Laboratory tools for lubricant deposit assessment

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Deposit formation remains a critical challenge in lubricant performance, impacting reliability, efficiency and equipment life. This article examines the complex mechanisms behind sludge, varnish and coke formation, and highlights the role of advanced laboratory testing methods in predicting, evaluating and mitigating deposit risks during lubricant development and formulation.

Introduction

Modern lubricant development is driven by efficiency, durability and sustainability objectives. While high-performance lubricants contribute to energy savings and longer equipment life, deposit formation remains a major cause of failure across industrial and automotive applications.

Deposits can impair lubricant circulation, promote component sticking and wear, reduce system reliability, and in severe cases lead to catastrophic failures. Field experience highlights their significant impact on maintenance costs and downtime.

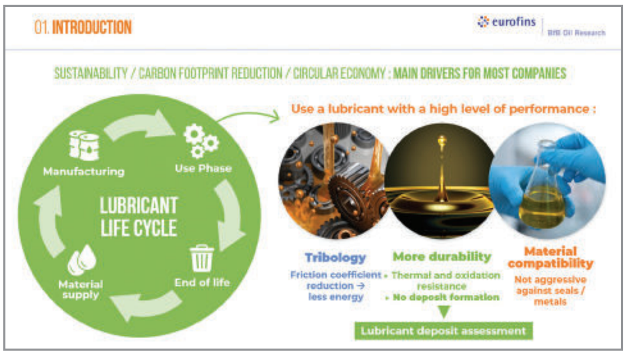

***Figure 1:** High-performance lubricants support sustainability goals.*

The increasing use of Group II, Group III and synthetic base oils, which generally exhibit lower solvency, further increases the need to control deposit formation through careful formulation design.

As a result, reliable laboratory tools are essential to evaluate deposit tendencies and support lubricant development at an early stage.

Deposit types: understanding their nature and impact

Lubricant deposits differ in composition, appearance and formation conditions.

Sludge is a soft, viscous material generated mainly by oxidation and contamination. It is commonly found in reservoirs, gearboxes and hydraulic systems, where it may impair heat transfer and increase wear.

Varnish is a thin, hard film formed from oxidised insoluble species. Frequently encountered in turbines and hydraulic systems, it is a common cause of valve sticking and operational instability.

Lacquer is a hard, glossy deposit produced under severe thermal stress, typically on pistons and other hot surfaces.

Coke consists of carbon-rich residues generated by thermal cracking at very high temperatures, particularly in turbochargers and local hot spots.

Because each deposit originates from different degradation mechanisms, no single test can adequately assess all deposit risk pathways, making it essential to use targeted laboratory methods for accurate assessment.

From thermal stress to deposits: degradation mechanisms

Deposit formation results from a combination of chemical and physical degradation processes that occur simultaneously in lubricated systems.

Oxidation plays a central role in deposit formation. It leads to the generation of organic acids, insoluble by-products and varnish precursors. This process is accelerated by several factors, including high temperatures, oxygen exposure, the presence of metal catalysts such as iron and copper, and the depletion of antioxidant additives. Oxidation therefore predominantly leads to the formation of sludge and varnish.

Thermal degradation becomes dominant at higher temperatures. Under these conditions, base oils undergo cracking and polymerisation reactions, which generate carbonaceous residues. This mechanism is mainly responsible for the formation of lacquer and coke, particularly in localised hot spots.

In addition to oxidation and thermal degradation, several other contributing factors must be considered. Phenomena such as micro dieseling can generate carbonaceous insolubles, while electrostatic discharge can promote degradation reactions leading to varnish formation. Contamination, water presence, base oil solvency limitations and repeated thermal cycling also significantly influence deposit formation.

In real operating environments, these mechanisms interact with one another, creating complex degradation pathways. This complexity explains why no single laboratory test is sufficient, and why multiple complementary methods are required for a comprehensive evaluation.

Laboratory tools for deposit assessment

Because field tests are costly and time-consuming, laboratory bench tests offer controlled and cost-effective solutions for screening and evaluating lubricant performance. As no single method can fully reproduce real operating conditions, combining complementary techniques is essential for a reliable assessment of deposit formation. A variety of laboratory tests has therefore been developed to simulate different stresses, including oxidation, thermal degradation and surface interactions.

