Electrically Conductive and Thermally Conductive Lubricants

Subjects: Metallurgy & Metallurgical Engineering

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Electrically as well as thermally conductive lubricants have drawn considerable attention and are an emerging research topic because they have unique advantages and advanced lubrication performance over traditional lubricants such as corrosion protection and efficient heat dissipation. For instance, some components of electric vehicles (EVs) such as bearings, seals, pads and gears require conductive lubricants to avoid premature failure and electromagnetic interference (EMI) problems due to induced shaft voltages and currents.

Keywords: tribology ; conductive lubricants ; lubrication

1. Introduction

The failure of the majority of engineering components is mostly caused by friction and wear [1]. Because friction accounts for 23–30% of global energy consumption, it is one of the biggest energy consumers in the world [2]. Therefore, lubricants are typically used in traditional systems to reduce friction between mating components, which is essential for the longevity and energy efficiency of mechanical devices [1]. The basic concepts of friction and lubrication, as well as the effect of lubrication on the coefficient of friction between two sliding bodies, were initially explained by Leonardo de Vinci (1452–1519) [3]. Lubricants are materials that are used to reduce friction between two surfaces in relative motion, thereby minimizing wear and tear and increasing the lifespan of the equipment [4]. Lubricants have a variety of functions, including decreasing noise and vibration, preventing corrosion and rust formation, minimizing friction and wear of mating surfaces, cooling and dissipating the heat created during operations, and many more [5]. The lubricants can be more effective and sustainable if they have good tribological qualities, such as a low coefficient of friction and a reduced rate of wear. The coefficient of friction, wear rate, conductivity of the lubricant materials, and additives used to increase lubricity are among the primary variables that influence the tribological performance of lubricants [6][7]. The current global industry demands lubricants with excellent electrical conductivity and thermal conductivity for numerous advance applications such as electric vehicles (EVs) [1][8][9][10], space systems [11][12][13], marine-related applications [14][15][16][17], and modern industrial machineries [18][19][20][21]. Lubricants must be able to operate at a wide variety of temperatures because the space system may lacks in thermal control. In EVs, the lubricating fluid is in contact with the electrical components requires that it has superior electric properties such as electrical conductivity, dielectric constant, and dielectric strength along with the good thermal management, and material adaptability [22]. As there are large number of variations in the type and performance of lubricants, it is crucial to select the right lubricant for the right application.

Conductive lubricants are typically formulated with a combination of conductive particles and a base lubricating fluid [23]. These lubricants may be silicone-based, graphite-based, or contain other conductive additives, depending on the desired properties and compatibility with the target materials and operating conditions [24]. The conductivity of the conductive lubricants can be enhanced by including conductive additives with the base lubricants. These additives offer extra critical features such as thermal conductivity, electrical conductivity along with anti-wear, resistance to extreme pressure, and corrosion prevention, chemical stability, and thermal stability. To meet the particular requirements of the application, the properties of the lubricant can be modified (**Figure 1** represents different application fields of conductive lubricants) by using various conductive nanoparticles, base fluids, and additives. Nano-sized titanium dioxide (TiO_2) [25], nanocomposite of Ag and graphene [26], nano-Ag/MWCNTs 5–15 nm [27], and carbon nanoballs (CNBs) [28] are the nano-sized additives used to enhance the desired properties of the conductive lubricants. Polyalphaole-fin oil (PAO) [28], Base Oils [29], PEG200 oil [30], hydraulic oil [31], SAE 10 mineral oil [32], paraffin oil [26], engine oil for diesel engine (CD 15W-40) [33] are the base lubricants for achieving desired. Nanoparticles can improve or modify the performance of lubrication in several ways [34]. The performance enhancement achieved by nanoparticles depends on factors such as the type, size, concentration, and dispersion of the nanoparticles added in the lubricant. Lubricants that contain nanoparticles can dramatically reduce wear and friction between surfaces [35]. High-hardness nanoparticles can operate as protective barriers by decreasing surface-to-surface contact and preventing wear. They also have great lubricating qualities. Some nanoparticles have very good heat conductivity. These nanoparticles can help lubricants better dissipate heat produced during operation, improving thermal stability and lowering the chance of lubricant breakdown [36].

The best electrical efficiency, reliability, and lifespan of electrical connections depend on the use of conductive lubricants, which also protect against wear and help to dissipate heat [37]. On the hand, thermally conductive lubricants are made to effectively transmit heat while also providing lubrication. To promote more effective heat dissipation, thermally conductive lubricants assist in moving heat away from heat-generating components and distributing it to cooler regions [38]. On the other hand, the electrical continuity between conductive surfaces, such as electrical contacts, connections, and terminals, is established and maintained by electrically conductive lubricants [39]. To ensure optimum electrical performance, reduce resistance, and avoid shortcomings such as voltage drop, arcing, or signal loss, it is essential to have this conductivity [40]. Therefore, it is crucial to increase the understanding of conductive lubricants to fill up the knowledge gap.

