, ensuring the system's durability and safety.

As automatic transmission fluid (ATF) degrades over time, its ability to effectively reduce wear and friction diminishes, leading to decreased transmission performance, increased wear on transmission components, and a reduction in overall longevity of the transmission system. This degradation poses a challenge for maintaining the smooth operation and durability of transmissions. Therefore, there is a need to explore effective solutions that can restore or enhance the tribological properties of used ATFs.

In order to restore or enhance the tribological properties of used ATFs, oil treatment is introduced. According to Sabri et al (2024), the combination of few additives are remarkably successful in enhancing physicochemical and tribological characteristics. For instance, Copper-Nicle-Iron (Co-Ni-Fe) coating is anticipated to function as an effective protective layer to enhance resistance to erosive wear, corrosion, and mechanical stress (Roseley et al., 2022). These additives offer the required heat resistance, frictional qualities, and other advantages. Moreover, the presence of glycerol monoisostearate as a friction modifier enhances the interaction between Ca-containing detergent and P-containing anti-wear additives in ATF, leading to the formation of a calcium hydroxyphosphate tribofilm, which improves anti-shudder performance by providing better surface coverage (Di et al., 2023). Notable for their exceptional lubricating properties, common additions including silicon, zinc, phosphorus, molybdenum, and titanium reduce wear and friction between surfaces as a solid lubricant in a variety of applications (Vazirisereshk et al., 2019). In addition, a previous study also reported that the titanium and molybdenum composite coating exhibited good low-friction behavior (Mu et al., 2013). Calcium phosphate (CaP) tribofilms form on the friction surface with all ATFs, which contribute to their antishudder characteristics(Di et al., 2020). Even though lubricants with additives containing nanomaterials have exhibited good anti-friction and anti-wear performances in conventional lubricants (Liñeira del Río et al., 2024; Wang et al., 2022), there is scarcely any investigation on oil treatments with regard to transmission and gearbox tribological needs.

There is a limited understanding of how this combination of additives, specifically in oil treatment, influences the tribological properties of degraded ATFs. Although some studies have examined their general impact on fluid quality, comprehensive data on their effectiveness in restoring friction and wear characteristics in used ATFs is limited. This study seeks to address this gap by investigating the effects of oil treatment on the tribological properties of ATFs after 20,000 km of use.

2. EXPERIMENTAL PROCEDURE

Two different brands of automatic transmission fluid (ATF), both fresh and used (after 20,000 km of mileage), of the same grade and oil treatment, were collected from JV Auto Resources (M) Sdn Bhd. The fresh ATF from the first brand was labeled ATF A0, while the corresponding used ATF, with 20,000 km of mileage, was labeled ATF A. Similarly, the fresh ATF from the second brand was labeled ATF B0, and its used ATF was labeled ATF B. The technical specifications for both fresh ATF A0 and B0 are listed in Table 1. The used samples, ATF A and B, were mixed with 4 vol.% of the oil treatment, denoted as ATF A1 and ATF B1, respectively. The 4 vol.% concentration of oil treatment was chosen based on typical industry practices and previous research (Shareei et al., 2022). This concentration range is commonly used to enhance ATF properties such as wear resistance and friction reduction without negatively affecting the fluid's original composition. The oil treatment was mixed into the ATFs using the ultrasonication method for 30 minutes at 75˚C (Shaari et al., 2015). Each sample underwent repeatability testing at least three times to ensure accuracy and consistency in the results.

Table 1: Technical specifications of ATF A0 and ATF B0.

Characterization	ATF A0	ATF B0
Colour	Red	Red
Kinematic Viscosity @40°C	~30-40 cSt	~34-37 cSt
Kinematic Viscosity @100°C	~6-7.5 cST	~7-8 cSt
Viscosity Index (VI)	~180	~170
Pour Point	-45°C	-45°C
Flash Point	>180°C	>180°C
Density @15°C	~0.860 g/cm³	~0.855 g/cm³

Elemental analysis that conforms to ASTM D6595 was carried out using spectrometer (Spectroil Q100), to analyze the element content of the identified ATF samples. Each sample was tested 5 times.

The viscosity of various ATFs was measured following ASTM D445, with each test repeated three times to accurately determine kinematic viscosity. The measurement was taken from 40°C and 100°C, with an increment of 10°C. The viscosity index was calculated based on ASTM D2770.

A four-ball testing was carried out to evaluate the friction and wear profiles of the ATF samples and find out what their tribological properties were. The test was run with ASTM D4172 Wear Preventive (WP). The wear scar was analyzed under microscope. The summary of test parameters for the WP tests is listed in Table 2.

Table 2: Four ball parameters according to ASTM standard.

Parameter	WP (ASTM D4172)
Rotating speed	1200 ± 60 rpm
Temperature	75 ± 2°C
Duration	60 ± 1 min
Load	392 N

3.0 RESULTS AND DISCUSSION

3.1 Elemental Analysis

Oil treatment consists of a few additives' elements package. The elemental analysis of oil treatment is shown in Table 3.

