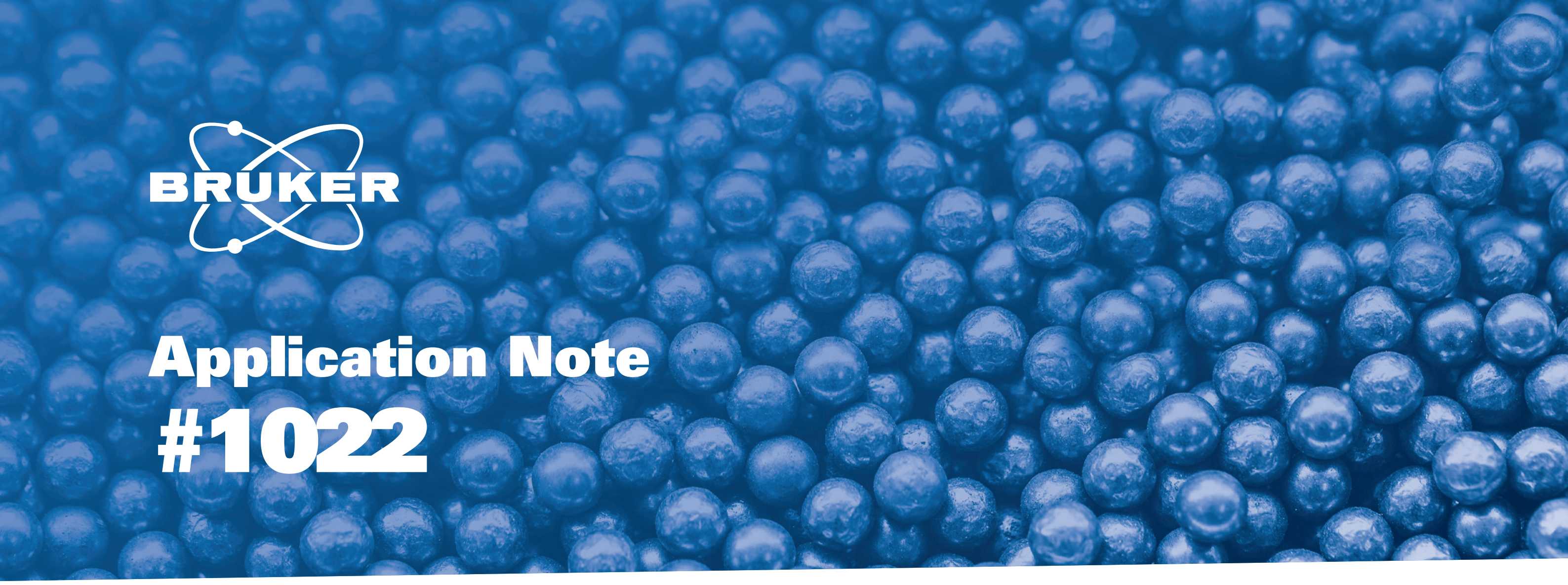


Application Note

#1022

Evaluation of Electric Motor Greases Using a Four-Ball Tester

Rapid advancement in electronic vehicle engine development is pushing the limits of conventional automotive greases, and new lubricants are required to withstand these extreme working conditions. High-performance lubricants for electric motor vehicles must withstand a wide range of loads, speeds, and temperatures to effectively reduce friction and wear.

Lubricant manufacturers and laboratories require tribological testing to screen and rank lubricant performance for specific applications, and to manipulate lubricant formulation for new applications and quality improvements. Although the ideal approach to assess grease performance is to test in a real system, this approach is expensive and time-consuming. Thus, there are numerous national and international testing standards to evaluate performance and load-carrying capability of various lubricants outside of a real system. One of the test methods widely used for lubricant additives selection and batch production quality control is the four-ball test.

This application note introduces a practical testing solution for critical and rapid assessment of electric motor greases in a controlled environment and with automated varying test conditions using the Bruker UMT TriboLab® system. Experimental values of wear rate, frictional torque, coefficient of friction, critical seizure, and weld points are determined to analyze the wear-resistant properties of commercially available electric motor greases.

