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TRIBOLOGICAL BEHAVIOR OF LOW VISCOSITY LUBRICANTS IN FOUR-BALL TESTS

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Abstract. *In the last years, lubricant manufactures have been increasing the development of low viscosity oils due to their effectiveness in reducing energy consumption. This effect is clearly related to the friction coefficient of the tribosystem in hydrodynamic condition. However, the oil viscosity is an important parameter to increase the lubricant film thickness which is essential to protect the surfaces against the wear. In addition, special additives are added to low viscosity lubricants in order to prevent very high friction in boundary regime, and finally to protect the surfaces against wear. Tests performed in four-ball tribometer have shown that, at some conditions, the measured friction coefficient with higher viscosity lubricants was smaller than the values obtained with lower viscosity lubricants. Thus, the tribological behavior under EHD conditions should be better understood to support a correct choice of low viscosity lubricants.*

Keywords: *Low Viscosity Lubricants, Extreme Pressure Additives, Antiwear Additives, Boundary Lubrication, Mixed Lubrication*

1. INTRODUCTION

The reduction of friction losses is necessary in order to optimize the energy consumption in machines and equipments. The friction coefficient in hydrodynamic lubrication is quite sensitive to lubricant viscosities, thus it is common to try to develop lubricants with lower viscosities to achieve lower friction losses. Low viscosity oils can reduce the energy consumption by reducing the oil film thickness and, simultaneously, due to other related losses, such drag losses. It shall be considered that low viscosities lubricants present kinematic viscosities under 100 cSt, at 40ºC. However, during the lubrication, the surfaces must be protected against the wear. According to Tomanik *et al.* (2010), low viscosity lubricants are typically applied for automotive application since they exhibit low coefficient of friction in the hydrodynamic regime. Such application requires the use of special additives to reduce friction under boundary lubrication.

In boundary condition, the oil film cannot support the load. The solid roughnesses have to share the supported load with fluid film. The solid contact involves wear, increase of friction and the kneading of the roughnesses. In order to reduce the friction, the wear and the damage of the metal surface, it was developed tribological additives such as friction modifiers (FM), antiwear additive (AW) and extreme pressure additive (EP).

According to Papay (1983), friction modifiers work as a thin coat of adsorbed molecules that is the major component that keeps the two surfaces and their roughnesses from plowing into each other. It consists of orderly, closely packed arrays multimolecular, loosely adhering to each other and with the polar of the lowest ones on the totem pole anchored on the metal surface. The outer layers of that film can be shared off easily, allowing a low coefficient of friction.

The antiwear (AW) and extreme pressure (EP) additives are among the type of compounds that provide good boundary lubrication too. Antiwear and extreme pressure performance does not work by lowering friction, but by protecting the mating metal surface from roughnesses physically gouging the opposite surface. Unlike the previous one, they are semiplastic deposits which are hard to shear off. Thus, under shearing conditions, their coefficient of friction is generally moderate to high (Papay, 1983).

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Morina *et al.* (2005) analyzed the influence of zinc dialkyldithiophosphate (ZDDP) and molybdenum dialkyldithiocarbamate (MoDTC) additives in synthetic base oil (PAO6) and Muraki *et al*. (1997) analyzed the comportment of these same additives in paraffinic mineral base oil. The both tests were performed in boundary lubrication. According to them, for the two types of base oils, ZDDP forms a tribofilm that has the ability to improve antiwear properties. At the same time, it helps the formation of MoS_2 through adsorption and decomposition of MoDTC which resulted in a decrease in friction; it means that MoDTC acts as a friction modifier.

Thus the tribological behaviors of the low viscosity lubricants under different conditions were investigated to improve the understanding about the lubrication ability of the formulations. Friction coefficients and scars of wear were measured by different sliding speeds, normal loads and oil bath temperatures in a four-ball tribometer to compare the behavior of two lubricants formulations, using mineral and synthetic base stocks. Both formulations have the same additive package. The results show that the synergy between the oil basis and the additive package can be more important than the viscosity to determine the tribological behavior of the lubricants.

Rico *et al.* (2009) compared the efficiency of mineral and synthetic oil, with and without PTFE additive, using a four-ball tester. PTFE exhibits a low coefficient of friction and a low wear rate. The two oils had the same viscosity. In their results it was found that the additive effectiveness is higher in the synthetic oil than in the mineral oil because its mechanical protection is greater, even though the film thickness is smaller in the synthetic oil case.

2. LUBRICANT FORMULATIONS

The oil formulations used in this investigation are shown in the Tab. 1.