Table 3: Type of elements of oil treatment.

Element	(ppm)
Ca	18.45
Mg	3.33
P	18.53
W	133.67
Zn	93.81
H	8576.3
C	21780

The elemental analysis of the oil treatment shows the presence of key elements specifically selected to enhance performance and durability. With calcium (Ca) at 18.45 ppm and magnesium (Mg) at 3.33 ppm, the oil contains detergents that neutralize harmful acids and maintain system cleanliness, preventing deposits (Di et al., 2020). Phosphorus (P) at 18.53 ppm and zinc (Zn) at 93.81 ppm serve as critical anti-wear additives, forming protective tribofilms on metal surfaces to reduce friction and wear under high-stress conditions (Mistry et al., 2013). A notable component is tungsten (W) at 133.67 ppm, which indicates the oil's capacity to handle extreme pressure and high-load environments. Tungsten's exceptional thermal stability helps prevent metal-to-metal contact, further reducing wear. This oil treatment formulation contains an additive of detergent, anti-seize, extreme pressure (EP), anti-foam and anti-wear. This formulation strikes a balance between detergent action, wear protection, and extreme pressure resilience, making it suitable for enhancing transmission longevity and efficiency under demanding operational conditions.

Table 4 shows the types of elements in ATF A0, A, A1, and ATF B0, B, and B1. Both ATFs consist of boron (B), calcium (Ca), phosphorus (P), hydrogen (H), and carbon (C) elements. The elemental analysis of ATFs provides valuable insights into the composition and wear characteristics of fresh, used, and treated fluids. Fresh ATFs (ATF A0 and ATF B0) serve as baselines, each containing essential elements for performance. ATF A0 comprises boron (B), calcium (Ca), phosphorus (P), and zirconium (Zr), while ATF B0 includes arsenic (As), iron (Fe), magnesium (Mg), silicon (Si), zinc (Zn), and Ca, highlighting differences in their formulation and additive focus.

Used ATFs (after 20,000 km) reveal significant elemental changes, suggesting wear and contamination. ATF A retains its original elements and also includes aluminum (Al), bismuth (Bi), copper (Cu), Fe, Mg, nickel (Ni), indium (In), molybdenum (Mo), lead (Pb), Si, and Zn. Similarly, used ATF B introduces additional elements such as As, Al, barium (Ba), Bi, Cu, Fe, Mg, Ni, potassium (K), manganese (Mn), sodium (Na), Si, Zn, and Zr, reflecting increased contamination and wear, likely due to extended mileage.

Treated ATFs (ATF A1 and B1), each with 4 vol.% oil treatment, show a reduction in wear metals and contaminants. ATF A1 maintains B, Ca, P, and Zr while reducing wear elements like Cu (24.26 ppm) and Fe (32.25 ppm). ATF B1 shows similar stability, retaining essential elements but lowering the presence of certain contaminants, confirming the treatment's efficacy in minimizing degradation and extending fluid life.

Table 4: Type of elements of samples ATF A and ATF B.

	ATF A0		ATF A		ATF A1		ATF B0		ATF B		ATF B1	
		(ppm)		**(ppm)**		**(ppm)**		**(ppm)**		**(ppm)**		**(ppm)**
Common elements	B	7.44	B	83.62	B	65.28	B	87.50	B	76.90	B	54.97
	Ca	3.01	Ca	49.80	Ca	48.67	Ca	287.52	Ca	78.53	Ca	71.54
	P	12.19	P	156.60	P	117.6	P	520.58	P	225.34	P	179.48
	H	6839.1	H	7034.6	H	6864.6	H	6726.7	H	6987.7	H	6883.4
	C	22290	C	23390	C	21739	C	22918	C	22852	C	21791
Elements presented in fresh ATFs	Zr	681.61	Zr	1.260	Zr	3.62	As	14.76	Fe	66.74	As	24.27
							Fe	1.32	Mg	10.06	Fe	52.08
							Mg	7.81	Si	23.99	Mg	4.04
							Si	2.18	Zn	16.89	Si	19.91
							Zn	217.11			Zn	10.31
Additional elements			Al	3.60	Al	3.49			Al	50.17	Al	43.059
			Bi	2.08	Cu	24.26			Ba	76.90	Ba	10.31
			Cu	25.89	Fe	32.25			Bi	5.00	Cu	35.80
			Fe	38.54	Mg	3.51			Cu	39.40	Ni	3.52
			Mg	4.09	Ni	3.71			Ni	5.32	Mn	4.91
			Ni	3.94	Si	4.71			K	4.87	Na	4.33
			In	1.30	Zn	15.27			Mn	7.59	Zr	3.46
			Mo	1.32					Na	5.87		
			Si	5.41								
			Zn	26.33								

Comparing elemental analysis underscores the role of specific additives in enhancing ATF performance and durability. For instance, ATF B0's higher Ca (287.52 ppm) and P (520.58 ppm) suggest an anti-wear and lubrication focus, while ATF A0, with lower levels of Ca (2.96 ppm) and P (11.29 ppm), may offer different protective qualities. Elevated wear metals in used ATFs, particularly Cu and Fe, point to significant internal wear, highlighting the need for monitoring and regular maintenance.

