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REVIEW ARTICLE

Solid Lubricants in Sustainable Manufacturing: A Review of Processing Techniques, Materials and Applications

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ABSTRACT – Achieving sustainability and a higher green index is a demand of modern manufacturing. In machining, various metal-cutting fluids are conventionally used, and their use and disposal pose a severe threat to operators and the environment. As a green alternative, solid lubricants have been proposed and implemented by the manufacturing and materials research communities. This field is attracting significant interest for its potential, and therefore, diverse solid lubricant candidates, ranging from traditional to novel materials, are reviewed here. Different techniques for manufacturing and applying solid lubricants, along with the tribological performance of these methods and the lubricants, have been reviewed. Emphasis is given to the use of solid lubricants in the field of machining and allied fields. Some pertinent problems and possible future trends are also highlighted. Recent developments in this field from this millennium, particularly from the last decade onwards, are reviewed. The review shows acceptance of solid lubricants as a great way to achieve better tribological performance in machining and allied fields, without harming operators or the environment. The applicability of high-temperature solid lubricants can extend even beyond 1000°C. This study aims to enhance readers' understanding of the applications of solid lubricants as an eco-friendly approach to sustainable manufacturing and green tribology.

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1. INTRODUCTION

Over the last decade, the world has been critically thinking about the environment, and the manufacturing industry, the backbone of human civilization, is no exception. Machining is one of the most versatile production methods in all manufacturing industries. Producing the best-quality product, free of defects, with ease and at an economical cost is the goal of any manufacturer. Effective design and control of the machining process are essential to achieving optimal outcomes. In this regard, the importance of the primary parameters governing machining, viz., cutting speed, feed, and depth of cut, is already evident from various research carried out in this field. Moreover, another critical factor, i.e., the heat generated during machining and its cooling, can greatly affect the quality of the product and the overall economics of production. The considerable heat produced, primarily due to high friction, negatively impacts tool geometry, thereby reducing tool lifespan and compromising the quality of the machined surface. Premature tool failure delays production and increases total production costs. Also, the tribological properties of the parts machined by a tool under these unfavorable conditions are hampered. Nowadays, superior tribological characteristics of manufactured parts' surfaces are a key decision factor owing to the ever-increasing use of high-speed applications. For this control, various cutting fluids (Metal Working Fluid, MWF) are typically used in the machining zone to remove generated heat and cool the tool and workpiece. Lubricants, as engineering fluids, play a vital role across industries, providing significant economic benefits while also posing ecological threats.

Recently, in this context, preserving resources and energy, as well as lowering emissions, have become critical issues. Selecting the right lubricant can increase energy efficiency by 10% [1]. Efficient lubrication reduces wear and extends machine life, resulting in the reduction of the consumption of non-renewable resources [1]. Cutting fluid's use, however, comes with several drawbacks, including contaminating the environment, causing dermatitis in operators, contaminating water and soil during disposal, and ultimately contaminating food and agricultural products. It is reported that 80% of all occupational disorders in operators are caused by direct skin contact with machining fluids. Reports reveal that each year, the production of MWFs exceeds 100 million gallons; their exposure exceeds 1 million employees [2]. Various types of MWFs, such as straight or soluble oils, synthetic oils, and semi-synthetic oils, are available. MWFs may be irritant or allergic due to their complex composition. Mainly for water-soluble cutting fluids, bacteria and fungi that produce microbial toxins are more injurious to operators. One may be exposed to MWFs by inhalation of aerosols, direct skin contact with the contaminated surfaces, and or splashing of fluids. Common problems reported by the U.S. Centers for Disease Control and Prevention [2], because of exposure to MWFs, include various skin disorders, viz., skin irritations,

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oil acne, and rashes; respiratory problems, including cough, asthma, or other breathing problems; as well as eye, nose, and throat irritation.

Furthermore, a significant amount of the manufacturing cost is also incurred by the cutting fluids [3]. Use of coolants accounts for about 15% of machining cost, and it is around 3 to 4 times the cost of cutting tools [4]. Therefore, research is nowadays directed towards achieving sustainability in manufacturing, where the focus is on lowering or doing away with the consumption of traditional cutting fluids. Dry machining, cryogenic machining, and Minimum Quantity Lubrication (MQL) are a few potential substitute cooling-lubrication concepts [5]. While processing difficult-to-machine materials, adequate lubrication is required when cutting fluid is not in abundance. In contrast to these, utilization of solid lubricant (SL) in various innovative ways has now set the trend in research in the field of machining and tribology. Tribology is concerned with the various phenomena and techniques associated with mating surfaces in motion relative to each other, encompassing the wear, friction, and lubrication examination. Tribological contacts consume energy, which is estimated to account for 23% of the global energy consumption [6]. In that, 20% is utilized in overcoming friction, and the remaining 3% goes to refurbishing parts that have worn out due to wear-related issues [6]. The 20th century has represented a time of large-scale production and extensive consumption, and hence it has also become the era of degradation of natural resources. This has adversely affected the whole ecology as well as mankind [7]. The realization of these problems and increased environmental awareness and regulatory norms have shifted the notion towards exploration and application of green technologies, including in the manufacturing sector. The world is talking about sustainable development nowadays, which is defined in the Brundtland Report [8] as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