Performing Four-Ball Tests

In a typical four-ball test setup on the Bruker UMT TriboLab (Figure 1), the upper holder contains a stationary steel ball which is loaded against three lower steel balls firmly secured in a rotating cup holder. Ball-to-ball contact areas are covered with test lubricant or grease. A heater equipped with a thermocouple and PID feedback loop is used to precisely control the operating temperature of the lubricant (up to 400°C). Constant or progressive load (up to 2 kN) can be accurately applied using a Bruker Gold Series linear-force sensor. Rotation is central along the symmetry axis of both the upper and lower holders, allowing even load repartition. The frictional torque (up to 10 N·m) is measured by a Bruker torque sensor connected to the tribotester.

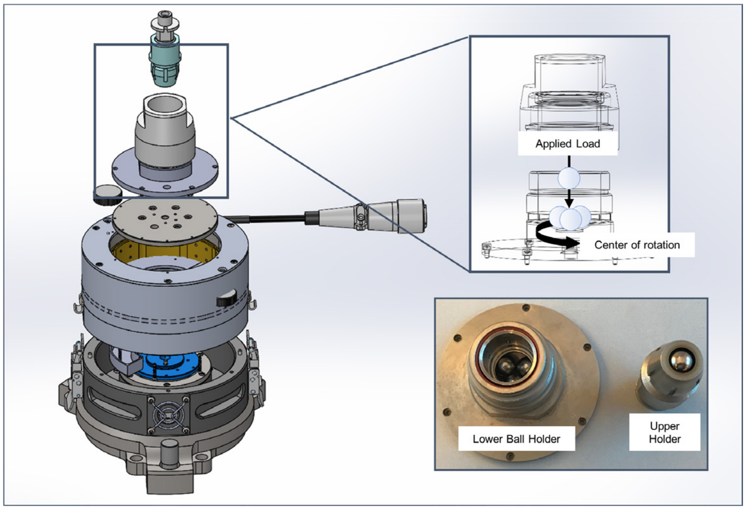


FIGURE 1

Schematic diagram of a four-ball rotary tester on the Bruker UMT TriboLab.

Table 1 summarizes a few standardized four-ball test protocols described by ASTM to evaluate the performance of various lubricating fluids and greases. All protocols in Table 1 can easily be performed with the UMT TriboLab due to its modularity.

TABLE 1

Summary of standardized four-ball tests to evaluate the performances of various lubricants.

TEST METHOD	DESCRIPTION	LOAD (N)	SPEED (RPM)	TEMPERATURE (°C)	TEST DURATION
ASTM-D2266	Wear prevention - Greases	392 ± 2	1200 ± 60	75 ± 2	60 ± 1 min
ASTM-D2596	Extreme pressure properties - Greases	Step load, starting from 784	1770 ± 60	27 ± 8	10 ± 2 s per load step. (New balls each step)
ASTM-D2783	Extreme pressure properties - Fluids	Step load, starting from 784	1760 ± 40	18 to 35	10 ± 2 s per load step. (New balls each step)
ASTM-D4172	Wear prevention - Fluids	147 ± 2 or 392 ± 2	1200 ± 60	75 ± 2	60 ± 1 min
ASTM-D5183	Coefficient of Friction - Lubricants	Wear-in: 392 Test: Step load, starting from 98.1	600	75 ± 2	Wear-in: 1 h Test: 10 min per load step
ISO-20623	Extreme pressure and anti-wear properties - Fluids	Step load, starting from 100	1450 to 1500	Room temperature	10 ± 0.2 s or 60 ± 0.5 s