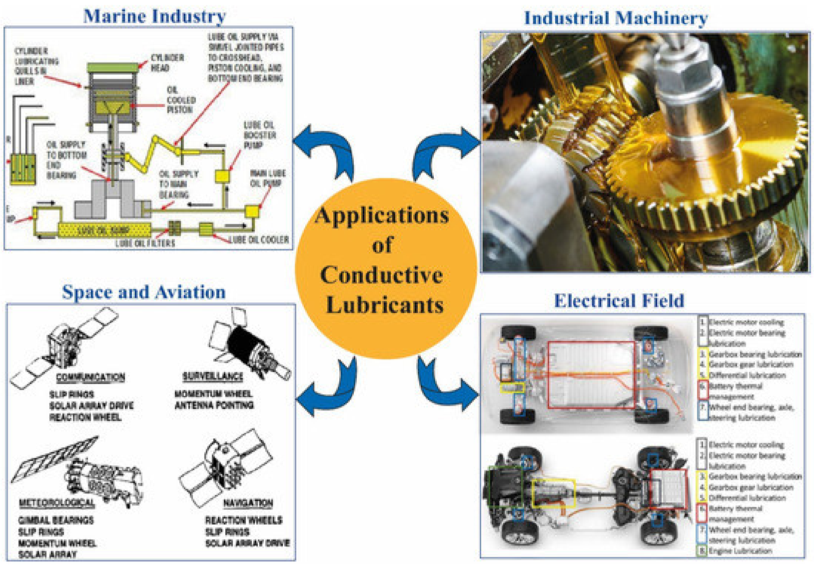

Figure 1. Different application fields of conductive lubricants. Source: The authors created based on [11][41][42][43].

Due to having outstanding mechanical, thermal, electrical, and tribological properties such as low coefficient of friction, and reduced wear rate enabling the lubricants more efficient and sustainable, one of the recent tribological research's main focus areas is conductive lubricants [44]. The substantial number of articles on tribological issues related to conductive lubricants that were published between the years 2013 and 2023 are represented in **Figure 2**. The customary methods have been used to obtain the data from the Elsevier Science Direct database. On the website's keywords search page, "Electrical and thermal conductivity and tribological property" is typed in as a search query. A total number of 4716 results were displayed for the customized range from 2013 to 2023. The left side of the screen displayed the number of related articles for each year. Then, on 10 June 2023, a graph indicating the number of articles related to the conductivity of lubricants by year was produced. In **Figure 2**, the number of publications is highest in the year 2022 and it seems to be more at the end of the year 2023 which indicates research on conductive lubricants is a current and burning issue. Moreover, **Figure 2** also clarifies the pattern of publications from the year 2013 to the year 2022 is increasing gradually therefore researchers need to focus more on this topic. Therefore, this field attracts tremendous attention from academicians all over the world.

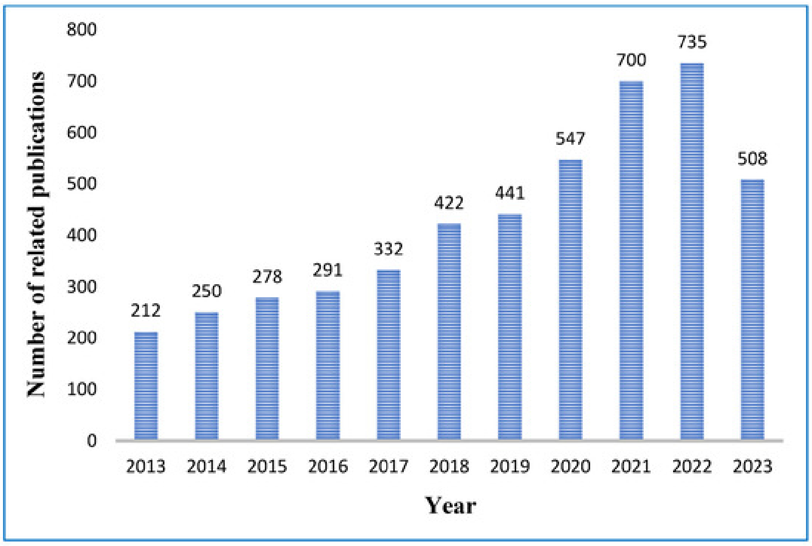

Figure 2. Statistical data for articles about, "Electrical and thermal conductivity and tribological property" during 2013–2023. The information was extracted on 10 June 2023, from the Elsevier Science Direct database. On the website's keywords search page, "Electrical and thermal conductivity and tribological property" is typed in as a search query.