The United Nations has introduced 17 sustainable development goals (SDGs), where SDG 9 and SDG 12 emphasize industry, innovation, and infrastructure as well as responsible consumption and production, respectively [9]. The advancement in the field of sustainable tribology can greatly influence the overall sustainable development, as seen in Figure 1. Embracing green manufacturing is another crucial concept that can help in resolving environmental issues [10], where the use of SL can play a vital role. Figure 2 shows the “International Energy Agency (IEA) (2014) estimation of key technologies for reduction of CO_2 emissions to limit the global warming to 2 °C above pre-industrial levels by 2050” [11]. Here, end-use energy efficiency is predicted to have the largest impact (38%). In this regard, the advancement in tribology could play a great role with novel materials and coatings, surface engineering, novel lubricants and additives (SLs, nanomaterials, hexagonal boron nitride, graphene, etc.) [6]. The novel concept of ‘green tribology’ is an amalgamation of various tribological disciplines with green chemistry and green engineering. It can be defined as ‘the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts’ [12]. In this context, Nosonovsky and Bhushan [12] formulated the famous 12 principles of green tribology, the first three of which are: i) minimization of heat and energy dissipation, ii) minimization of wear, and iii) Reduction or complete elimination of lubrication and self-lubrication. Also, the three major areas of green tribology having the maximum environmental impact are (i) biomimetic and self-lubricating materials/surfaces, (ii) biodegradable and environment-friendly lubricants, and (iii) tribology of renewable and/or sustainable sources of energy [12].

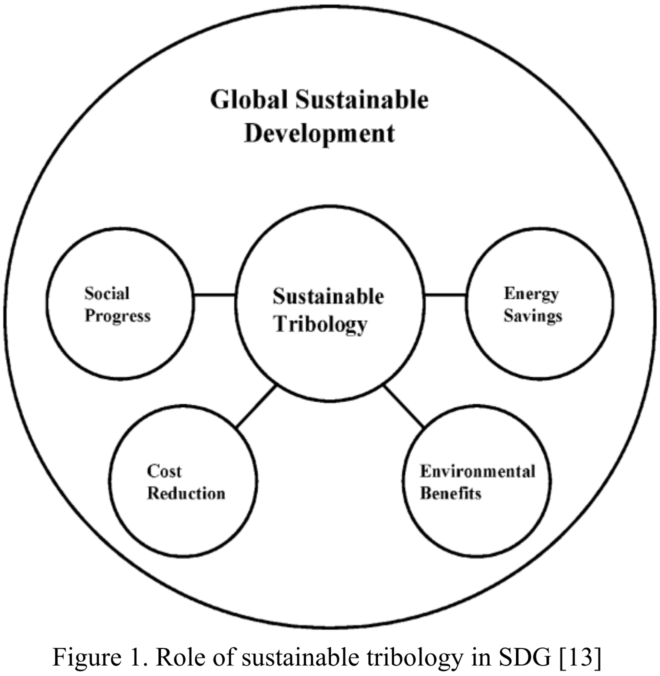

Figure 1. Role of sustainable tribology in SDG [13]

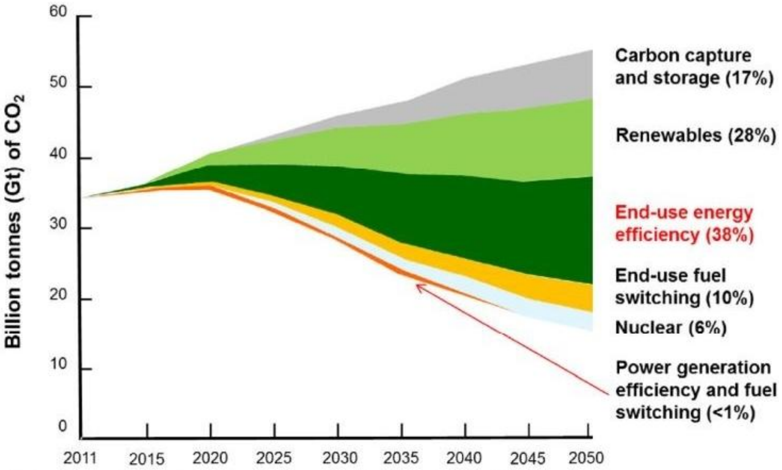

Figure 2. Key technologies for limiting global warming to 2°C by reducing CO_2 emissions [11]

