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Solid Oil Bearings - Breakthrough Innovation in bearing lubrication

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Introduction:

All throughout history, many have looked for ways to reduce friction. Certainly, ancient armies used grease as a weapon where by they would ignite the oil and wield it at their foe. Grease and oil was used for medicinal purposes as applied to the body. On a more industrious note, while building the pyramids, ancient Egyptians used crude types of greases to lubricate the axels of pharaoh's chariots.

Time has passed since the introduction of lubrication in industry; the sophistication of machinery has changed as well. The different materials used in combination to increased loads and speeds have forced lubrication manufacturers to meet growing needs. The traditional method for lubricating ball and roller bearings is with grease and oils. Even though these are proven solutions, at times these lubricants can be messy, causing significant housekeeping problems, requiring periodic maintenance to replenish the lubricant, environmental impact due to spillage, leakage & importantly, disposal.

Lack of lubrication and contaminant damage are leading causes of premature bearing failure in industrial applications. Maintenance technicians can overlook critical bearings, especially those in hard-to-reach locations. Lubricant can get thrown out under high rotational forces. Metal and dirt particles can enter bearing spaces, quickly damaging the rollers and races. Automatic lubrication systems aren't always the answer; they can be expensive to install and difficult. With the innovation of Solid Oil bearing a new era of lubrication of ball and roller bearings has begun.

Solid Oil is an oil-saturated, polymer matrix that fills the entire free space in the bearing, encapsulating both the rolling elements and cage. The polymer material has a porous structure, with millions of micro-pores, to hold the lubricating oil. The pores are so small that the oil is retained in the material by surface tension. As the oil-filled polymer material is injected into the bearing, a very narrow gap forms around the rolling elements and raceways, enabling the bearing components to rotate freely. When Solid Oil slides against the rolling elements or raceways of a bearing, the metal is coated with an even and consistent film of oil. Then, with only a moderate increase in operating temperature, oil is pushed toward the surface of the polymer matrix. This "flow" of oil within the polymer matrix occurs because the oil has a higher coefficient of thermal expansion than the polymer matrix and because the viscosity of the oil decreases with increasing temperature. When the bearing stops running, excess oil is reabsorbed into the polymer matrix.

A bearing with Solid Oil contains two to four times more oil than conventional grease lubricated bearings. This is because the bearing is entirely filled with Solid Oil, whereas a grease-lubricated bearing normally operates with approximately one third of its free space filled with grease. Because Solid Oil fills the bearing cavity entirely, it is difficult for solid or liquid contaminants to reach the bearing contact surfaces, even without bearing seals. In highly contaminated environments, however, it is recommended using bearings with Solid Oil and integral contact seals.

When should Solid oil be used?

In most applications, ordinary greases and lubricating oil will provide satisfactory lubrication to the bearing giving it an acceptable service life. However, there may be cases where lack of accessibility means that relubrication is virtually impossible or where very good contaminant exclusion is required. Solid oil may be the answer, as it provides "lubrication for life" and good sealing.

How does Solid Oil work?

Oil and polymer moulded into the bearing in a solid texture. Completely filling the internal space in a bearing and encapsulates the cage and rolling elements. The polymer uses the cage as the reinforcing element and rotates with it. Upon rotation the polymer releases the oil and provides good lubrication for the rolling elements and raceways. Very high oil content compared to for example grease (60 to 75% & depending on variant, grease approx. 30%)

Temperature limits:

The temperature limits for bearings with Solid Oil are valid for both open and sealed bearings. The relevant limits are:

maximum 85 °C (185 °F) for continuous operating conditions

maximum 95 °C (205 °F) for intermittent operating conditions

Minimum -40°C start up temperature for standards oil

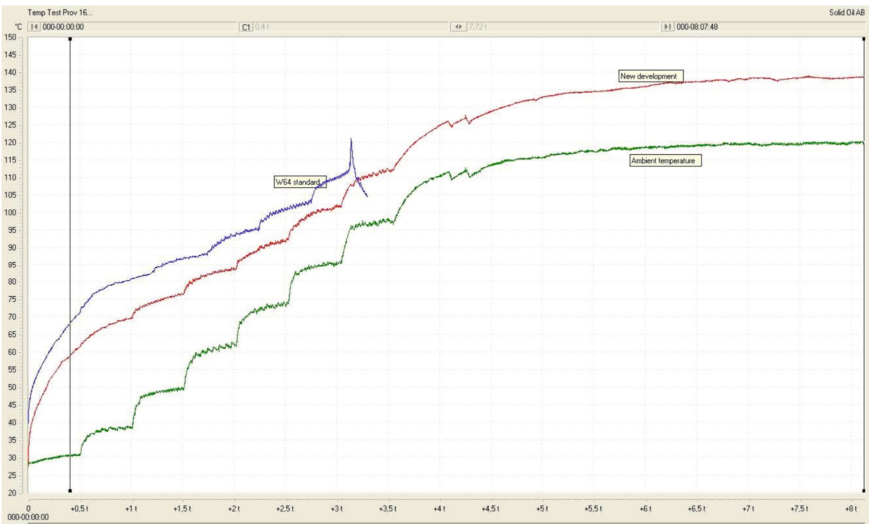
Bearings with Soild oil can be heated to a maximum of 100'C for mounting purpose.

