TRIBOLOGICAL PERFORMANCE OF GELLED OILS FOR SPACE MECHANISMS LUBRICATION

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ABSTRACT

Bearing lubrication is an important point in various fields, particularly in space applications where the lubricants must maintain their performance in very low temperatures and under high vacuum.
Grease based on PTFE/MoS2 fillers are currently used. However, these greases exhibit frictional torque peaks in bearings at low speeds [1] due to the composition and structure of the grease [1, 2]. A good alternative is to use grease-like products such as gelled oils with higher viscosity than the oil alone [3].
The rheological and tribological tests performed on two new gelled oils formulated showed performance equivalent or even superior to the reference grease. The new lubricants performance (friction torque, noise and endurance life) are also evaluated with an innovative test bench which directly assess gelled oils in bearings in high vacuum environment.

1 INTRODUCTION

All classical space greases (Braycote, Maplub SH101-c, Lubcon, etc…) are actually PTFE/MoS_2 suspensions in oils and then, they may generate high torque peaks when used in ball bearings at low rotation speeds [1][2]. This phenomenon is due to the grease composition and structure: at low rotation speed, PTFE/MoS_2 particles accumulation at the contact entrance generates sudden increases of torque when these clusters enter into the contact [2] [3].
Such torque peaks could be easily avoided by using pure oils but with the risk to face the loss of the lubricant from the contact due to creeping, especially during storage under gravity. Location of the lubricant near the contact is needed to insure its correct feeding. Thus, as greases are really necessary to insure lubrication of space mechanisms, CNES and POLYMER EXPERT companies, developed new processes to thicken oils and to propose new grease-like products but which are not PTFE/MoS_2 suspension in oil. Theoretically, due to their specific gelled structure without solid particles, these new products will not have the problem of today's ones.
Investigation was done with the two main space oils used in most of space mechanisms: Fomblin Z25 oil (PerFluoroPolyEther Oil - PFPE) and NYE 2001A oil (Multi Alkylated Cyclopentane oil - MAC)
Unfortunately, gellification of PFPE Fomblin Z25 oil was not achieved because of its poor/low miscibility with other products even with solvents.
On the other hand, several NYE 2001A oil based gelled products was successfully developed. Among them, two gelled oils seem to be really interesting for a space use [3] and are still being characterized.

2 EXPERIMENTAL CONDITIONS

2.1 Lubricants materials tested

These two gels of polyolefine-based polyurethane of medium molecular weight (PU1-10) and high molecular weight (PU2-12) in NYE2001A oil were characterized and their properties (rheology, outgassing, lubrication capability in ball bearings, etc…) were compared to similar greases used in space mechanisms [3][4].
Today, this characterization campaign is being finalized by performing tribological tests on samples and long duration tests on ball bearings. 4 lubricants were tested: the two new gelled oils, a classical grease (Maplub SH101-c) and their base oil (NYE2001A) which can be considered as reference lubricants.

Table 1. Viscosities of gels obtained with PU1 and PU2 in NYE2001A oil

PU Concentration in NYE2001A (%)	Visual aspect	Viscosity at $10s^{-1}$ (Pa.s)	Viscosity at $100s^{-1}$ (Pa.s)
Pure oil	Transparent liquid	0.20	0.20
PU1-10	White and opaque gel	42.84	4.93
PU2-12	White and opaque gel	20.57	3.28
Maplub SH101-c [4]	Black Grease	37	7.9

2.2 Tribometer Scale test

To better understand the behaviour of the gelled oils at the contact scale, tribometer scale tests have been carried out at FEMTO-ST. Pin-on-disc based tests have been performed in two contact configurations (pure sliding and rolling with 10% sliding) and in two kinematics (continuous rotation and alternative motion over a portion of the disc). Contact conditions are summarized in Tab. 2.

Prior friction, all discs and balls are cleaned following a cleaning procedure defined with CNES, and then wrapped in clean wipes. All cleaned samples are stored in clean boxes. Tested samples are stored in individual clean boxes after friction.

