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**RELIABILITY OF POWERTRAIN COMPONENTS EXPOSED TO EXTREME  
TRIBOLOGICAL ENVIRONMENTS**

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**ABSTRACT**

*Results are presented from tests on a formulated 15W-40 mil-spec engine/transmission fluid to examine the impact of additives on improving its reliability and durability under extreme tribological conditions. A block-on-ring (BOR) configuration was used to measure the effect of five additives (an emulsion-based boric acid, tricresyl phosphate, particulate-based boron nitride, particulate-based MoS<sub>2</sub>, and particulate-based graphite) on the critical scuffing load as a function of additive concentration and time to scuff during oil-off tests (starved lubrication). A four-ball configuration was used to evaluate the impact of simulated engine grit/sand on the abrasive wear of steel as a function of grit size and loading.*

*The results demonstrated that the additives increased the load for scuffing by 50 to 100% for the formulated oil and by 50 to 150% for the unformulated base fluid used in the formulated oil. Two of the additives (emulsion-based boric acid and tricresyl phosphate) doubled the time to scuffing for the formulated fluid. The use of boric acid and tricresyl phosphate in the base fluid increased the time to scuff significantly more. In both fluids, a low-friction regime was frequently observed during the tests and, when present, resulted in greatly increased survival times.*

*Oil-off tests were performed to simulate a loss-of-lubricant condition. The results revealed a novel trend – the formation of a low-friction regime under the starved (drained-oil) lubrication condition. When a low-friction regime occurred (after the oil was drained from the test cup), the time to scuffing increased dramatically.*

**INTRODUCTION**

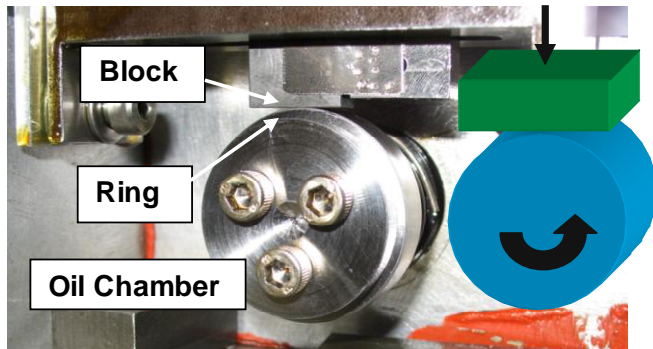
Friction, wear, and lubrication of military fighting systems have an important impact on the ability to achieve military missions. Accelerated vehicle (including helicopter) failures in theatre have raised concern about the design and capability of ground- and air-based military systems to carry out critical missions in desert combat climates (i.e., hot, arid, and sandy). Some of these failures may be traced back to the extreme tribological (friction, wear, and lubrication) environments in which the systems must operate. They can involve situations as simple as sidearms that jam due to accelerated wear in abrasive sand to complex failures with dire consequences, such as the failure of helicopter

transmissions that seize in mid flight after critical lubrication systems are compromised.

The efficiency, durability, and reliability of complex mechanical systems rely heavily on the performance of the tribological system, e.g., the combination of materials, surface finish, lubricants, and local environment (temperature, speed, stresses, etc.). Operation under off-normal, extreme conditions often leads to catastrophic failure or accelerated wear/degraded durability of critical components. Advanced additives can under certain conditions provide an added level of protection beyond that expected under normal operating conditions. The results

presented below summarize a series of tests that was performed to investigate the potential of several different additives to improve the resistance to scuffing and wear of a mil-spec engine lubricant.