Limiting speeds

An indication of the limiting speeds for bearings with Solid Oil is provided by the speed factor - $A = nXd_m$ – rotational speed (r/min) times the bearing mean diameter (mm). It is important to note that the higher the speed, the higher the operating temperature. It may therefore be necessary to limit the bearing speed for high temperature operations so that the temperature limit for the solid oil is not exceeded. As with most lubricants, the theoretical bearing life is extended if the operating temperature is kept low. These speed limits apply to open (unsealed) bearings. For bearings with integral seals 80% of the quoted values should be used.

Where

A	=	speed factor mm/min
n	=	rotational speed, r/min
dm	=	mean diameter of bearing = 0,5 (d + D), mm



Load Carrying Capacity
The basic dynamic load ratings for solid oil bearings are the same as for corresponding standard Bearings.

Composition of Solid Oil
Solid oil is normally produced with very high quality synthetic oil which is suitable for most applications.

Oil Viscosity: 140 mm^2/s at 40°C (105 °F)
19 mm^2/s at 100°C (210°F)

Oils having other viscosities can also be used successfully, as can special oils for the food industry. Additives, such as rust inhibitors, can be added to solid oil to provide extra protection.

Grease Lubrication V/s Solid Oil Bearing

Grease Lubrication	Soild Oil Bearing
During hygienic wash downs, grease will absorb water	The lubricant is molded into the bearing Large lubrication reservoir, lubricated for life
Leaves the bearing where frequent wash down occur	
Leaves the bearings in vibrating applications or in vertical shaft applications	
Grease life is limited, requires re-lubrication	Synthetic oil giving a long oil life
	No churning (no over rolling of the polymer matrix)

Manufacturing Process:

In Soild Oil Bearing, polymer matrix is made by mixing proprietary polymers, oils and special additives. The mixture is packed into the bearing and subsequently thermally processed. repeated trimming and cleaning operations are performance before packing. Alternately the mixture can be extruded into cross-sectional shapes or injection molded into specific parts & than embedded in bearing.

Advantages of Soil Oil Bearings:

- **Consistent Lubricant Supply:** When a metal surface, like the raceway of a bearing, slides against solid oil, it is coated with an even and consistent film of oil. Then, with only a moderate increase in operating temperature, oil is pushed toward the surface of the polymer matrix. This “flow” of oil within the polymer matrix occurs because the oil has a higher coefficient of thermal expansion than the polymer matrix and because the viscosity of the oil decreases with increasing tem perature. When the bearing stops running, excess oil is reabsorbed into the polymer matrix.

- **More Lubricant Available:** A bearing with solid oil contains two to four times more oil than a conventional grease-lubricated bearing. This is because the bearing is completely filled with the solid oil, whereas a grease-lubricated bearing normally operates with approximately one third of its free space filled with grease.
- **Keeps Contaminants Out:** Because solid oil fills the bearing cavity completely, it is difficult for contaminants to reach the bearing contact surfaces. In highly contaminated environments, SKF recommends filling the free space in the housing with a suitable grease to provide an additional layer of protection.
- **Eliminates Relubrication:** Solid oil contains such a large reservoir of oil that relubrication is not required.
- **No Seals Required:** Seals are not needed to retain the lubricant in the bearing, even on vertical shafts. However, if the arrangement already incorporates seals, they should be retained as extra protection against contamination.
- **Resistant to Chemicals:** The solid oil polymer matrix is unaffected by most chemicals. However, organic solvents like kerosene, will remove the oil from the polymer matrix.
- **Withstands high g-forces:** Solid oil becomes an integral part of the bearing so that lubricant cannot be expelled, even when subjected to high centrifugal forces.

