SUSTAINABLE GREASE FORMULATIONS: EVALUATING KEY PERFORMANCE PARAMETERS AND TESTING METHODOLOGIES

1 Introduction

Grease is an essential lubricant used across various industries to ensure the efficiency and longevity of machinery by reducing friction, wear, and corrosion. Grease forms a protective barrier that seals out contaminants such as dirt, dust, and water, preventing corrosion and damage, especially in harsh operating environments [1]. Moreover, grease reduces maintenance costs by prolonging the intervals between necessary servicing and repairs, as its ability to stay in place and continue lubricating over extended periods reduces the need for frequent reapplication (2].

However, traditional grease formulations derived from petroleum-based mineral oils have a significant environmental footprint, contributing to greenhouse gas emissions and environmental degradation throughout their lifecycle [3]. With global energy consumption predicted to increase substantially in the coming decades by as much as 50% by 2050, the grease industry's reliance on mineral oil exacerbates environmental pressures associated with traditional grease production and use. Therefore, there is an urgent need for more sustainable alternatives [4].

One promising solution is the development and adoption of bio-based greases derived from renewable resources such as vegetable oils, animal fats, or microbial sources [5-7]. Compared to petroleum-based greases, bio-based greases offer several advantages: reduced dependency on finite fossil fuels, lower carbon footprint, and often improved biodegradability, minimizing environmental impact in case of leaks or spills [8, 9].

Despite the clear environmental benefits, the adoption of bio-based greases faces challenges. Their performance characteristics, such as viscosity, thermal stability, and wear protection, must meet or exceed those of traditional greases to gain widespread market acceptance [6, 10]. Furthermore, the economic feasibility and scalability of producing bio-based greases for a global market need to be addressed.

This paper provides a comprehensive overview of grease formulations, lubrication, and the key performance parameters of lubricating grease, with a particular focus on the ASTM standards and test apparatus used to evaluate these parameters. The paper also examines the challenges and research directions necessary to advance the field of sustainable grease formulations, considering the broader implications for the environment and energy consumption within the grease industry.

2 Overview of Grease

2.1 Grease formulations

Unlike oil, which can be thin and runny, grease contains a thickener system that provides consistency and structure allowing grease to excel in applications where fluidity makes oils unsuitable. Thicker consistency allows grease to adhere to surfaces, making it ideal for high-pressure environments where oil can be squeezed out, high-speed applications where oil gets flung away, and environments with water or dust where oil can be washed away or contaminated. Grease acts as both a lubricant, reducing friction and wear, and a sealant, keeping out contaminants and protecting machinery in harsh environments with extreme temperatures, moisture and abrasive particles [1].

Grease formulations typically consist of three main components: base oils, thickeners, and additives. Each component plays a role in determining the performance and suitability of the grease for various applications.

Table 1. Various vegetable oils and their applications [15-19].

Vegetable Oil	Major Applications	World Production (Mt/year)
Canola oil	Hydraulic oils, tractor transmission and metal working fluids	49.7
Castor oil	Gear lubricants, greases	1.9
Coconut oil	Gas engine oils	3.4
Jojoba oil	Cosmetic industry, lubricant applications	0.018
Linseed oil	Stains, varnishes, lacquers	0.66
Olive oil	Automotive lubricants	18.7
Palm oil	Grease, rolling lubricant	73
Rapeseed oil	Air compressor-farm equipment, chain saw bar lubricant	27.4
Safflower oil	Enamels, light-colored paints, diesel fuel, resins	0.08
Soybean oil	Plasticizers, hydraulic oil, printing inks, pesticides, disinfectants	59.2
Sunflower oil	Grease, diesel fuel substitutes	19.4
Tallow oil	Lubricants, plastics	9.8

2.1.1 Base oils

The base oil is the primary lubricating component, typically constituting 65-95% of the grease formulation. It provides essential properties, including viscosity and film strength, which are crucial for reducing friction and wear between moving parts [10]. Base oils can be classified into three main categories: mineral, synthetic, and vegetable oils.

Mineral oils derived from crude petroleum are cost-effective and perform well across a wide range of applications. They offer good lubrication properties and thermal stability, making them suitable for many industrial and automotive applications. Synthetic oils, such as polyalkylene glycol (PAG) and polyalphaolefins (PAO), offer improved oxidative stability, low-temperature fluidity, and high-temperature viscosity retention, making them ideal for applications involving high loads, high speeds, or extreme temperatures [11]. Vegetable oils, derived from plant sources such as soybean, rapeseed, or palm oil, are biodegradable and renewable, making them attractive for environmentally friendly grease formulation. However, they may require stabilizing additives to enhance their oxidative stability and performance characteristics [12]. Oxidative stability is crucial for any base oil due to oxidizing reactions within the base oil composition. If the oil is too unsaturated, it breaks down faster, leading to ineffective grease. This is particularly important for vegetable oils, as many are unsaturated and require stabilizers for additional support. Table 1 shows various vegetable oils and their applications in grease formulations.