Fuel economy and durability are important to commercial and military applications [1]. Another property of critical importance that can have a significant impact on the ability to accomplish military missions is reliability – especially under harsh, off-normal conditions. In contrast to durability, which involves gradual degradation of components over time and is predictable, reliability issues typically involve sudden, unpredictable degradation of a system. Scuffing is a prime example. Scuffing [2,3] is characterized as a sudden catastrophic failure of the lubricated sliding surface characterized by a sudden rise in friction, contact temperature, vibration, and noise, resulting in surface roughening through severe plastic flow and loss of surface integrity. Once scuffing occurs, the friction remains high even though the operating conditions are returned to pre-scuffing values. Scuffing is a common failure mechanism that is addressed in the design of vehicle systems, in particular, combustion chamber components [4], as well as gears and valve-train components.



**Figure 1: Photograph of the Block-on-Ring Test Configuration Used to Evaluate Scuffing Resistance of Lubricant Additives**

Military ground vehicles must often operate under extreme tribological environments, including environments where the vehicle lubrication can be compromised or disabled to the point where the engine and/or drivetrain operate under starved lubrication. In such cases, scuffing can occur and lead to sudden failure/seizure of critical components and thus impact the ability to complete a mission safely.

A potential solution to mitigate the impact of sudden catastrophic failure on mission critical systems is the application of advanced additives to increase scuffing

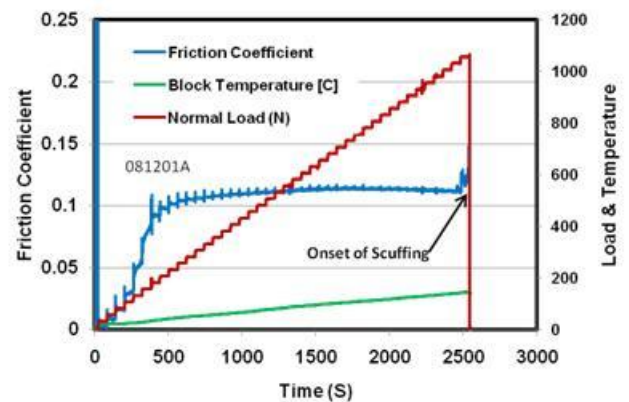
resistance. Results are presented below on a series of bench-top experiments designed to investigate the impact of advanced additives on the critical scuffing load of a qualified mil-spec 15W/40 diesel engine lubricant.

**APPROACH**

Figure 1 illustrates the block-on-ring [3,5] technique that was used to evaluate the scuffing load performance. The technique involves pressing a flat block against a rotating ring, producing a highly stressed line contact. The load is increased in 25-N increments every 60 sec until scuffing occurs (as denoted by a sudden increase in friction). The technique is used to compare the effectiveness of additives relative to a baseline condition.

During operation, the rotating speed was held constant (at speeds of 750, 1000, and 1500 rpm), while the applied load was increased from 0 up to 2000 N. The block-and-ring specimens were contained in an enclosure that was filled with the lubricant (and additives) to a level approximately 1/3 of the way up from the bottom of the ring. The oil wetted the ring and was transported to the contact region between the block and ring. The rings (35 mm O.D. x 9 mm wide) were fabricated from AISI 4620 steel hardened to 58-63 Rc with a surface finish of 6-12 rms, while the blocks (15.7 mm x 6.2 mm wide x 10 mm tall) were fabricated from SAE grade 01 steel, hardened to 58-63 Rc with a surface finish of 4-8 rms.

This technique was used to quantify the scuffing load of an engine/driveline lubricant based on a mil-spec mineral. Tests were performed on the as-received oil and oil mixed with five additives: emulsion-based boric acid (EBA), tricresyl phosphate (TCP), graphite, boron nitride (BN), and