Case Study - Traveling wheels on a converter crane at steel plant

- **Major Issues:**
    - Grease leakage affecting the breaking performance (safety issue)
    - Poor asset reliability
    - High grease consumptions presented environmental concerns
    - Heavily contaminated environment

- **Benefits with Soil Oil Bearings:**
    - No braking issues
    - Significantly improved safety
    - No re-lubrication required
    - Lifetime expected to be 10 years, compared to 6 years with old solution

Soil Oil Bearing – Key Applications:

Paper Making – Soil oil has been found beneficial in the papermaking industry. First in the wood treatment process where it protects the bearing against impurities and then in pulp preparation where the chemical stability of the polymer is invaluable. In the papermaking machine itself, Soild Oil has been used successfully **on the wire rolls of the wet section. Finally the Soild oil has** the advantage when cutting the paper to size as the absence of lubricant leakage means clean paper.

Equipment for snow and ice: Soild oil has a very low starting torque in the cold compared with grease as the rolling elements do not need to overcome the stiffness of grease. This energy- saving property has been appreciated, for example for ski lifts and piste machinery.

Pneumatically Operated Couplings: When the bearing outer ring rotates in grease lubricated bearing arrangement, grease is thrown out of the bearing and inadequate lubrication may result. The expelled grease is deposited on the engaging members and the function of the coupling is endangered. These problems have been completely eliminated using Soil Oil Bearings.

Cranes and Traverses: The freedom from maintenance provided by Soil Oil can be exploited in many applications where bearings are difficult to reach. Example: Overhead cranes and hoists.

Mixers: In equipment used to stir and mix chemicals, example: Electrolyte for dry cell batteries, the resistance of solid oil to aggressive substance is valuable.

The Effect of Thickener on EP Additive Response

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Abstract

It is recognized in the industry that thickener used in lubricating greases can interfere and negatively impact additive function. Extreme pressure and antiwear additives that function at the interface of the lubricant and mating surfaces are particularly affected. This study measured the effect of thickener concentration on load-carrying ability of lithium complex grease system. Specifically, Timken EP tests were conducted on grease formulation at three consistencies treated with a constant amount of a sulfur-phosphorus (S-P) gear oil additive package. The testing showed that Timken OK loads were not affected by soap thickener concentration. Timken EP tests were also performed on corresponding base oil formulation over a range of passing loads that encompassed the highest passing load and ensuing failure load of the greases. The effect of the thickener was demonstrated by comparing differences in test temperatures, wear scar widths and tribo-film coverage and composition. Another objective of this study was to elucidate mechanism by which thickener interferes with S-P additive system. For this effort, oil separation experiments were conducted and the resulting oils were analyzed to measure decreases in additive concentration. These experiments showed that sulfur concentrations in the grease bleed oils were not significantly different than the formulated oil. On the other hand, phosphorus was not detected in the separated oil indicating that phosphorus antiwear additives were completely retain in the bulk of the grease, probably due strong interaction with soap thickener. These results correlated well and helped explain differences in test temperatures, wear scar widths and tribo-film compositions observed between the greases and the corresponding base oil formulation.

Introduction

Greases are typically described as lubricating compositions composed of base oil and additives entrapped in a network of solid thickener particles, platelets, clumps and/or fibers. Thus, the physical and chemical interactions of thickener with additives are recognized by many in the industry as having a significant effect on additive performance[1-2]. However, there are few published studies that have detected these interactions and/or measured the effect of these interactions on lubrication performance. This does not imply that grease lubrication, specifically of rolling bearing, has not been studied. Numerous models have been published to explain the mechanism by which grease lubricate roller bearings in elastohydrodynamic lubrication (EHL) regime. For the most part, bleeding, which is the separation of base fluid, additives and/or thickener from the bulk grease is recognized as an important factor in these models[2-3]. In one such study, Cousseau and co-workers used a ball-on disc test rig and optical interferometry to measure the film thickness produced by different formulated greases, their bleeds and base oils. They found film thickness of grease resembled that of their bleeds more than their base oils. This observation underscores the importance of understanding how thickener-additive interaction and surface competition effect load-carrying ability of greases.

In one study focused on thickener-additive interactions, Sivik and co-workers utilized phosphorus Nuclear Resonance Spectroscopy (^{31}P NMR) to analyze the interaction of zinc dithiophosphate (ZDDP) with lithium 12-hydroxystearate grease[4]. Their analysis revealed that ZDDP underwent chemical changes in grease containing residue amounts of lithium hydroxide raw material. The changes involved the formation of lithium dithiophosphate along with a decrease in neutral ZDDP and an increase in basic ZDDP levels. Sivik proposed a mechanism in which neutral ZDDP reacts with lithium hydroxide to form lithium dithiophosphate, zinc oxide and water. The resulting ZnO then reacts with neutral ZDDP to produce additional basic ZDDP. More pertinent to effect of these interactions was the analysis of the basic lithium 12- hydroxystearate grease after "exhaustive" hexane washing. The result of ^{13}P NMR study showed that a significant amount of neutral ZDDP was retained in grease, which Sivik and co- workers proposed was due to polar-polar "association" of the ZDDP with the lithium soap fibers.