Table 2. Tribometer scale test_Contact condition

Lubricants	PU1-10% PU2-12% Maplub SH101-c			
Deposited thickness	100 µm thick layer			
Samples	Ball: ASI 440C, Ø5 mm Disc: ASI 440C, Ra > 0.1 µm			
Contact pressure	1 GPa			
Vacuum	4.10^{-7} mbar			
Kinematics	Continuous rotation Alternative motion			
Configuration	Pure sliding		Rolling + 10% sliding	
Sliding speed (mm/s)	10	225	10	125
Nb Cycles	100	1000	100	1000

After friction, the topography of the friction tracks of the disc are analysed with Alicona Infinite Focus microscope. 3D reconstructions of the friction tracks are hence performed to compare the wear of the stainless-steel disc after friction. All samples are cleaned prior analysis through gentle cleaning using clean room grade wipes and isopropyl alcohol. Samples are mostly lightly damaged and presenting only smoothened surfaces (cf. results section). Consequently, only samples from the most damaging configuration are analysed with SEM and EDX to determine which wear mechanism would prevail depending on the testing lubricants.

2.3 High Vacuum Bearing Tests

2.3.1 High Vacuum Bearing test Bench

A new bearing test bench have been designed at InS in order to assess gelled oils behaviour in various test conditions and long-run time. One of the main interests of this new test bench is to allow for testing four bearings at the same time and directly compare torque evolution (Fig. 1). The main drive has been purposely over-sized to achieve high torques in comparison with expected torque measurements. Each driven shaft enables the rotation of a bearing inner race. Each outer race is coupled with his own strain gauge reaction torque sensor (Fig. 2).

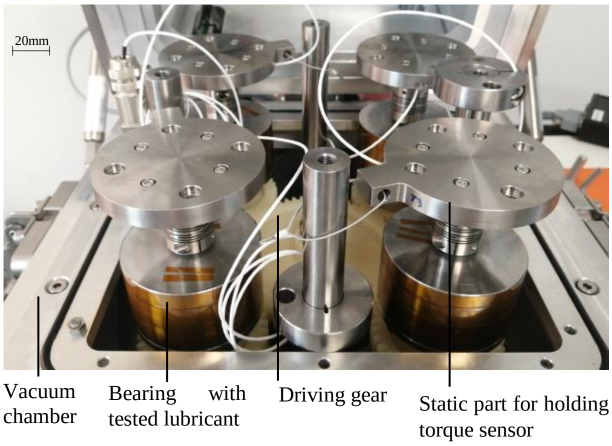


Figure 1. InS four bearings vacuum test bench

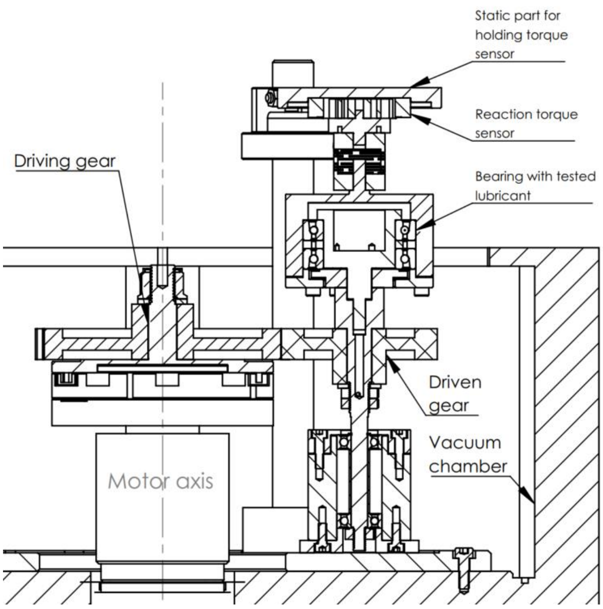


Figure 2. Cross section view of one test axis.

2.3.2 Materials and contact parameters

The 4 bearings are lubricated with lubricants presented in Tab. 1. Tab.3 deals with bearing characteristics.