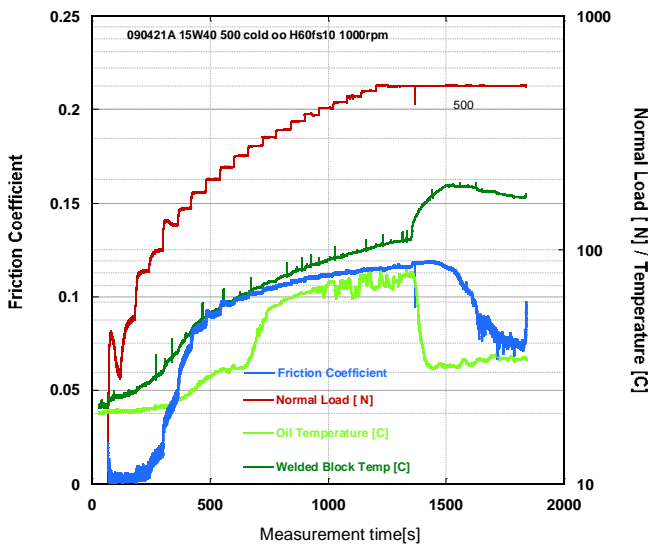


**Figure 2: Friction, Applied Load, and Block Temperature as a Function of Time during a Block-on-Ring Test at 750 rpm**

molybdenum disulfide (MoS<sub>2</sub>). The oil-to-additive ratios were 5:1, 10:1, and 25:1 by weight. A limited number of tests were performed at 50:1 and 100:1 ratios for the EBA, TCP, and BN additives.

Figure 2 shows an example of the friction, applied load, and block temperature as a function of time during a test on the as-received formulated 15W/40 lubricant. Initially, the friction is low, but then increases to steady-state values around 0.12, until scuffing occurs at a critical load around 1050 N. At that point, the friction increases rapidly, and the test is stopped.

A second series of tests, “oil-off” test, was performed to examine the impact of additives on extending the lifetime of oil under starved lubrication conditions. These tests used the same block-on-ring configuration, but rather than ramping up the load until scuffing/failure occurs, the load was ramped up to a predetermined value (less than the critical load for scuffing), at which point the oil was drained from the container, and the test continued until scuffing/failure occurred (under dry/starved conditions).



**Figure 3: Friction, Load, and Temperature as a Function of Time during an Oil-Off Test**

Figure 3 shows an example of the data recorded during an oil-off test (in this case mil-spec 15W40). The load was ramped up to 500 N using the same protocol as before (25-N increments every 60 sec). After reaching 500 N, the load was held constant, and the oil drained 60 sec after reaching the 500-N limit. The block temperature increased after the oil was drained. Several minutes after the oil was drained, the friction decreased, and the sample eventually scuffed several minutes later. The reduced friction (after the oil was

drained) was not necessarily typical. Quite often the friction remained relatively steady after the oil was drained until scuffing occurred.

Following the tests, an advanced characterization technique, focused ion beam spectroscopy (FIBS), was used to prepare transmission electron microscopy (TEM) cross sections to analyze the structure and composition of the protective “tribofilms” that formed during the tests and to use such information to develop a better understanding of the roles that additives play in extending the reliability and durability of critical components.

**TEST CONDITIONS**

The scuffing and oil-off tests used re-refined mineral oils – both formulated and unformulated. The unformulated oil was the basestock oil used in the formulated oil, but without the additive package. The formulated oil is “qualified” oil that meets mil-spec (MIL PRF-2104G) requirements and is formulated to function as both a diesel engine lubricant (15W40) and a transmission lubricant. Properties of the fluids are given in Table 1.

**Table 1: Lubricant Properties**

	Formulated	Unformulated
Specific Gravity @ 15°C	0.89	0.87
Viscosity @ 40°C (cSt)	118	46.0
Viscosity @ 100°C (cSt)	15.7	7.0
Viscosity Index	140	108
Pour Point (°C)	-33	-12
Sulfated Ash (%)	0.98	<0.04
Sulfur (ppm)	-	340

The additives examined in these tests and their particle size where appropriate are given in Table 2.