The choice of base oil depends on factors such as the intended application, operating temperatures and speeds, load conditions, and environmental considerations. In some cases, a blend of different base oils may be used to achieve the desired performance characteristics. For example, blending rapeseed oil with PAO significantly improves its low-temperature properties, enhancing fluidity and reducing pour point temperature from -22°C to -31°C [13]. Additionally, a mixture of safflower oil with polyol esters has shown promising results in enhancing oxidation stability [14]. These blends are not only effective in improving specific performance attributes but also maintain compatibility with anti-wear additives, ensuring that the lubricity of the final product is not compromised. Such blends can be used as base stocks in the production of environmentally friendly greases, meeting multiple performance criteria while also being eco-friendly.

2.1.2 Thickeners

Thickeners, comprising 5-35% of the grease formulation, are responsible for giving grease its characteristic semi-solid consistency [20]. Their primary function is to stabilize grease positioning and maintain continuous contact with the lubricated surfaces, preventing leakage or being squeezed out under pressure. Thickeners play a crucial role in ensuring effective lubrication, even in applications involving high loads or complex geometries.

In addition to providing the desired consistency, thickeners also influence other important properties of the grease, such as mechanical stability and water resistance. The choice of thickener can significantly impact the grease's ability to withstand mechanical shear forces, as well as its resistance to water washout or degradation in the presence of moisture.

The most commonly used thickeners in grease formulations are metallic soaps, particularly lithium, calcium, sodium, and aluminum soaps [21]. These soaps are classified as surfactant amphiphiles, which are compounds with a dual affinity for both water (hydrophilic) and oil (lipophilic) [20]. The unique molecular structure of amphiphiles, with a nonpolar hydrocarbon tail and a polar ionic head group, allows them

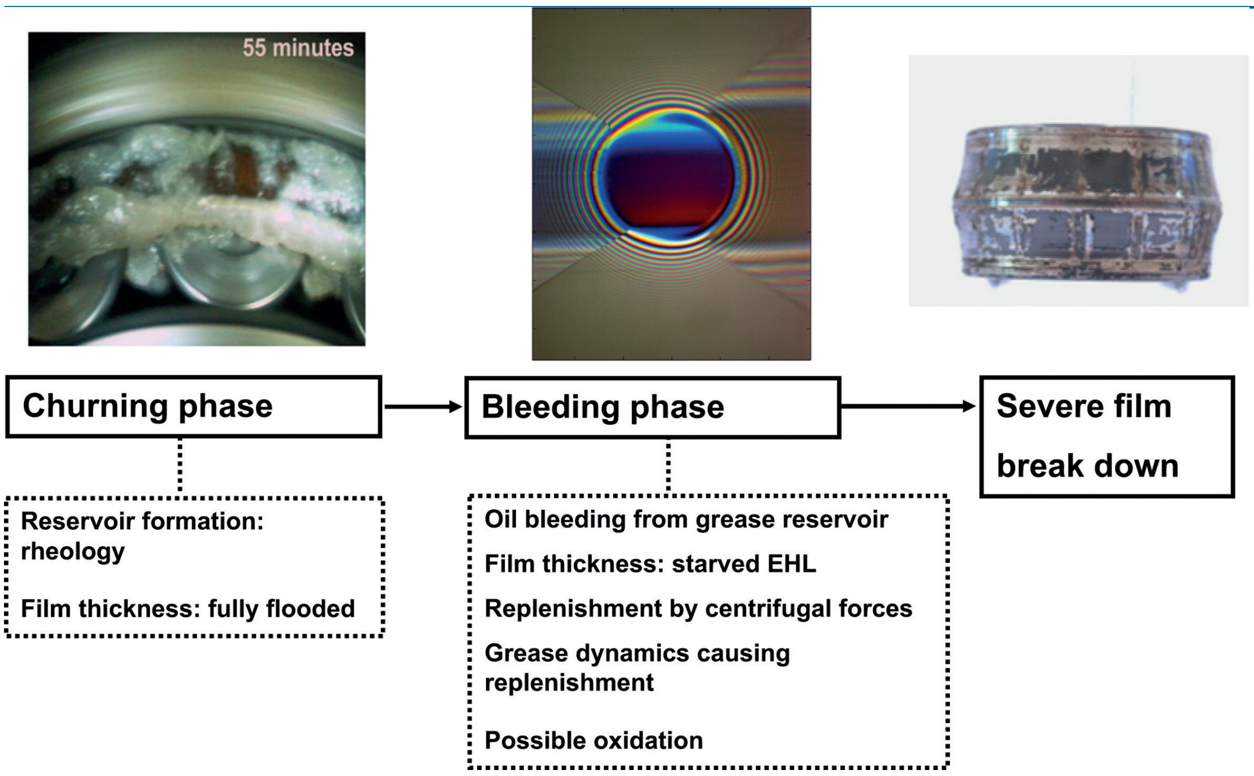

Figure 1. The phases in the grease lubrication process and the lubrication mechanisms [6].

to stabilize emulsions and reduce surface tension effectively. This dual affinity makes metallic soaps excellent thickeners, as they can interact with both the base oil and the polar additives present in the grease formulation.

Table 2 presents a comprehensive list of organic soap greases alongside their respective physical and tribological properties, providing a useful reference for selecting the appropriate thickener based on the specific application requirements.