Researchers, around the world, are constantly striving to reduce the coefficient of friction and wear rate of lubricants. Recently, Chang Du et al. investigated a study to enhance the performance of lubrication and examine how temperature affects the tribological characteristics of the oils used to lubricate the piston rings in the cylinder liners [45]. Their result reports that the tribological properties of lubricating oils change with the increase in temperature. Hongxiang Yu et al. also conducted a study to explore the impact of functional groups on the tribological performance of lubricants [46]. A study conducted by Corina Birleanu et al. [47] examines the effect of TiO_2 nanoparticles on the lubricating properties of oil. Ali et al. [48] used nanoparticles as additives in lubricants to improve their tribological properties. Their review reported that the nanoparticles improved tribological characteristics, exceptionally reduction in friction temperature emissions and minimizing material degradation over time at solid surfaces. Numerous studies have been performed to enhance the tribological performance of lubricants along with different additives. However, very little or no literature has yet examined thoroughly the impacts of lubricant conductivity on tribological characteristics. Therefore, it is a clear-cut study gap to find the impacts of using conductive lubricants for enhancing the tribological performance of the lubricant compounds. Even if there are sufficient amounts of works on lubricants conductivity, these are represented individually, and very few studies have combined thermally and electrically conductive lubricants [49][50][51]. For instance, Yanqiu Xia et al. [52] experimented on the conductivity and tribological properties of ionic liquid-polyaniline/tungsten disulfide (IL-PANI/WS2) composite. Xiaoqiang Fan et al. [53] also accomplished research on the improvement of tribological properties of conductive lubricating greases. Further, combined research on the conductive and tribological characteristics of copper-sliding electrical contacts was carried out by Zhengfeng Cao et al. [49].

Experts are investigating the connections between conductivity and tribological features using different methods. For example, a separate study by M. Kaneta and P. Yang [54] demonstrated the impact of contacting surfaces' thermal conductivity on elastohydrodynamic lubrication (EHL). Their findings demonstrate that the thermal conductivity of the contact materials controls the temperature in the lubricant layer and, consequently, the viscosity of the lubricant. Md Golam Rasul et al. [55] conducted a study employing functionalized boron nitride nanosheets to primarily increase the heat conductivity and tribological characteristics of polyethylene. Gyorgy Czel et al. [56] investigated how different fillers affected the thermal conductivity and tribological characteristics of polyamide. A study by Shaoli Fu et al. [57] considers only the electrical conductivity along with tribological properties of carbon nanotube-reinforced copper matrix composites. Moreover, Yang Fu et al. [58], in their research, concentrate on how surface roughness and conductive grease filling affect the tribological characteristics and electrical conductivity of carbon brushes. Likewise, Zhengfeng Jia et al. [59] investigated the tribological characteristics and electrical conductivities of the vacuum hot-pressed Cu/reduced graphene oxide composite. A study conducted by Tianhua Chen et al. [60] realized the elastic roll ring's current-carrying tribological capabilities under various currents.

The creation of innovative lubricant formulations is essential given the rising demand for enhanced lubricant performance to increase energy efficiency, sustainability, and cost reduction. Conducive lubricants are the ideal substitutes for tribological performance because the conventional lubricants used in internal combustion engines (ICE) have some limits for cutting-edge applications including electric vehicles, aerospace, and electromagnetic interference. For accurate and efficient identification of tribological conditions for cutting-edge applications such as EVs and spacecraft, a thorough analysis of the performances of recently produced lubricants is a prerequisite. The effectiveness of several solid, semisolid, and liquid lubricants is examined, and their effectiveness is assessed in terms of electrical compatibility and thermal management. Further, a comprehensive list of conductive lubricant additives to enhance the conductivities of lubricant materials along with their tribological performances have been identified and summarized. Lubricants are also grouped together based on the physical state, organic–inorganic, metallic–nonmetallic, and conductive–nonconductive properties. The goal is to compile the research on formulations of thermally and electrically conductive lubricants and to produce an easily readable, tabular summary. Researchers offer the reader a comparative analysis of several additives to enhance thermal and electrical conductivities as well as the performance of the lubricant.

2. Classification of Lubricants and Lubrication

The lubricants may be conventionally classified into four major classes such as solid lubricants, semisolid lubricants, liquid lubricants, and gaseous lubricants [61]. Solid lubricants are substances that transmit a thin coating of solid material onto the surfaces in contact to reduce friction between them [62]. Solid lubricants do not flow or need a carrier medium, unlike grease or liquid lubricants. They are utilized in situations where conventional lubricants might not be appropriate or effective. Examples of solid lubricants include graphite, chalk, talc, mica, Teflon, soap, way, and gold [63]. Likewise, semisolid lubricants, also known as greases, are a type of lubricating material that combines the properties of a solid and a liquid. They consist of base oil, a thickening agent, and various additives. Semisolid lubricants are characterized by their semisolid or viscous consistency, which allows them to adhere to surfaces and provide long-lasting lubrication [64]. To stick to surfaces and offer long-lasting lubrication, semisolid lubricants have a semisolid or viscous viscosity [65]. Moreover, liquid lubricants are compounds with a liquid condition that are intended to lubricate and minimize friction between two surfaces that are moving relative to one another [66]. These lubricants often flow more freely and can fit into narrow areas since they have a lower viscosity than semisolid lubricants. Liquid lubricants prevent direct metal-to-metal contact and reduce heat generation, wear, and friction by forming a thin film or coating between the moving surfaces [67]. Furthermore, gaseous lubricants, also known as vapor-phase lubricants or lubricating gases, are substances in a gaseous state that are used for lubrication purposes. Unlike liquid or semisolid lubricants, gaseous lubricants do not exist as a liquid film or layer between the moving surfaces [68]. Instead, they function by providing a boundary layer of gas that reduces friction and wear between the surfaces. Depending on the particular application and requirements, the lubrication becomes usually in different forms [69][70]. In boundary lubrication, a small layer of lubricant separates the two surfaces. A layer of protection is created by the lubricant molecules' adhesion to the surface. The lubricant film, however, may break down under high loads or low speeds, causing metal-to-metal contact and increased friction [71]. The technique of hydrodynamic lubrication involves the development of a fluid film between the surfaces under pressure [72]. The relative motion of the surfaces forces the lubricant into the gap, forming a hydrodynamic wedge. This kind of lubricant works well with fast speeds and large weights. Elastohydrodynamic lubrication (EHL) combines the advantages of boundary lubrication and hydrodynamic lubrication. When the lubricant layer thickness is equal to or less than the surface roughness, this happens [73]. The lubricant can deform elastically due to pressure and viscosity, which improves protection between the surfaces.

