

THE TRIBOLOGICAL CHARACTERISTICS OF SELECTED BASE OILS UNDER OSCILLATORY SLIDING CONDITIONS

Lubrication fundamentals

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INTRODUCTION

The main function of a lubricant is to reduce friction between interacting materials taking cost implications into consideration [1]. By selecting a suitable lubricant, the energy usage in mechanical systems can be optimized. Since no single lubricant is fit for all applications, the knowledge about the lubricants ability to reduce friction over another becomes of critical importance during lubricant selection [2]. Polyalphaolefin (PAO) base oils are known to have superior lubricating properties [1]. However, their high cost places them at a disadvantage [3]. The development of severely hydrocracked Group III+ (group three plus) base oils has shown great potential to achieve a balance between the base oil cost and competitive lubricity [4]. The physical characteristics of Group III+ base oils vary between ultra-high viscosity base oils (Group III) and polyalphaolefins (Group VI). These oils are categorized as Group III+ base oils [5]. This category is not officialised by the American Petroleum Institute (API), but it is recognized by industry for marketing purposes. Although the Group III+ base oils have superior physical properties, their overall tribological performance still stands to be confirmed [4, 5]. The aim of this study was to determine and compare the friction and wear characteristics of the Group III+ base oil to those of the less expensive solvent refined mineral base oil (Group I) and the PAO base oil in the mixed lubrication regime at different temperatures [3]. The comparative analysis was done using the average coefficient of friction data and inspection of the wear scars which were generated under a constant load and speed of 150 N and 0.2 m.s⁻¹, respectively, using the oscillating ball-on-disc SRV4® tribometer at five temperatures (i.e., 40, 60, 80, 100 and 120 °C). Firstly, the viscosity and pressure-viscosity (α) behaviour were determined at the chosen experimental temperatures. This was followed by the confirmation of the operating regime at the chosen temperatures through Stribeck curves using a modified Stribeck parameter, and this was then followed by the generation of wear scars under a constant load of 150 N for a period of 120 minutes, under a controlled relative humidity (RH) of 20 %. **Table 1** shows the properties of the base oils selected.

Table 1. Base oil properties at atmospheric pressure [2, 4, 6].

Base Oil	Formulation process	Kinematic Viscosity (η_k) (cSt)		Density (ρ) at 15 °C, (g/cm ³)	Sulfur (% w/w)	Saturates (% w/w)
		40 °C	100 °C			
Group I (GI)	Solvent refined	28.38	5.03	0.86	> 0.03	< 90
Group III+ (GIII+)	Severely hydrocracked	17.74	4.00	0.82	≤ 0.03	≥ 90
Group IV (PAO)	Oligomerized	18.00	4.10	0.82	-	≥ 90

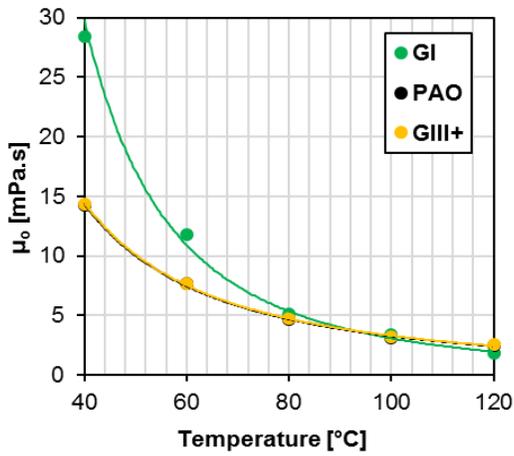


Figure 1. Dynamic viscosity (μ_0) variation with temperature.

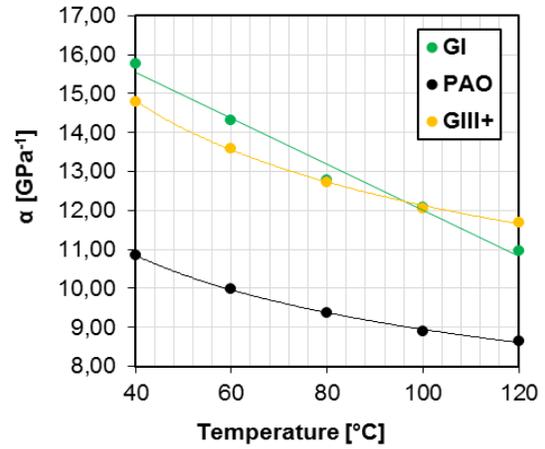


Figure 2. Pressure-viscosity (α) coefficient with temperature, $\alpha = s/\eta_k^t$.

