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A Critical Review on Semi-solid and Solid Lubricants for Industrial Applications

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Abstract

Friction materials are very important for the safe moving of automobiles and the safety of people. As the pad slides against its match, the moving energy is turned into heat by the friction. As the vehicle's speed is lost as heat in the pads and rotors, the friction at the contact slows it down. Lubricants are compounds that are applied to moving parts to reduce friction and wear. Used primarily at the point where they intersect. This paper investigates and reviews the application of solid and semi-solid lubricants in a range of industries. The use of solid lubricants as a substitute for petroleum-based oils has increased in recent years due to their perceived environmental benefits. When a thickening agent is used with a liquid lubricant, the resulting lubricating grease has a consistency somewhere between "solid to semi-fluid." The next sections contain reviews of articles that can help you learn more about lubricants, their qualities, grades, and so on. Furthermore, the differences between solid and semisolid lubricants are highlighted. There were also displays of other solid and semi-solid lubricants that serve the same audience as the featured product. With a focus on high temperatures, this research summarizes the most current advancements in solid lubricants, self-lubricating composites/coatings, and their important functionalities across a variety of operating settings. Several representative soft metals, layered structure materials (e.g. graphite, hexagonal boron nitride, transition metallic dichalcogenides, MAX phase), chemically stable fluorides, binary or ternary metallic oxides, especially alkaline earth chromates, and sulfates are considered, as are the additive properties of these solid lubricants.

Keywords: Lubricants, Solid, Semi–Solid, Grease, Oils.

INTRODUCTION

Methods for reducing friction losses are crucial; for many steady-state applications, lubricants made from mineral or synthetic oils are used to reduce friction and wear-related losses. When operating temperatures and pressures are just right, lubricants can drastically cut friction losses and reduce wear. If a thin lubricating film separates rubbing partners and the speeds of the mating components are compatible with the qualities of the film, friction, and wear can be reduced to a minimum. When surface roughness becomes elastic, this is known as Elasto-Hydrodynamic Lubrication (EHL). Although viscosity is the most important aspect in establishing EHL, there are other factors at work during the dynamic operation of moving components at varied speeds that may prevent lubricating oils from achieving the optimal regime on their own. The boundary lubrication (BL) regime is the operating regime when the elasto-hydrodynamic regime does not apply and the surfaces are in close contact with one another. Wear in a boundary lubrication regime may be mitigated by the use of surface-interacting extreme-pressure (EP) additives. Chemical adsorption of EP additives to surfaces, followed by the formation of

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a molecular boundary layer, is a popular method for modifying wear behavior in materials. In order to improve wear-reducing additives, two main approaches have been proposed: (i) a conventional approach centered on molecular liquid additives that can interact with surfaces chemically to form protective films, and (ii) an unconventional approach centered on solid, nanoparticle-based additives that can be present in the asperities regions to carry load and reduce friction and wear behavior. Interest in using nano particles (including ceramic) in lubricating lubricants has increased recently, coinciding with the trend toward greener technologies. However, due to a lack of knowledge regarding how such particles behave when subjected to frictional pressure [1], their use remains limited.

Solid lubricants, as they are now commonly known, are a relatively recent area of study and use. It wasn't until after their widespread use in aeroplanes that scientists began investigating these substances systematically. In the 1950s, when the jet engine was first being developed, a number of labs began a systematic investigation into high-temperature solid lubricants. The primary focus was on developing specifications for solid lubricants. Increased investigation into solid lubrication, with an emphasis on the role of environment, was motivated by space lubrication needs in the 1960s. It was determined how to best use solid lubricants. Most studies ceased in the early 1970s when the majority of the issues were answered and their boundaries established. However, a number of novel uses have emerged in recent years, sparking increased interest. These include lightweight gear and bearing systems, low-cost bearing systems for automobiles and industrial machinery, and cages for turbopump bearings operating in liquid hydrogen and oxygen. Other uses include piston tings for low-heat-rejection engines, lubricating cages for advanced gas turbines, gears and bearings for long-term service in space mechanisms, and cages for conventional pump bearings. Longevity and versatility in terms of operating temperature are two of the most prominent new criteria. There is a demand for newly developed solid lubricants that can fulfil these criteria.