2.1.3 Additives

Although comprising only a small percentage (typically 0-10%) of the grease composition, additives are vital components that enhance the performance and functionality of the grease formulation. These additives impart additional properties, such as improved oxidation stability, corrosion resistance, and extreme pressure (EP) tolerance, tailored to meet the specific needs of different applications and operating conditions [23].

Oxidation inhibitors, or antioxidants, help to prevent the base oil from degrading due to exposure to oxygen and high temperatures, prolonging the grease's service life and preventing premature breakdown [21]. Anti-wear additives, such as zinc dialkyldithiophosphates (ZDDPs) and other organic compounds, form protective films on metal surfaces, reducing friction and wear, particularly in boundary lubrication regimes [21].

Rust inhibitors and corrosion inhibitors protect metal components from corrosive attack by forming barrier films or neutralizing corrosive agents [6, 24]. EP additives, like sulfur-based compounds or chlorinated paraffins, improve the grease's ability to withstand high loads and prevent seizure or welding of metal surfaces under extreme pressure conditions. Other additives, such as viscosity index improvers, pour point depressants, and friction modifiers, can be incorporated to optimize the grease's performance in specific applications or operating environments [25]. Viscosity index improvers help maintain a consistent viscosity across a wide temperature range, ensuring the grease remains effective under varying conditions. Furthermore, pour point depressants reduce the temperature at which the oil forms a thick wax layer, which is particularly beneficial during the winter months. Friction modifiers decrease the energy required for surfaces to move past one another, enhancing efficiency. Collectively, all these additives contribute to improved grease performance across various applications.

By carefully selecting and combining the appropriate additives, grease manufacturers can tailor the formulation to meet the specific performance requirements of various applications, ensuring optimal lubrication, protection against wear and corrosion, and extended service life for machinery and equipment under diverse operating conditions.

2.2 Grease lubrication

Grease lubrication operates through three primary phases or mechanisms: churning, bleeding, and starvation [6]. In the initial churning phase, the freshly applied grease undergoes macroscopic flow, providing a fully flooded lubrication regime. During this phase, the grease is distributed evenly across all contact surfaces of the machinery components, ensuring they are adequately coated and lubricated. This even distribution is essential during initial start-up, as it helps to prevent immediate wear and friction between moving parts.

As the machinery continues to operate, the grease transitions into the bleeding phase. In this phase, the grease releases, or bleeds, a thin film of base oil by phase separation from the thickener matrix [26]. This oil release is governed by a balance of supply from the grease reservoir and loss mechanisms such as evaporation, centrifugal forces, or absorption into porous materials. The released oil creates a starved elastohydrodynamic lubrication (EHL) regime, ensuring that a thin lubricating film is consistently present at the contact surfaces. This film reduces friction and wear between moving components. The bleeding phase allows the grease to perform its protective lubrication functions over an extended period, even under varying operational conditions.

However, in extreme conditions or near the end of the grease service life, when the grease can no longer maintain an adequate supply of oil to sustain the EHL regime, it enters the starvation phase [27]. During this phase, the lubricating film may disappear entirely, leading to direct metal-to-metal contact between moving surfaces. This direct contact can cause significant wear, increased friction, and potentially catastrophic seizure or failure of the machinery components. Reaching the starvation phase represents the failure point of the grease's protective capabilities and must be avoided. Visual examples of each phase are illustrated in Figure 1.

Table 2. Common organic soap greases with their respective physical and tribological properties as well as common applications [22].

Thickener	Key characteristics	Applications
Lithium soaps	Good lubricity, shear stability, thermal resistance, low oil separation, high dropping points (~180°C)	Bearings in automotive and industrial applications
Calcium soaps	Improved water resistance over the lithium greases, good shear stability	Used in applications up to 110°C, bearings of water pump, wheel bearing and agricultural vehicles
Sodium soaps	High dropping points (~175°C), good shear stability and lubricity	Bearings in aerospace, wheel bearings, universal joints, and axle journal boxes
Aluminum soaps	Excellent oxidation resistance, good water resistance	Vibrating screens, elevator drive motors and governors where reverse motion occurs and large electric motors with bearings operating at high linear speeds

Proper grease formulation aims to minimize the occurrence and prolong the onset of the starvation phase, thereby preventing premature machinery failure. This is achieved by optimizing the balance and compatibility of the base oils, thickeners, and additives [28]. Selecting high-quality base oils that provide the necessary viscosity, thermal stability, and oil-bleed characteristics is crucial. Moreover, choosing thickeners that can withstand mechanical stress, extreme temperatures, and environmental conditions helps maintain the grease structure and consistency. Incorporating performance-enhancing additives, such as antioxidants and anti-wear agents, further extends the grease's service life and protective capabilities.

Figure 2. Penetrometer with a penetration cone: Conforms to ASTM and related specifications for penetrometers.

3 Key Performance Parameters of Lubricating Grease

3.1 Consistency

Consistency is a critical parameter that determines the ability of grease to resist deformation under applied force, indicating its thickness or stiffness. It is a measure of the grease's semi-solid nature and its ability to stay in place and maintain continuous contact with the lubricated surfaces.