Treated ATFs show reduced wear metals, indicating that oil treatments can effectively stabilize ATF composition, mitigate wear, and restore performance. High concentrations of essential elements in fresh and treated ATFs support lubrication and anti-wear properties, while lower levels of contaminants post-treatment illustrate the treatment's protective benefit in extending ATF service life.

The comparison of elemental analyses underscores the crucial role that oil treatments play in enhancing the performance and longevity of ATFs. The elemental composition of fresh ATFs reveals significant differences in their formulations. ATF B0, with its high concentration of calcium (Ca) and phosphorus (P), is specifically designed for enhanced anti-wear protection and lubrication, making it more reliable compared to ATF A0, which has significantly lower concentrations of these elements.

As the ATFs are used over time, fluid degradation becomes evident through the increasing presence of wear metals such as Cu and Fe, particularly in ATF A, which shows significant internal wear after 20,000 km. This accumulation of wear metals and contaminants signals a decline in fluid performance, raising concerns about potential transmission damage if the issue is not addressed. Regular monitoring of these elemental changes is essential for maintaining transmission health. The application of oil treatment proves highly effective in mitigating these degradation effects. In both ATF A1 and B1, a noticeable reduction in wear metals, especially Cu and Fe, is observed post-treatment, indicating that the oil treatment not only stabilizes the fluid but also restores some of its protective properties. The inclusion of P, Zn, and W in the oil treatment plays a vital role in this restoration process. Known for their anti-wear, anti-oxidation, and extreme pressure properties, these elements form protective tribofilms on metal surfaces, reducing friction and wear (Alias et al., 2018; Fatima et al., 2015; Parenago et al., 2017). Their presence helps counteract wear and contamination.

Overall, the elemental analysis of both fresh and used ATFs, combined with the effects of oil treatments, emphasizes the critical role of fluid maintenance and additives in preserving transmission performance. Fresh ATFs, rich in essential elements like calcium and phosphorus, provide initial protection, while the gradual accumulation of wear metals in used fluids reflects degradation over time. However, oil treatments significantly mitigate these effects by reducing the concentration of wear metals and contaminants, effectively restoring the fluid's protective capabilities. This process stabilizes the ATFs, prolongs its service life, and ensures reliable transmission performance under demanding conditions. The analysis gives an insight that a balance between fluid formulation and regular treatment is essential for sustaining long-term transmission efficiency, minimizing wear, and optimizing operational reliability.

3.2 Viscosity

The test results are reported in Figure 1 as below. As referring to the kinematic viscosity, both oils have adequate thickness to lubricate well at high temperatures during steady-state operation. ATF A0, ATF A and ATF A1 show almost the same kinematic viscosity across the temperature. While ATF B and B1 show a slight difference compared to fresh ATF B0.

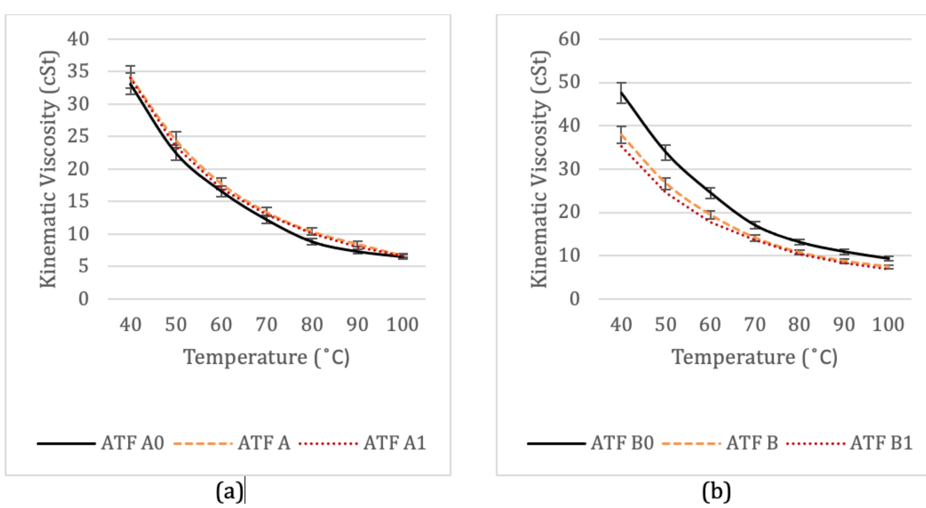


Figure 1: The kinematic viscosity of (a) ATF A and (b) ATF B.