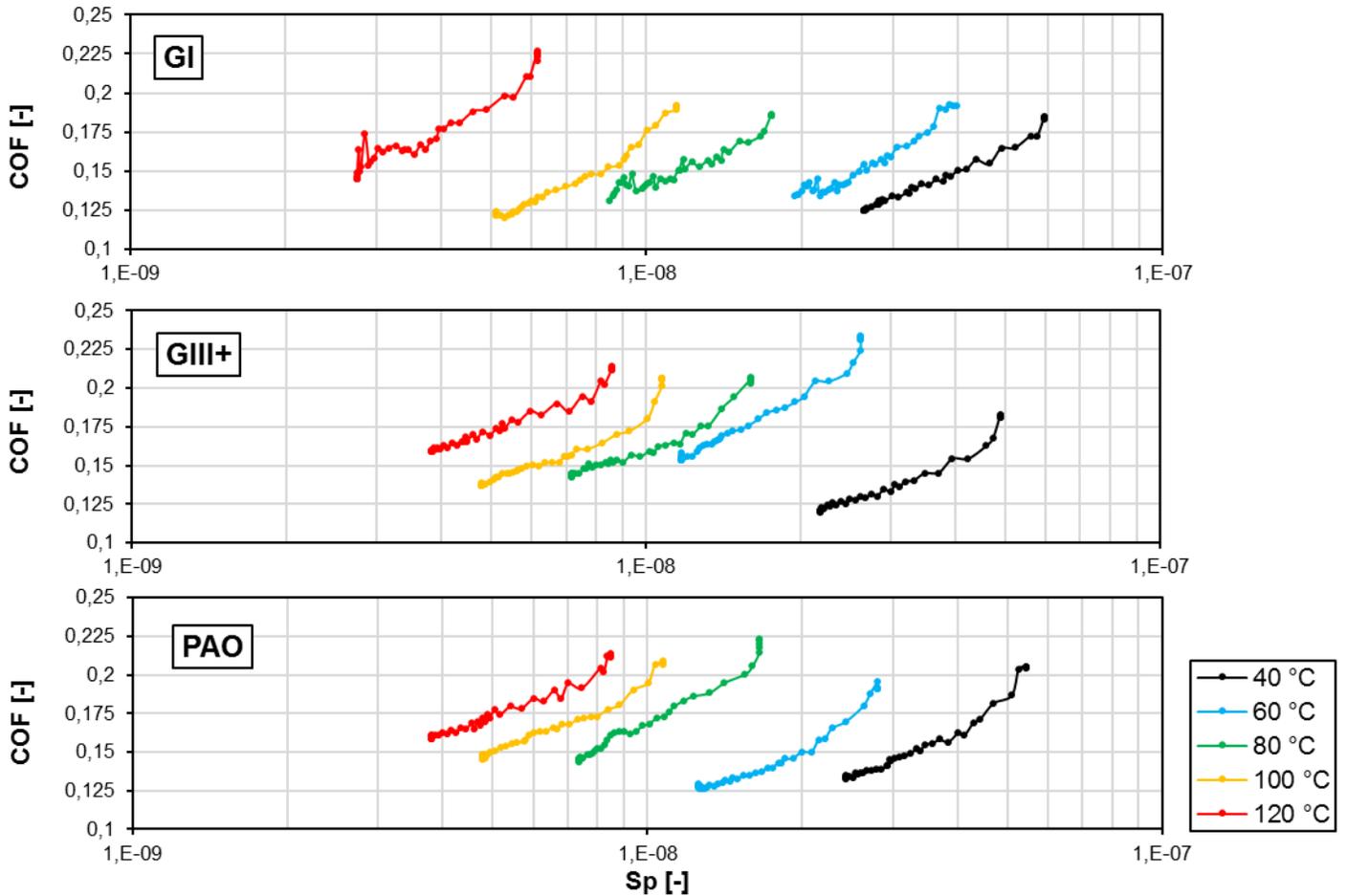


Figure 3. Lubricating regimes: Stribeck curves with modified Stribeck parameter, $Sp = u_b \eta_0 \alpha^{0.5} F_N^{-0.5}$