HISTORY

The usage of lubricants predates the invention of the wheel. Since those early days, lubrication and the production of lubricating media have developed into one of the world's important industries, despite the fact that one-third to half of all produced energy is still lost to friction. Animal fats and oils were the primary ingredients in lubricants until the early 1800s. The technology of lubrication has come a long way since the first oil well was dug in Titusville in 1859. In the middle of the 1930s, new compounds were introduced to the market that would significantly enhance petroleum oils. These substances, known as additives, could enhance the oils' ability to carry a load, lubricate, prevent corrosion, and resist thermal oxidation.

The use of increasingly high temperatures in mechanical components has been on the rise since the 1930s. New synthetic lubricant materials were developed as it became clear that petroleum oils wouldn't perform well at the required temperatures. Even synthetic lubricants have a temperature threshold beyond which they are ineffective in today's supersonic aircraft, spacecraft, and some industrial uses. As a result of this tendency, solid lubricants have been developed and used to achieve the required lubrication of sensitive parts even at extreme temperatures and pressures.

Graphite and molybdenum disulfide have been around for a while, but it's only been in the last couple decades that they've been put to use as solid lubricants due to their slick feel and look. Graphite is known by many different names, including black lead, carbon minerals, carburet of iron, caryon noir, plumbago, potelot, reissblei, and silver lead. For a long time, it was misidentified as molybdenite ($MoS2$) and other, visually similar minerals. It wasn't recognized as such until 1565, and it wasn't until its oxidation to carbon dioxide in 1779 that its identity as carbon was established.

HISTORY OF SOLID LUBRICATION

Molybdenum, in the form of molybdenite, may be found everywhere across the Earth's crust. Climax, Colorado is where the mineral is produced commercially from granite that naturally contains the ore in a very finely split form. Molybdenum disulfide ranges in hue from a metallic blue-grey to a deep black.

The wheels of the Conestoga wagons used by early settlers to traverse the Climax region were lubricated with powdered rock. One of the earliest applications of molybdenum disulfide (MoS2) as a solid lubricant [2].

Self-lubricating materials are another class of components that are essential for bearings because of their connection to solid lubricants. They function better in high-temperature environments and require no additional lubrication thanks to their self-lubricating properties. Graphalloy (Graphite/metal) alloys take advantage of graphite's unique features, such as its stackable structure (like a deck of cards) that allows for easy removal of individual layers. Since grease and oil typically evaporate, coagulate, or solidify, causing the material to fail prematurely, this phenomenon provides it with a self-lubricating ability that is unrivaled by most other materials. Protective against catastrophic failure are the low friction coefficient and enhanced chemical, mechanical, and tribological qualities achieved by incorporating lubricants into graphite's matrix. Moving in a straight line has no effect on the lubrication or the dust. The use of micro-porous polymeric lubricants (MPL) in solid bearings is a new innovation. In MPL, oil (and maybe other additives) is trapped inside the polymer's pores by using a polymer with a continuous microporous network. Sponage made from microporous polymer can have an oil concentration of more than 50% by weight [3], allowing it to both release and absorb oil on demand.

REVIEW OF LITERATURE

Hot tribology is becoming increasingly popular as the number of high-temperature activities (HTupto 1000 °C) continues to rise dramatically (Figure 1a). Early wear can occur in many different types of industrial processes while working with high temperatures (Figure 1b). Material science, bearings, automobiles, metalworking, hot forging, stamping, and shaping are just a few examples. Because of the increased friction and wear that occurs when operating outside of the typical temperature range, the reliability and performance of many components is significantly unclear. The HT wear process typically involves modifications to the tribo-contacts of the interacting bodies and, in certain cases, the development of whole new phases. Tribo-bodies are profoundly impacted by the interplay between oxidation, diffusion, and tribological stress, which results in a multifaceted alteration in physical, mechanical, and surface reactivity. The tribo-oxide coating formed on the surface of several materials during HT sliding is regarded to be beneficial, especially steel and its alloys. However, the generated tribo-oxide layer rapidly spalls [4] due to adhesion difficulties, the Pilling-Bedworth ratio, or lattice mismatch.