The consistency of grease is typically measured using the cone penetration test, as outlined in ASTM D217 or ASTM D1403. In this test, a standardized cone, as depicted in Figure 2, is allowed to sink into the grease sample at a controlled temperature (usually 25°C) for a specified time (typically 5 seconds) [29]. The depth of penetration, measured in tenths of a millimeter, is used to classify the grease into various consistency grades, established by the NLGI, ranging from 000 (semi-fluid) to 6 (block-like solid), shown in Table 3 [21]. Examples of such greases include Tufoil, which is classified as a 000-grade grease suitable for low-viscosity applications. On the other end of the spectrum, 6-grade greases are used in applications where maintaining containment is imperative. These examples illustrate the range of applications and performance characteristics associated with different grease consistencies.

Higher penetration numbers indicate softer consistencies, while lower numbers denote harder or stiffer greases. The appropriate consistency grade is selected based on the specific application requirements, such as the type of bearing, operating temperature range, and the degree of mechanical stress involved. For example, greases with higher consistencies are typically preferred for applications involving high loads or high temperatures, as they resist being squeezed out or thinning under these conditions.

Maintaining the desired consistency is crucial for ensuring that the grease can continue to provide effective lubrication over an extended period. This is especially important in applications where the grease is subject to mechanical working, as it must retain its consistency to function properly.

3.2 Operating temperature range

The operating temperature range is a critical parameter that defines the temperature window within which a grease can perform effectively. This range is typically defined by two key limits: the Low Temperature Performance Limit (LTPL) and the High Temperature Performance Limit (HTPL) [21]. These

Table 3. NLGI grades with their corresponding penetration [21].

NLGI Grade	Worked Penetration Range, 25°C
000	445 – 475
00	400 – 430
0	355 – 385
1	310 – 340
2	265 – 295
3	220 – 250
4	175 – 205
5	130 – 160
6	85 – 115

performance limits are more complex than a single test, involving multiple assessments and factors, such as grease life and friction, to accurately determine them.

The LTPL refers to the grease's ability to flow and deliver oil to the lubricated surfaces during startup and cold operation. Factors influencing low temperature performance include oil viscosity, thickener type, and the presence of pumpability improvers. Below this limit, the grease may become too stiff, hindering oil bleeding, which can lead to increased friction, wear, and potential startup issues.

The HTPL defines the maximum temperature at which the grease maintains its lubricating properties and structural integrity. Various test methods assess high temperature performance, such as the high-temperature grease life test (ASTM D3336) in Figure 3 and the dropping point test (ASTM D2265) in Figure 4 [29].

ASTM D3336 measures the duration a grease can lubricate a bearing under high temperatures without failure. On the other hand, ASTM D2265 determines the temperature at which the grease changes from a semi-solid to a liquid state. These tests measure factors like wear rate, torque increase, and changes in consistency at elevated temperatures. While the dropping point provides a general indication of high-temperature resistance, it is not the sole indicator. A safety margin is always applied to account for real-world conditions and ensure reliable performance.

Figure 3. High temperature grease life tester (230 V, 50 Hz): Conforms to ASTM D3336.

Figure 4. High temperature dropping point apparatus: Conforms to ASTM D2265 and ASTM D4950.

Within the established LTPL and HTPL, grease formulations can be optimized for specific needs, such as extending bearing life, reduced friction, or noise control, depending on the application and service conditions. Thus, it is essential to select a grease with an appropriate temperature range that aligns with the expected conditions of the application. Greases with broader operating ranges offer greater versatility and can accommodate potential fluctuations in operating temperatures. However, it is equally important to remember that a broader range of greases might involve trade-offs in terms of other performance characteristics compared to a more specialized option.

3.3 Stability

Stability is a performance parameter that encompasses several aspects, including structural, chemical, oxidation, and thermal stability [21]. These factors determine the ability of a grease to maintain its desired properties and performance under various operating conditions and environmental exposures.

3.3.1 Structural integrity

Structural integrity, also known as mechanical stability or shear stability, refers to the ability of grease to maintain its consistency and structure under mechanical stress or shearing forces. This parameter is particularly important for applications involving repeated or continuous motion, such as bearings, gears, or other dynamic components. The structural integrity of grease is typically assessed using the cone penetration test (ASTM D217), which measures the change in consistency after the grease is subjected to mechanical working or shearing for a specific period [30, 31]. ASTM D217 simulates the shearing forces experienced by the grease during operation but does not directly measure performance. This test helps determine how well the grease can withstand dynamic conditions, such as those in rolling element bearings or gear systems.

Greases with high structural integrity or mechanical stability exhibit minimal changes in consistency after being worked or sheared, indicating their ability to maintain their structure under dynamic conditions. Structural integrity is influenced by factors such as the type and concentration of thickener used in the grease formulation, as well as the interactions between the thickener and the base oil [32]. Greases with higher thickener concentrations exhibit better mechanical stability, as the thickener network provides resistance to shearing forces through stronger chemical bonding. Conversely, greases with poor structural integrity may experience thinning or softening under shear, leading to potential leakage, decreased lubrication performance, and increased wear on components.