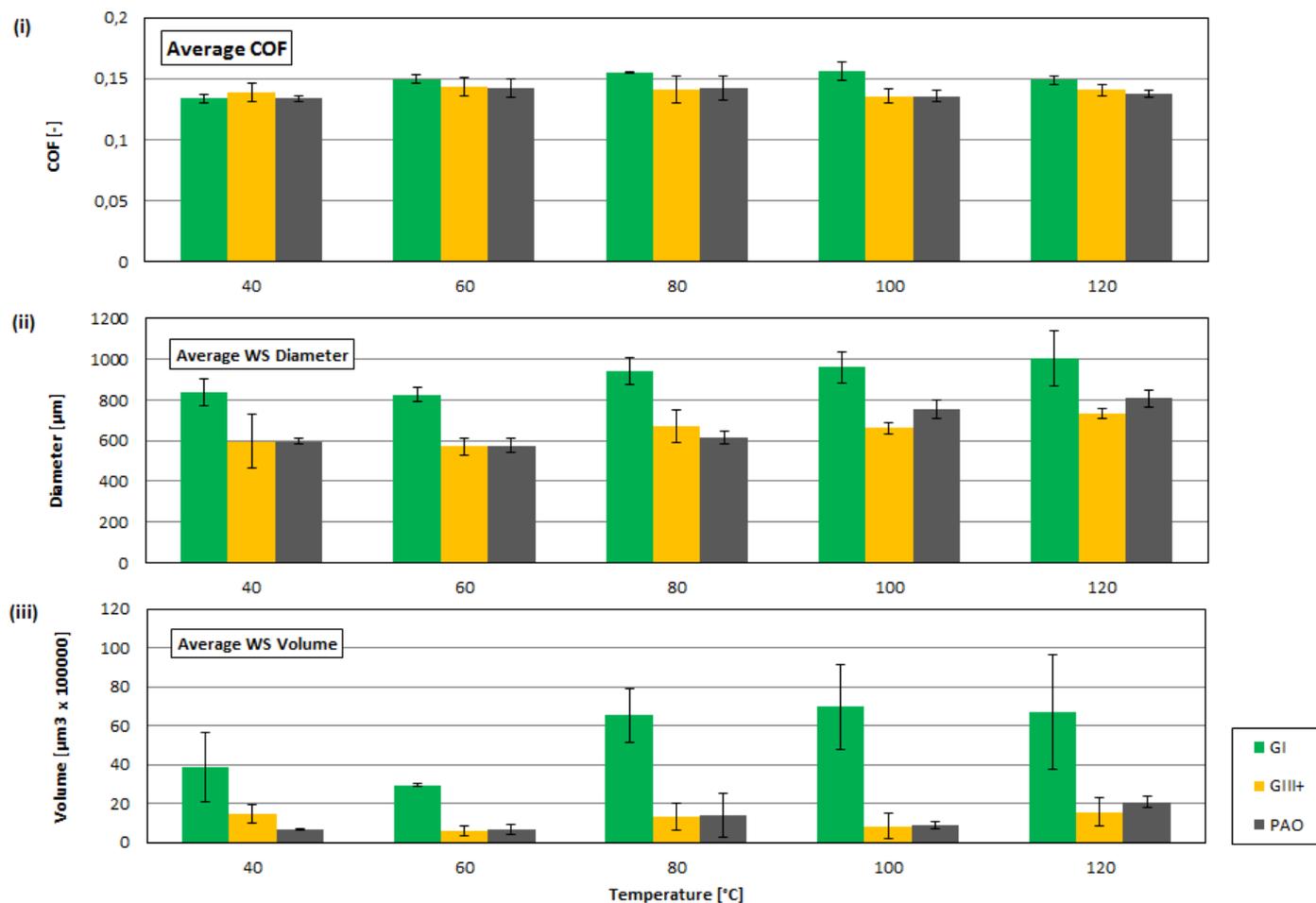


Figure 4. Coefficient of friction and wear characteristics with temperature.

RESULTS

Results demonstrate that the GI base oil has the lowest viscosity index (VI), whereas the GIII+ and PAO show higher and similar viscosity behaviour. This is shown in Figure 1. In Figure 2, the PAO demonstrates the lowest pressure-viscosity coefficient, which is an indication of low intermolecular restrictions under the application of normal stress [6, 7]. This suggests that the PAO's viscosity can be expected to increase the least with an increase in normal pressure. Figure 3 shows that the mixed lubricating regime was the predominant lubricating regime under all experimental conditions [2]. In Figure 4, the friction and wear results demonstrate that in the mixed lubrication regime the viscosity of the base oil plays a major role in forming a thick lubricating film which prevents metal-to-metal contact and ensures low friction, especially at low temperatures [2]. This is demonstrated in Figure 4 (i) by the GI base oil which was found to have the highest viscosity at 40 °C compared to the PAO and GIII+ base oils. The GI base oils gave the lowest average COF at 40 °C compared to the latter. As the temperature was increased, the resulting COF given by the GI base oil increased substantially, compared to that of the PAO and GIII+ base oils. This was found to be a result of the low VI of the GI base oil, which results in significant losses in viscosity with the increase in temperature. This causes substantial thinning and loss in stability of the lubricating film, which allows for more direct collisions of asperities, significant deformation and possible removal of the softer asperities from the metals. This causes substantial wear which can be abrasive and erosive [8]. This phenomenon is demonstrated in Figure 4 (ii) and (iii) by the larger wear scar diameters and wear volumes of the GI base oil, which increase with the increase in temperature. The GIII+ and the PAO base oils demonstrate similar COF behaviour to one another, especially between 60 and 120 °C. Also, the change in the average COF with the increase