This review highlights the impact and the importance of SL in the direction of green tribology and shows its applicability in terms of the principles of green tribology. It highlights and recommends SL as a green and sustainable alternative to the traditionally used MWFs for machining, as well as various types and ways of lubricating tribological parts. Here, a review of a diverse range of SLs from traditional to the trendy ones is presented. Different techniques for their preparation and methods of application in various scenarios have been emphasized. This study primarily focuses on the development in the field of machining and tribology over the last decade. Some newly trending and potential SL candidates are discussed, which can lead to the future trend of application of SL towards applicability in extreme environments, self-healing capability, tailored lubrication property, etc.

2. METHODS AND MATERIAL

A SL is a solid material offering effective lubrication between two mating surfaces having relative motion [14]. According to Lansdown [15], “a solid lubricant is basically any solid material, such as a thin film or a powder that can be placed between two bearing surfaces and that will shear more easily under a given load than the bearing materials themselves”. In the scenario of prevailing conditions of boundary lubrication, SLs are used. The temperature resistance property and absence of sealing problems greatly enhance the employability of SLs. Some important properties expected from SLs include (1) a low level of shear strength, (2) fine ability of thin film-formation, and (3) transfer films formability, for SL materials. There are a variety of classes of SLs, viz. (1) particulates, (2) soft metals, (3) polymers, (4) composites, and (5) glasses. Other classifications of SLs include mechanical lubricants, structural lubricants, chemically active lubricants, and soaps (reactive). Surface conversion coatings are used too, which chemically convert the solid surface in situ to achieve minimal shear strength [16].

The last decade has seen increased attention for employing SL in the cutting processes. SL-assisted machining has emerged as an environmentally clean technology that can help in desirable control of cutting temperature [17]. By the application of SL, the machining process performance is significantly improved. In SL-assisted machining, the cutting forces and tool wear are reduced due to the reduction of the coefficient of friction (COF). The production cost is reduced due to lower specific energy requirement as a result of a decline in cutting forces, and the surface quality of the machined part is improved [3]. The motive of SLs is to form a continuous adherent film (soft or hard) on the interacting surfaces. For applying the films, physical, mechanical, or (electro) chemical processes can be undertaken. The friction coefficient of an SL can be determined by following ASTM D 2714 test procedures [1]. Outstanding lubrication properties have been attributed to their layered structure, achieving a COF as low as ~0.05 (MoS_2) and ~0.1 (graphite) [5]. Various SLs, viz. WS_2, boric acid, MoS_2, graphite, and TiO_2 have been researched as additives in oils or emulsions, where the effect of particle size and concentration variation has been studied. Using MQL or flooding lubrication, these SLs were applied to the machining zone, resulting in reduced cutting forces, enhanced tool life, and better surface finish in contrast to pure oils or emulsions [5]. Commonly available SLs include transition metal disulfides (e.g., MoS_2, WS_2, TaS_2), soft noble metals (e.g., Au, Ag), inorganic fluorides (e.g., CaF_2, BaF_2), and metal oxides (e.g., NiO, Cr_2O_3, etc.) [18]. Other examples of common SLs include polytetrafluoroethylene (PTFE) admixed with organic and inorganic lubricants and other polymers containing fluorine, layered sodium silicates [19]. Some other options of SL include magnesium stearate dihydrate (MgSt-D) and hydrogenated castor oil. In high-speed conditions or when the contact point loading is high, SLs are more effective compared to fluid lubricants. SLs can be used in applications not endured by most of the traditional lubricants (e.g., extreme pressure/temperature conditions). Plating the wearing surfaces of a material with another metal may lead to reduced friction [1]. The selection of SL is also influenced by the cutting temperatures. E.g., graphite, transition metal dichalcogenides (e.g., MoS_2, WS_2), and polymers are best suited below 500°C; whereas, fluorides, oxides, and sulphates (e.g., CaF_2, ZnO, CuO, $CaSO_4$, etc.) are found to be the solution for higher temperatures working [20].

Table 1 enlists friction data for some particulate compounds used as SLs. Some early applications for selected SLs are listed in Table 2.