Therefore, selecting greases with adequate structural integrity for the specific application is crucial to ensure reliable performance and extended service life of the lubricated components. This selection can help reduce maintenance costs and downtime, ultimately contributing to more efficient and cost-effective operations.

3.3.2 Water stability

Water stability, or water resistance, is an important aspect of chemical stability, particularly for lubricants used in environments prone to water exposure, such as marine and outdoor applications where moisture or high humidity is common. Water resistance addresses the ability of a grease to stay put and maintain its lubricating properties when faced with water.

To evaluate this characteristic, the water washout tester depicted in Figure 5, which adheres to ASTM D1264 specifications, is employed. This test evaluates this by rotating a lubricated ball bearing at 600 rpm while spraying it with water at controlled flow rates and temperatures of 100°F and 175°F (38°C and 79°C) [29]. The test setup includes a reservoir with a heater and thermoregulator for precise temperature control, and a circulation system with a pump and flowmeter directing water through a 1 mm nozzle aimed at the bearing. After testing, the bearing and shields are weighed to determine the amount of grease loss, thereby assessing the grease's resistance to water washout. Although this test does not measure direct lubricating performance, it is essential for determining a grease's ability to maintain its position and function in wet conditions.

Figure 5. Water washout tester: Conforms to ASTM D1264, D4950 and related specifications.

Advancements in grease formulations have led to the development of sustainable grease products that incorporate water-resistant additives. These additives are often non-toxic and biodegradable, enhancing the environmental compatibility of the grease [33]. They function by forming a protective barrier around the grease, repelling water, and minimizing the risk of emulsification or breakdown of the grease structure. This protective barrier not only prevents washout but also ensures long-lasting protection against water ingress.

In addition to water resistance, these additives may also provide improved corrosion protection, oxidation stability, and overall grease life. However, it is important to note that while water resistance is crucial, it should be balanced with other performance requirements, such as compatibility with seals and materials, and overall environmental impact and biodegradability, to ensure a comprehensive and sustainable grease solution [6].

3.3.3 Oxidation stability

Oxidation stability measures the resistance of grease to chemical reactions with oxygen, which can lead to the formation of harmful deposits like gum, sludge, and lacquer [34]. These deposits can cause sluggish operation, increased wear, and reduced clearances, shortening the grease's service life. Long-term exposure to high temperatures accelerates the oxidation process.

To assess the oxidation stability of greases, methods such as the rotating bomb oxidation test (ASTM D942) using the apparatus shown in Figure 6 and the pressurized differential scanning calorimetry (PDSC) are commonly used [29]. The ASTM D942 test evaluates the grease's ability to resist oxidation by measuring the pressure drop in a sealed vessel containing the grease and oxygen at elevated temperatures. In contrast, PDSC assesses the oxidative stability by measuring the heat flow associated with oxidation reactions under controlled temperature and pressure conditions. These tests provide valuable insights into how greases will perform over time when exposed to oxidative environments.

Figure 6. Oxidation stability test apparatus for lubricating greases: Conforms to ASTM D942, IP 142, DIN 51808, FTM 791-3453.

Greases with better oxidation stability exhibit minimal changes in consistency, color, and other properties over time when exposed to oxidative conditions. Improving oxidation stability can be achieved using antioxidant additives, which inhibit or slow down the oxidation reactions [35]. Common antioxidants include amine-based and phenolic compounds, which can interrupt the oxidation process by neutralizing free radicals and decomposing peroxides, respectively [36].

Additionally, selecting base oils and thickeners with inherent resistance to oxidation can also contribute to enhanced oxidation stability. For instance, synthetic base oils such as PAOs and esters are known for their excellent oxidation resistance compared to mineral oils [11]. PAOs, derived from polymerizing alpha-olefin monomers, provide high oxidative stability due to their uniform molecular structure and lack of impurities. Esters, on the other hand, offer superior thermal and oxidative stability due to their chemical composition and strong ester bonds.

Similarly, thickeners also play a role in determining the oxidation stability of greases. Lithium complex thickeners, for example, provide excellent oxidative stability and are widely used in high-performance greases [22]. Calcium sulfonate thickeners are another option, known for their inherent resistance to oxidation and ability to maintain consistency under severe conditions.

3.3.4 Thermal stability

Thermal stability refers to the grease's ability to resist changes in its physical and chemical properties when exposed to high temperatures. It is a measure of the heat resistance of the grease, defining the upper temperature limit at which it can retain its structure and lubrication performance. The Dropping Point Test (ASTM D2265) is commonly used to assess thermal stability [29]. This test determines the temperature at which the grease becomes fluid enough to drip through an orifice under standardized conditions. However, it is important to note that the dropping point does not directly indicate the grease's performance at elevated temperatures.

High-temperature life tests, such as ASTM D3527 (Figure 7) and ASTM D3336 (Figure 8), are more accurate for evaluating thermal stability in practical applications [29]. ASTM D3527 measures the durability of grease in wheel bearings by assessing its ability to maintain performance over extended periods at elevated temperatures, simulating real-world conditions in automotive applications. Similarly, ASTM D3336, already discussed, evaluates how long a grease can effectively lubricate a bearing at high temperatures without significant degradation. These tests offer a better indication of a grease's thermal stability and suitability for high-temperature applications.