Assessing Anti-Wear Performance of Electric Motor Greases

In this study, the wear-preventive characteristics of electric motor greases were critically evaluated using TriboLab. The four-ball standard test procedure (ASTM D2266-01) was adopted to determine the lubricated wear behavior and wear rate of two commercially available synthetic bearing greases: polyolester (POE) and polyurea (PU).
The tests were carried out by imposing a 392 N load against three lower balls (AISI 52100 steel, Ø12.7 mm) covered with a layer of the test grease. Tests were carried out at a speed of 1200 rpm for 60 min in a temperature-controlled environment of 75°C. The average wear scar on the three lower balls was then measured with an optical microscope under 4.5x magnification to compare anti-wear properties. Subsequently, the wear volume for a given scar diameter and the wear coefficient were determined from the following equations obtained from available literature[1,2]:

$$\mathrm{V} = (1.55\mathrm{e}^{-2}\mathrm{d}^3 - 1.03\mathrm{e}^{-5}\mathrm{L})\mathrm{d}$$

where *V* is the wear volume, *d* is the wear scar diameter in mm and *L* is the applied load in kg.

$$\mathrm{K} = \frac{\mathrm{V} \times \mathrm{H}}{23.3\mathrm{t}} \times 0.408\mathrm{L}$$

where *H* is 720 g/mm², *t* is the test duration in minutes, and 23.3 is in rpm. Literature also reports direct wear calculation from white light interferometry areal topography measurements, combining a large field of view and unique nanometer vertical resolution (Figure 2 and Table 2).

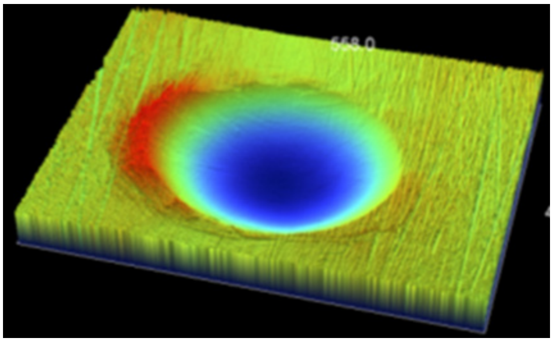


FIGURE 2

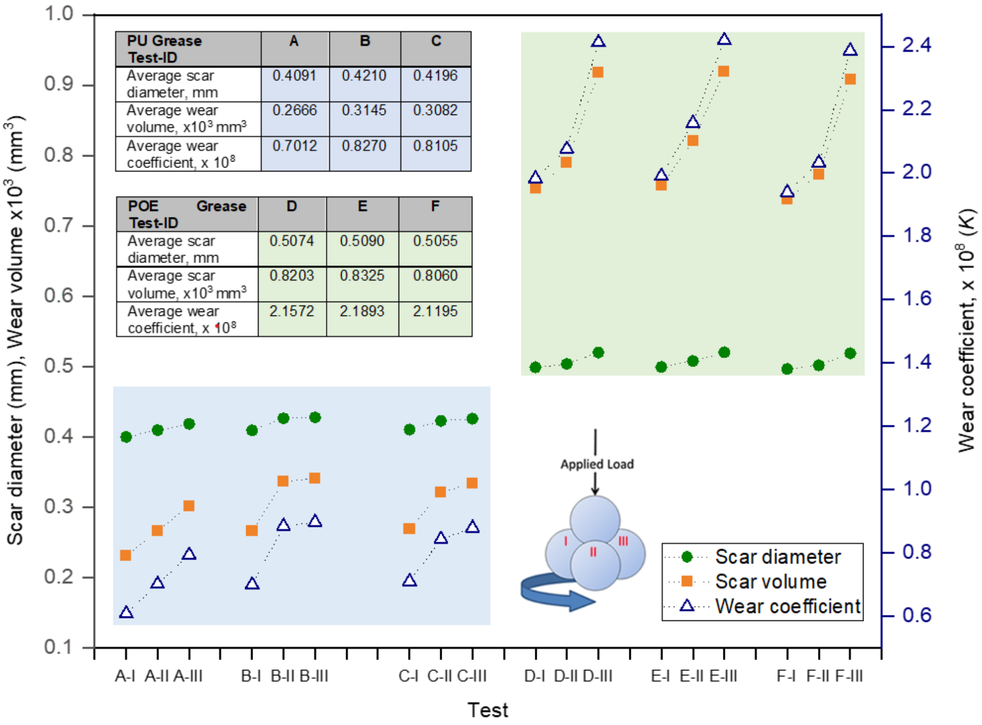
Topography mapped using a Bruker white light interferometry 3D profiler.