Table 1. Friction data at different temperatures for various compounds used as SLs [16]

Material	Coefficient of friction		
	26.7 °C	260 °C	538 °C
LiF	0.3–0.4	0.9	0.65–0.75
$AlPO_4$	0.6	—	0.51
PbS	0.47	0.27–0.47	0.15–0.19
PbS/MoS_2	0.16–0.13	0.13	0.37
PbS/Graphite	0.20	0.29	0.21
Graphite	0.14–0.30	0.06–0.12	0.20–0.27
MoS_2	0.34	0.10	
BN	0.3	0.15	
PbF_2	0.6	0.6	
TiS_2	0.7	0.6	
WS_2	0.17–1.6	0.2	-
Mica	0.38–0.89	-	-
Talc	0.13–0.89	-	-

Traditionally, various cutting fluids are utilized during machining. But for high temperature (HT) environment, particularly for those above 350°C, liquid lubricants degrade rapidly, and high temperature SL is the only viable solution for lubrication [21]. Also, conventional petroleum and mineral oil-based MWFs are harmful to both the environment and health [22,23]. Petroleum-based machining fluids can lead to lung, skin, and genetic diseases [24]. Due to fungi/bacterial growth on aqueous-based fluids or emulsions, their exposure is harmful to men, as well as reducing their service life [25]. The biocides contained in commonly discharged machining fluids emit formaldehyde to the environment, which is carcinogenic [26]. In contrast, the alternative SLs are biodegradable and environmentally friendly [25,27]. Machining hard-to-machine materials via traditional methods presents many difficulties. For this, researchers have explored the non-traditional machining processes, viz. Electrical Discharge Machining (EDM) and Wire-EDM [28,29], where eco-friendliness has been of growing interest [30].

Table 2. Example of some SLs and their early applications [31]

SL		Use	Remarks
Inorganic	Graphite	As additives in semi-SLs [32], electrical bushes [33]	Used in most SL films and coatings, viz. Polyimide-bonded coatings; in electrical motors, in various composites as self-lubricating films
	MoS_2	Friction reduction coatings during plastic extrusion of TiN and Al_2O_3 [34]	Evaluation of the film on services, e.g., stamping and spline gears in automotive; It provides wear resistance as well as some level of solid lubrication upon film wear
	hBN	hBN-filled resin shapes [35]	Applied as sliding components, viz., ring, seal, bearing, sleeve, and various other coatings.
	WS_2	C and WS_2-based hollow nanostructured tubes [36]	Find use in sliding applications owing to superior mechanical strength, low COF
Organic	PTFE	Seal, bearing, and counterface surfaces [37]	Possess a high melting point, low COF, and is chemically resistant to a variety of solvents.
	Ceramics	Versatile and broader industrial applications	They can benefit from the advantages of many combinations of solo lubricants.
	Polymers	Aluminium/soft material extrusion [33]	Used in advanced applications where regular lubrication is challenging and comes with the benefit of self-lubricating property.

However, machining processes like turning and drilling are still versatile due to the ability to generate various important part configurations. In this context, applying SLs, the machining process can be controlled. The use of molybdenum disulfide *(*MoS_2) as SL and additive has been studied by many researchers [38-41]. Dudarev [42] used stearine and MoS_2-based SLs in drilling samples of 14Cr17Ni2 steel and KMU-4e CFRP. Also, hexagonal boron nitride (hBN) has been used in turning superalloys like Inconel 800H. Researchers used [43] 0.20 wt% hBN admixed with olive oil and found good machinability. Sns/ZnO nanoscale SLs, hybrid nano cutting fluids were also used in machining different steels [44-45]. Researchers also used nano SL emulsion as a way to generate a better surface during the turning process [46]. Though SLs have various advantages including usability in harsh environment, derived design advantages due to weight reduction in mechanism, minimization of seals required in system; they also have some drawbacks including- i) absence of/negligible damping effect ii) solid sliding contact gives rise to some wear; which can be theoretically zero in case of hydrodynamic lubrication iii) oils act as coolant too, whereas SLs normally don't function as coolant iv) bonded coatings have finite wear rate and upon the coating's wearing, it is very difficult to replenish lubricant [47].

2.1 High Temperature Solid Lubricants

High temperature (HT) environments often cause lubrication challenges. Traditional liquid lubricants tend to degrade rapidly in applications involving temperatures above 350°C; hence, these conditions warrant the use of HT SLs to meet the desired outcome [48]. For some SLs, the applicability may even reach beyond 1000°C. The aerospace (including satellite components), tooling, material forming, automotive, energy, turbo-machinery, gas turbines, and military industries require the application of HT lubrication [49]. Additionally, mechanisms used in cutting-edge applications like ballistic missiles, nuclear power, and aviation demand operation over a very wide range of temperatures [50]. Several HT SL materials are available, such as NASA-PS coatings, self-adaptive SL coatings, Ni matrix strength-lubricating integrated composites, Ni_3Al intermetallic matrix composites, ZrO_2 ceramic matrix composites, and other emerging lubricating materials. Owing to the peculiar crystal structure, Transition Metal Dichalcogenides (TMDCs) are trending as HT SLs and/or SL additives. Particularly, MX_2 type TMDCs are very popular, where M = Mo, W, Nb, Ta, etc.; X = S, Se, etc. [51]. Some common TMDCs used in HT solid lubrication are shown in Figure 3. SL for HT comes in many varieties with a complex lubrication mechanism.