Figure 7: High temperature wheel bearing grease tester: Conforms to ASTM D3527, D4290 and D4950.

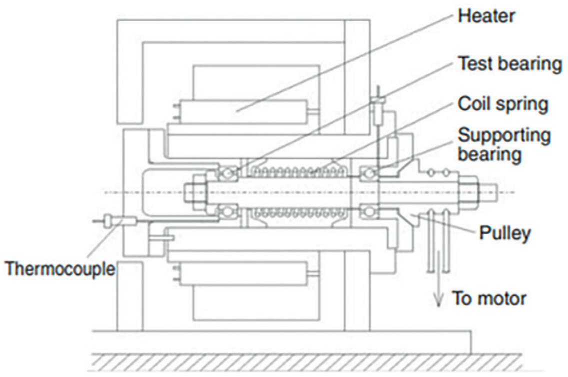

Figure 8: ASTM D3336 test: High temperature bearing endurance test machine [36].

Achieving high thermal stability in grease formulations typically involves the use of high-performance base oils and thickeners that are resistant to thermal degradation. Bio-based and synthetic esters are increasingly used due to their excellent thermal properties, ensuring that the grease remains effective at both high and low temperatures, thereby reducing the need for frequent re-lubrication and minimizing waste [37].

3.3.5 Thermo-oxidative stability

Thermo-oxidative stability refers to the ability of a grease to resist chemical breakdown and maintain its properties under prolonged exposure to elevated temperatures and oxygen [21]. Greases with high thermo-oxidative stability ensure consistent lubrication, prevent the formation of harmful deposits, and extend the intervals between re-lubrication.

The degradation of lubricating grease due to heat and oxygen can lead to the formation of sludge, varnish, and acidic compounds, which can impair the lubricating film, cause corrosion, and increase wear on metal surfaces. To combat these issues, high-quality greases are formulated with antioxidants and thermal stabilizers. Antioxidants inhibit the oxidation process by neutralizing free radicals and decomposing peroxides, thereby preventing the oxidative degradation of the grease. Thermal stabilizers enhance the grease's ability to withstand high temperatures without breaking down. Among these additives, alkylated naphthalene is particularly effective due to their exceptional thermal stability and antioxidant properties, making them ideal for high-temperature applications [38].

3.4 Lubrication

Effective lubrication is crucial for minimizing friction and wear in bearings and other moving components. The lubrication efficiency of a grease depends on two key factors: the properties of the base oil and the grease's ability to release enough oil (bleeding rate) to maintain a protective lubricating film [6]. Importantly, the optimal balance between these factors will vary depending on the specific application.

For optimal lubrication performance in rolling element bearings, formation of an EHL lubricating film is essential. This film separates the moving surfaces, preventing direct metal-to-metal contact and reducing friction and wear [21]. The thickness of the EHL film depends on various factors, including the operating conditions (speed, temperature, and load), as well as the presence of contaminants. Base oil properties, such as viscosity and viscosity index, play a crucial role in determining the grease's ability to form and maintain an adequate EHL film [40]. Additionally, the bleeding rate of the grease is vital for continuously replenishing the lubricating film as it is depleted or displaced during operation.

For conventional greases, a minimum bleeding rate is necessary to ensure sufficient oil supply to the lubricated surfaces. This bleeding rate dictates the maximum viscosity of the base oil that can be effectively utilized in the grease formulation. Higher viscosity base oils may provide better load-carrying capacity but may also require trade-offs with formulation adjustments to ensure adequate oil release.

3.5 Friction management

Effective friction management in machinery extends beyond environmental benefits to deliver substantial cost savings and enhance overall equipment effectiveness (OEE). Studies indicate that minimizing friction can significantly reduce energy consumption, with potential savings ranging from 5% to 24% [41]. This translates to tangible financial advantages, considering friction was estimated to cost the global economy €2.54 trillion ($2.37 trillion USD) in 2017, as shown in Figure 9 [42]. By implementing friction management strategies, businesses and industries can achieve greater operational efficiency for reduced energy expenditures and lower overall operating costs, all while contributing to a smaller CO2 footprint. Additionally, proper friction management can minimize wear and tear on components, extending their lifespan and reducing maintenance requirements. This contributes to improved uptime and machine availability, ultimately boosting OEE.

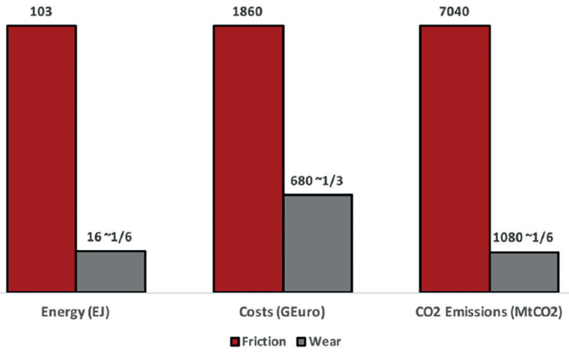

Figure 9. Global friction and wear effects on energy, costs, and CO2 emissions [42].