In another study, Kaperick used Timken test methods to compare the load-carrying capacity of a sulfur-phosphorus gear oil additive package treated into lithium complex grease and the corresponding base oil formulation[5]. Since the rate of lubricant delivery for the grease and oil test methods are different, Kaperick first adjusted the delivery systems to investigate the effectof lubricant delivery rates. It was found that differences in delivery rate of the lubricant did not affect Timken response. The major finding was a large decrease in Timken response for the S-P gear oil package in the grease formulation. It was concluded that decrease response was due to thickener-additive interactions that reduced the ability of additives to get to the mating surfaces or interfered with additive function.

This paper is an extension of the Kaperick's work. Specifically, the Timken test methods were again used to compare the response of an S-P additive package in lithium complex grease and the corresponding base oil formulation. The study was broadened to include different grease consistency grades to determine if additive response was affected by thickener/base oil concentration. The thought was that softer grease formulations containing less thickener would behave more like the base oil formulation. The study also incorporated an extended test protocol to further demonstrate differences in the lubricating mechanism of grease versus its corresponding base oil formulation. These measurements and techniques are briefly described below:

- Temperature readings were taken to measure rate and extent of temperature increasegenerated by frictional forces during Timken runs.
- Wear widths on test blocks were measured on some partial grease Timken runs and all complete Timken runs.
- Scanning Electron Microscope-Energy-Dispersive X-Ray Spectroscopy (SEM-EDX) wasused to get a measure of tribo-film coverage and composition.
- Oil separation experiments were performed on greases to compare additive content ofbleed oils against base oil formulation.

The investigation showed that grease consistency did not affect the load-carrying capacity. Allgrease consistencies were judged to pass the Timken test at a 40 lb. load and to fail at a 50 lb.load due to metal pulling or scoring after complete 10 minute runs. As expected, the base oil formulation passed the Timken test at 30, 40, 50 and 60 lb. loads. Additional measurements showed that the base oil formulation at all test loads had rapid rates of temperature increase that plateau at approximately 2 minutes and produced relatively constant wear scar widths covered with tribo-films rich in phosphorus content. On the other hand, grease formulations had much slower rates temperature increase, generated wider wear widths that increased withtest time and produced sparser tribo-films rich in sulfur content and containing none detectableto trace amounts of phosphorus. These results are consistent with oil separation experiments that revealed that phosphorus components in additive package were unable to bleed away from greases regardless of consistency while sulfur levels matched that of the oil formulation.

Experimental

Timken Testing

Tests were carried out using "Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Fluids (Timken Method)", ASTM D 2782 and "Standard Test Method for Measurement of Load-Carrying Capacity of Lubricating Grease (Timken Method)", ASTM D2509 on oil and greases respectively. Both Timken test methods consist of passing lubricant through an interface that consists of steel cup rotating against steel block at a static spindle speed of 800 ± 5 rpm and static load for a 10 minute test period. For each test, loads are increased until film rupture is detected by either excessive wear or scoring on the test block.

For this study, temperature readings were collected at one minute intervals using Control Company Traceable® infrared thermometer gun. Temperature readings were taken on test cups at approximately 180 degree position from ring on block contact. Wear scar widths were measured using low power microscope (4X) with filar micrometer to measure with accuracy of ±0.05 mm (±0.002 in.).

Surface Analysis

Test block surfaces were analyzed FEI Quanta 650 Scanning Electron Microscope (SEM) and Oxford Instruments X-Max 150 Energy-Dispersive X-Ray (EDX) detector. Analyses were performed on the same 4 mm by 3.5 mm area of each block containing part of the wear scar. The beam energy was kept at 5 kV to increase surface sensitivity. AZtec Version 2.2 software by Oxford Instruments was used to create images of the mapped area that consisted of three phases: 1) block background, 2) tribo-film and 3) carbon deposits. The AZtec software was also used to perform elemental quants of EDX spectra.