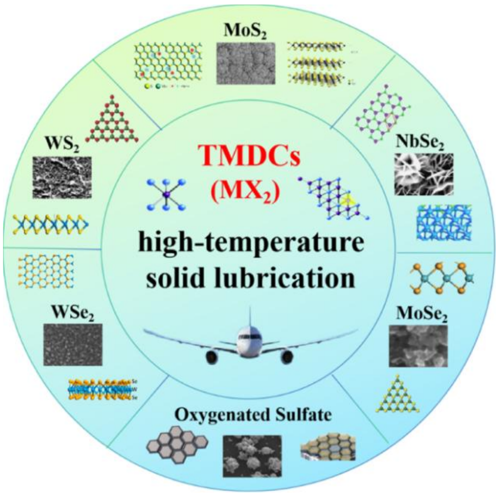

Figure 3. Common types of TMDCs used in high-temperature lubrication [51]

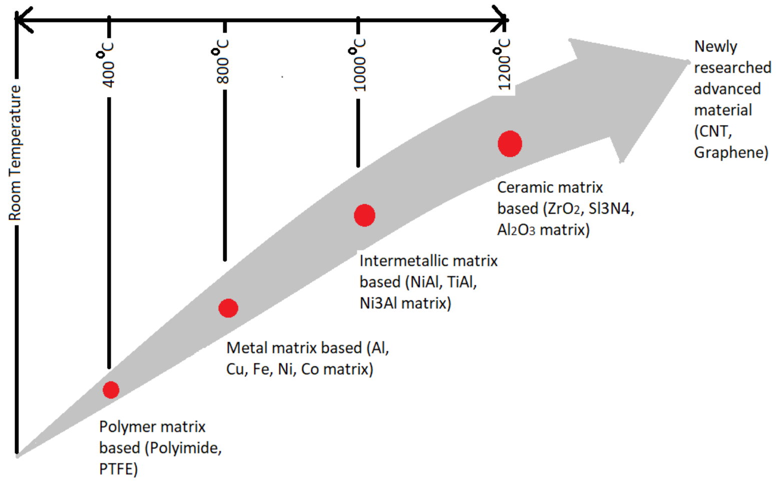

Figure 4. High temperature SLs with allowable temperature ranges

Based on the chemical composition, their main types are: (i) layered structure substance having feeble interlayer force (e.g., MoS_2, graphene, graphite, TMDs, WS_2, hBN), (ii) soft metal having several slip planes (e.g, Ag, Bi, Au, Pb), (iii) metal oxides with thermal softening (e.g., PbO, $AgMoO_4$, MoO_3, WO_3, V_2O_5, magneli phases) iv) Alkaline earth fluorides; e.g., BaF_2, CaF_2 [52,53]. Figure 4 shows different SLs with an allowable temperature range. Some of the material properties expected in an HT solid lubricating candidate include [54]: i) low shear strength at elevated temperature, ii) continuous film formation and retention on the surface, which have good elastic properties and should form a powerful chemical and physical bond with the surface, iii) high melting point along with great thermal stability, and iv) greater thermal conductivity for avoiding localized melting.

2.2 Surface Texturing and Use of Solid Lubricant

Surface texturing can potentially reduce friction at mating surfaces [55]. It is an efficient way to increase wear resistance during tribological applications [56]. By producing artificially generated micro surface patterns, surface texturing can improve the performance and functioning of tools when lubricants are present. These patterns can range from nanometric to micrometric in size and can have various geometries, such as circle, triangle, groove, square, and hexagon (protruded or recessed), as illustrated in Figure 5. Figure 6 shows an actual micro-textured drilling tool. The selection of the texture pattern is often influenced by the ease of fabrication, but the geometry and orientation can greatly affect friction and load-bearing capacity. Textured surfaces with planned micro/nano-features offer several innovative functional qualities in contrast to plain smooth surfaces or those made using conventional production techniques. Microscopic features, such as pockets a few micrometers deep, can serve as reservoirs for lubricants, store wear particles, and help the die and workpiece separate hydrodynamically during relative movement [57]. Jianxin et al. [58] created self-lubricating tools by using micro-EDM to make micro-holes on the rake and flank faces of WC/Co tools and then filling them with MoS_2 SLs. When compared to traditional tools, these infused tools performed better in dry cutting tests on hardened steel. Researchers also used an Nd: YAG laser to create microscale textures on the surfaces of cemented carbides and deposited W-S-C SL coatings on them [59].