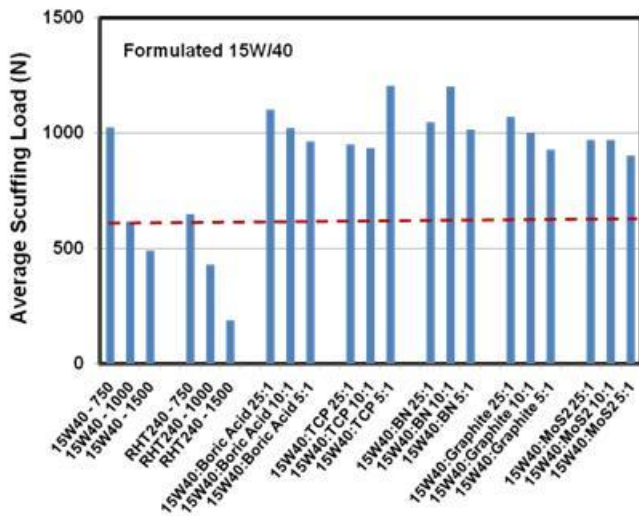
**Table 2: Particle Size for Additives**

Additive	Particle Size
Boric Acid	N/A – emulsion
Tricresyl Phosphate	N/A – liquid
Boron Nitride	6 µm
Graphite	2 – 15 µm
Molybdenum Disulfide	< 2 µm

Scuffing tests were performed on as-received formulated 15W40 and base fluids at three rotational speeds (750, 1000, and 1500 rpm), corresponding to linear sliding speeds of 1.4, 1.8, and 2.7 m/s. The majority of the oil-off and additive tests were performed at 1000 rpm (1.8 m/s).

**RESULTS**

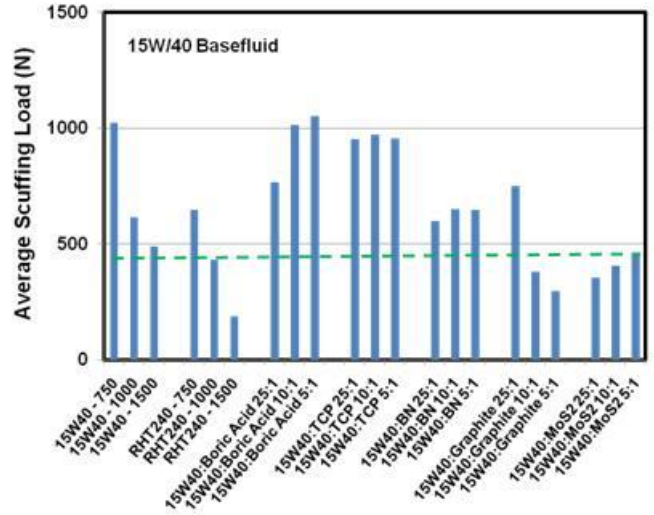
Figure 4 summarizes the results for the series of tests designed to evaluate the impact of the additives on the scuffing load of the formulated 15W/40 mil-spec diesel engine lubricant. The data shown in fig. 4 represent the average scuffing load obtained from a minimum of three repeat tests at each run. The first three tests show the impact of speed on scuffing, while the next three show the impact of speed on the scuffing load of the unformulated base fluid used in the as-received formulated oil. The remaining tests show the average scuffing load for the five additives at the three oil-to-additive levels. The dashed red line in fig. 4 represents the average scuffing load for the formulated 15W40 oil at a speed of 1000 rpm – the speed used for the tests with the different additives. As seen in fig. 4, all of the