Table 1. Lubricant formulations

Lubricant	Basis	Formulation	Additive Package
A1	Synthetic	PAO-4 + Ester	Viscosity Index Improver
A5	Mineral	Solvent Light Neutral +	Friction Modifier
		Solvent Medium Neutral	Anti-wear
			Extreme Pressure

These samples were formulated to achieve similar kinematic viscosities at 100ºC, closed to 12 cSt, and the viscosities results at 40ºC and 100ºC and the viscosity index are shown in the Tab. 2. These formulations were chosen to compare the tribological behavior between a mineral lubricant and a synthetic lubricant with the same additive packages.

Table 2. Viscosities of the lubricant formulations

Sample	Kin. Visc. at 40°C [mm^2/s]	Kin. Visc. at 100ºC [mm^2/s]	Visc. Index
A1	60.34	11.90	198
A5	88.92	12.17	131

3. FOUR-BALL TRIBOMETER AND THE FRICTION COEFFICIENT TESTS

The friction coefficient tests were conducted in a four-ball tribometer Plint TE92, which enables to apply normal loads until 1000 N, with rotation speeds between 60 rpm and 3000 rpm. In a four-ball test, a rotating ball is pressed against three fixed balls in a lubricant bath, as illustrated in Fig. 1. After the tests, each fixed ball has a circular scar. In order to achieve all the lubrication regimes, the tests were designed with four different normal loads. By a normal load, the rotation speed was increased between 60 rpm (0.02 m/s, sliding speed) and 2570 rpm (1.0 m/s sliding speed). Each rotation speed was maintained for 10 minutes, and, because at that time, the value of the coefficient of friction was stabilized at a relatively constant value, which was taken as the friction coefficient of the combination lubricant-normal load, sliding speed and temperature. This procedure has shown good repeatability. The oil bath temperature was controlled and the temperatures of 40ºC and 100ºC were chosen to reproduce the same temperatures of the viscosity measurements. In the Tab. 3, it can be observed the sliding speeds and Hertz pressure of each normal load.

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Table 3: Friction coefficient tests conditions

Temperatures [ºC]								
40					100			
Normal Loads [N] (Hertz Pressure [GPa])								
98 (2.17)		196 (2.73)		392 (3.45)		588 (3.94)		
Sliding speeds [m/s]								
0.02	0.05	0.10	0.20	0.30	0.40	0.60	0.80	1.0

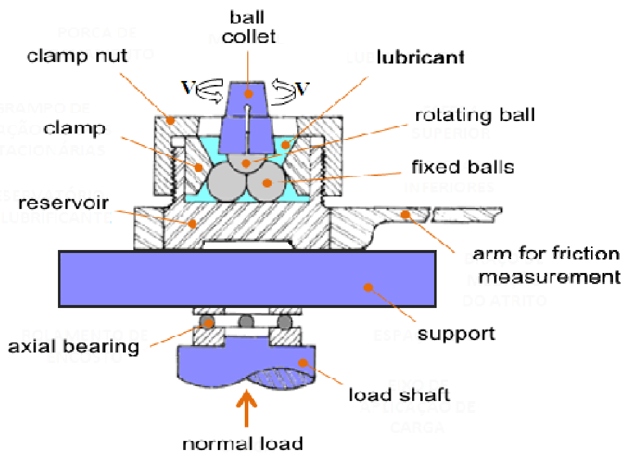
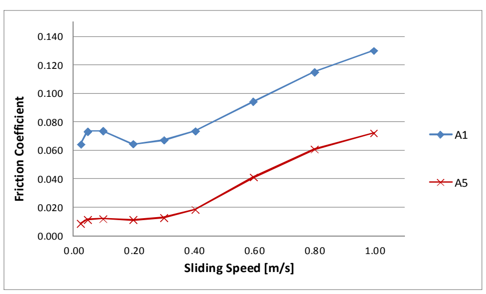


Figure 1. Four-ball test (ASTM International D-4172-94, 2004)

The friction coefficient behaviors at oil bath temperature of 40ºC with the sliding speeds are shown in the Fig. 2.



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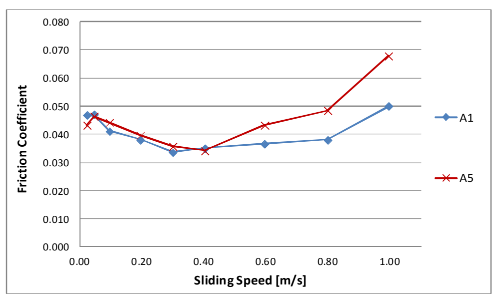

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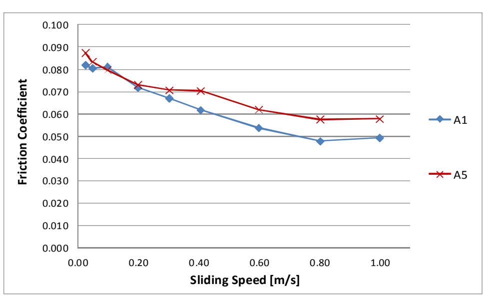