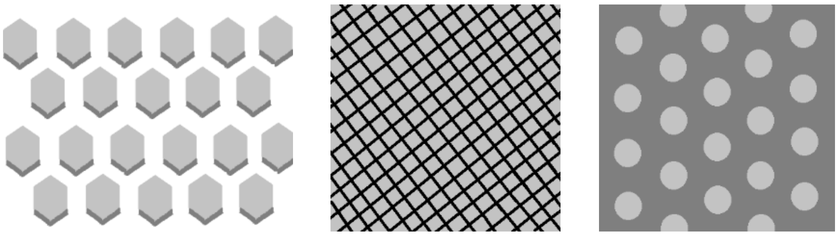
(a) (b) (c)

Figure 5. Sample illustration of different surface texturing (nanometric/micrometric dimension) on cutting tools: (a) hexagonal, (b) square, (c) circular

Using textured cutting tool inserts with SLs is an effective cooling method during machining [48,60]. Various methods, such as liquid, paste, and soft-coated forms, have been researched to supply SL to textured cutting inserts during the turning process [61]. Soft-coated forms of SL were found to be the most effective. Gangopadhyay et al. [62] used a hard-composite SL coating of TiN and MoS_x while dry machining AISI 1080 high-carbon steel. “Pulsed DC closed-field unbalanced magnetron sputtering (CFUBMS)” was used to develop the coating. Parts machined with a tool having this coating exhibited reduced roughness compared to machining with a bare cemented carbide tool. Wenlong et al. [63] created microholes via micro-EDM in a cemented carbide tool and infused MoS_2 SL to achieve self-lubricating behavior. Machining results obtained confirmed the positive influence of this method in decreasing tool wear at the rake and flank surfaces, increasing tool life, and enhancing the machined part surface.

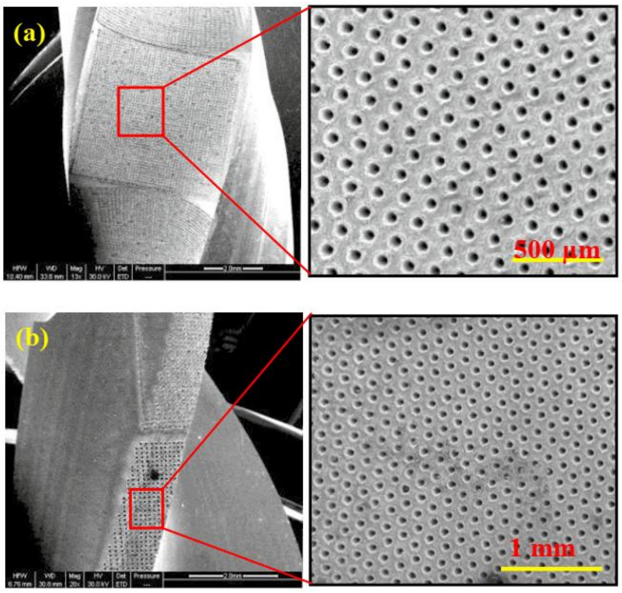

Figure 6. Micro textures at the (a) flute side and (b) margin side of a drilling tool [55]

Despite the advantages of surface texturing, textures created using thermal techniques have certain challenges. One significant concern is the heat-affected zone associated with these textures. Moreover, the production of low-quality textures through focused energy beams leads to increased abrasive wear. Gajrani et al. [64] investigated and compared the performance of six distinct mechanical micro-textured (MμT) cutting tools. Initially, using Vickers hardness and micro-scratch testers, three types of MμTs on the cutting tool rake face have been fabricated. After that, a set of MμT tools with MoS_2 has been coated. Dry machining experiments revealed that MoS_2-coated perpendicular MμT tools performed better than all others, showing their potential. In another study [65], MμT cutting tools with three different geometries were fabricated for machining. MoS_2 SL coating was applied to a set of MμT cutting tools, and hard machining experiments using uncoated, coated MμT, and untextured (UT) cutting tools were conducted. Their comparative analysis of machining performance showed that both uncoated and MoS_2-coated self-lubricating tools diminished cutting force, feed force, machining region temperature, and the interfacial COF in comparison to UT tools. Combining the advantages of SL with tool texturing, the resultant hybrid machining can be a very effective and sustainable machining process. Hoghoughi et al. [66] studied the machining and sustainability characteristics of this hybrid process based on various attributes and found favorable and promising values for the sustainability index (SI). Under investigated conditions, they showed that the textured tool with SL performed better in terms of energy consumption, CO_2 emission, unit cost of production, and production rate.