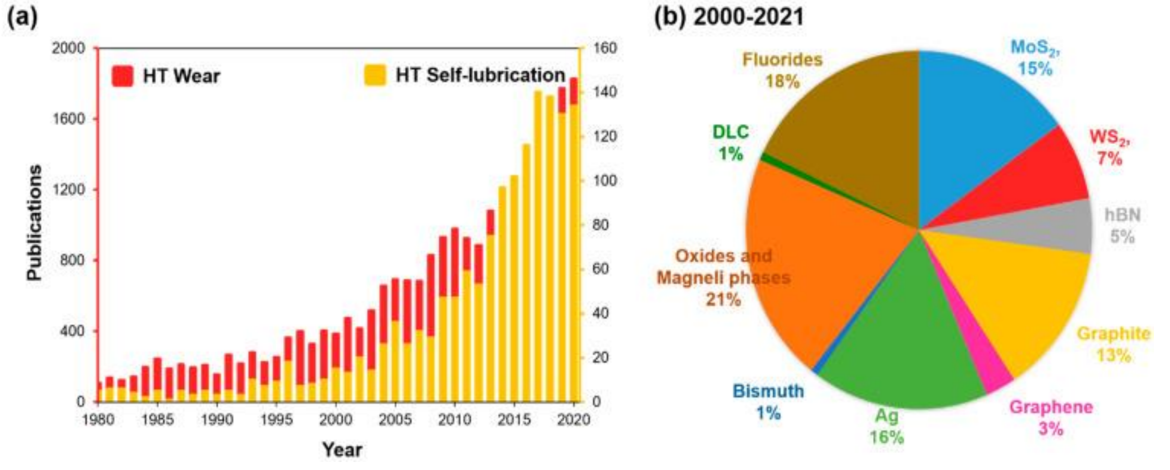


Figure 1. Retrieval from the Scopus database of the total number of publications on (a) wear and self-lubrication at high temperatures (1980-2020) and (b) wear and self-lubrication at high temperatures based on different solid lubricants (percent, 2000-2021).

It is usual practice to use a traditional liquid lubricant to reduce tribo-body wear. Oils and greases have a number of uses, but they pose health and environmental hazards when heated above 300 degrees

Celsius. In aircraft, piston-cylinder designs, optical or thermal control surfaces, etc., oil and grease lubricating media are known to become volatile, mitigate, and condense under high conditions (temperature, pressure, altitude). Due to these constraints, mechanical systems subjected to extreme working conditions may experience a shortened lifespan when employing liquid lubricants. MoS2, WS2, graphite, PTFE, Ag, hBN, and so on are all examples of solid-based lubricants (SL) that can be utilized to reduce friction and wear across a wide temperature range (from room temperature to negative one thousand degrees Celsius). Solid lubricants introduced into materials (or at the interface of two mating surfaces) during relative motion are predicted to undergo tribo-chemical reactions, leading to the formation of a lubricious phase or compound that then provides a continuous transfer of lubricant at the tribo-interface. Under certain conditions (including temperature, humidity, and material composition), they are reported to develop a 'glazed' self-lubricating coating on the material surface during sliding wear [4, 5], drastically lowering the coefficient of friction (CoF) and wear. It has issues with operating dampening and heat dissipation [6]. Superior lubricity, thermal and chemical stability, dimensional stability for high-precision finishing, etc. are just a few of the benefits that SL offers over liquids. Few works have investigated the use of cutting fluids or vegetable oils in combination with solid lubricants (such as PTFE, hBN, CaF2, WS2, boron oxide, etc.) to achieve near-dry or minimum quantity lubrication (MQL) or minimum quantity cooling (MQC) during the machining of hard-to-cut materials (Ni superalloy) [6]. However, their widespread use is still limited by negative environmental outcomes and an absence of positive HT tribological research. Figure 1b displays the proportion of HT tribology research publications published between the years 2000 and 2021 that focus on significant solid lubricants.