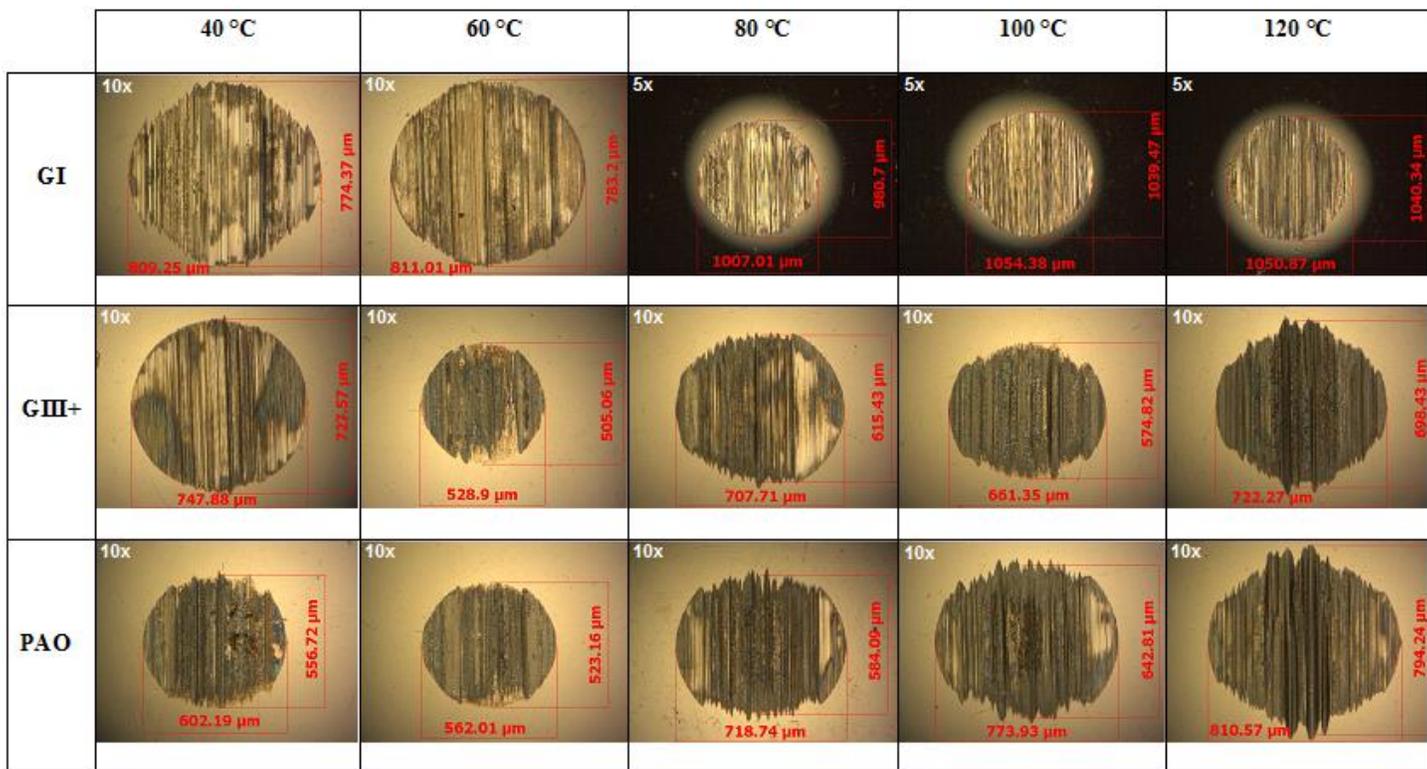


Figure 5. Wear mechanisms with increasing temperature.

in temperature appears minimal. This is subject to the high VI's of these two base oils which comes as a result of their high saturation levels [2]. The increase in temperature caused an increase in wear scar diameters, which is more significant between 100 and 120 °C, and the effect on wear volumes appears complex. Between 100 and 120 °C, the GIII+ resulted in the smallest wear diameters and volumes, with better repeatability in terms of diameter compared to the PAO and the GI base oil. Figure 5 shows the wear scars generated from the friction tests. The GI base oil demonstrated less abrasive sliding wear at high temperatures, whereas the GIII+ and PAO base oils show a gradual increase in abrasive wear with increasing temperature. The increase in temperature catalyzes better the chemisorption with the GI base oil, which minimizes abrasion. Due to the low VI, though adsorption is improved with temperature, the protective film forms is still not thick enough to prevent increased sliding wear as temperature increases [1, 2, 3, 5, 9, 10]. On the contrary, the high VI's of the GIII+ and PAO base oils lead to lubricating films, with significant load transfer between asperities through the lubricant film at high temperatures leading to increased abrasion. However, although these two base oils tend to follow physisorption, the overall sliding wear is lower compared to that of the GI base oil [1, 2, 3, 5, 9, 10].

CONCLUSION

The viscosity index (VI) and pressure-viscosity (α) coefficient are functions of molecular composition. Base oils which the same 100 °C kinematic viscosity but different molecular composition have different VI and α behaviour under increasing temperature [5]. The effect of normal load on viscosity behaviour cannot be ignored when selecting base oils. According to the results, the mixed film lubrication regime was the predominant lubricating regime under all experimental conditions. The GI base oil demonstrated less abrasive sliding wear at high temperatures, whereas the GIII+ and PAO base oils show a gradual increase in abrasive wear with increasing temperature. The GIII+ base oil demonstrated improved temperature stability accompanied by better friction stability and wear performance compared to the latter. Furthermore, the GIII+ base oil follows similar wear mechanisms to the PAO base oil with increasing temperature [1, 2, 3, 5, 9, 10]. The GIII+ base oil is a strong competitor for the PAO base oil in the mixed lubrication regime.

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KEYWORDS

base oil, coefficient of friction, saturation, viscosity, wear

The tribological characteristics of selected base oils under oscillatory sliding conditions

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OUTLINE

- INTRODUCTION
- AIM
- EXPERIMENTAL DETAILS
- RESULTS
- CONCLUSION

INTRODUCTION

- There is always a need for more efficient, environmentally friendly and cost effective base oils [1].
- PAO base oils have superior lubricating properties with a high cost [1, 2, 3].
- Development of Group 3 plus base oils promises high lubricity at a low cost [3,4].

American Petroleum Institute (API) base oil classification [1, 3, 4]

API Group	Sulfur (% w/w)		Saturates (% w/w)	Viscosity Index (VI)
I	> 0,03	and/or	< 90	80 - 120
II	≤ 0,03	and	≥ 90	80 - 120
III	≤ 0,03	and	≥ 90	> 120
III+	≤ 0,03	and	≥ 90	≥ 140
IV	All polyalphaolefins (PAO)		≥ 90	> 135
V	All base oils not included in Groups I-IV			

- The characteristic lubricity behavior of Group 3 plus base oil still stands to be confirmed.