Blocks were clean before putting them in the SEM by the following procedure:

1) Heptane rinse
2) Wiping with heptane-soaked Kim wipes
3) Heptane rinse
4) Isopropyl alcohol rinse
5) Wiping with isopropyl alcohol-soaked Kim wipes
6) Isopropyl alcohol rinse
7) Nitrogen blow dry

Oil Separation Experiments

Greases were subjected to a modified IP 121 standard test method. In the standard method, grease is placed in a 240 mesh woven wire cloth cone and loaded with 100 gram weight. The cone is placed on stainless steel cup and bleed is collected for 168 hours at 40 °C. For this study, the collection period was decreased to 8 hours and collection temperature was increased to 140 °C. The 140 °C temperature was selected based on maximum temperatures measured during Timken tests. The test time was decreased to eliminate any oxidation effects. Collected bleed samples were analyzed for phosphorus and sulfur content.

Phosphorus content was measured by inductively coupled plasma atomic emission spectroscopy (ICP) using a modified version of ASTM D 4951 standard test method. Sulfur content was measured using LECO Corporation SC-432 analyzer following ASTM D 1552 standard test method.

Lubricant Compositions

All lubricant compositions, oil and greases, were based on ISO 220 mineral oil blend and were formulated with 3 mass percent of a proprietary gear oil package consisting of sulfur based extreme pressure agents and phosphorus based antiwear additives. The grease formulations were made using unadditized, lithium complex base grease with penetration (60 x worked) of 185 m^{-1}. All compositions were blended with standard laboratory equipment with mild heating (60 ± 5 °C) for time judged sufficient to thoroughly incorporate the additive package and achieve homogeneous mixtures (1-2 hours). A summary of lubricant compositions are provided in Table 1:

Table 1: Lubricant Compositions:

Components	Oil	Grease NLGI 1	Grease NLGI 2	Grease NLGI 3
S-P Package (Weight %)	3	3	3	3
ISO 220 Base Oil Blend (Weight %)	97	45	35	22
Lithium Complex Base Grease (Weight %)	---	52	62	75
Penetration (60 x worked) ASTM D 1403, (mm-1)	---	318	284	244

Results and Discussion

As summarized by Figure 1, Timken testing of the oil formulation showed no significant loss of load-carrying capacity of over a range of loads (30, 40, 50, and 60 lb). All wears scars had no visible signs of scoring and wear scar widths were narrow and did not change significantly with increasing test load. Average scar width for the four loads was 1.04 mm with a range 0.14 mm. The grease formulations carried 40 lb. loads without scoring but wear widths were significantly larger than the oil formulation with an average and range of 1.45 mm and 0.26 mmrespectively. As expected, the greases were unable to carry 50 lb. load without scoring. Wearwidths increased to average of 2.21 mm with a range of 0.39 mm.

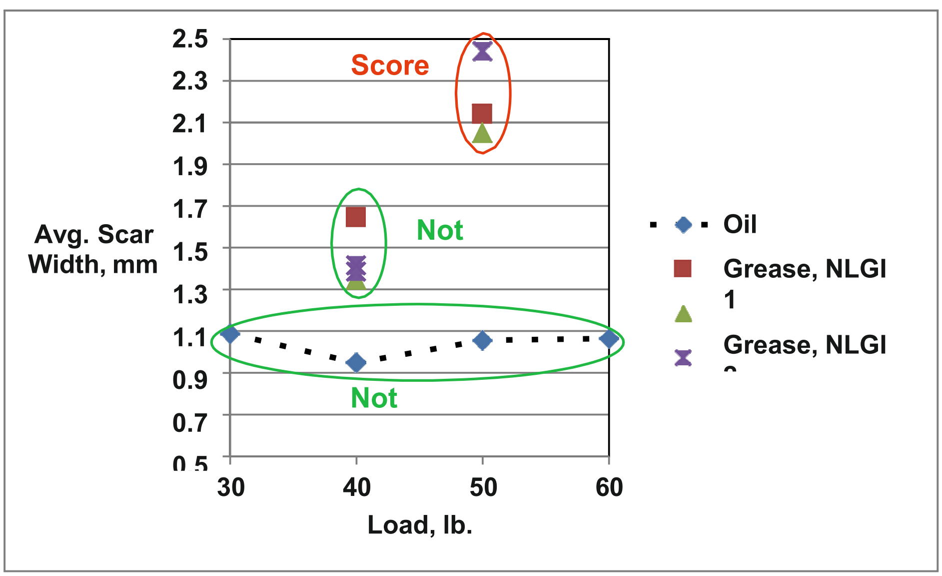


Figure 1: Graph summarizing anti-scoring and antiwear performance of the S-P package in oiland grease.