The kinematic viscosity data for the various ATF sample types, ATF A and ATF B, offers important information about the fluid's performance and state over time. The kinematic viscosity of ATF A0 is 33.1 cSt at 40°C and drops to 6.5 cSt at 100°C in a steady pattern as temperature rises. In order to compare with the used ATF samples, this establishes the baseline. The kinematic viscosity of used ATF A at 20,000 km mileage is greater at 40°C (34.2 cSt), and it decreases to 6.7 cSt at 100°C. This increased viscosity is the result of oxidation, pollution, and the gradual degradation of additives (Omar et al., 2021). The kinematic viscosity of treated ATF A1 is 34.06 cSt at 40°C and drops to 6.59 cSt at 100°C.

While fresh ATF B0 at 40°C has a viscosity of 61.85 cSt and drops to 7.96 cSt at 100°C, suggesting a high starting viscosity that dramatically declines with temperature. The viscosity of used ATF B at 20,000 km is initially lower at 45.92 cSt at 40°C and drops to 14.5 cSt at 100°C. ATF B's initial viscosity would be greater on the graph than ATF B1's, but lower than ATF B0's, indicating thinning and deterioration over time as a result of wear, contamination, and additive breakdown (Omar et al., 2021). At 40°C, the viscosity of treated ATF B1 is 37.66 cSt; at 100°C, it drops to 11.09 cSt. At all temperatures, ATF B1's viscosity curve is smaller than ATF B's, although it does not show incomparable changes indicating that the oil treatment does not have much impact on the used ATF B.

Overall, the viscosity graphs profile for both ATF A and ATF B samples show a linear downward trend with increasing temperature. For ATF A, the fresh ATF A0 has the lowest initial viscosity, with the used ATF A slightly higher and the treated used ATF A1 slightly lower but close to the used ATF A. For ATF B, the fresh ATF B0 has the highest initial viscosity and steepest decline, while the used ATF B shows a moderate decline, and the treated used ATF B1 does not have much impact on the viscosity profile of used ATF.

The viscosity index (VI) is a crucial indicator of an ATFs' ability to maintain consistent viscosity across varying temperatures. The kinematic viscosity of samples ATF A does not give a significant change, but samples of ATF B do change over temperature. Figure 2 displays the viscosity index for samples ATF B as well as the curve for kinematic viscosity at 40°C and 100°C.

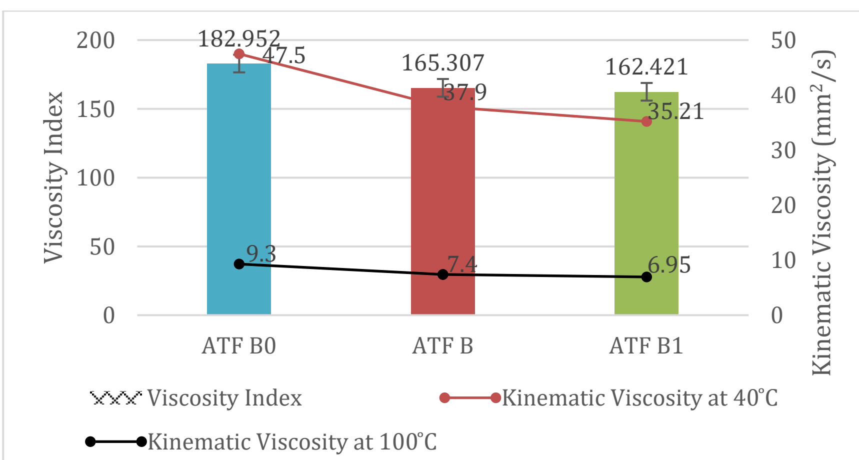


Figure 2: Graph of viscosity index (VI) and kinematic viscosity at 40 °C and 100 °C of ATF B.

For ATF B0, it starts with a higher VI of 182.95, indicating excellent viscosity stability. A higher viscosity index indicates less viscosity change with temperature, preferred for automotive engines due to better viscosity stability across temperature ranges (Boussaid et al., 2024). After

20,000 km, the VI of ATF B drops significantly to 165.31, reflecting a notable degradation in its viscosity performance due to usage. When oil treatment is added to this used ATF, resulting in ATF B1, the VI further decreases to 162.42.

In summary, while the introduction of oil treatment to used ATFs may provide various improvements, they tend to result in no significant changes in the viscosity index compared to both fresh and used ATFs without oil treatment. This indicates a trade-off between maintaining optimal viscosity stability and enhancing other fluid properties through oil treatment used. These variations highlight the importance of monitoring viscosity and using oil treatments to enhance the longevity and performance of ATF. The results likely reflect the absence of viscosity improvers in used ATF, preventing it from achieving normal viscosity as fresh ATF. The oil treatment appears to help maintain viscosity characteristics of the ATFs, particularly at higher temperatures, suggesting improved thermal stability while restoration of some of the fluid's original properties.