On the other hand, lubricants can also be categorized into two major classes based on the conductivity of the lubricant materials. These are conductive and nonconductive lubricants [6][74]. The conductive lubricants can be either electrically conductive or thermally conductive (a detailed classification of lubricants is shown in **Figure 3**) [75]. Thermally conductive lubricants are formulated to enhance the transfer of heat. When two mating surfaces come in contact produces a high temperature (more than 300 °C). The resultant high temperature breakdowns the lubricants, but the resulting compounds must be lubricants to avoid the occurrence of corrosion or abrasion of mating surfaces [62]. The thermal conductivity of the lubricant materials enables the contacting materials to dissipate heat generated by rubbing [8]. They contain components that improve the lubricant's capacity to dissipate heat, such as thermally conductive additives such as ceramic particles (such as aluminum oxide, and boron nitride) or metallic fillers (such as silver, and copper) [76]. These additives enhance the lubricant's thermal conductivity, enabling it to effectively transmit heat away from lubricated surfaces. When heat generation is a concern, such as in electric motors, power electronics, heat sinks, or LED lights, thermally conductive lubricants are utilized. These lubricants help maintain ideal operating temperatures, avoid overheating, and increase the lifespan of the lubricated components by promoting efficient heat dissipation [77].

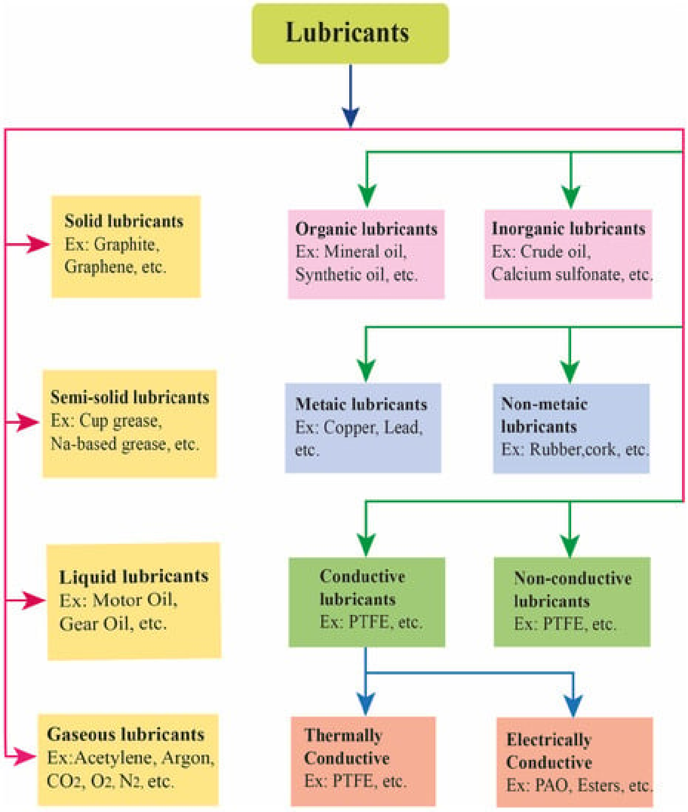

Figure 3. Classification of lubricants based on their physical state, organic–inorganic, metallic–nonmetallic, and conductivity–nonconductivity.

Electrically conductive lubricants are designed to ease the flow of electric current. They have conductive additives such as metallic particles (silver or copper) or carbon-based substances (such as graphite or carbon nanotubes) that help the lubricant forming a conductive network [41]. After the inclusion of additives, the lubricant can function as an electrical conductor. When working with electrical contacts, connections, switches, or grounding points, lubricants that conduct electricity are frequently employed. Electrically conductive lubricants have a staggering potential for electric vehicle (EVs) lubrication. Even if electric vehicles (EVs) are quite energy efficient, there is a challenge to enhance their efficiency even more [68][78]. These lubricants are used to reduce the friction in gears and bearings and to prevent copper corrosion and to cool the electric motor of EVs [74]. These guarantee appropriate electrical continuity, lower resistance, and guard against problems such as electrical arcing and static charge buildup. In fields including electronics, electric vehicles, automotive, aerospace, and power generation these lubricants are frequently used [79]. Recently, electric vehicles (EV) and electric hybrid vehicles (EHV) are attracting enormous attention. Yan Chen and their group reviewed the current requirements and the future proposal of advanced lubricants for EVs, and EHVs [41]. Even then, conventional lubricants for internal combustion engine vehicles (ICEVs) are utilized in EVs with reasonable performance; however, these fluids have not been produced specifically for the evaluation of EV needs [80]. Many different types of lubrication is used to reduce friction: metallic lubrication, soft metals, ionic grease lubrication, and ionic liquid lubrication.