**Figure 4: Average Scuffing Load of Formulated 15W/40 and 15W/40 with Additives**

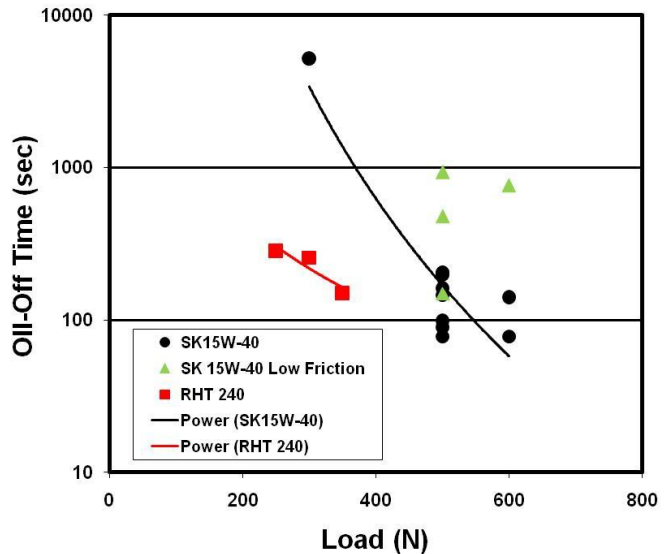
additives increased the scuffing load of the as-received formulated lubricant. The magnitude of the improvement ranged from 50% to 95%, depending on the additive and oil-to-additive level.

Figure 5 shows comparable information on the impact of the five additives in the unformulated oil, i.e., the base fluid without the additive package added at the factory. The dashed green line in fig. 5 represents the average scuffing load of the base fluid at 1000 rpm – the speed used for the tests on the base fluid with the five additives. In contrast to the formulated 15W/40 oil, the graphite and MoS<sub>2</sub> additives were ineffective in improving the scuffing load.



**Figure 5: Average Scuffing Load of 15W/40 Base Fluid and 15W/40 Base Fluid with Additives**

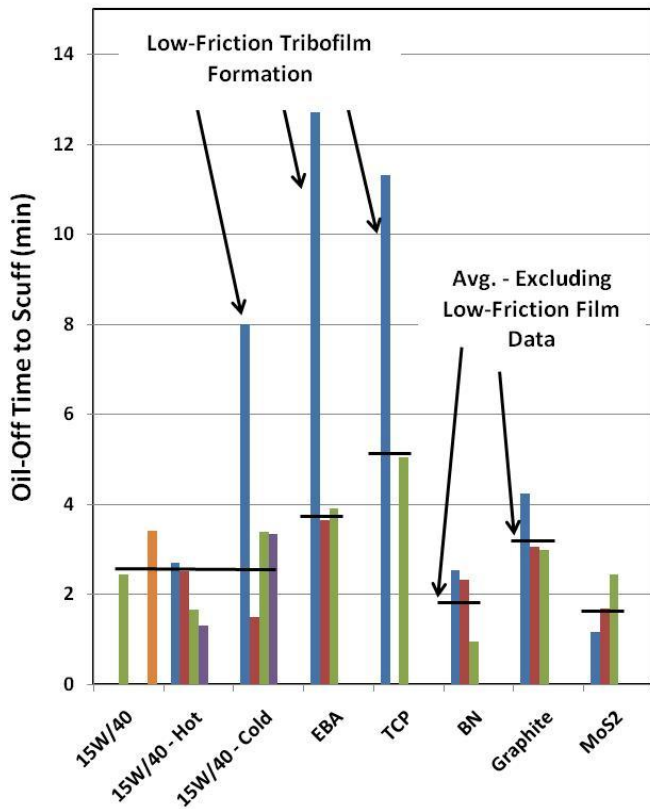
The scuffing data in figs. 4 and 5 indicate that the average scuffing loads for as-received formulated and base fluids were ca. 615 N and 435 N, respectively. A series of oil-off tests was performed at loads below these values to select an acceptable oil-off load for each fluid – a load that provided sufficiently long oil-off times that were statistically meaningful, yet not too low such that the samples endured overly long oil-off times.