Oxidation tests (Dry-TOST, Sludge-TOST)

Oxidation tests are widely used to assess lubricant resistance to degradation. The conventional Turbine Oil Stability Test (TOST, ASTM D943) evaluates oxidation by exposing the oil to oxygen, water and metal catalysts at around 95°C, with oxidation monitored through the increase in acid number.

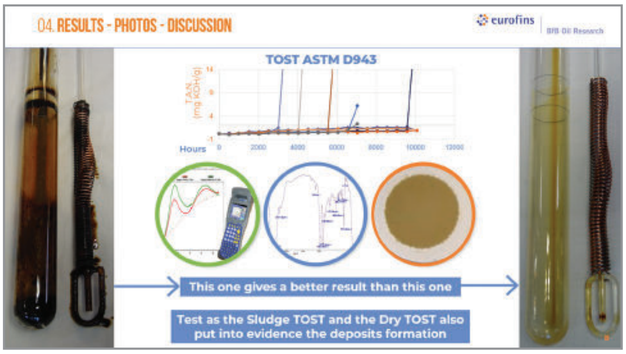

Figure 2: *Conventional TOST does not assess deposit formation.*

However, its relevance for deposit formation is limited. Greater emphasis should be placed on the Dry TOST method, performed without water and at higher temperatures (typically 120°C), which promotes the formation of insolubles and varnish precursors. As such, Dry TOST provides a more representative evaluation of deposit formation, particularly for modern low-solvency base oils.

The Sludge TOST further complements this approach by focusing on the gravimetric quantification of insoluble materials formed during oxidation, providing a direct indication of sludge-forming tendencies.
To complete the assessment, it is essential to go beyond standard parameters and include insolubles, antioxidant depletion (Remaining Useful Life Evaluation Routine (RULER)), varnish potential (membrane patch colorimetry (MPC)) and Fourier Transform Infrared (FTIR) oxidation markers.

Micro-Coking Test (MCT)

The Micro Coking Test (GFC Lu 27-A) specifically targets high-temperature deposit formation. In this method, a small oil sample is subjected to a controlled temperature increase, typically ranging from approximately 230°C to 280°C, although other temperature profiles can be applied depending on the test objectives, on a heated surface. This promotes the formation of thermal residues under severe conditions.

The test provides key outputs such as the initial temperature at which deposits begin to form and a cleanliness rating commonly referred to as lacquer merit. It is particularly useful as a rapid screening method, allowing efficient comparison between formulations and evaluation of additive performance.

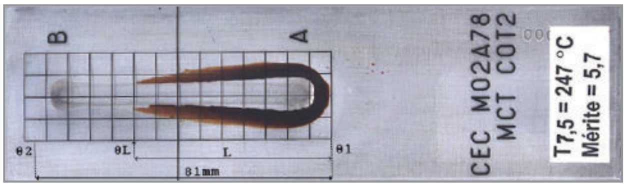

Figure 3: *Example of Micro Coking Test (MCT) results.*

The MCT is especially relevant for engine oils, including heavy duty diesel oils (HDDO), and for applications involving high thermal stress. It complements oxidation tests by providing insight into thermal stability and cleanliness under extreme conditions.

Panel Coker Test (PCT)

Panel Coker Tests are widely recognised tools for evaluating the tendency of lubricants to form deposits on hot surfaces, which are representative of critical components such as pistons, turbochargers and turbine parts. Unlike bulk oxidation tests, these methods provide a direct and visually intuitive assessment of deposit formation under severe thermal conditions.

Panel Coker Test – GFC Method

The Panel Coker Test GFC (GFC-Lu-29) evaluates the tendency of a lubricant to form deposits on a continuously heated metal surface under oxidative conditions. Oil is delivered at a controlled flow rate onto an inclined panel maintained at 288°C or 305°C, while an air flow promotes oxidation. Over a typical 24-hour period, thermal and oxidative stresses generate deposits such as varnish, lacquer and coke.