2.1. Metallic Lubrication

To reduce friction and wear between metal surfaces by using metallic materials or compounds as lubricants or lubricant additives is termed as Metallic lubrication. It can withstand higher temperatures and pressures than organic lubricants and are more resistant to oxidation and degradation by providing excellent boundary lubrication that occurs when the metal surfaces come into direct contact inorganic anion [81].

Researchers have collected several types of metallic lubricants including solid lubricants and lubricants additives Cu-based composites (Cu-Sn-Al- Fe-h-BN graphite-SiC) and Ni-P-h-BN alloy. The COF and WR of Cu-based composites (Cu-Sn-Al- Fe-h-BN graphite-SiC), at 25 °C are approximately 0.5 and 1.3×10^{-5}–4.3×10^{-5} mm^3 N^{-1} m^{-1}, respectively [82]. Again, The COF and WR of Ni-P-h-BN alloy at 25 °C are 0.2 and 1.24×10^{-6} N^{-1} m^{-1} [83]. So, in alloy composition, when the number of metal is low, the value of COF and WR is low. That means the tribological properties are improved.

2.2. Soft Metals

In **Table 1**, researchers can see various soft metals, such as silver, tin, and lead, as self-lubricating films on hard substrates due to their low melting temperatures and shear strength. These soft metals can form a shear-simple tribolayer and exhibit increased ductility, providing lubrication through mechanisms such as the correction of microstructural faults during sliding. While soft metals such as zinc, lead, tin, and their alloys with low melting points and multi-slip systems are effective for low-temperature and lightly loaded conditions, metals such as silver, gold, and platinum have low hardness and high melting temperatures, limiting their lubricating capabilities. However, coatings of binary alloys such as Sn-Co or ion-plated lead coatings have been developed as alternatives to hard chromium coatings in tribological applications. In recent developments, various techniques and multi-layered approaches involving metals such as Al/Cu/Fe/Cr, Cu/Mo, Zn/W, Ni/Ti, and Au/Cr have been used to create films for tribological applications in turbomachinery parts, fretting interfaces, seals, and bearings, operating at temperatures up to 580 °C. **Table 1** displays the tribological behavior of materials that self-lubricate and contain soft metals. The use of different soft metals helps to increase the tribological performance of solid lubricants. From **Table 1**, researchers can see Ta-Ag materials where Ag as a soft metals at 6000 C the COF of Ta-Ag alloy is 0.2 and the wear resistance is 5.2×10^{-5}. Additionally, for TiN-In alloy the COF is 0.5 and WR is 5.2×10^{-5}. For Ni-Cr/Cr3C2-NiCr/h-BN at 20 °C, the COF and WR are 0.65 and 5.3×10^{-5} N^{-1} m^{-1}, respectively.

Table 1. Tribological data of different conductive solid lubricants.

Lubricants	Lubricant Material	Application	Tribological Behavior		Ref.
			COF	WR	
B_4C-h-BN	Solid	High loads and high-speed application	0.591–0.321	2.07×10^{-5}–1.94×10^{-4} N^{-1} m^{-1}	[62]
Cu-based composites (Cu-Sn-Al-Fe-h-BN graphite-SiC)	Metallic	High-temperature application	~0.5	1.3×10^{-5}–4.3×10^{-5} mm^3 N^{-1} m^{-1}	[62]
5% Graphite	Solid	A mechanical seal's rubbing component, an electrically conducting motor, and generator brushes.	0.2	0.0002 mm^3/Nm	[84]
Molybdenum diselenide ($MoSe_2$)	Solid	Optical sensors, biosensors, electrochemical biosensors	0.039	5×10^{-6} mm^3/Nm	[85]
Molybdenum disulfide (MoS_2)	Solid	Satellites and the space shuttle	0.075	4.78×10^{-5} mm^3 N^{-1} m^{-1}	[86]
Ni-P-h-BN	Solid	Relay and switch contacts, threaded parts	0.2	1.24×10^{-6} N^{-1} m^{-1}	[62]
Ni-Cr-W-Mo-Al-Ti-h-BN-Ag	Solid	Sleeve bearings, and metal-forming dies	0.37	7×10^{-4} N^{-1} m^{-1}	[62]
Ni-Cr/Cr_3C_2-NiCr/h-BN	Solid	Aerospace, automotive, power generation, industrial machinery, metalworking	0.65	5.3×10^{-5} N^{-1} m^{-1}	[62]
Ni-P-h-BN alloy	Metallic	Engine components, transmission systems, and bearings, aircraft engines, landing gear, and actuation systems	0.2	1.24×10^{-6} N^{-1} m^{-1}	[62]
NiMoAl-6Al_2O_3-10Ag	Solid	Seals, gears, bearings	0.53	1.47×10^{-5} mm^3/Nm	[87]
NiMoAl-Ag	Solid	Space mechanics, preventing rust	0.3	4.64×10^{-5} mm^3/Nm	[88]
5% Polytetrafluoroethylene (PTFE)	Solid	Mechanical components in companies such as GE Aircraft Engine, Pratt & Whitney, and Rolls Royce	0.1904	1.605×10^{-5} mm^3/Nm	[89]
Ta-Ag alloy	Solid	Spacecraft, high-temperature application	0.2	5.2×10^{-5} mm^3/Nm	[62]
TiN-In alloy	Solid	Metal-forming dies	0.5	5.2×10^{-5} N^{-1} m^{-1}	[62]