2.3 Coating and Deposition of Solid Lubricant

For a given tool material and design, surface roughness is a crucial factor affecting machining performance, as it has a direct connection to surface quality and fatigue strength. Efforts focus on manufacturing and applying SL-based coatings to parts in relative motion, under heavy loading, or experiencing friction that generates heat, potentially causing detrimental effects. The goal is to enhance the tribological performance of coated parts and their contacts, achieving other goals by modifying tribological characteristics as desired. The reasons for this include increasing the service life of parts in motion, reducing tool wear during machining, easing chip movement over the tool face, reducing tool loading, eliminating unwanted ploughing phenomena, decreasing heat generation at the contact zone, dissipating heat effectively, improving tool life, minimizing lubricant use, and making the process more economical, greener, sustainable, and eco-friendly. Bonded solid lubricating coatings (BSLCs) are extensively utilized for reducing friction and minimizing wear in both military and civilian sectors, greatly prolonging the lifespan of coated materials due to their straightforward preparation techniques. Lia et al. [67] developed an innovative eco-friendly water-based polyamide-imide (PAI)-graphite-LaF_3 BSLC and examined its tribological characteristics and mechanisms. The findings indicated that when the nano-LaF_3 content was 5 wt%, the developed BSLCs demonstrated tri-mechanical properties comparable to those of organic-solvent-based BSLCs.

In coated carbides, the tool features a durable, nonreactive exterior that acts as a diffusion barrier. This is accomplished by applying a thin ceramic layer (generally 5–7 μm) to a carbide substrate, such as TiN, Al_2O_3, TiC, or HfN. It is possible to stack multiple layers on top of one another (for example, using TiC as the base, followed by Al_2O_3 and TiN) [68]. Cemented carbides like WC-12Ni, WC-10Ni, and WC-17Ni are considered excellent materials for coating surfaces in the aerospace, military, and machining industries. These provide outstanding mechanical characteristics, including elevated hardness, strength, and robust corrosion resistance. Surface loss is primarily responsible for failure in cemented carbide materials under friction and wear conditions. With the advancement of modern technology, traditional lubrication methods (such as oil and grease) have become ineffective in harsh operational environments like high temperature-pressure, vacuum, and radiation. In these scenarios, incorporating SLs to create self-lubricating coatings presents a viable solution. To create self-lubricating composite coatings, HT physical methods and low-temperature chemical methods are frequently employed. Wang et al. [69] incorporated MoS_2 SL into thermal spray WC-12Ni particles using an electroless Ni-MoS_2 co-deposition process, resulting in a Ni-MoS_2 composite layer on WC-12Ni powders. Wu et al. [70] introduced a new self-lubricating ceramic cutting tool material by integrating metal-coated SL powders. Through the electroless plating technique, researchers synthesized nickel-coated CaF_2 composite powders with a core-shell structure and studied the growth process of the nickel coating on the SL CaF_2 powders. Doddamania et al. [18] applied NiCrAlY/WC-Co/Cenosphere/MoS_2/CaF_2, NiCrAlY/WC-Co/Cenosphere/ MoS_2/$CaSO_4$, and NiCrAlY/WC-Co/Cenosphere coatings on MDN 321 steel using atmospheric plasma spraying. The assessment of the tribological properties and performance under dry lubrication conditions demonstrated their broad applicability from room temperature to 600°C. Plasma spray methods have also been effectively utilized to create $NiCaF_2$ and $NiCaSO_4$ coatings on MDN 321 steel. Zhu et al. [53] offered detailed recommendations for utilizing soft porous materials in lubrication, which are anticipated to significantly influence the advancement of soft lubrication in industrial applications.

Carbon nitride (CNx) coatings possess favorable characteristics like low friction and wear, high hardness, along with robust thermo-chemical stability, making them ideal for challenging mechanical and tribological uses [71,72]. Adachi and Kato [73] showcased the appealing friction and wear attributes of CNx coatings sliding against Si3N4, CNx-coated silicon wafers, or CNx-coated Si3N4. Dittrich and Oelsner [74] focused on traditional hard coatings (TiN, TiCN, TiAlN, or TiAlCN) and incorporated a top layer of amorphous carbon (diamond-like carbon, DLC) as a dry lubricant coating for the tool processing sector. It has been observed that, except for the maximum application temperature, TiCN has better properties than TiN coating. The additional element of carbon improved the nano-hardness and service life of the tool compared to TiN coating [75]. Zhu et al. [76] previously developed two distinct coatings, nitrocarburized (CN) and TiCN, on M2-grade tool steel utilizing conventional diffusion and physical vapor deposition (PVD) methods, respectively.