Volume Calculations	[μm³]
Natural Volume	294813.28
Normal Volume	0.82
Negative Volume	97191.68
Positive Volume	17990.81
Net Missing Volume	79100.87
Total Displaced Volume	115182.49

TABLE 2

Example of direct wear volume calculation using topography information from Figure 2.

For a tetrahedral-geometry four-ball test, rotational symmetry influences the homogeneity of the force applied and distributed among the three lower balls. TriboLab achieves this homogeneous force distribution through its unique four-ball cup design that firmly secures the lower balls to positions parallel to the axis of rotation, thus contributing to accurate measurements and meaningful conclusions.



PU Grease Test-ID	A	B	C
Average scar diameter, mm	0.4091	0.4210	0.4196
Average wear volume, $\times 10^3$ mm^3	0.2666	0.3145	0.3082
Average wear coefficient, x 10^8	0.7012	0.8270	0.8105

POE Grease Test-ID	D	E	F
Average scar diameter, mm	0.5074	0.5090	0.5055
Average scar volume, $\times 10^3$ mm^3	0.8203	0.8325	0.8060
Average wear coefficient, x 10^8	2.1572	2.1893	2.1195

FIGURE 3

The scar diameters, wear volumes, and wear coefficients of PU grease (A, B, C) and POE grease (D, E, F). The triplicate tests demonstrated highly repeatable and reproducible results. The roman numbers I, II and III denote the three steel balls in the test cup.

One-hour metal sliding tests with PU and POE greases showed very consistent wear scars, as depicted in Figure 3. The circular shape of the scars (see Figure 4) confirms that the balls remained affixed during the tests. It is also worth noting that the average scar diameter of 0.4166 mm from PU grease matches the result reported in the manufacturer's technical datasheet. This tool-to-tool correlation not only confirms the accuracy of TriboLab's four-ball test implementation, but also supports the suitability of TriboLab for grease quality control.

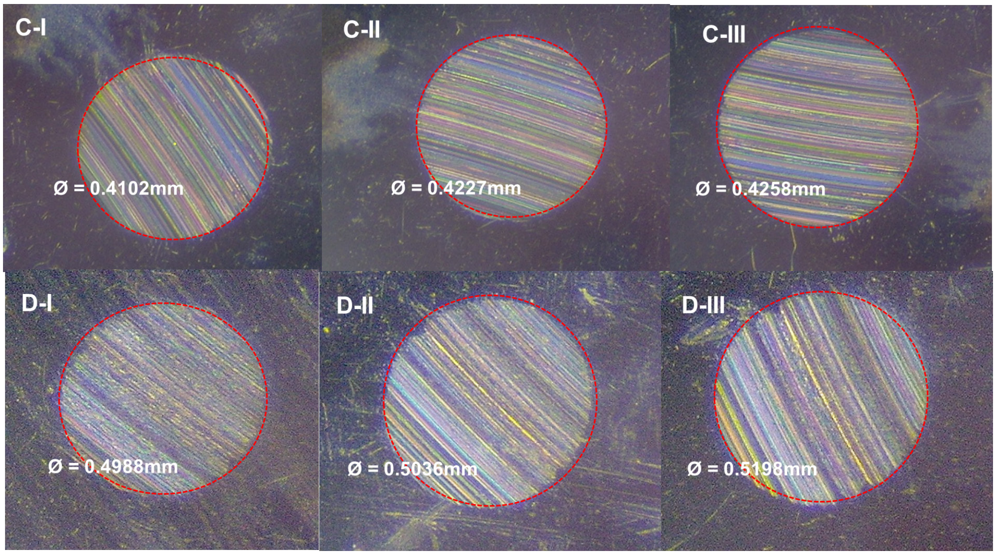


FIGURE 4

Optical micrographs of wear scars on each of the lower steel balls. The test with PU grease (C-I, C-II, and C-III) produced smaller scars compared to the test using POE grease (D-I, D-II, and D-III).