Table 3. Bearing characteristics

Inner diameter	35mm
Outer diameter	55mm
Geometry	Pair of angular contact ball bearings
Angular contact	15°
Number of balls	2 x 26
Ball diameter	3.969mm
Preload	100±10N
Theoretical Hertz contact pressure	1.1GPa

The tests have been performed following various steps, including "Low Speed Torque Evaluation" (LSTE), run-in, endurance and Stribeck test. LSTE test consists in 1 minute in Clock Wise (CW) direction, at 2rpm, and 1 minute in Counter Clock Wise (CCW) direction at the same speed. LSTE conditions are chosen in order to assess peak torque occurrences and evolutions between longer steps. Tab.4 summarizes test conditions in a chronological order.

Table 4. Bearing test conditions

Step	**1**	**2 - Run-in-A**	**3 - Run-in-B**	**4**
Environment	Air ; Ambient temperature			
Spindle speed (rpm)	LSTE	10	10	LSTE
Direction		CW	CCW	
Time (h)		24	24	
Step	**5-Endurance**	**6**	**7 – Stribeck -A**	**8 – Stribeck -B**
Environment	Vacuum 4.10^{-6} mbar ; Ambient temperature			
Spindle speed (rpm)	50	LSTE	0,1 - 50	0,1 – 50
Direction	CW		CCW	CW
Time (h)	333			

3 RESULTS AND DISCUSSION

3.1 Tribometer Scale Test Results

Friction coefficient from the pure sliding test configuration, in continuous motion, allowed to discriminate the gelled oil from the Maplub SH101-c grease (Fig. 3). Both are indeed demonstrating steady state friction coefficient (0.03-004) that is twice lower than the friction coefficient obtained with the Maplub SH101-c grease (0.07). Interestingly, the PU1-10% reaches steady state friction within 10s to 20s (30 to 60 cycles) of friction at both low and high sliding speed. PU2-12%, although it exhibits the same trends than PU1-10% at low sliding speed, it requires close to 250s (750 cycles) to reach steady state friction. PU2-12% having a texture similar to a "marmalade", rather than a "jelly" like PU1-10%, it might suffer from lower capabilities to return to a fluid, which may explain the lower performances here.
In reciprocating motion, at low speed, the twofold friction difference is observed for both gelled oils versus the grease. At high speed, friction appears similar for all three lubricants.

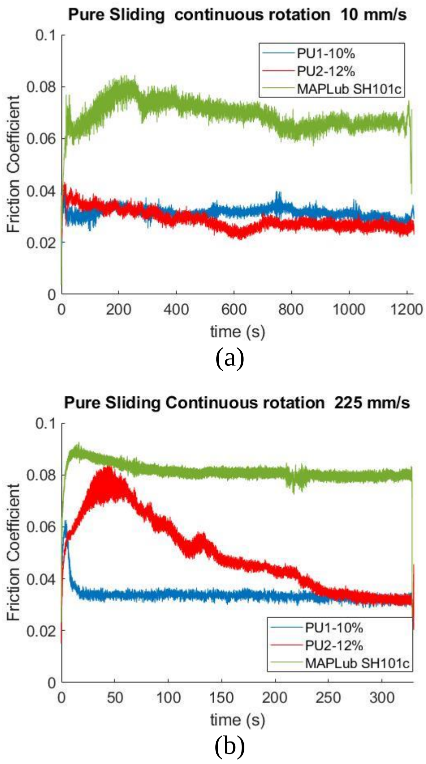
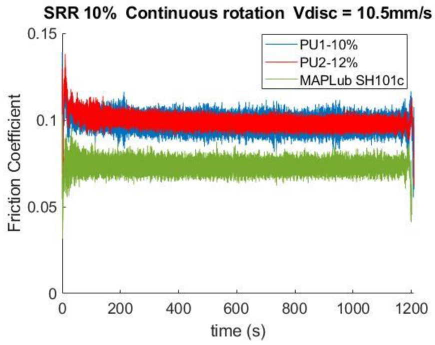
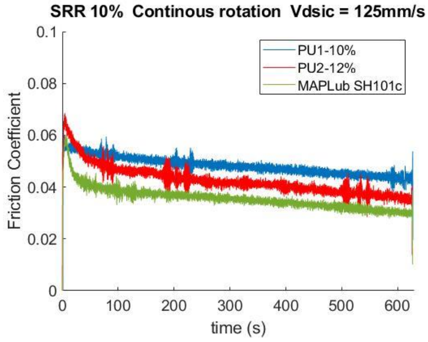