As summarized Table 2, surface analysis of block wear scars revealed that tribo-film compositions for oil and grease formulations were indeed very different. The oil formulation at all four loads produced tribo-films high on phosphorus and oxygen content, likely signifying thepresence of phosphate films that are known to provide excellent antiwear protection[6]. Greases

Table 2: SEM-EDX Data on 3 mm X 4.5 mm Area of Timken Block

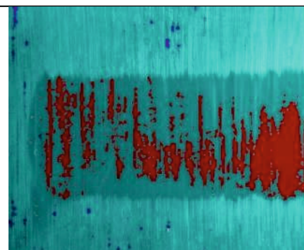
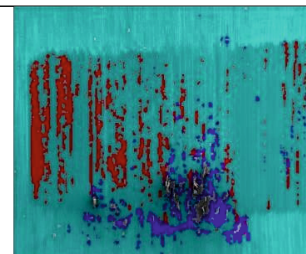
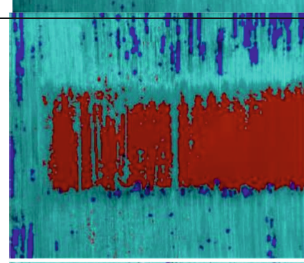
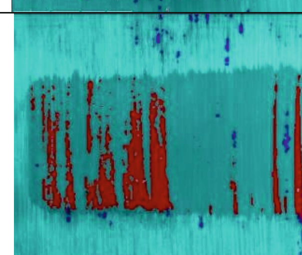
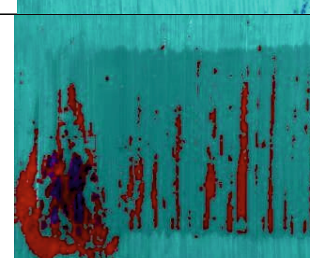
Formulation	Load, lb.	Time, minute s	Tribofilm Area (mm^2)	P (at.%)	O (at.%)	S (at.%)
Oil	30	10	1.432	6.78	27.39	2.12
	40	10	2.709	5.80	22.66	2.31
	50	10	2.048	6.20	22.74	1.85
	60	10	2.644	5.21	19.47	2.55
Grease						
NLGI 1,	40	10	2.106	0.00	5.36	9.48
NLGI 1	50	10	1.559	0.00	9.32	9.57
NLGI 2	40	10	3.824	0.14	4.72	9.13
NLGI 2	50	10	1.610	0.18	7.95	10.58
NLGI 3	40	10	4.354	0.00	7.33	8.46
NLGI 3	50	10	2.341	0.14	12.53	9.72

on the other hand produced films with undetectable to trace amounts of phosphorus but four times more sulfur content than the oil formulation, possibly signifying the presence iron sulfideand/or sulfate tribo-films generally generated by sulfur EP agents[7]. Thus, the tribo-film and wear data correlate well each other. Specifically, the data suggests that thickener interfered with the phosphorus antiwear function and that load-carrying capacity of the greases was left to only sulfur EP additives that form iron sulfide and sulfate tribo-films that wear and smooth mating surfaces to prevent metal-metal adhesion. More importantly, tribo-film area data in Table 2 and SEM-EDX images in Table 3 implies that sulfur tribo-film generation was not fast enough to keep up with increased wear rate at the 50 lb test load.

The effect of wear rate on sulfur tribo-film formation was further investigated by stopping Timken tests at 3 and 4.75 minutes for the NLGI 1 grease. As per Figure 2, surface wear rate at the 50 lb load was close to linear and was approximately 1.5 times faster than 40 lb wear rate and about twice as fast as wear rates produced by the oil formulation. As shown in Table 4, SEM-EDX analysis for 3 and 4.75 minute tests detected almost no sulfur tribo-film formationbut surprisingly, no scoring was visible for the 3 minute test and only slight scoring was evidentfor 4.75 minute test. These observations infer thickener participated in load-carrying but the same time interfered and slowed down tribo-film generation by competing for surface area with sulfur EP additive. A better understanding of how soap thickener lubricates and interferes with sulfur EP additive could be gained by replicating this study using oil and grease formulated with only the sulfur EP additive.

Temperature data (Figures 3 and 4) also revealed significant differences between the oil and the grease formulations. The oil formulation at all loads produced rapid rates of temperature increase that plateaued quickly at approximately 2 minutes. This behavior correlated well withlow surface wear and SEM-EDX data that showed the formation of dense phosphorus based tribo-films at all test loads. On the other hand, grease formulations produced much slower and linear rates of temperature increase that plateaued at approximately 6 minutes. This behavior aligned well with higher wear rates and tribo-film data that pointed to the formation of iron sulfide and/or iron sulfate tribo-films that wear mating surfaces and reduce friction and temperature by smoothing surfaces at the contact zone.