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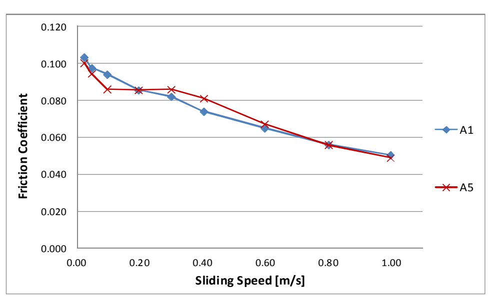

(d)

Figure 2. Friction coefficient behavior at 40ºC. Loads: a) 98 N, b) 196 N, c) 392 N, d) 588 N

The friction coefficient behaviors at oil bath temperature of 100ºC with the sliding speeds are shown in the Fig. 3.

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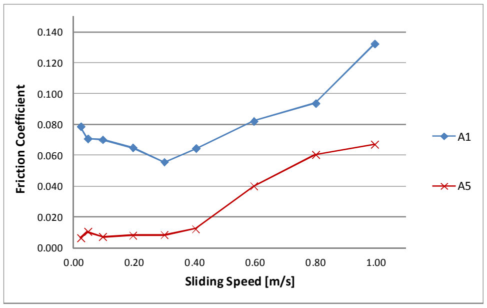

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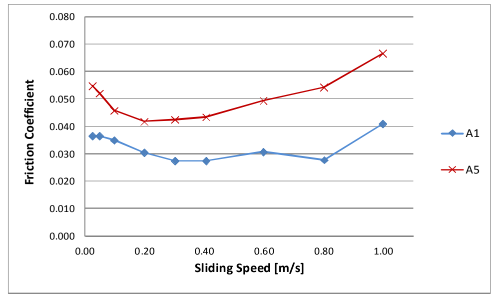

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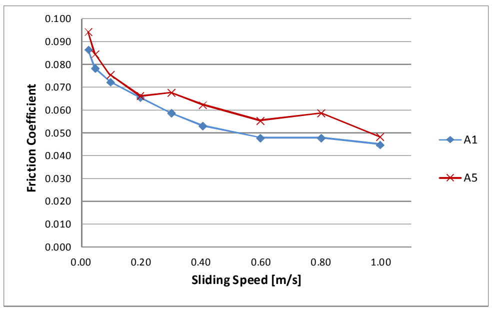

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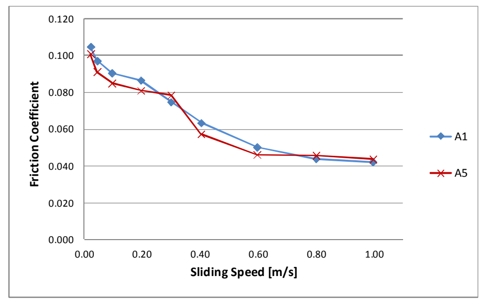

(d)

Figure 3. Friction coefficient behavior at 100ºC. Loads: a) 98 N, b) 196 N, c) 392 N, d) 588 N

It can be observed that the friction behavior coefficient is quite similar in both oil bath temperatures. It is important to highlight that the friction coefficient grows as the sliding speed increases at normal load (98 N), but decreases at higher normal loads (392 N and 588 N). These results show that the tribological response of the lubricant formulations is different with the contact pressure. Under the lower contact pressure, the more viscous lubricant shows lower friction coefficients, but under higher normal loads, the less viscous formulation had quite similar or lower values of friction coefficient than the more viscous. Thus, it can be stated that the formulations with lower viscosities can show higher friction coefficients. The Hertz pressure appears as an important parameter to determine the tribological behavior of the lubricant, if the contact pressure is low, the additive package, especially the EP, plays a less important role. In these conditions, the higher viscosity improves the film thickness and avoids the metal-metal contact. Under higher contact pressures, the role of the synergy between the additive package and the lubricant basis becomes more important. In spite of the higher viscosity, the combination between the synthetic basis and additives shows more effectiveness than the mineral basis in the reduction of friction coefficients.