AIMS

- To determine the friction and wear behaviour of the selected base oils.
- To determine the predominant lubricating regime(s) through Stribeck curves.
- Compare the friction and wear behaviour in terms of the coefficient of friction (COF) and wear, as affected by temperature.

EXPERIMENTAL

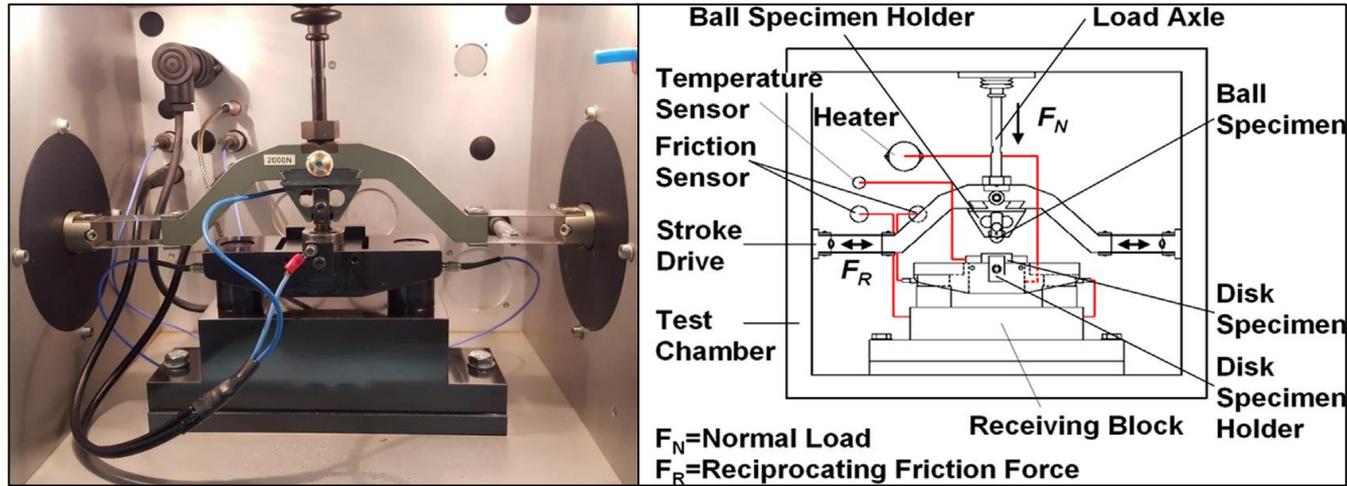
- Base oil properties at atmospheric pressure [2,3,4].

Base Oil	Formulation process	Kinematic Viscosity (η_k) (cSt)		Density (ρ) at 15 °C, (g/cm ³)	Sulfur (% w/w)	Saturates (% w/w)	VI
		40 °C	100 °C				
Group I (GI)	Solvent refined	28.38	5.03	0.86	> 0.03	103	103
Group III+ (GIII+)	Severely hydrocracked	17.74	4.00	0.82	-	125	131
Group IV (PAO)	Oligomerized	18.00	4.10	0.82	□ 0.03	129	125

- Dynamic viscosities - Stabinger SVM 3000/G2 Viscometer, ASTM D7042(11) [5].
- Viscosity Index - ASTM D2270(93) [6].

EXPERIMENTAL

- SRV4 machine - ASTM D6425(11) [7].



- Non-conformal point contact.
- Friction mainly controlled by rheological properties of lubricants such as its limiting shear stress and pressure–viscosity coefficient (α) [1, 3, 8, 9].