3.3 Wear Preventive (WP) Measurement

3.3.1 Coefficient of Friction

Figure 3 shows the friction coefficient behavior of fresh, used and treated of ATF A and B.

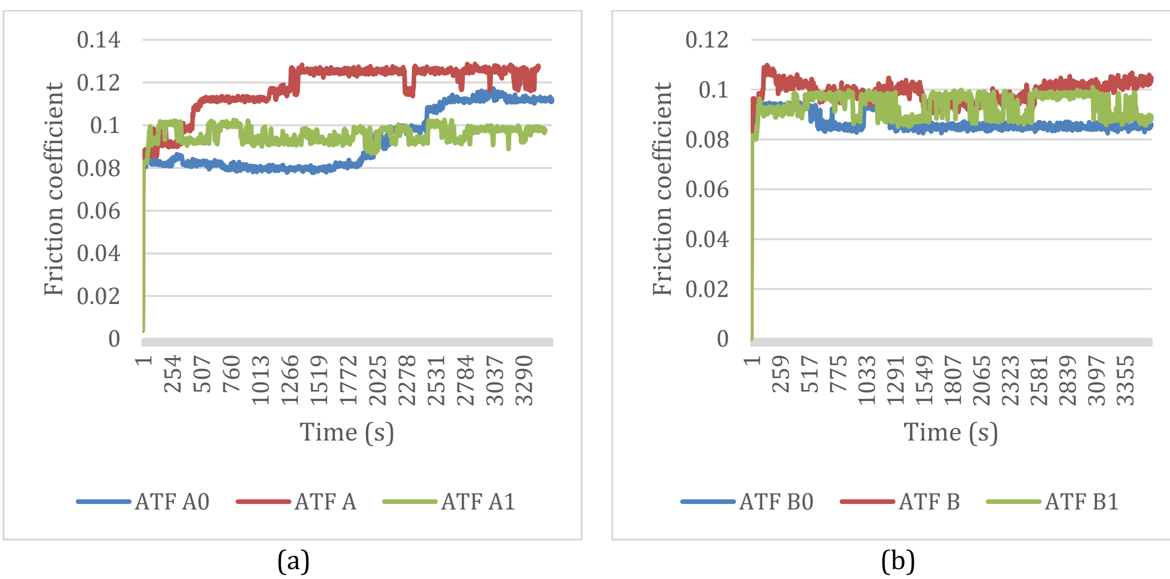


Figure 3: The friction coefficient over time of (a) ATF A and (b) ATF B.

Both treated ATF (ATF A1 and B1) show a more stable graph line compared to others. While new and used ATFs (ATF A0, ATF A, ATF B0 and ATF B) show a slightly unstable and inclined pattern at some point.

Across the running period, the average values of the friction coefficient were obtained and measured as shown in Figure 4. From the graph, treated ATF A1 and B1 achieved the lower average coefficient (CoF) of 0.0954 and 0.0934, respectively. However, both treated ATF were unable to reach the initial result as fresh ATF.

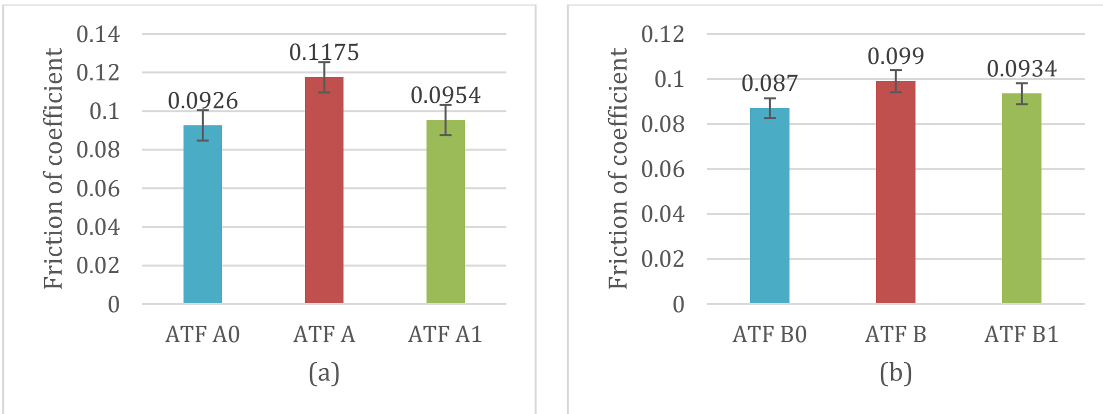


Figure 4: The friction coefficient of (a) ATF A and (b) ATF B.