2.3. Ionic Grease Lubrication

Ionic grease is type of specialized lubricant that is generally electrical conductive containing conductive particle or additives that allow the grease to conduct electricity with reducing friction; it is primarily used in electrical and electronics application. Grease is often use with ionic liquids as additives. Ionic liquids have been demonstrated as effective additives to promote lubrication in base oils and greases. Using benzotriazole group grafted imidazolium IL as additive in poly (ethylene glycol) (PEG) and polyurea grease, which effectively reduced friction/wear of steel pairs that outperforms commercial zincdiakyldithiophosphate-based additive (T204). Synthesizing lubricating grease by using 1-octyl-3-methylimidazolium hexafluorophosphate and 1-octyl-3-methylimidazolium tetrafluoroborate as base oil and the polytetrafluoroethylene as thickener to reduce friction and wear on steel/steel contacts. In **Table 2**, researchers have used several types of ionic grease lubricants such as [Li(PAG)]BF4 grease, [Li(PAG)]PF6 grease, [Li(PAG)]NTf2 grease, 1-hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl) amide (L-F106). For example, in **Table 2**, researchers can see for [Li (PAG)]PF6 grease the COF becomes 0.092 and also for [Li(PAG)]NTf2 grease the COF becomes 0.095. Thus, the COF and wear resistance is increased after using conductive particles as additives.

Table 2. Tribological data of different conductive semisolid lubricants.

Lubricants	Lubricant Material	Application	Tribological Behavior		Ref.
			COF	WR	
Attapulgite-based grease	Grease	High-temperature applications, water resistance.	0.132	Wear volume $9/10^{-4}$ mm^3	[90]
Attapulgite with 1-butyl-3-methylimidazolium hexafluorophosphate [L-P104]	Grease	Thixotropic additive, rheology modifier	0.128	Wear volume $0.8/10^{-4}$ mm^3	[90]
Attapulgite with 1-hexyl-3-methylimidazolium hexafluorophosphate [L-P106]	Grease	Anti-wear agents, EP (extreme pressure) additives	0.1255	Wear volume $0.67/10^{-4}$ mm^3	[90]
Attapulgite with 1-octyl-3-methylimidazolium tetrafluoroborate [L-B108]	Grease	Automotive engines, industrial machinery, and oven equipment	0.128	Wear volume $0.55/10^{-4}$ mm^3	[90]
Bentone-based grease	Grease	Bearings, gears, slides, bushings, marine environments, and wet processing industries	0.128	Wear volume $2.5/10^{-4}$ mm^3	[90]
Bentone with 1-butyl-3-methylimidazolium hexafluorophosphate [L-P104]	Grease	Outdoor equipment, and other conditions where moisture is present	0.128	Wear volume $1.7/10^{-4}$ mm^3	[90]
Bentone with 1-hexyl-3-methylimidazolium hexafluorophosphate [L-P106]	Grease	Gearboxes, bearings, it is useful in applications where grease consistency and adhesion are important	0.1275	Wear volume $1.2/10^{-4}$ mm^3	[90]
Bentone with 1-octyl-3-methylimidazolium tetrafluoroborate [L-B108]	Grease	Bearings, gears, and slides, construction and mining equipment, against harsh conditions, water exposure	0.1275	Wear volume $1.5/10^{-4}$ mm^3	[90]
2% Boron nitride (BN)	grease	Semiconductor, aerospace and aviation, vacuum	0.19	Wear scar width 0.375 mm	[10]
1% Carbon nano-additives in grease	Grease	Tribological coatings, aerospace, automotive, and heavy machinery, brushes, gears, bearings	0.022	Wear scar diameter 0.24 mm	[91]
1-dodecyl-3-methylimidazolium hexafluorophosphate ($[C_{12}mim][PF_6]$)	Grease	Surface coating, lubrications	0.09	Scratch width 0.226 mm	[92]
1-dodecyl-3-methylimidazolium bis (trifluoromethanesulfonyl) imide ($[C_{12}mim][NTf_2]$)	Grease	High-temperature lubrication, extreme pressure (EP) lubrication, anti-wear and anti-friction coatings	0.12	Scratch width 0.225 mm	[92]