Results plotted in Figure 3 were also highly repeatable and reproducible, demonstrating high repeatability of wear scar measurements (PU: 0.4166 ± 0.0065 mm and POE: 0.5073 ± 0.0018 mm) with a 95% confidence limit. However, such minimal variation when translated into wear volumes resulted in large variations in wear coefficients (wear rates). Literature suggests the variation is due to running-in effects that depend on the speed, load, temperature, and grease additives.[1,3] Nonetheless, it is accepted that suitable greases are those with lower wear rates (smaller wear coefficients and wear volumes). Based on the experimental data obtained in this study, it can be concluded that PU grease, with lower wear scar and wear rate, gives better wear protection than the POE grease.

Determining Friction Coefficient through Step-Load Tests

Another critical parameter for grease is to minimize frictional forces between surfaces in contact. Hence, coefficient of friction (COF) is a very common metric for lubricant evaluation and is derived from well-known step-load tests (ASTM D5183-21). Due to inherent flexibility and programmable load, the UMT TriboLab allows step-load testing within the same platform as four-ball testing. As an example, the PU and POE greases were subjected to step-load tests. The measured friction torque was used to calculate the coefficient of friction based on the following equation, and those COF results are summarized in Table 3.

$$\mu = 0.22248\frac{\mathrm{T}}{\mathrm{W}}$$

where T is the frictional torque (kg·mm) and W is the applied load (kg). The test protocol described in ASTM D5183 is suitable for field performance assessments and tool-matching correlation studies.

	Wear-in	Test
Temperature	75 ± 2°C	75 ± 2°C
Speed	600 rpm	600 rpm
Duration	60 min	10 min
Load	392 N per 60 min	98.1 N per 10 min increment to a load that indicates incipient seizure

TABLE 3

Test protocols to determine coefficient of friction of lubricants, as described in ASTM D5183-21.

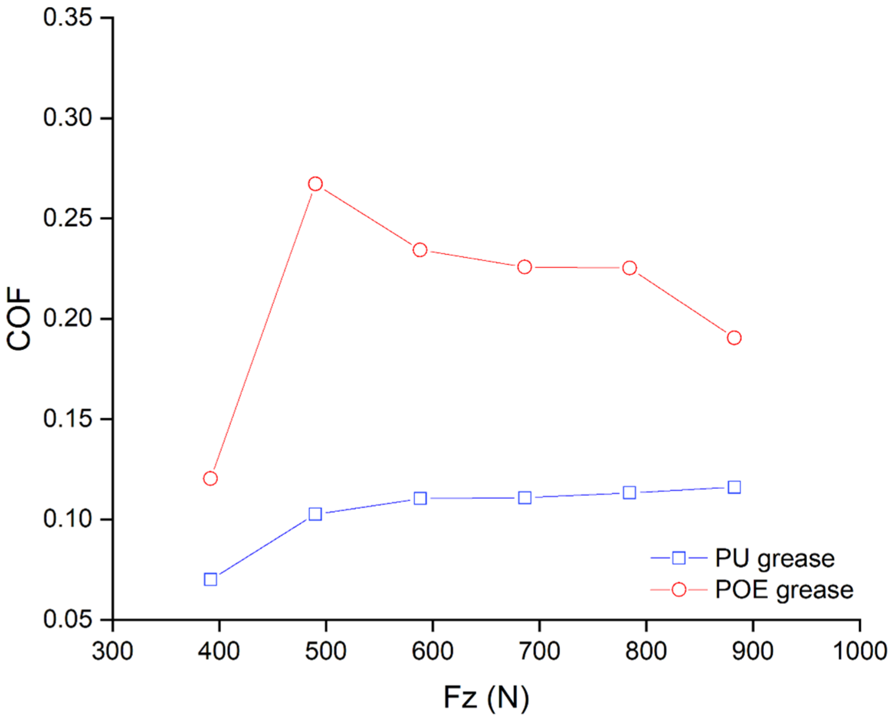


FIGURE 5

Coefficient of friction as a function of applied load for POE and PU greases.