Based on the results, both ATF A1 and B1 show better coefficients of friction (CoF) compared to ATF A and B. Specifically, ATF A1 improved by 18.81%, while ATF B1 improved by 5.66%. This improvement is due to the presence of elements such as Zn and P in the oil treatment, which act as anti-wear and extreme pressure additives. These additives, known as friction modifier additives, are extensively used as nanoparticle additions in lubricating oils, and their efficacy in reducing friction and wear has been well-documented (Chen, 2010; Shahnazar et al., 2016). Additionally, another study by Wang et al., (2018) has proven that the phosphorus elements in their used additives exhibit strong superlubricity in an aqueous solution, maintaining very low resistance to shear across different additive concentrations, contact pressures, and sliding velocities. This suggests that the presence of these additives in the oil treatment contributes significantly to the improved friction and wear characteristics observed in ATF A1 and B1. These results indicate that while the treated ATFs do not fully restore the CoF to the level of fresh ATFs, they show significant improvements over the used ATFs, highlighting the effectiveness of the oil treatment in enhancing the wear preventive measures of the ATFs.

3.3.2 Wear Scar Diameter

The wear scar under microscope for the tested ATF samples were illustrated in Figure 5 and 6. Figure 7 shows that the wear scar diameter for ATF A0, ATF A and ATF A1 were 0.249mm, 0.208mm and 0.219mm respectively. While ATF B0, ATF B and ATF B1 were 0.315mm, 0.879mm and 0.202mm respectively.

The wear scar analysis of ATFs reveals significant changes in wear protection with the application of oil treatment. Initially, ATF A shows a wear scar diameter of 0.249 mm for fresh ATF, decreasing to 0.208 mm after 20,000 km of use. However, treating the used ATF A with oil treatment results in a slightly increased wear scar diameter of 0.219 mm, representing a percentage change of approximately 5.29% compared to used ATF A. The oil treatment, while beneficial, was less effective in fully restoring wear resistance in the degraded fluid.

In contrast, ATF B starts with a wear scar diameter of 0.315 mm, escalating to 0.879 mm after similar mileage, highlighting substantial degradation. Oil treatment in ATF B reduces the wear scar diameter dramatically to 0.202 mm, reflecting a percentage improvement of about 76.96% compared to used ATF B. This result aligns with findings from other studies, which show that adding additives to automotive lubricants can reduce wear scar diameter by more than 9% (Szabó et al., 2023; Thachnatharen et al., 2022), further validating the effectiveness of the treatment.

These findings underscore the critical role of oil treatment in mitigating wear and preserving ATF performance, demonstrating their efficacy in enhancing lubrication and protective capabilities under demanding operating conditions.