In addition to providing chemical, corrosion, thermal, and mechanical stability, the fundamental role of a solid lubricant is to reduce friction and wear during high temperature (HT) forming, forging, stamping, cutting, and areas of relative motion in engines, etc. Not only does it need to exhibit low friction and steady wear rates throughout a broad temperature range, but it also needs to be able to withstand the high temperatures that can be reached during operations, which can reach above 1000 °C in a short amount of time [7]. For minimal friction and wear throughout a broad temperature range, [8] a combination of solid lubricants is required. The solid lubrication window has been significantly widened by the discovery that the same small number of SLs that reduce friction at low temperatures also chemically react to form a lubricious glazing layer at HT. Table 1 summarizes the shared characteristics of HT solid lubricants (self-lubricating materials). In what follows, we'll examine the differences between the several HT solid-lubricants that can be identified by their chemistry (structure) and general approach to lowering friction (Figure 2).

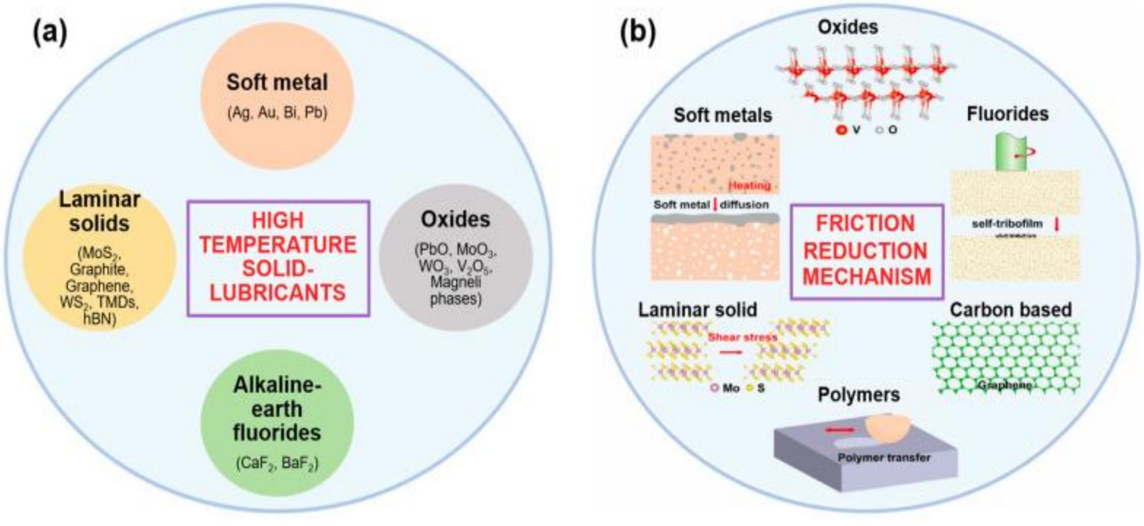
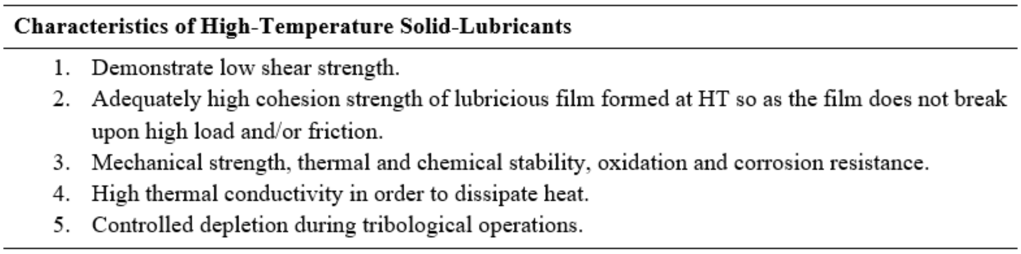


Figure 2. (a) Chemical composition-based categorization of HT solid-lubricants; and (b) a diagram illustrating how they reduce friction.

Table 1. Important features of solid lubricants (self-lubricating substance) that can withstand high temperatures.



Characteristics of High-Temperature Solid-Lubricants
1. Demonstrate low shear strength.
2. Adequately high cohesion strength of lubricious film formed at HT so as the film does not break upon high load and/or friction.
3. Mechanical strength, thermal and chemical stability, oxidation and corrosion resistance.
4. High thermal conductivity in order to dissipate heat.
5. Controlled depletion during tribological operations.