Table 3: SEM-EDX Images of Timken Blocks for Grease Formulations and 10 minute Runs

Grease	40 lb. Load	50 lb. Load
NLGI 1		
NLGI 2		
NLGI 3		

Aqua, red and blue area represents block background, tribo-film and high carbon content deposit respectively.

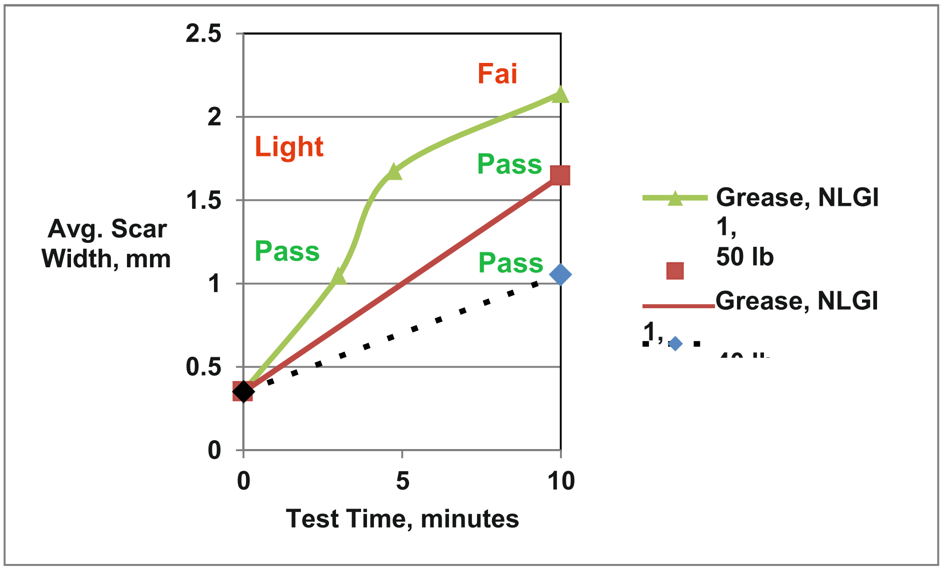
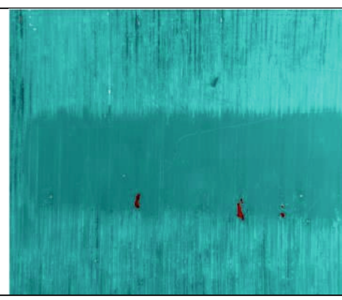
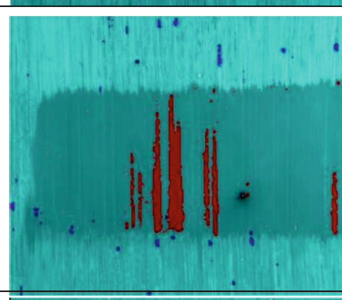
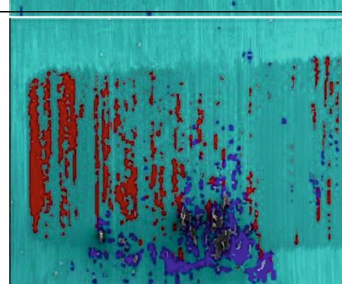
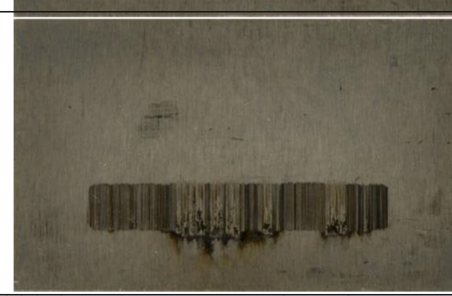


Figure 2: Graph showing wear increase of grease formulation with time.

Table 4: Images of Wear Scars for NLGI 1 Grease at 50 lb. Test Load

Test Time, minutes	SEM-EDX	
3		
4.75		
10		
Aqua, red and blue area represents block background, tribo-film and high carbon content deposit respectively.		