Lubricants	Lubricant Material	Application	Tribological Behavior		Ref.
			COF	WR	
1-ethyl-3-methyl imidazolium hexafluorophosphate (L-P102)	Ionic grease	Batteries, super capacitors, and electrolytes	0.093	Wear volume 0.55 μm^2	[93]
1-hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl) amide (L-F106)	Ionic grease	Automotive, industrial, or machinery applications	0.071	Wear volume 0.56 μm^2	[93]
Lithium complex grease (LCG) with 3% MoS_2	Grease	Aerospace and defense, mining and construction equipment, automotive, hinges, gears, and aircraft, spacecraft, and defense	0.17	Wear volume $9/10^{-4}$ mm^3	[94]
Lithium conductive grease	Grease	Semiconductor manufacturing, antistatic applications, EMI/RFI shielding	0.12	Wear widths 0.375 (mm)	[95]
[Li(PAG)]BF_4 grease	Ionic grease	Wheel bearings, chassis parts, and universal joints	0.09	Wear volume 0.58 μm^2	[93]
[Li(PAG)]PF_6 grease	Ionic grease	Gearboxes, bearings, and slides	0.092	Wear volume 0.56 μm^2	[93]
[Li(PAG)]NTf_2 grease	Ionic grease	Aerospace, defense, or marine, where high-performance lubrication is required	0.095	Wear volume 0.65 μm^2	[93]
2% Niobium selenide ($NbSe_2$)	Grease	Extreme pressure (EP) lubrication, anti-wear and anti-friction coatings	0.18	Wear scar width 0.35 mm	[10]
Polyalkylene glycol (PAG)	Grease	Pumps, fans, and conveyors excavators, loaders, wind turbines, marine bearings, propellers	0.121	Wear width 0.33 mm	[96]
Polyalkylene glycol (PAG)	Grease	Aerospace industry, spark plug threads, ignition systems, electrical connectors, furnaces, ovens	0.119	Wear width 0.31 mm	[96]
Polyalkylene glycol (PAG)	Grease	Packaging industry, paper manufacturing, printing industry, textile industry	0.111	Wear width 0.325 mm	[96]
Polyurea grease (PG)	Grease	Pumps, motors, conveyors, and bearings, universal joints	0.175	Wear volume $4.7/10^{-4}$ mm^3	[94]
Polyurea grease (PG) with 3% MoS_2	Grease	Pumps, gears, and bearings, pins, loaders, bulldozers	0.225	Wear volume $3.75/10^{-4}$ mm^3	[94]
Polyurea grease (PG) with 3% Pentaerythritoltetrakis (diphenyl phosphate) (PDP)	Grease	Large gears, bearings, open gears, and heavily loaded sliding surfaces	0.10	Wear volume $0.5/10^{-4}$ mm^3	[94]
Polyurea grease (PG) with 3% trimethylolpropane tris(diphenyl phosphate) (TDP)	Grease	Aviation and aerospace, automotive industry, robotics, defense, power generation	0.125	Wear volume $0.6/10^{-4}$ mm^3	[94]
Polyalkylene glycol (PAG)	Grease	Battery separators, adsorbents, aerospace, automotive, sports equipment	0.062	Wear width 0.032 mm	[97]

2.4. Ionic Liquid Lubrication

Ionic liquids (ILs) consist of large, asymmetric organic cations and usually an inorganic anion [81]. Ionic liquid lubricant has high thermal stability, low volatility, reduce friction, nonflammability, low melting point and good at stability. It has been discovered that the most significant mechanism controlling the molecular behavior of ionic liquids in the gap in the dynamic state is their contact with the solid wall. So, the use of ionic lubricant as boundary is getting more and more.

Liu et al. [98] indicates that, in alcohol-based ionic liquid with the increase in alkyl chains, the wear resistance and friction reduction properties of the liquids were improved. As a comparison, in **Table 3**, the wear scar of 1- ethyl-3-hexylimidazolium tetrafluorobo-rate (L206) and 1-ethyl-3-octylimidazolium tetrafluorobo-rate (L208) is 0.30 mm and 0.27 mm, respectively. Again, COF and WR of 1-octyl, 3-methyl (L106) and 1-octyl, 3-methyl (L108) at 100 °C are, 0.08, 0.04 and 7.27 × 10^{-4} mm^3/m, 5.22 × 10^{-4} mm^3/m, respectively. So, the wear resistance and friction reduction properties of the liquids were improved [98].

Acid-based ionic liquids improved the anti-corrosion. Additionally, act as a good lubricant. Wang et al. [99] indicates that, with the increase in alkyl chain length, the COF of the acid-based ionic liquid gradually decrease. As a comparison, in **Table 3**, the COF of choline-based lauric acid ([Ch][DA], choline-based palmitic acid ([Ch][PA]) and choline-based stearic acid ([Ch][SA]) is 0.35, 0.30 and 0.11, respectively.

Table 3. Tribological data of different conductive liquid lubricants.