Figure 3. Friction coefficient from continuous rotation pure sliding tests at low (a) and high (b) sliding speeds

Surprisingly, in rolling with 10% sliding configuration, continuous rotation, the grease is demonstrating the lowest friction coefficient (Fig. 4). At low sliding speed, it remains at 0.07, similar to pure sliding case. It rises to 0.1 for the gelled oils, which is almost 3 times the friction coefficient obtained in pure sliding. At high speed, friction is low: twice lower than in pure sliding for the grease (0.04) and slightly higher for the gelled oils (0.4 to 0.05). In oscillating configuration, friction coefficient alone does not allow for discriminating oils from the grease.



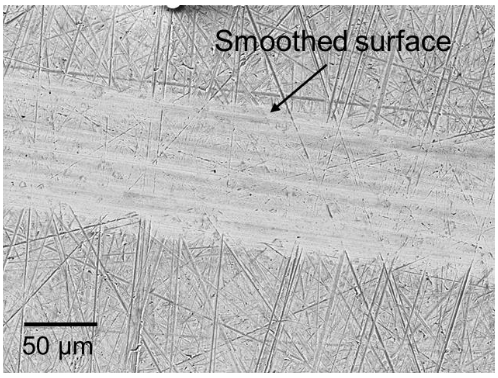
(a)



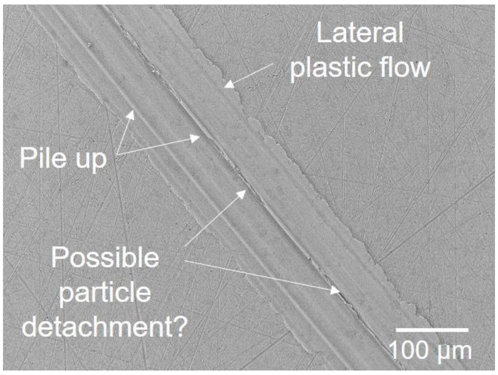
(b)

Figure 4. Friction coefficient from continuous rotation, rolling with 10% sliding, tests at low (a) and high (b) sliding speeds

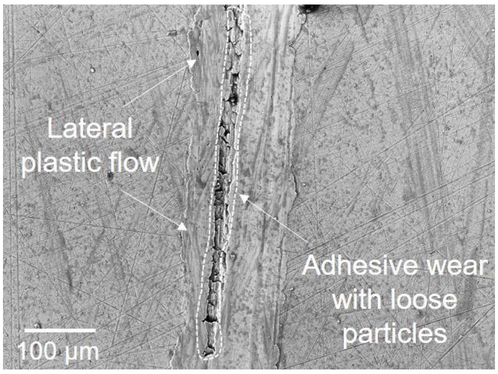
Surface topography allows for discriminating gelled oils from the grease, in all contact configurations. The lowest damage is observed for PU1-10% lubricated contacts, then comes PU2-12% and grease. In pure sliding configuration PU2-12% lubricated contacts exhibit lower damages than grease lubricated contacts (Fig. 5), while they are equivalent in rolling with sliding configurations. Note that in the latter case, and in the worst case of rolling+sliding configuration (oscillating, high speed), surfaces are barely damaged and only exhibit smoothed surfaces. In the PU1-10% lubricated contact, valleys of the surface roughness are still visible.



(a) PU1-10%



(b) PU2-12%



(c) Maplub SH101-c

Figure 5. SEM images of the friction track on the disc, after friction test in pure sliding configuration, at high speed, in oscillating motion

In the pure sliding configuration, surface damages are more pronounced. Fig. 5 displays SEM images of the friction track from the worst contact configuration (oscillating, high speed). Surface ploughing, and plastic flow with minimum particle detachments, are visible in the PU2-12% lubricated case. In the grease lubricated contact, ploughing and grooves resulting from adhesive wear are visible.