EXPERIMENTAL

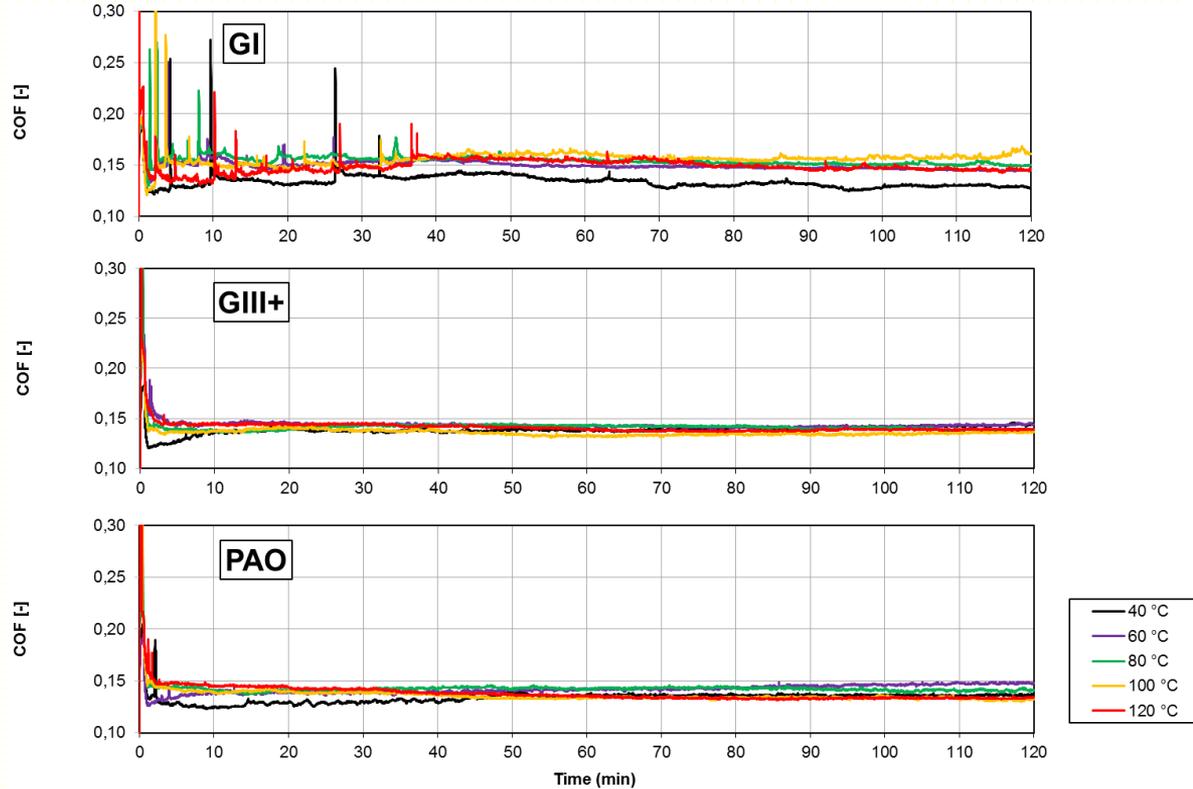
- Experimental conditions and properties of test specimen.

Test conditions		Material properties for ball and disc	
Stribeck curve load	30 – 150 N (gradient: 8 N/s)	Bulk modulus	140 GPa
Test load	150 N	Modulus of elasticity	210 GPa
Stroke length	2 mm	Hardness (Rockwell)	600 HV
Frequency	50 Hz	Shear modulus	80 GPa
Temperatures	40, 60, 80, 100 & 120 °C	Thermal conductivity	46.6 W/mK
Relative Humidity (RH)	20 %		
Properties	Ball	Disc	
Material	AISI E52100 steel	AISI E52100 steel	
Surface finish (R_a)	0.025 +/- 0.005 μm	0.45 to 0.65 μm R_z lapped	
Diameter	10 mm	24 mm (Height: 7.9 mm)	

- Speed: 0.2 m.s⁻¹
- Test duration 120 min

RESULTS

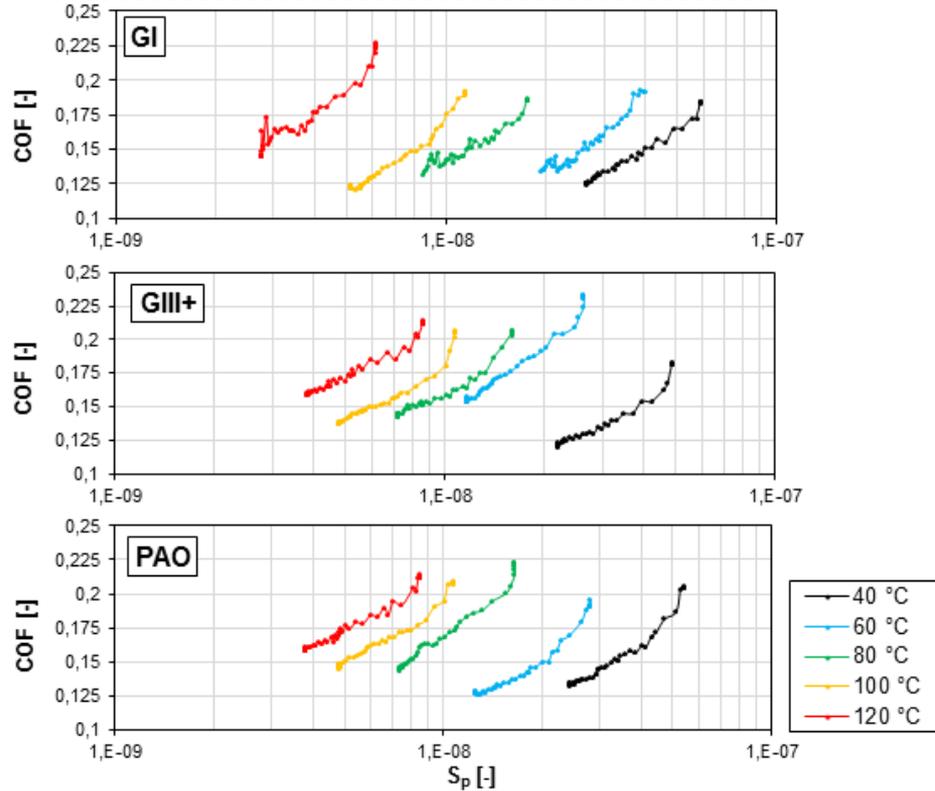
Friction profiles of base oils in terms of the COF with increasing temperature.