In order to reduce friction and wear at HT under dry sliding circumstances, this study provides an overview of some of the more famous SLs currently used in tribological applications. The theory and technique behind their lubricity, chemical composition, and reduced friction are all broken down. In addition, a summary chart depicting the range of allowable temperatures for dry sliding, as well as the CoF displayed by different SLs, is provided. A'smart' tribo-material of the future is offered as a potential innovation.

TRIBOLOGY OF SOLID LUBRICANTS

In extreme conditions, liquid lubricants cannot deliver optimal tribological performance. Solid lubricants were incorporated into various matrices to improve the lubricating material's reliability and self-adaptability. This has led to the predictable occurrence of adequate lubrication. Solid lubricants' lubricious activity may be traced back to their layered structure, which is the major reason for their outstanding lubrication capabilities. Lamellar structures are particularly notable in solid lubricants like TMDs, h-BN, and graphite. As a result, these solid lubricants are used as a coating in MMA that operates in harsh environments and as a reinforcing phase in self-lubricating composites [9–11]. The coefficient of friction between two surfaces drops when their layers are perpendicular to the direction of the driving force and slide over one another. Solid lubricants are often distributed in diverse matrices to provide higher lubricity in difficult conditions; this section will cover the tribological behavior and features of such lubricants [12–14]. Standard solid lubricants utilized by self-lubricating materials in severe conditions are shown in Figure 2. Table 2 displays the potential intervals we considered in our analysis.

Soft Metals

Multiple slip planes and a consistently low CoF across a wide temperature range characterize soft metals [15–17]. These characteristics, such as reduced surface roughness and high viscosity, originate from the nature of soft metals. Silver, tin, gold, lead, indium, and platinum are all examples of soft metals. The lattice imperfections, such as dislocations and vacancies, in soft metals are eliminated by the frictional heat generated during sliding [18]. Inadequate work hardening, caused by the elimination of lattice flaws, is the process responsible for the exceptional lubricity observed under severe conditions. Due to its high diffusion coefficient, silver is widely utilized as a solid lubricant in matrices, making it a popular reinforcement among soft metals. The lubricating coating may form quickly and easily due to the high diffusion coefficient. As a result, it boasts excellent tribological characteristics. Tribological conditions have been used to tests of silver-reinforced self-lubricating materials in intermetallic matrices, ceramic matrices, and polymer matrices. They found that a range of compounds and temperatures produced the best lubricity and wear resistance. Different solid lubricants have different stable operating temperature ranges, as shown in Figure 3 and Figure 4.

MECHANISMS OF SOLID LUBRICATION

There is a strong link between them when both surfaces are clean (a new metallic surface or under an ultra-high vacuum) and free of any chemical coatings or adsorbates. Physical and chemical contacts are the two main categories used to describe adhesion. Machines that slide or spin more slowly due to sticking experience more wear and tear. Extreme friction damage, cold welding, scuffing, or even disintegration is the inevitable result of subjecting tribo-stressing surfaces like gears and bearings to tremendous loads, rapid velocities, and rising temperatures. When it comes to adhesion, material pairings such crystal structure, crystallographic orientation, mutual solubility, chemical activity, and separation of charges are more important than interface factors like normal load, temperature, atmosphere, duration of contact, and velocity. High temperatures, mechanical dynamic loads, and high velocities all contribute to the severe plastic deformation wear and fatigue that occurs on parts during hot metal forging [19]. Proper lubrication at high temperatures protects against seizure, galling, and direct metallic contact, and also reduces friction strains during the forming process. There are a few reasons why tools wear down quickly during high-speed dry machining [19]. Wear can occur from a variety of sources, such as adhesives, abrasives, chemicals (through heat diffusion), and electricity. Wear on electric train pantograph contact strips is caused by arc discharge attack, which causes mechanical impact, adhesion, and particle transfer at extremely high temperatures. Thin-strip steel casting relies on refractory side dams, which must endure high temperatures and pressures. An assortment of environmental challenges, such as adhesive degradation, abrasive degradation, thermal/corrosive degradation, fatigue wear, and blistering, must be tolerated by abrasive seals in gas turbine engines. Rolling-contact bearings are commonly used in environments with low pressure and high temperatures [20], but they are susceptible to failure due to fatigue spalling under cyclic contact straining and severe adhesive wear (also known as scuffing or smearing).