The calculated COF for both electric motor greases are represented in Figure 5. Welding was not observed for either grease, but the load-carrying capacity of the PU and POE are distinctly different under extreme pressure (EP) conditions. Firstly, it is observed that the PU grease demonstrates lower friction coefficient and wear scar than the POE grease under the same operating conditions; thus, the former is identified as a better grease for high-load and high-pressure applications.

Secondly, the COF of the PU grease is almost constant when loaded incrementally from 490.1 N to 882.5 N. This suggests that the PU grease promotes hydrodynamic effects in the step-load tests, ensuring no seizure occurred. On the other hand, the POE grease has poor resistance to seizure. The COF of POE drastically increases by more than double when the applied load increases from 392 N (μ = 0.1204) to 490.1 N (μ = 0.2673). It is very likely that the incipient seizure can be attributed to EP film or lubrication failure, where the POE grease undergoes chemical reaction changes with possible decomposition.[4] The decrease in friction coefficient for applied loads above 500 N is attributed to a mixed-lubricant regime caused by direct asperity contacts between steel balls. In such a regime, metal-to-metal contact induces oxide formation, leading to a thin tribofilm layer which further reduces friction.

Identifying Seizure and Weld

Most bearings could theoretically outlive the equipment on which they are installed, but deterioration and improper use of lubricant can lead to premature failure. Lubricant loses its load-carrying capacity as the lubricating film becomes too thin to prevent metal-to-metal contact between rolling elements and raceways, leading to seizure and welding.

While field testing the load-carrying capacity of a lubricant is expensive and infeasible for lubricant manufacturers, TriboLab offers a quick solution where lubricant failure can be detected using the four-ball test kit. In a simulated test to induce seizure and welding, the steel balls covered with a thin layer of PU grease were subjected to a 1000 N load at 1000, 1500, 2000, and 2500 rpm, with results shown in Figure 6.

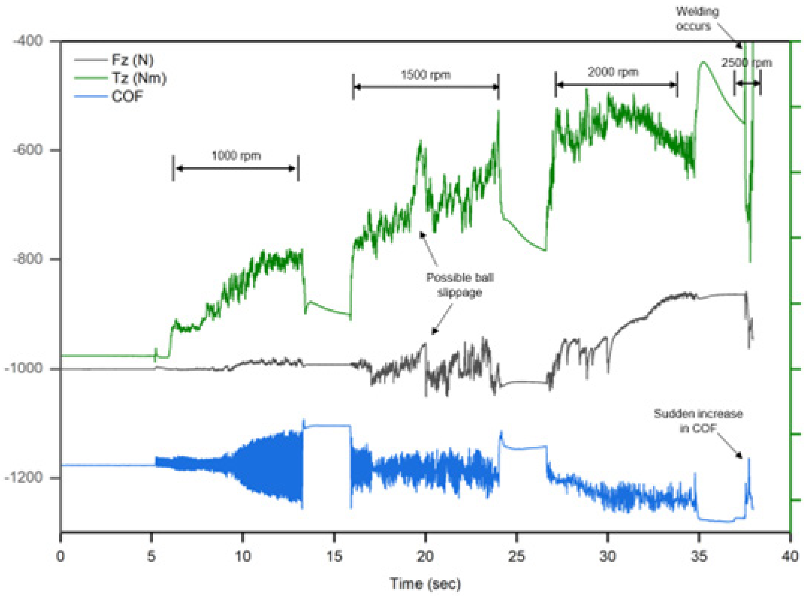


FIGURE 6

Changes in frictional torque (T_z) at rotation speeds of 1000, 1500, 2000, and 2500 rpm. The drastic T_z surge at 2500 rpm corresponding to an increase in COF indicates complete seizure, where welding of the steel balls took place.