The tribological characteristics of selected base oils under oscillatory sliding conditions

RESULTS

Stribeck curves modified for point contacts [1, 3, 8, 9, 10]: $S_p = u_b \Gamma_o \alpha^{0.5} F_N^{-0.5}$



Lubrication regimes:

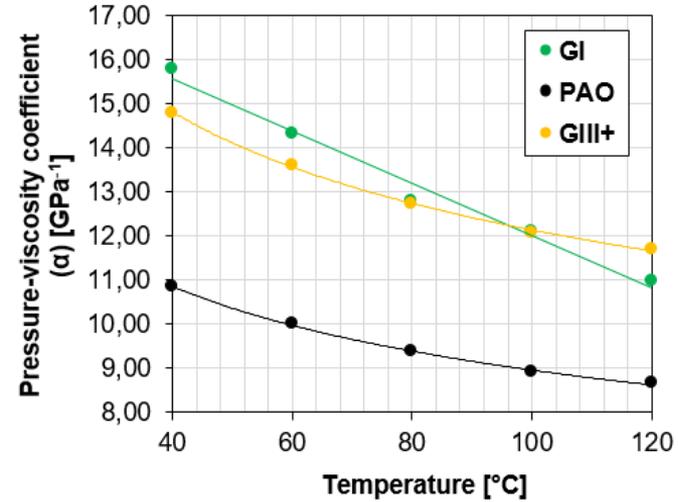
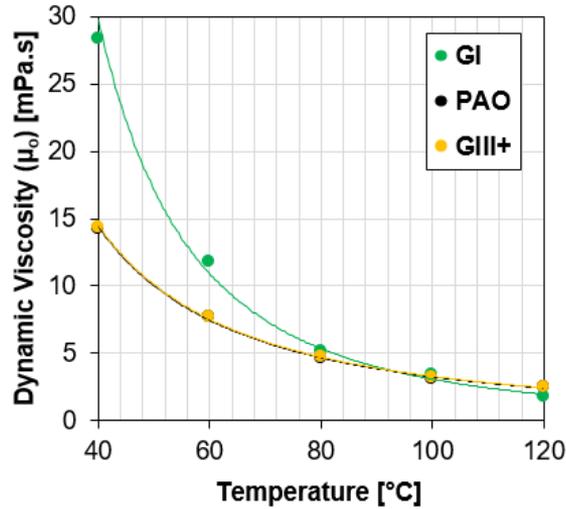
$S_p \geq 1 \times 10^{-7}$: Elastohydrodynamic (EHD) lubrication.

$1 \times 10^{-9} \leq S_p \leq 1 \times 10^{-7}$: Mixed lubrication.

$S_p \leq 1 \times 10^{-9}$: Boundary lubrication.

RESULTS

Viscosity and Pressure-viscosity (α) behaviour with increasing temperature.

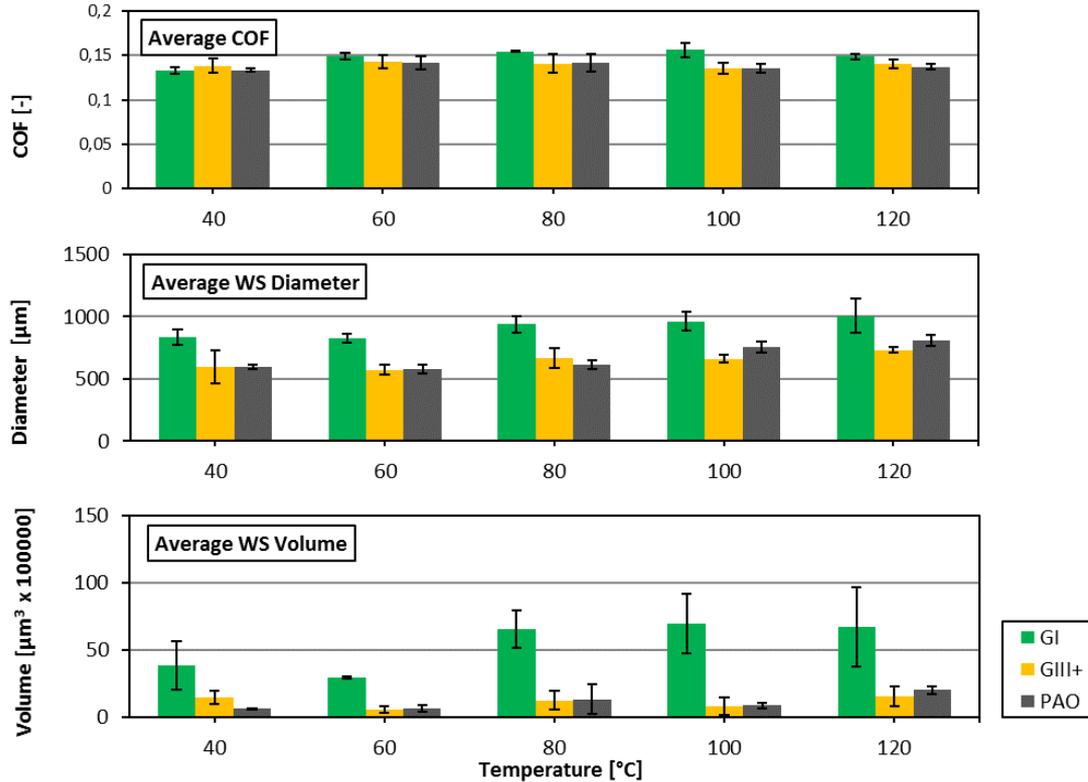


Parameters for the Gold pressure viscosity equation, $\alpha = s\eta_k^t$ [1,3, 8,9,10]