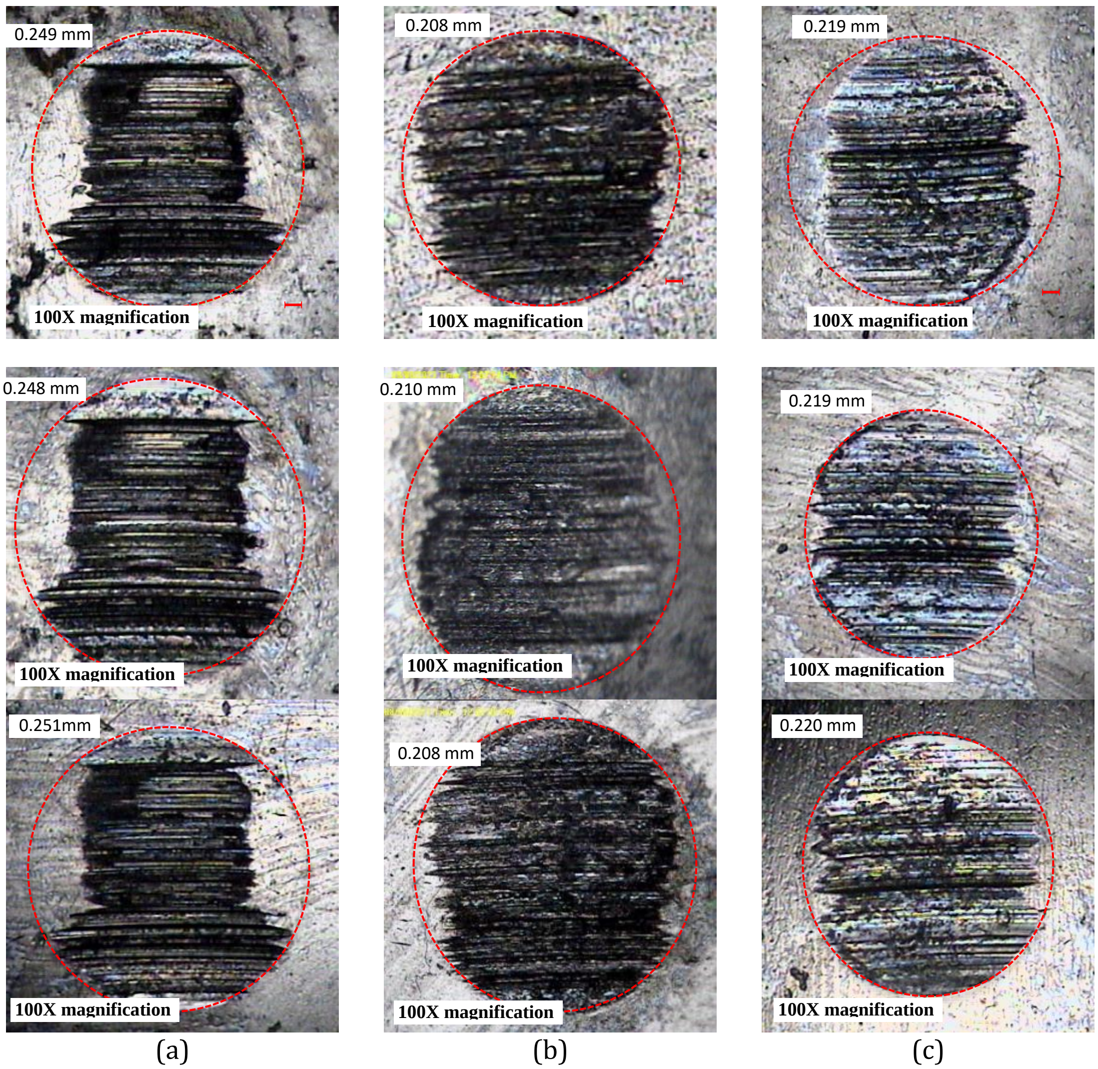


Figure 5: Wear scar of 3 balls of (a) ATF A0, (b) ATF A and (c) ATF A1.

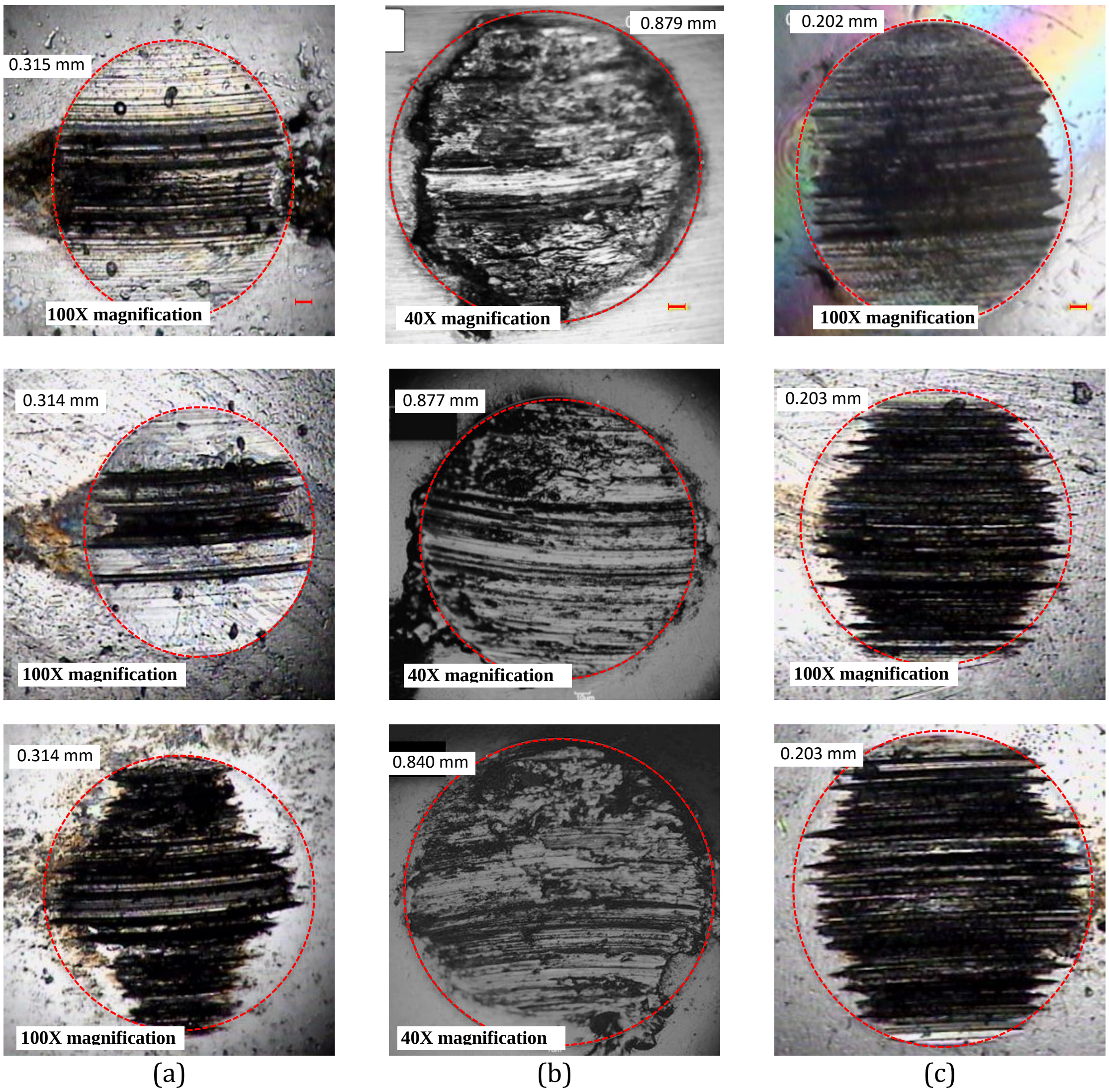
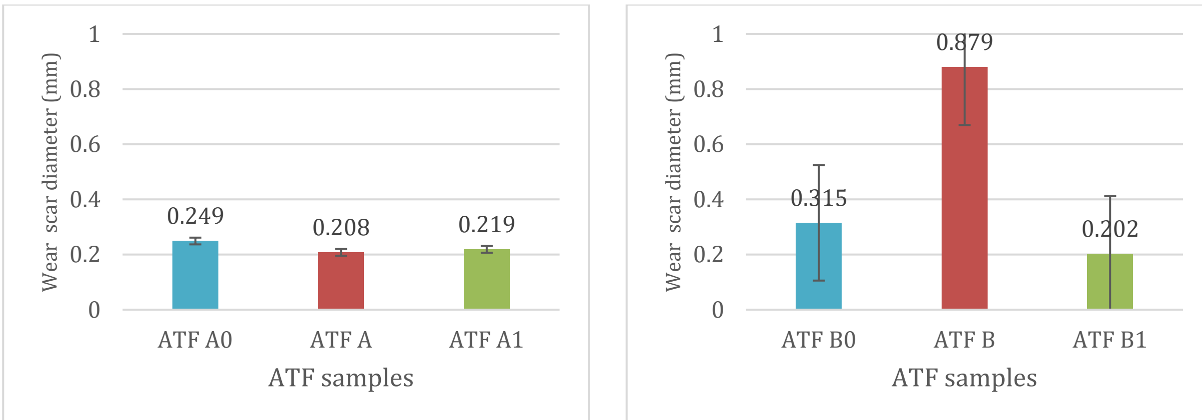