Table 2. The scope of extremes used in practice.

Conditions	Lower Limit	Upper Limit	References
Temperature	−269 °C	1000 °C	[10]
Pressure	0.1 MPa	12 MPa	[11,12]
Humidity	10%	70%	[13]
Velocity	0.1 m/s	3 m/s	[14]
Load	1 N	100 N	[15,16]

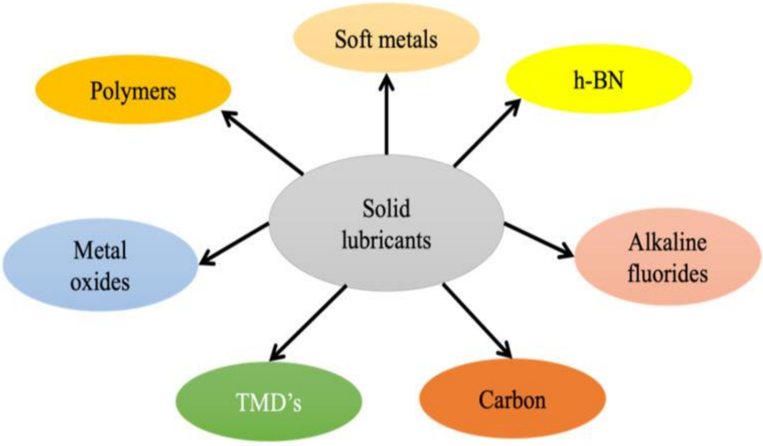


Figure 3. Typical solid lubricants.

Several sliding and rolling contact components have benefited from the use of lamellar solids and soft films, the two primary kinds of solid lubrication. Tribo-chemical reactions in air or water vapor atmospheres allow for the formation of lubricious and wear-resistant coatings from a wide variety of metals, intermetallic compounds, and ceramics. Low-friction films formed through tribochemical reactions provide a shear-strength layer between metal and ceramic. For example, vanadium and chromium are often used as alloying agents in metals or nitride coatings because they produce strong and lubricious oxide layers that help to reduce friction at high temperatures [21].