3.2 High Vacuum Bearing Tests Results

3.2.1 Low speed results

Torque measurements during the first LSTE test shows differences between the 3 lubricant technologies (Fig. 6). Gelled oils torque is slightly higher than those of oil and much lower than those of grease. The difference between gelled oils and oil is probably due to the higher viscosity of the gelled oils. However, except on start-up of the test, the grease does not exhibit significant peaks of torque, as shown in [1].

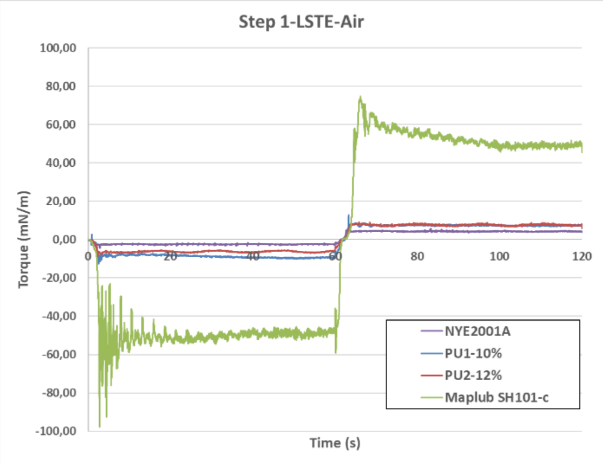


Figure 6. Step 1

Nevertheless, after the 2nd and the 3rd step (run-in), grease torque shows much more fluctuation (Fig. 7). Those differences for the grease between steps 1 and 4 are due to PTFE/MoS2 particles location and the formation of clusters, as explained in the introduction and in [1]. Indeed, step 1 have been performed on a homogenous grease without historical rolling and particles displacement. At the opposite, successive runs-in (steps 2 and 3) may generate particles accumulation at the contact entrance. At low speed, those particles seem to inhibit pure rolling motion and speed accommodation and generate “stick-slip” effect.

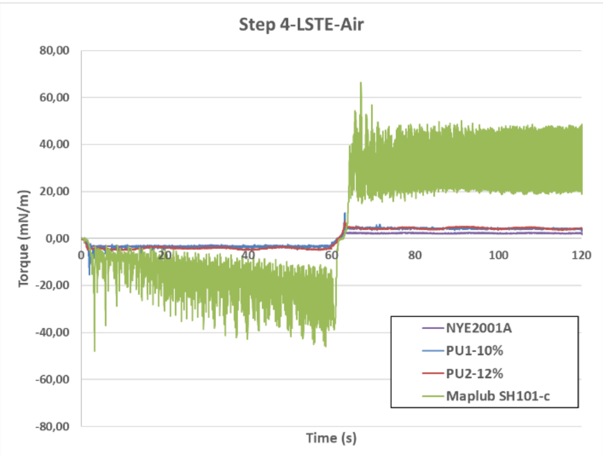


Figure 7. Step 4

A third LSTE test is made after step 5 (endurance), still showing torque peaks for the grease, but with some differences (Fig. 8). A first difference is the mean torque value of the grease, which has decreased significantly. Moreover, torque peaks are more noticeable. A peak frequency of 0.375Hz is found, which exactly corresponds to the 2nd harmonic of rotating frequency of the balls. Thus, peak torque occurs for each ball pass inner and outer ring. Fig. 9 summarizes the 3 LSTE tests. It is interesting to observe that after endurance test (10^6 cycles), mean torques of oil and gelled ones remain very low and close, demonstrating first data about gelled-oil excellent stability whatever the environment is. Even if grease torque decreases, peak magnitude remains very high.