Figure 6: Wear scar of three balls of (a) ATF B0, (b) ATF B and (c) ATF B1.



(a) (b)

Figure 7: Wear scar diameter of (a) ATF A and (b) ATF B.

Overall, the wear surface analysis reveals that ATFs can produce better wear scars when treated with oil treatment, indicating improved wear protection. This might be as a result of the elements P and Zn. Previous research has demonstrated the usefulness of those components as lubricant additives for the reduction of friction and wear (Barton & Karathanasis, 2002). According to Stachowiak and Batchelor's (2006), synthetic lubricants contain compounds with phosphides and sulphide ions that have a propensity to react with the steel ball surfaces, preventing metallic contact to some extent and reducing wear. Additionally, additives containing metals like Zn and Fe may contribute to the production of tribofilm on worn surfaces, claim Zhao's. in their study (Zhao et al., 2014). The wear scars become more noticeable with usage, but the presence of oil treatment helps to minimize the diameter of the wear scars. This emphasizes the importance of using oil treatments to enhance longevity and wear resistance of ATF, ensuring better protection for transmission components over time.

CONCLUSIONS

In conclusion, oil treatment has a significant impact on the tribological properties of ATFs. The tribological properties were evaluated through wear preventive (WP). The following conclusion can be drawn:

a) The elemental analysis of both used ATFs (ATF A and B) shows an additional element from new ATFs (ATF A0 and B0). However, with the addition of oil treatment, the elements were reduced from the used ATF A and B, but unable to achieve the initial elements as new ATFs.
b) The viscosity of all ATF A0, A and A1 does not give a significant change across the temperature. However, used ATF B shows a lower viscosity profile as compared to new ATF B0, and ATF B1 with oil treatment does not show a significant change in viscosity.
c) Both treated ATFs showed improvements in CoF compared to used ATF A and B, which is ATF A1 by 18.81% and ATF B1 by 5.66%.
d) ATF A1, with oil treatment, maintains a wear scar diameter of 0.219 mm after 20,000 km, compared to 0.208 mm for used ATF A, marking a 5.02% difference. ATF B1 shows a significant reduction in wear scar diameter from 0.879 mm to 0.202 mm with oil treatment, a 76.96% improvement compared to used ATF B.

The effects of oil treatment on the tribological properties of ATFs show that oil treatment effectively improves fluid properties by introducing anti-wear, anti-oxidation, and corrosion inhibition components. These additives counteract contamination and restoring and maintaining the fluid's performance characteristics close to those of fresh ATF. This ensures prolonged transmission life and optimal performance under varying conditions. Thus, the use of oil treatment is essential in enhancing ATF durability, minimizing wear, and maintaining effective transmission operation over extended service intervals.

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