Grease formulations play a key role in optimizing friction management. These lubricants are specifically designed with additives that minimize friction between moving components [43]. This aligns with implementing friction management as a driving principle for modern grease formulations. Effective friction management requires consistent friction behavior during operation, avoiding unpredictable friction behavior like stick-slip, which can be detrimental in different industrial contexts.

3.6 Noise reduction

Noise reduction is an essential aspect of grease performance, particularly in precision applications such as electric motors and household appliances, where noise levels can significantly impact user experience and product quality [43]. Noise generation in bearings is influenced by the quality and composition of the lubricating grease.

Low-noise greases are characterized by their high purity and the use of finely dispersed thickeners. The structure of the grease, known as the grease matrix, is formed by the base oil, thickener, and any additives and plays a role in noise reduction. A well-formulated grease matrix can minimize noise by preventing hard particles from forming or existing within the grease. Noise in bearings can be generated by particles traveling through the rolling element-ring contacts, which can originate from contaminants or the thickener itself. Solid additive particles, such as graphite and calcium carbonate, can increase noise levels by introducing additional abrasive elements into the bearing system [6]. In contrast, finely dispersed thickeners help suppress noise by eliminating interactions between hard particles.

To further decrease noise levels, greases with higher base oil viscosity, typically up to 100 cSt at 40°C can be utilized. These greases help reduce noise by providing better dampening of high-frequency excitations and vibrations [44]. The increased viscosity contributed to a smoother lubrication film, minimizing the transmission of vibrations and noise. In addition to base oil viscosity, advanced thickeners and additives can be incorporated into grease formulations to enhance their noise-reducing capabilities. These specialized components work by dampening vibrations and absorbing high-frequency excitations, resulting in quieter operation and improved product quality.

Noise reduction is important in both industrial and consumer applications, as excessive noise can lead to worker discomfort, product dissatisfaction, and even regulatory compliance issues [45]. Sustainable grease formulations now incorporate additives and design considerations that prioritize noise reduction by damping vibrations and providing a smooth, consistent lubrication film. These low-noise greases are particularly valuable in applications such as electric motors, automotive components, and household appliances, where noise reduction contributes to overall product quality, user comfort, and environmental impact.

3.7 Corrosion resistance

Corrosion resistance is another key performance parameter for lubricating greases, especially in environments where metal surfaces are exposed to moisture, salts, and other corrosive agents [21]. Effective corrosion resistance extends the life of machinery, reduces maintenance costs, and ensures operational reliability. Lubricating greases that excel in corrosion protection typically incorporate advanced additive technologies that form a protective barrier on metal surfaces. This barrier prevents the ingress of water and corrosive substances, thus safeguarding the metal components from oxidative damage and corrosion.

One of the primary mechanisms through which greases provide corrosion resistance is by including inhibitors that neutralize acids formed during operation. These inhibitors are carefully selected to ensure compatibility with other grease components while providing robust protection against rust and corrosion. Additionally, some greases utilize film-forming agents that create a continuous, hydrophobic layer over metal surfaces. This layer repels water and other corrosive agents, further enhancing the corrosion resistance of the lubricated components.

3.8 Fretting corrosion and false brinelling

Fretting corrosion is crucial in applications involving oscillatory motion that causes wear in contact areas. Fretting occurs between the outer ring and housing or inner ring and shaft, while false brinelling occurs in rolling element-ring contacts [21]. Lubricating greases must reduce friction and wear by providing an adequate supply of lubricant to these contact areas, preventing ingress of oxygen and moisture. Additives such as molybdenum disulfide (MoS2) and boric acid can help reduce wear and improve protection against fretting and false brinelling [46]. These additives form protective tribofilms on the metal surfaces, reducing friction and wear during oscillatory motion. High oil bleed rates and lower consistency greases are better suited for managing these wear conditions [23]. A high oil bleed rate ensures a steady supply of lubricant to the contact areas, preventing lubricant starvation and reducing wear. Lower consistency greases can provide better coverage protection, as they can more easily flow and penetrate the contact areas.

3.9 Environmental impact and biodegradability

Environmental impact and biodegradability have become increasingly important performance metrics for lubricating greases, particularly in environmentally sensitive applications such as agriculture, marine environments, and areas with strict environmental regulations. Biodegradable greases are designed to decompose through microbial activity, reducing their environmental impact and minimizing soil and water contamination. To evaluate biodegradability, the grease is subjected to controlled conditions where bacteria consume biodegradable materials, and the consumption of oxygen (O2) and release of carbon dioxide (CO2) are measured. A grease is considered biodegradable if it undergoes at least 60% degradation within 28 days, as per standard laboratory tests such as OECD 301B or OECD 301F [21]. This property is especially important for greases used in areas where environmental contamination is a concern, such as outdoor machinery, agricultural equipment, and marine applications.

The choice of base oils and additives significantly influences a grease's environmental impact. Vegetable oils and synthetic esters are popular choices in biodegradable formulations due to their inherent biodegradability and low toxicity. While vegetable oils offer excellent biodegradability, they may require stabilizing additives to enhance performance. Synthetic esters, on the other hand, provide superior oxidative stability and biodegradability, making them ideal for formulating environmentally friendly greases.