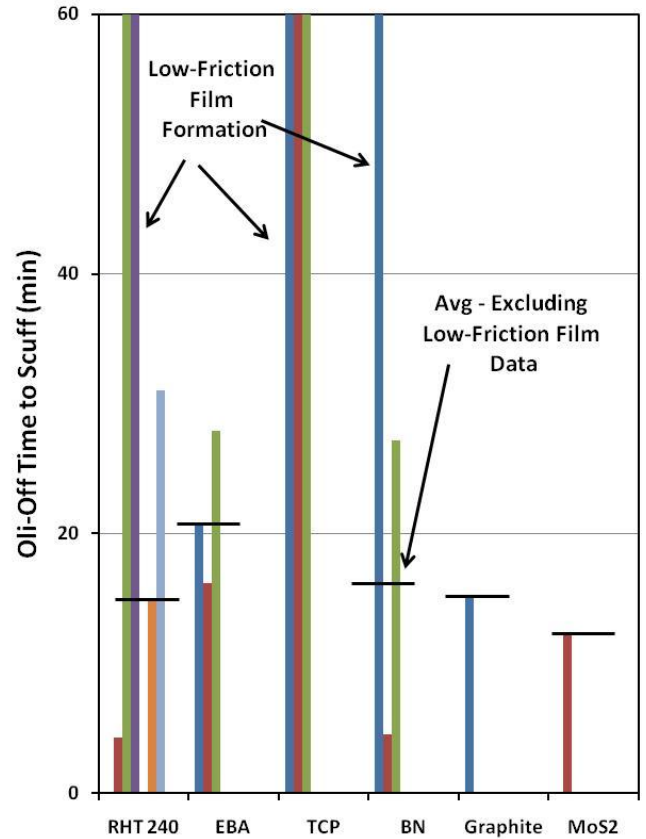
**Figure 6: Oil-Off Time as a Function of Final Load**

The results presented in fig. 6 are for the oil-off load tests with formulated and unformulated fluids. The black and green data points represent the time required for scuffing to occur after the oil is drained from the contact zone/container. The green points indicate conditions where an enhanced low-friction regime formed, in contrast to the black points, where a low-friction regime was not observed. The red data points represent the oil-off times for the unformulated fluid. Based on the data in fig. 6, the load for the oil-off tests with formulated oil was set at 500 N, while the load with the unformulated fluid was set at 300 N.

Results of a series of oil-off tests performed at 1000 rpm and an additive loading of 10:1 (10 parts by weight oil to 1 part additive) are shown in fig. 7 for tests on formulated 15W40 oil. The as-received 15W40 oil scuffed approximately 2-1/2 min after the oil was drained from the containment.



**Figure 7: Oil-off Time for 15W40 Oil with 10:1 Additives. Final test load = 500 N.**



**Figure 8: Oil-off Time for Unformulated Oil with 10:1 Additives. Final test load = 300 N.**

The EBA additive increased the time to scuff to an average value of approximately 3-1/2 min, while the TCP additive increased the oil-off time to roughly 5 min. A few cases exhibited a low-friction regime, which significantly extended the oil-off time.

Oil-off data for the unformulated fluids with and without the additives are shown in fig. 8. The untreated, as-received unformulated fluid scuffed approximately 15 min after the oil was drained. The EBA additive scuffed approximately 21 min after the fluid was drained, while the unformulated fluid treated with TCP lasted in excess of 300 min before the test was terminated (without scuffing).

**DISCUSSION**

Tables 3 and 4 summarize the results of the scuffing and oil-off tests. The critical load for scuffing of the formulated 15W40 oil was increased by 50 to 100% at 1000 rpm, depending on the additive and loading. The unformulated base fluid experienced a decrease up to 30% and an increase of up to 140%, depending on the additive and loading.

Graphite and MoS<sub>2</sub> actually decreased the scuffing performance.