Lubricants	Lubricant Material	Application	Tribological Behavior		Ref.
			COF	WR	
Automatic transmission fluid (ATF) with 1% N-hexyl-N-methylpiperidinium bis(2-ethylhexyl)phosphate ($[P_{6,6,6,14}]$[BEHP]) at load 5N	Ionic liquid	Power steering systems	0.15	Wear volume 1.9 μm^3	[100]
Choline-based stearic acid ([Ch][SA])	Ionic liquid	Industrial lubrications, bio-based lubricants, automotive lubrication, aerospace	0.11	Wear volume is 11 × 10^{-4} mm^3	[99] [101] [102]
Choline-based palmitic acid ([Ch][PA])	Ionic liquid	Metalworking and cutting Fluids, forming and stamping, anti-seize and assembly lubrications	0.30	Wear volume is 14 × 10^{-4} mm^3	[99] [102] [103]
Choline-based lauric acid ([Ch][DA])	Ionic liquid	Metalworking and cutting fluids, industrial lubrication	0.35	Wear volume is 9 × 10^{-4} mm^3	[99] [102]
Combination of black carbon and 1% alkyl-phosphonium-based IL trihexyltetradecyl-phosphonium docusate ([p66614�66614][DOC]-[CB])	Ionic liquid	Bearings and electrically loaded bearings, self-lubrication	0.55	Wear volume 0.05 mm^3	[7]
Combination of carbon nanotubes and 1% alkyl-phosphonium-based IL trihexyltetradecyl-phosphonium docusate ([p66614�66614][DOC]-[CTN])	Ionic liquid	To improved creep resistances and strength, applied in electrically loaded bearings, self-lubricating	0.59	Wear volume 0.059 mm^3	
1,2-dimethyl-3-propylimidazolium tetrafluoroborate ([C2C6�2�6im]BF_4)	Ionic liquid	Metalworking and cutting fluids, corrosion protection, electrical contacts, energy storage systems, applicable in industries such as aerospace and automotive	0.07	0.05/10^{-4} mm	[66]
1-ethyl-3-hexylimidazolium tetrafluoroborate (L206)	Ionic liquid	Used in gears, bearings, and chains	0.039	Wear scar 0.30 mm	[98]
1-ethyl-3-octylimidazolium tetrafluoroborate (L208)	Ionic liquid	Used as electrolytes, used in gears, bearings, and chains	0.039	Wear scar 0.27 mm	[98]
1-ethyl-3-hexylimidazolium-bis(trifluoromethylsulfonyl)-imide (L-F206)	Ionic liquid	Pump, membranes	0.08	Wear volume 0.1 × 10^{-4} mm^3	[104] [105]
1-ethyl-3-hexylimidazolium tetrafluoroborate (L-B206)	Ionic liquid	Aviation, space technology, automobile industry	0.045	Wear volume 0.2 × 10^{-4} mm^3	[104] [106]

Lubricants	Lubricant Material	Application	Tribological Behavior		Ref.
			COF	WR	
1-hexyl-3-methylimidazolium tetrafluoroborate ([hmim][PF_6])	**Ionic liquid**	**Tribological applications, electrical contacts, gears, bearings, and chains**	**0.056**	**1.8×10^{10} mm^3/mm**	[107]
1-hexyl-3-methylimidazoliumhexafluorophosphate ([hmim][BF_4])	**Ionic liquid**	**Applied for separation of organic compounds, electrochemical cells**	**0.048**	**2.4×10^{10} mm^3/mm**	[107]
Motor oil SAE 30 with 0.3% Cu additive	**liquid**	**High-temperature applications, marine and aerospace applications**	**0.023**	**Wear path is 33 m**	[108] [109]
1-octyl, 3-methyl (L106) at 100 °C	**Ionic liquid**	**High-temperature turbine and space applications, solar energy**	**0.08**	**7.27×10^{-4} mm^3/m**	[110] [111]
1-octyl, 3-methyl (L108) at 100 °C	**Ionic liquid**	**Automotive lubrication, electrical contacts**	**0.04**	**5.22×10^{-4} mm^3/m**	[110]
Polyethylene glycol (PEG)-based 1-ethyl-3-methylimidazolium cations (([C1imC10imC1]) and bis(trifluoromethylsulfonyl)imide anions (NTf2) [2,2′-methyl-[C1imC10imC1](NTf_2)$_2$])	**Ionic liquid**	**Lubricants and tribology, biocompatible lubricants, energy storage systems, extraction and separation processes, green chemistry and catalysis**	**0.12**	**1×10^{-8} mm^3/Nm**	
Polyethylene glycol (PEG)-based 1-ethyl-3-methylimidazolium cations ([C1imC10imC1]) with methyl substitution	**Ionic liquid**	**High-temperature lubrication, metalworking and cutting fluids, corrosion protection**	**0.13**	**25×10^{-8} mm^3/Nm**	[66]
Polyethylene glycol (PEG)-based 1-ethyl-3-methylimidazolium cations ([C1imC10imC1]) with methyl substitution at the 2 and 2′ positions, and tetrafluoroborate anions (BF4-) ([2,2′-methyl-[C1imC10imC1](BF_4)$_2$])	**Ionic liquid**	**Electrical contacts, corrosion protection, lubricants and tribology**	**0.11**	**6×10^{-8} mm^3/Nm**	

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