At the end of the test, the panel is assessed visually and quantitatively through deposit ratings, gravimetric measurements and oil weight loss. The method is particularly relevant for applications involving continuous exposure to hot surfaces, such as turbochargers, piston under crowns and circulating systems.

The PCT GFC method is highly discriminating and useful for:

- Optimising detergent and dispersant systems
- Evaluating antioxidant robustness
- Assessing base oil solvency effects

In addition to its technical value, the visual appearance of the panels provides a simple and effective way to compare formulation performance.

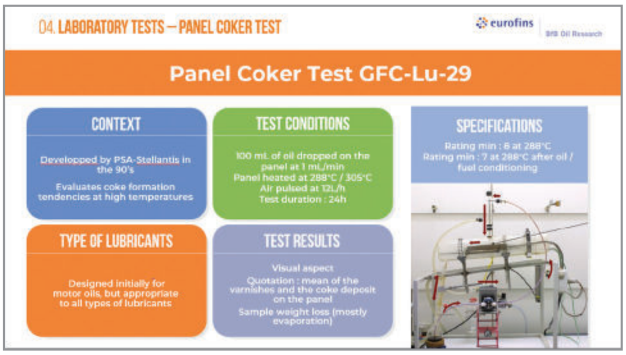

Figure 4: *Panel Coker Test (PCT) – GFC method.*

Panel Coker Test – method FTM

The Panel Coker Test FTM (FTM-791B-3462) offers a complementary approach by introducing dynamic mechanical stressing in addition to thermal exposure. In this method, approximately 300 mL of lubricant is placed in a reservoir inclined at around 25°, while a comb-like rotor rotates at high speed (about 1000 rpm). This mechanical action splashes the oil onto a heated aluminum or steel panel maintained at around 315°C or higher.

Unlike the GFC method, where the oil flows continuously, the FTM method subjects the lubricant to intermittent high-temperature contact, closely simulating conditions such as those encountered in engines, bearings or gear systems where oil is repeatedly projected onto hot surfaces.

The test is typically conducted over a shorter duration (around 8 hours), incorporating start–stop cycles that further increase stress severity and better replicate real operating conditions. During the test, the repeated projection of oil droplets onto the hot panel promotes rapid thermal degradation and the formation of carbonaceous deposits.

At the end of the test, the deposits formed on the panel are evaluated both visually and by measuring their mass. The total weight of coke deposited provides a quantitative indicator of the lubricant's tendency to form hard carbonaceous residues. Oils can thus be ranked according to their deposit-forming tendency, with lower deposit masses corresponding to better performance.

The FTM Panel Coker Test is particularly sensitive to:

- Base oil thermal stability
- Additive package behavior at very high temperatures
- Volatility and evaporation characteristics

Its ability to reproduce severe dynamic conditions makes it a valuable screening tool during formulation development. The combination of deposit mass measurements and visual assessment provides rapid and highly discriminating results.

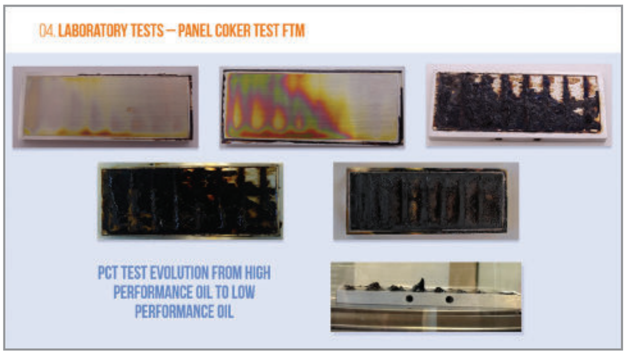

Figure 5: *Panel Coker Test (PCT) results – FTM method.*

Conclusion

Deposit formation represents a critical challenge for both automotive and industrial oils. It results from a complex interplay between oxidation, thermal stress and operating conditions.

Laboratory tests such as TOST, Micro Coking and Panel Coker provide complementary insights into lubricant behavior under severe conditions. Their combined use enables early detection of deposit-related risks, optimisation of additive packages and improved reliability and durability in service.

Ultimately, the laboratory assessment of deposit formation is an essential pillar of lubricant development, enabling the selection of formulations that ensure cleanliness, performance and long-term equipment reliability.

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