Base oil type	s	t
Paraffinic mineral	0.99	0.14
Polyalphaolefin	0.73	0.13

RESULTS

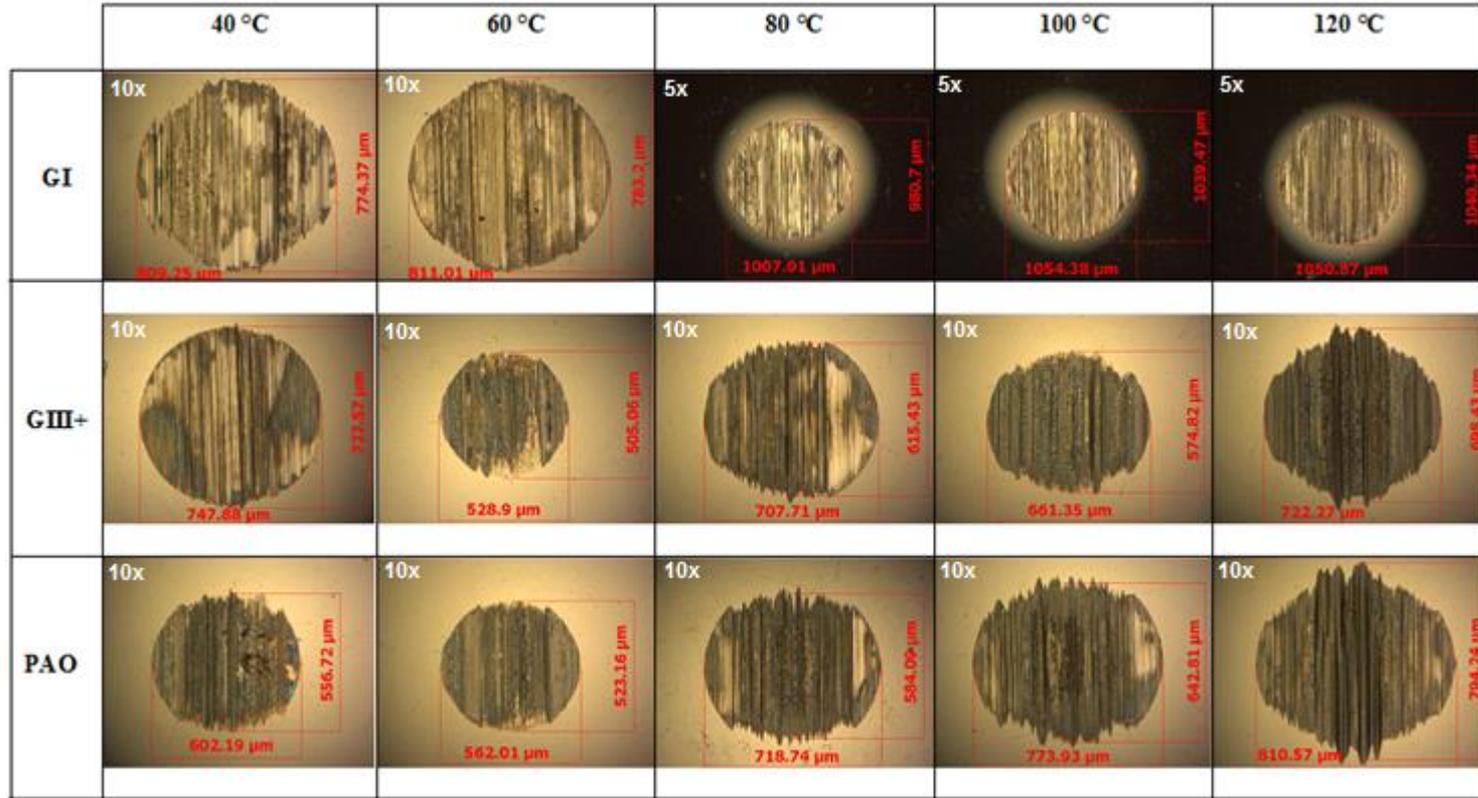
Coefficient of friction and wear characteristics with increasing temperature. Wear Scar (WS) volume: ASTM D7755(11) [11] .



The tribological characteristics of selected base oils under oscillatory sliding conditions

RESULTS

Wear profiles with increasing temperature: GI less abrasion at high temperatures. GIII+ and PAO more abrasion at high temperatures.



The tribological characteristics of selected base oils under oscillatory sliding conditions

CONCLUSION

- The mixed lubrication regime was the predominant operating regime under all experimental conditions.
- The effect of pressure on viscosity behaviour cannot be ignored when selecting base oils.
- Base oils with the same 100 °C kinematic viscosity but different molecular composition will have different VI and α behaviour under increasing temperature.
- The GIII+ base oil demonstrated high friction stability, temperature stability and wear reduction compared to the GI and PAO base oils.
- The GIII+ demonstrates similar wear mechanisms to the PAO base oil with increasing temperature.
- Based on the laboratory results obtained, the GIII+ base oil is a strong competitor to the PAO base oil in the mixed lubrication regime.

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Thank you