Beyond biodegradability, the overall environmental impact of grease also includes factors such as toxicity, eco-toxicity, and renewability of raw materials. Non-toxic additives and thickeners are preferred to minimize harmful effects on aquatic and terrestrial ecosystems. Grease formulations that utilize renewable raw materials, such as vegetable oils, contribute to resources sustainability and reduce dependence on petroleum-based products. Life-cycle assessment (LCA) further assesses a grease's environmental impact from production to disposal. LCAs help identify areas for improvement, such as reducing energy consumption during manufacturing, optimizing formulations for longer service life, and ensuring proper disposal and recycling of used greases [47].

With the growing focus on sustainability, research and development efforts are continuously directed towards formulating even more environmentally friendly lubricating greases. Advancements in base oil technology, thickener design, and additive development aim to further improve biodegradability, performance, and overall environmental impact.

4 Challenges and Future Research Directions

The development of sustainable and high-performance lubricating greases has made notable strides, yet several challenges continue to hinder widespread adoption and optimization. These challenges necessitate ongoing research and innovation to strike a balance between performance and sustainability, cater to application-specific needs, ensure long-term stability, maintain cost-effectiveness, and establish standardized testing methodologies.

4.1 Balancing performance and sustainability

One of the foremost challenges in the formulation of sustainable greases lies in balancing performance characteristics with environmental compatibility. Traditional greases often rely on petroleum-based thickeners and additives, which are effective but pose environmental concerns. Sustainable alternatives must maintain or even enhance key performance parameters such as consistency, thermal stability, and corrosion resistance, while also offering improved biodegradability and reduced toxicity.

Future research should prioritize the development of novel bio-based thickeners that can rival or surpass the performance of conventional metallic soap thickeners. Furthermore, enhancing the oxidative and thermal stability of vegetable oil-based formulations without compromising their biodegradability is crucial. Exploring the synergistic effects between bio-based components and additives could lead to formulations that achieve optimal performance across multiple parameters, ensuring that sustainable greases do not compromise on quality or functionality.

4.2 Addressing application-specific requirements

Different industries present unique lubrication challenges that sustainable grease formulations must address. For instance, high-temperature applications in the aerospace industry or high-pressure environments in offshore drilling require specialized greases that can withstand extreme conditions. Similarly, sensitive ecosystems, such as marine environments or agricultural applications, demand biodegradable greases that minimize environmental impact while providing reliable performance.

Research in this area should focus on tailoring sustainable grease formulations to meet the rigorous demands of specific applications. This could involve developing specialized biodegradable greases for use in sensitive ecosystems or improving the noise-reduction capabilities of eco-friendly greases for precision machinery and consumer products. Addressing these application-specific requirements will be essential for the broader adoption of sustainable greases across various industries.

4.3 Ensuring long-term stability and service life

Another challenge for sustainable greases, particularly those based on bio-derived components, is ensuring long-term stability and extended service life. Traditional petroleum-based greases often exhibit superior oxidative and hydrolytic stability, contributing to their durability. However, bio-based alternatives may be more susceptible to degradation over time, which can limit their effectiveness in demanding applications.

Research efforts should focus on improving the oxidative and hydrolytic stability of bio-based greases, extending their useful life without compromising their environmental benefits. Developing more effective antioxidant and anti-wear additives that are both environmentally friendly and compatible with bio-based components is another priority. Also, investigating the impact of various environmental factors, such as temperature fluctuations and exposure to moisture, on the long-term performance of sustainable greases will provide valuable insights for formulation improvement.

4.4 Achieving cost-effectiveness and scalability

For sustainable greases to gain widespread market acceptance, they must be cost-competitive with traditional petroleum-based products. The high cost of bio-based components and the complexity of their production processes currently pose significant barriers to large-scale adoption.

To overcome these challenges, research should focus on optimizing production processes for bio-based components, thereby reducing manufacturing costs. Exploring alternative sources of renewable raw materials could also ensure a stable and affordable supply chain. Furthermore, developing innovative formulation techniques that maximize performance while minimizing the use of costly additives will be essential in making sustainable greases economically viable for a broad range of applications.

4.5 Establishing standardization and testing methodologies.

As the field of sustainable grease formulations continues to evolve, the lack of standardized testing methodologies and performance criteria remains a significant challenge. Without standardized methods, it is difficult to compare the performance and environmental impact of different formulations, hindering industry-wide adoption.

Research in this area should aim to develop and validate new test methods specifically designed for bio-based and sustainable grease formulations. Establishing industry-wide standards for evaluating the environmental impact and sustainability of lubricating grease is crucial for ensuring consistency and reliability in product assessments. Additionally, creating comprehensive life-cycle assessment tools tailored to sustainable grease formulations will provide a more accurate understanding of their overall environmental footprint.

5 Conclusion

By addressing these challenges and focusing research on these key areas, the lubricating grease industry can make significant progress toward more sustainable and high-performance products. This will not only meet the growing demand for environmentally responsible lubrication solutions across various sectors but also contribute to the global effort to reduce the environmental impact of industrial processes.

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