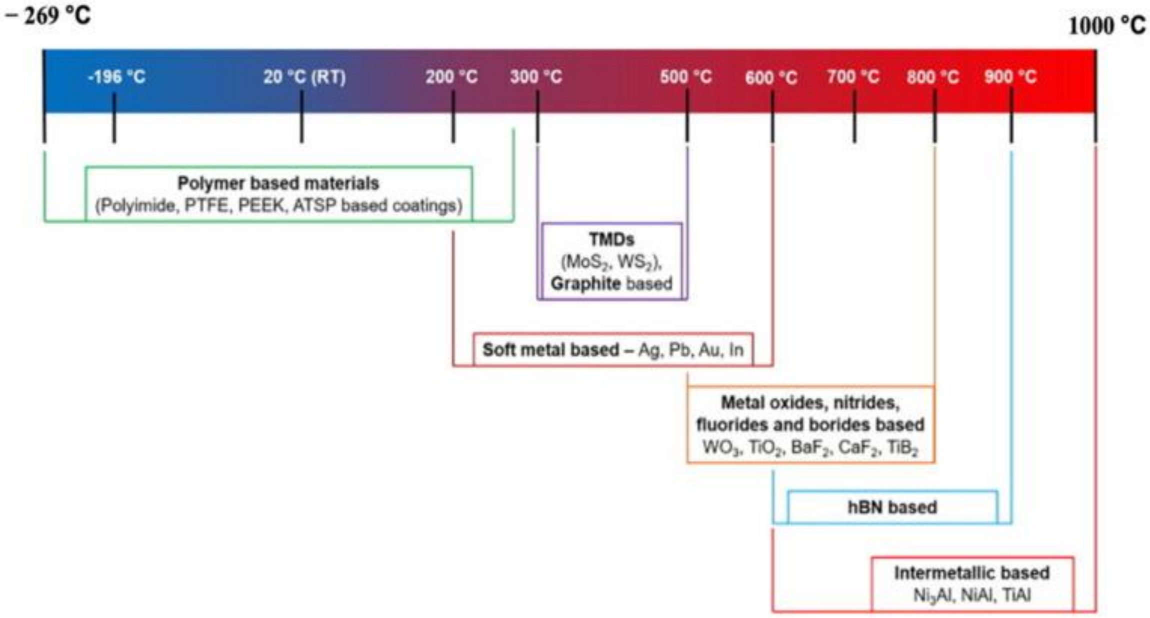


Figure 4. Solid lubricants with stable operating temperatures.

CLASSIFICATION OF SOLID LUBRICANTS

Due to its strong resistance to wear, corrosion, and high temperatures, polyimide, a polymeric synthetic resin that contains the imide group, is most often used as a coating or film. Polyimide varnishes with additional solid lubricants, such as CFx or MoS2, reduce friction and wear even at room temperature and increase the coatings' tribological capabilities up to 500 °C. Foil gas bearings can use a backup lubricant made of CFx films bonded together with polyimide up to roughly 350 degrees Celsius. While polyimides are resistant to many solvents and chemicals, they are easily dissolved by alkalis.

Stator bushings of the compressor in the BR710 engine were made out of polyimides like Vespel CP-8000 from DoPontTM, which were used by GE Aircraft Engine, Pratt & Whitney, and Rolls & Royce. Graphite fibers, with their impressive strength, thermal conductivity, and lubricity, have piqued the interest of the aviation industry, leading to extensive study into their potential use in aircraft structures and gas turbine engines. Foundry Service & Supplies, Inc. in Ontario, California, USA, produces Fibercomp, a chopped fiber/graphite-reinforced polyimide. At 260 °C, its compressive strength is 172 MPa, and its friction coefficient is between 0.1 and 0.2. Lubricious polyimides can only be used up to about 350 degrees Celsius when they are exposed to air. Surface brittle fracture is a frequent wear hazard when working with polyimides [22].

Polyimide has the potential to be 3D printed in aerospace, aviation, vehicles, and microelectronics, and 3D polyimide designs can be built using UV-assisted direct ink writing (DIW) with minimal volume shrinkage of just under 6% [23]. Self-lubricating devices are now a reality thanks to digital processing and post-heat treatment of PTFE-filled photosensitive polyimide (PSPI) that allowed for 3D printing of lubrication in a targeted location. Because of their superior mechanical properties, such as tensile strengths more than 90 MPa, heat stability up to 384 °C, and interlayer bonding, 3D-printed PSPI-7wt.%PTFE composites reduce friction coefficients and wear rates by 88% and 98%, respectively. At 20 N, for instance, surface-lubricating friction coefficients drop to 0.09 while alternate-lubricating ones drop to 0.04. Importantly, a bearing that self-lubricates in a specific region was successfully demonstrated using a 3D-printed model [24].

Solid lubricants are used when liquid lubricants do not meet the advanced requirements of modern technology. They are less expensive than oil and grease lubrication systems for many applications. Solid lubricants also reduce weight, simplify lubrication, and improve materials and processes. Figure 5 [25, 26] list applications needed to meet critical operating conditions for which fluid lubricants are ineffective or undesirable. Changes in critical evironmental conditions, such as pressure, temperature, and radiation, affect lubricant efficiency. Further, in the cost-conscious automotive industry, solid lubricants are replacing oils and greases in many applications and helping to make highly efficient automobiles possible.