**Table 3: Percent Increase in Scuffing Performance/Load**

Oil/Additive	5:1	10:1	25:1	50:1	100:1
Untreated 15W40	-	-	-	-	-
15W40/EBA	79	66	79	85	N/A
15W40/TCP	95	52	54	66	73
15W40/BN	64	95	70	68	N/A
15W40/Graphite	51	62	74	N/A	N/A
15W40/MoS <sub>2</sub>	47	58	57	N/A	N/A
Untreated Basefluid	-	-	-	-	-
Basefluid/EBA	143	134	77	N/A	N/A
Basefluid/TCP	121	124	19	N/A	N/A
Basefluid/BN	50	50	38	N/A	N/A
Basefluid/Graphite	-32	-12	73	N/A	N/A
Basefluid/MoS <sub>2</sub>	4	-6	-15	N/A	N/A

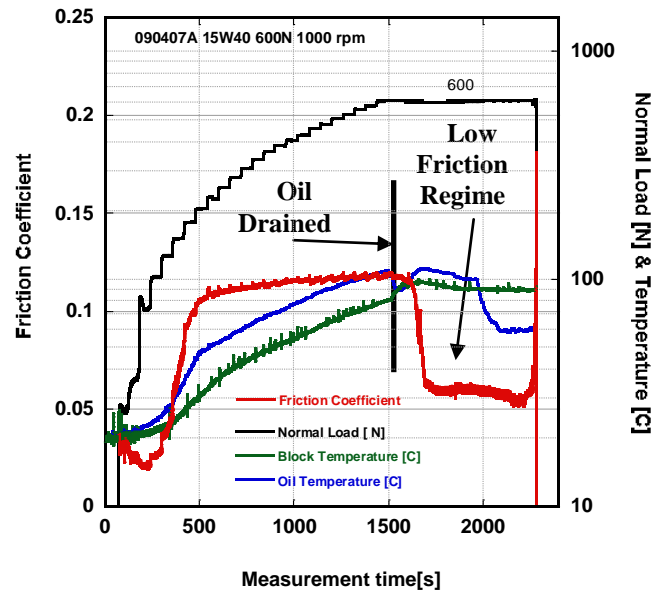
**Table 4: Average Oil-off Time (min), Excluding Low-Friction Tribofilm Run**

	15W40	Unformulated Fluid
Untreated	2.5	17
EBA	3.9	21
TCP	5	>300
BN	1.9	16
Graphite	3.4	15
MoS <sub>2</sub>	1.8	12

The EBA, TCP, and graphite additives increased the oil-off performance of the formulated 15W40 oil significantly and, in some instances, exhibited the formation of a low-friction tribofilm that further enhanced the oil-off performance. Tricresyl phosphate also produced a dramatic improvement in the oil-off performance for the unformulated basefluid.

The observation of a dramatic decrease in friction in a number of oil-off tests (particularly for those treated with TCP) prompted further investigation of this phenomenon. Figure 9 shows an example of the friction trace during a run on as-received formulated 15W40 oil that formed a low-friction tribofilm after the oil was drained from the container. Oil drained at approximately 1500 sec into the run after the load was increased to 600 N and held constant for 60 sec. Approximately 200 sec after the oil drained, the friction decreased dramatically, from ca 0.12 to ca 0.06. The

low-friction regime continued for another 500 sec, until scuffing occurred at approximately 2300 sec.