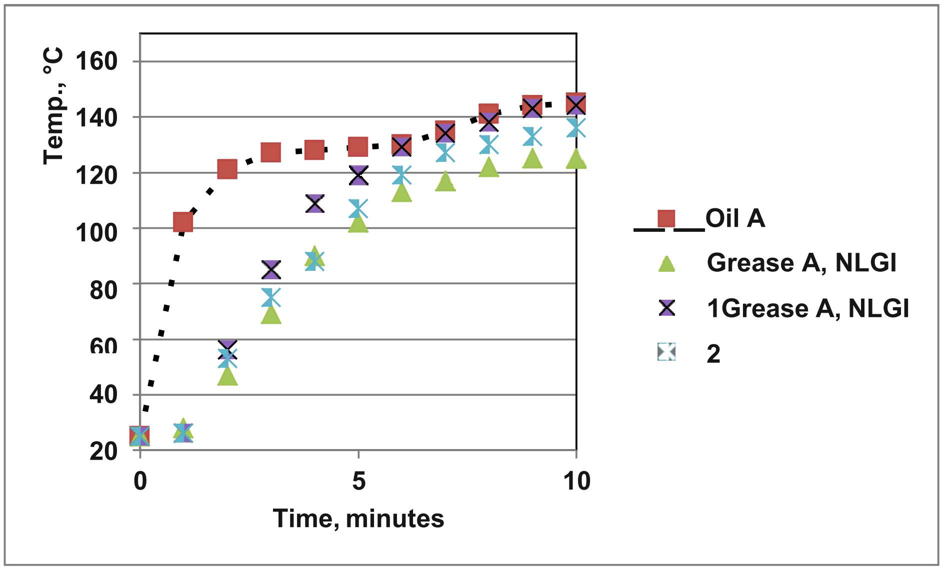


Figure 3: Graph summarizing temperature profiles for 40 lb. Timken test runs.

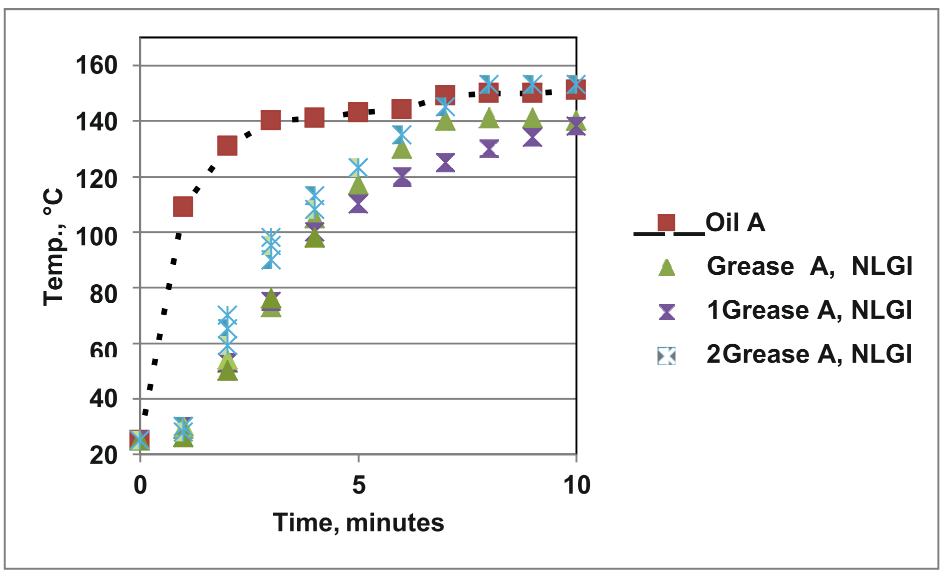


Figure 4: Graph summarizing temperature profiles for 50 lb. Timken test runs.

In regards to lack of phosphorus content in grease tribo-films, oil separation experiments wereespecially insightful. As per Table 5, bleed oil that separated from greases contained equal amount of sulfur content as the oil formulation but no detectable amount of phosphorus. Thus, it is concluded that a strong interactions with soap thickener inhibited phosphorus compounds from adhering and reacting metal surfaces.

To conclude, the study demonstrated that lithium soap thickeners can inhibit the function of EP and antiwear additives. Two basic mechanisms were proposed based on experimental observations. One mechanism involves soap blocking additives from metal surfaces as was the case with sulfur EP additives of this study. The second mechanism involves chemical interactions between the soap and additives that prevent the additives from adhering and reacting with metal surfaces. This mechanism would be more in effect with polar and ionic additives such as phosphorus compounds that are commonly used in gear oil additive packages.

Table 5: Phosphorus and Sulfur Contents for Oil Formulation and Grease Bleed Collected at140 °C for 8 h.

Formulation	Phosphorus Content (ppm)ICP, modified ASTM D 4951	Sulfur Content (Wt. %)ASTM D 1552
Oil	330	0.96
Grease Bleed		
NLGI 1	0	1.02
NLGI 2	0	1.08
NLGI 3	0	1.15

References

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