4. THE WEAR TESTS

In order to complement the understanding about the tribological behavior of the formulations, wear tests were conducted in the four-ball tribometer with two different sliding speeds with both lubricants. The tests conditions are shown in the Tab. 4:

Table 4. Wear tests conditions

Test	Sliding speed [m/s]	Duration [s]	Load [N]	Temperature [ºC]
1	0.2	9600	588	40
2	0.8	2400		

It was chosen the higher normal load to perform the wear test, because it was interesting to investigate the lubricant behavior under high contact pressures. The machine components, for example the transmission gears, are required to transmit more power with the same geometric dimensions, resulting in an increase of the contact pressures in operation. This brings the need for better component materials and lubricants, with the capability to protect the surfaces. Therefore, the objective of the wear tests was to investigate the ability of the lubricants to protect the surfaces against the wear under high contact pressures. The ASTM D-4172-94 (2004) establishes a wear test with sliding speed of 0.47m/s during 3600 s with normal load of 392 N. Thus, the proposed tests durations have a distance of wear of 1920 m, lightly higher than the established by the standard. These sliding speeds were chosen to investigate the tribological

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behavior with two different film thicknesses. Do Carmo (2012) has calculated the film thicknesses in the proposed test conditions with the Eq. (1) based on Cheng (1983).

$$h_{min} = R' U^{0.68} G^{0.49} W^{0.073} \left(1 - e^{-0.68k}\right) \tag{1}$$

Where h_{min} is the minimum film thickness, R' the equivalent radius, U the velocity parameter, G the material parameter, W the load parameter and k the elliptical parameter. In order to evaluate the tribological conditions, it will be used the lambda parameter (Kuo, *et al.*, 1996) with Eq. (2).

$$= \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}} \tag{2}$$

Where R_{q1} and R_{q2} are the roughnesses of the surfaces. The balls have R_q = 0,015 µm. The results are shown in the Tab. 5.

Table 5. Predicted minimum film thickness

Oil	**Sliding speed [m/s]**	**h_{min} [µm]**	**λ[adim]**
A1	0.2	0.0192	0.90
	0.8	0.0445	2.10
A5	0.2	0.0270	1.27
	0.8	0.0529	2.49

According to Kuo *et al.* (1996), when λ<1, there is boundary lubrication and when 1<λ<3, there is mixed lubrication. Thus, the wear tests will verify the behavior of the lubricant under severe conditions.

After the tests in the tribometer, the scar diameters were measured in all the fixed balls, in optical microscopic with *x-y* table, whose movement is performed by two micrometers with resolution of 0.01 mm. Each scar diameter was measured in two orthogonal directions. The scar diameter, presented in the Tab. 6 is the mean value of the measured scar diameters. Furthermore, the scar profiles are measured with the profilemeter Taylor Hobson, Talysurf 50, as it is shown in Fig. 4. The results are shown in the Tab. 6.

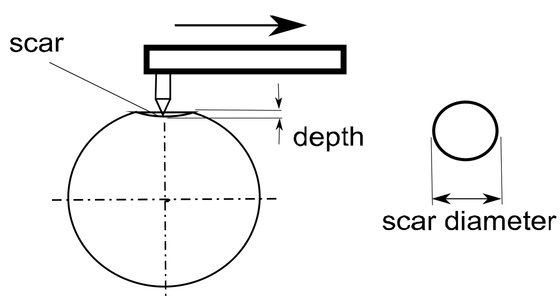

Figure 4. Scar depth measuring in a fixed ball with a profilemeter

Table 6. Geometric wear results

Oil	**Sliding speed [m/s]**	**Scar diameter [mm]**	**Wear depth[µm]**
A1	0.2	0.45	1.82
	0.8	0.39	0.75
A5	0.2	0.43	3.50
	0.8	0.69	13.12

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The results are very interesting and show that the synergy between the oil basis and the additive package is very important to obtain good tribological results. It is visible that the wear protection of the synthetic basis was better than the mineral, despite the smaller viscosity. Since the additive package is the same, this result is probably an effect of the protection provided by the ester, due to its high polarity. Under mixed lubrication the synthetic basis, A1 has presented a very low wear, but the mineral, A5 had a high wear, even with a prediction of a thicker lubrication film. It is possible that the mineral basis could not support the high shear rate under higher sliding speeds. The same results found by Rico *et al.* (2009).

5. CONCLUSION

The combination between friction and wear tests can be a good tool to support the developing of new lubricants. The comparison between two low viscosity lubricants, one with a synthetic basis and the other with a mineral basis and both with the same additive package, has confirmed that there is a synergy between the basis and the additive package. The low viscosity lubricants are developed to reduce friction coefficients, however the friction coefficient tests showed that under lower contact pressures the more viscous formulation had lower friction coefficients. It seems that under lower Hertz pressure, a thicker lubricant film can reduce the friction. Under higher contact pressures the synergy between the additive package and the lubricant basis was more important. The friction coefficients of the synthetic basis were lower or similar to the mineral basis. Furthermore, the wear tests under high contact pressures showed that the synthetic basis has protected the surfaces better than the mineral, despite the lower viscosity.

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