The COF shows a decreasing trend as the rotation speed increased (0.019 at 1000 rpm, 0.018 at 1500 rpm, 0.011 at 2000 rpm), which indicates a switch from the boundary regime to mixed boundary of the PU grease. The sudden changes in rotational torque (T_z) and coefficient of friction (COF) in Figure 6 give a good indicator for seizure and weld. At 2000 rpm, the T_z increases from 4.2 N·m to 6.8 N·m at $t = 20$ s before dropping back to ~5 N·m. Although the COF remains in the range of 0.018, the F_z variations suggest the possibility of balls slipping due to incipient seizure. Complete seizure took place around $t = 38$ s, where T_z drastically increased above 10 N·m and the COF value increased suddenly. The high torque value brings the tribometer to a forced stop as it exceeds the maximum drive torque of the tribometer motor. This safety feature not only protects the components of Bruker UMT TriboLab sensors from overstress and damage, but it also provides convenient automatic seizure detection, enabling unattended tests and fast screening.

Figure 7 shows the surface of the welded steel balls, where the upper ball is severely worn out, and its metal surface has been transferred to the lower balls. The growth and extension of the localized damage on the lower balls constitutes seizure. This visual, non-standardized evaluation is suitable for quick performance assessment of various lubricating fluids and greases.

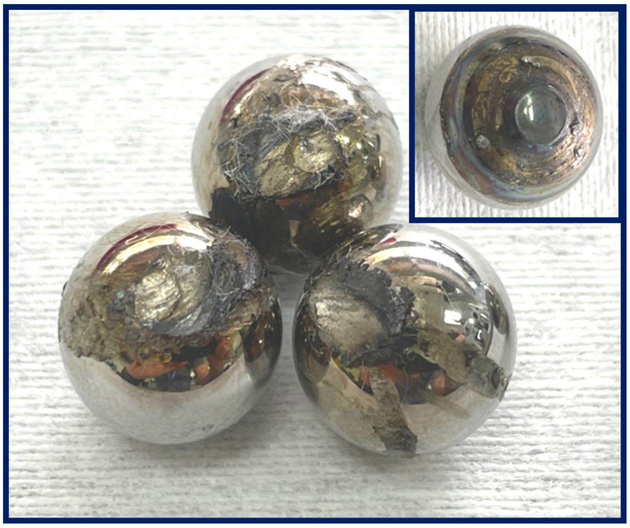


FIGURE 7

Severely damaged steel balls with signs of oxidation, slipping, and welding.

Conclusions

In the scope of rapidly evolving electric vehicle technology, the Bruker UMT TriboLab provides an agile platform enabling accurate simulation of real tribo-conditions and fast screening for lubricants and greases that sustain high rotational speed together with high torque at zero speed. This application note has demonstrated high-precision four-ball tribotesting to discern the anti-wear and extreme properties of lubricants at various loads and rotating speeds according to internationally adopted and recognized standards. The four-ball test kit is designed with rotational symmetry to allow proper assessment of lubricant properties such as friction, load-wear index, last non-seizure load, initial seizure load, weld point and many others. The unique modular concept of TriboLab provides complete and uncompromised testing of a wide range of friction-wear mechanisms and operating conditions to benchmark innovative lubricants and greases.

References

1. Torbacke, M., Rudolphi, A., and Kassfeldt, E. “Lubricants: Introduction to Properties and Performance,” *John Wiley & Sons*. (2014). http://dx.doi.org/10.1002/9781118799734
2. Rowe, C., Peterson, M., Wiler, W. “Wear Control Handbook”, *American Society of Mechanical Engineers*. (1980).
3. Peterson, M. ”Design Considerations for Effective Wear Control”, *American Society of Mechanical Engineers*. (1980).
4. Sethuramiah, A., Okabe, H., Sakurai, T., “Critical Temperatures in EP Lubrication,” *Wear*. (1973). https://doi.org/10.1016/0043-1648(73)90134-8

Relevant Standards

ASTM D2266-01, “Standard Test Method for Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method),” *ASTM International*. (2015).

ASTM D2596-20, “Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method),” *ASTM International*. (2020).

ASTM D2783-19, “Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Fluids (Four-Ball Method),” *ASTM International*. (2019).

ASTM D4172-20, “Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method),” *ASTM International*. (2020).

ASTM D5183-21, “Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine,” *ASTM International*. (2021).

ISO 20623:2017, “Petroleum and related products - Determination of the extreme-pressure and anti-wear properties of lubricants - Four-ball method (European conditions),” *ISO*. (2017).

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