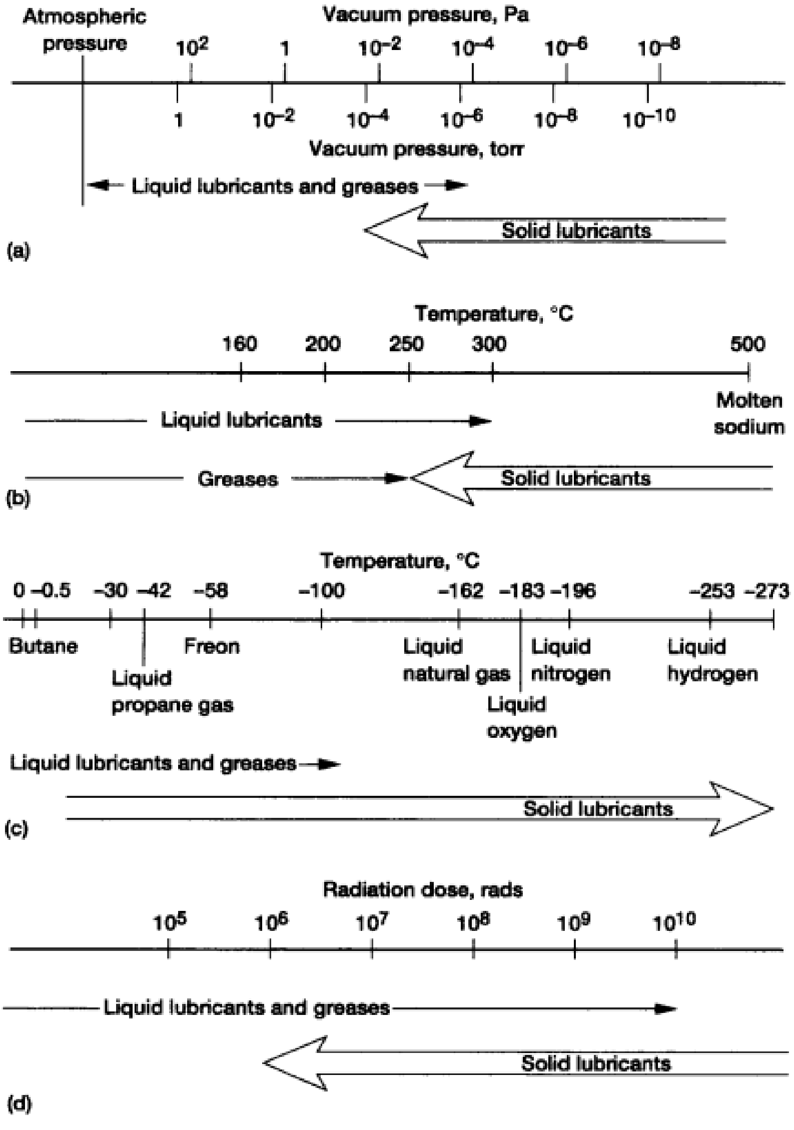


Figure 5. Ranges of application of solid lubricants in (a) high vacuum, (b) high temperature, (c) cryogenic temperature, and (d) radiation environments.

CONCLUSIONS

Understanding the friction and wear behaviour of different solid lubricants and self-lubricating composites in extreme environments is crucial for the development of advanced propulsion systems in the aerospace and aviation, nuclear power engine, automobile, metal processing (cutting, forming, forging), metallurgy, electric railway, and other industries. Studies have been conducted on a wide variety of compounds to assess whether or not they meet the criteria for use as solid lubricant materials that are gentler on the environment. Solid lubricants come in a wide variety of shapes and sizes. Mixtures of the aforementioned are also instances, as are polymers, soft metals, laminar solids, chemically stable fluorides, binary or ternary oxides, chromates, and sulfates. This report summarizes the uses of solid and semisolid lubricants over the previous five years and reviews the related research. Several authors argue that by adding another component to the lubricant, it may be used in higher temperatures and withstand wear better. It is possible to produce hybrid lubricants if the necessary infrastructure and precautions against potential hazards are in place. Lubricants play a significant role in aircraft because of their ability to create frictionless motion between moving parts and ensure that sliding contact is faultless. They are also frequently utilized in the aviation and aerospace sectors for use in the military, naval, and marine industries. More work needs to be done on lubricants so that state-of-the-art condition monitoring systems may be used to make them more practical for use in military and heavy applications. Lubricant characterization in the future will rely on high-tech tools like Raman spectroscopy and micro viscosity testing.

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