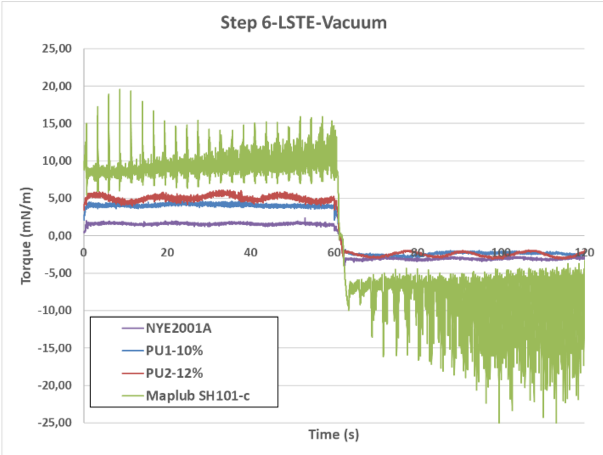


Figure 8. Step 4

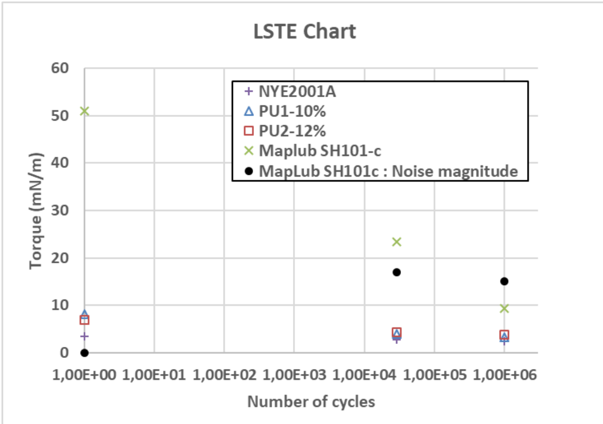
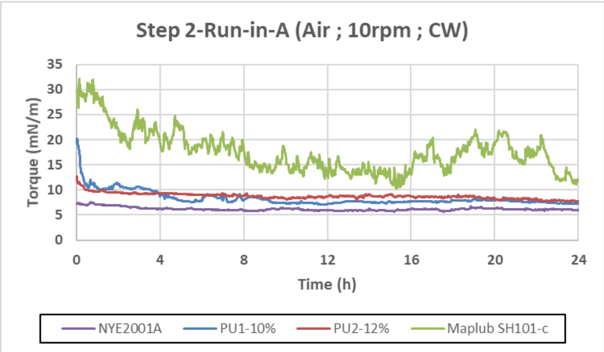


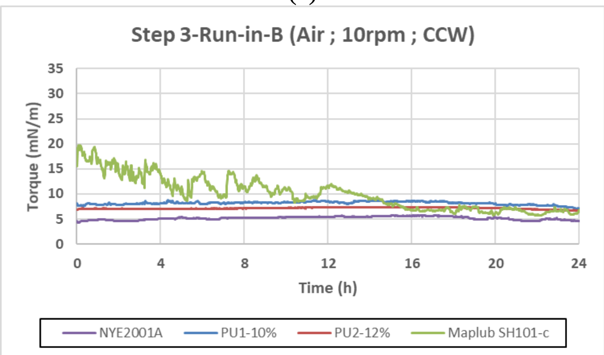
Figure 9. LSTE chart

3.2.2 Run-in and endurance tests

Fig. 10 presents torque evolution during run-in test (steps 2 and 3). The grease exhibits a very progressive torque decrease, from 30mN/m to 6mN/m, and a slight decrease is observable for the gelled oil, from around 10mN/m to 7.0mN/m. For both grease and gelled oil, the modification of rotating direction does not seem to affect torque. At the end of run-in, the steady and low torque reached illustrates a very good lubrication of the interface, for each lubricant.



(a)



(b)

Figure 10. Steps 2 (a) and 3 (b)

Fig. 11 shows torque evolution during endurance test. First, no failure was recorded during whole the test duration, whatever the lubricant. Secondly, the speed influence is confirmed, e.g a higher speed leads to respectively a lower torque for the grease (7mN/m at the end of the test) and a higher torque for both oil and gelled oils (14mN/m for oil and PU2-12%, and 15mN/m for PU1-10%). The speed may increase PTFE/MoS2 particles efficiency for the grease but can lead to a higher torque for oils due to viscous drag. Thus, it is interesting to notice that gelled oils behaviour is very close to pure oil.