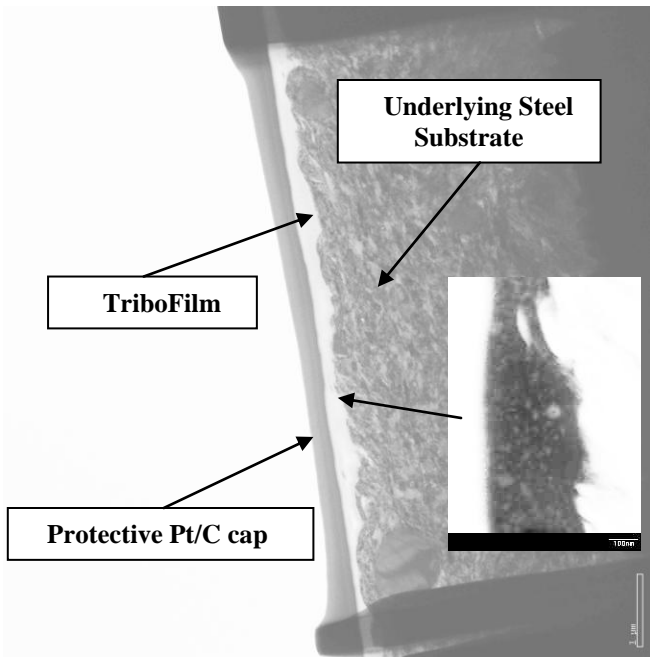


**Figure 9: Data Trace during Run that Exhibited Formation of a Low-Friction Regime**

To examine this further, an advanced analytical tool, FIBS [6,7], was employed to extract ultrathin, electron-transparent, slice of material from the block located inside of the contact zone between the rotating disc and block (from the sample that exhibited the low-friction behavior shown in fig. 9).

The FIBS process allows one to extract thin slices of material near the surface of samples. The thin slices (approximately 10 μm x 5 μm x 0.1 μm) are transferred to a TEM grid for subsequent imaging and analysis.

Figure 10 shows a low-magnification TEM image of a FIBS section extracted from a region that exhibited low-friction behavior prior to scuffing. The tribofilm is approximately 100-nm thick. The insert in fig. 10 shows a high-magnification dark-field image of the tribofilm. The insert reveals the presence of a large number of precipitates (10 to 20 nm in diameter) in the tribofilm. The film is heterogeneous, consisting of a matrix with smaller second phase material.



**Figure 10: TEM Image of Tribofilm on Steel Block Segment**

These samples, as well as samples from tests that did not exhibit low-friction regimes, were analyzed to determine if significant differences in the composition and structure of the precipitates and matrix of the tribofilm can account for the low-friction behavior.

It is anticipated that the information and knowledge gained from such studies will provide insight on the fundamental mechanisms involved in the complex chemical reactions that occur at tribological interfaces. Such information, coupled with nanomechanical properties (e.g., hardness and modulus) of the tribofilms will contribute to the development of models of tribofilm formation, and, eventually the development of advanced additive packages optimized for specific environments.

The goal of these activities is the development of models that predict the boundary friction properties as a function of environment. Current approaches [8, 9] assume boundary friction is constant and then proceed to calculate overall friction (e.g., Stribeck curves) as a combination of asperity/boundary friction and viscous (oil shearing) losses, taking into account lubricant viscosity, speed, temperature, configuration, and surface finish. The asperity friction is typically assumed to be a constant. Yet, in reality, the mechanisms that determine boundary friction, in particular, the shear strength of the tribofilm, are not constant. They depend on temperature and shear rate. In addition, the

composition and structure of the tribofilm are not necessarily constant, especially during severe off-normal events. Thus, it is critical to develop fundamental information on the chemistry and structure of tribofilm formation and their impact on the mechanical properties of the tribofilm.

## CONCLUSION

A series of lab-scale tests was performed to evaluate the impact of several different additives on the scuffing resistance of a formulated and unformulated mil-spec diesel engine lubricant. The results of the tests and subsequent analysis revealed the following:

- The scuffing resistance of formulated 15W/40 mil-spec oil was increased with additions of EBA, TCP, BN, MoS<sub>2</sub>, and graphite by 50 to 100%.
- The scuffing resistance of the unformulated base fluid increased by 50 to 150% with additions of EBA, TCP, or BN. Additions of MoS<sub>2</sub> or graphite had no effect, or slightly decreased the scuffing resistance.
- TCP and EBA increased the time to scuff of 15W/40 oil at 500 N under starved lubrication conditions by a factor less than two. The additives BN, MoS<sub>2</sub>, and graphite had little or no effect on the time to scuff.
- The time to scuff for unformulated oil (at 300 N) was dramatically increased with additions of TCP. Other additives showed little or no impact.
- Oil with additives that resulted in dramatic increases in time to scuff exhibited a low-friction regime after the oil was drained.
- The structure of the low-friction tribofilm is not homogeneous and consists of small nanometer-size precipitates.

## ACKNOWLEDGMENT

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