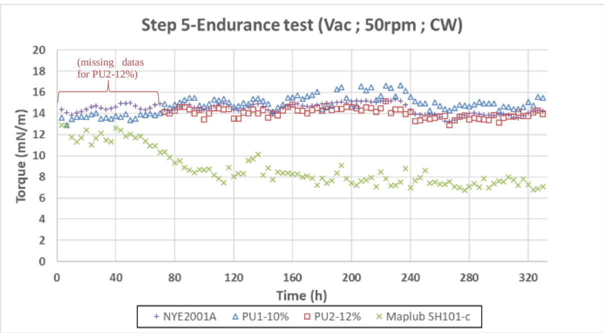
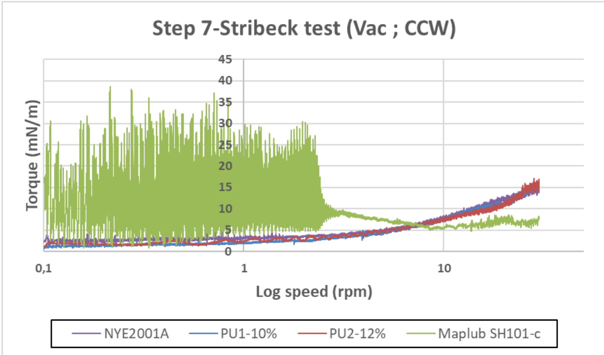


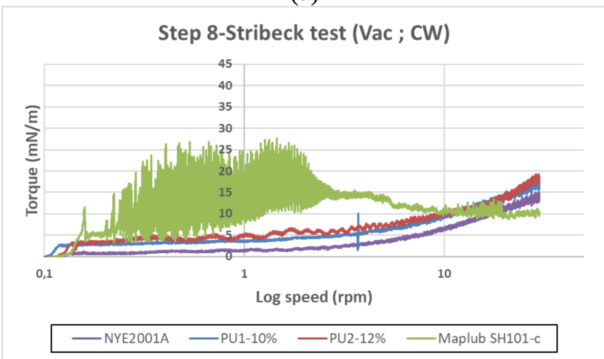
Figure 11. Step 5: endurance test

3.2.3 Stribeck test

After the endurance test and the 3rd LSTE test, 2 short-time tests are made, in order to characterize operating range of lubricants by applying speed sweep (Fig. 12).



(a)



(b)

Figure 12. Stribeck tests: CCW (a) and CW (b)

These additional tests confirm previous observations, regarding torque peaks for grease at low speed, and the slight increase of torque in presence of oil or gelled oil when speed increases. Moreover, the very slight increase of speed highlights transient phenomena for the grease, because "stick-slip" phenomena is reduced from 2,5rpm and is no longer present after 3rpm, for both spindle direction. In addition, a curve crossing is observed between 8 and 10rpm, as the grease torque becomes lower than oils one (pure and gelled).

4 CONCLUSIONS

The test campaign carried out on gelled oils and including a new bearing test protocol based on innovative bench design, has demonstrated the true interest of these lubricants for lubricating ball bearings in air and/or vacuum. Indeed, the gelled oils exhibit very consistent results, performing pin on disc test as well as bearing test.

From the pin on disc test, it has been shown that the gelled oils was not ejected from the contact during the friction tests even at high speed, similarly to the grease behaviour. However, under shear conditions, it appears that the gelled oils lose their gelled texture to fully return to a fluid, and hence behave as regular oil within the contact. Such a phenomenon happening only within the contact area in the friction track, the oil is maintained with the track by the "wall" formed by the remaining

gelled oil. The contact is consequently benefiting from easier replenishment. This observation has been confirmed by the very similar torque measurements of oil and gelled oils during the various steps of bearing test.
Under 8rpm, peaks torque occurring with grease have been clearly noticed at the opposite of gelled oils, which present a better anti-friction behaviour.
Lastly, even if a higher spindle speed leads to a torque increase, gelled oils have performed endurance test without any starved contact, as the torque remain quite steady. Consequently, it has been decided to continue the tests for few million cycles, to more discriminate gelled oils behaviour over the long term in air and in vacuum. A new expertise will be performed on bearings at the end of the entire cycle.
Finally, according to the most severe tests (i.e. pin on disc), PU1-10% is the gelled oil exhibiting the best performances in terms of friction coefficient and wear protection.

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