Physical vapor deposition (PVD) techniques allow for the application of thin films (generally 1-5 µm) with unique characteristics at significantly low temperatures, in contrast to chemical vapor deposition (CVD), plasma-assisted chemical vapor deposition (PA-CVD), and Thermal Spray Coating (TSC). The primary objectives of these technologies are to achieve high hardness, high wear resistance, and low COF. Hard, low-friction, and wear-resistant coatings are generally produced by various processes such as electrochemical or electroless methods, thermochemical processes, spray technologies, PVD, and CVD [76]. Self-lubricating composite coatings can also be prepared through HT physical methods (e.g., thermal spraying and laser cladding) and low-temperature chemical methods (e.g., electrodeposition and electroless plating). Atmospheric plasma spraying is also used for coating deposition on target substrates, resulting in coatings with homogeneous thickness and good reproducibility. These coatings improve the resistance of cutting tools. Compact materials are used to make most tools, but some tools are fabricated via powder metallurgy. Current tools are primarily based on WC-Co, with sintered materials being utilized as structural components for manufacturing specific machine parts. Coating techniques also enhance the particular properties of these materials, such as wear resistance and fatigue under contact. Rodziňák et al. [77] analyzed the effects of TiCN-type coating on the tribological properties of sintered steel, focusing on the COF and wear rate. Their findings indicated that the wear resistance of CrL + 0.3/0.7c, coated with TiCN, showed considerable improvement.

SL thin films created using PVD methods, such as magnetron sputtering, provide distinctive capabilities to diminish friction-related losses even under extreme conditions (high contact pressures, very low/high temperatures, high humidity, vacuum) or in scenarios where there are ecological concerns about liquid lubricant usage. Transition metal dichalcogenide (TMDC)-based low-friction thin films have established themselves as leading solid lubricants in various domains, including bearings, firearms, and deep-space applications. A new strategy for diminishing COF in lubricant-free sliding interfaces is through solid lubricant coatings deposited by plasma-assisted deposition techniques. MoS_2 is arguably the most prominent and widely applied solid lubricant; however, its reduced hardness and susceptibility to environmental factors pose challenges. Hudec et al. [78] revealed that incorporating a specific nitrogen content into MoS_2 alloying could lead to dense, hard films capable of delivering very low COF and wear even in humid terrestrial conditions. The literature also indicates that $MoSe_2$ and WSe_2 yield similar tribological performance to MoS_2, especially in humid environments.

2.4 MQL Strategy and Solid Lubricant

The MQL strategy assisted by SL is gaining wider attention as it significantly improves fluid performance. Enhanced performance is attainable by regulating both heat production and friction between the tool and workpiece without significantly raising process expenses. This approach also circumvents challenges associated with cryogenic temperatures typically seen in hybrid methods. MQL is a trade-off between dry machining and machining with a continuous supply of cutting fluids. It addresses problems associated with dry machining, viz., low tool life and surface quality [36], and also has the potential to mitigate the ecological and health hazards posed by cutting fluids. MQL's advantages can be further enhanced by adding SLs [20, 79-82].

Nanofluid Minimum Quantity Lubrication (NF-MQL) has also been reported using CuO, hBN, and MoS_2 nanoparticles during the machining of Inconel 718, Co-based Haynes 25 superalloy, Inconel 625, etc. [83-85]. The most environmentally friendly and sustainable approach is to use SL, which improves machined surface quality while reducing power requirements and tangential force [86-88]. Sartori et al. [20] assessed the effectiveness of SL-assisted MQL and Minimum Quantity Cooling (MQC) methods in semi-finishing turning of the Ti6Al4V titanium alloy, focusing on tool wear and surface integrity. The comparison of the results obtained with dry, traditional wet, and pure MQL methods indicated superior outcomes. Zailani et al. [17] further examined SL-assisted machining using high-purity graphite powder concerning surface quality and tool wear while machining M/S, achieving improved results with SL-assisted machining.

Makhesana and Patel [89] analyzed the effectiveness of CaF_2 SL-assisted MQL in the turning of EN31 steel, which is commonly utilized in the production of bearings, bearing rings, ball screws, cams, pawls, gauges, forming tools, punches, and more. It has been demonstrated that the use of SL with MQL represents a low-cost and environmentally friendly option. Reddy and Nouari [90] explored the application of MoS_2 as an SL to enhance tribological characteristics in turning and alleviate the drawbacks associated with the use of MWFs or dry machining. A statistical analysis of variance (ANOVA) was performed to determine significant trends in tangential cutting force. The ANOVA technique was used to ascertain the relative impact of each factor on cutting forces. A comparative evaluation of the performance of MoS_2 SL under conditions of high contact pressure and sliding speed revealed its potential among dry, flooding, MQL, cryogenic, and combined cryogenic and MQL scenarios [5].

SLs can be incorporated into cutting fluids to improve their thermal and tribological properties, as seen in oil used for MQL. Damera and Pasam [91] utilized boric acid as an eco-friendly lubricant during the turning process. The findings indicated a noticeable improvement in machining performance when compared to conventional dry and wet machining. Research has also been conducted with graphite, MoS_2, and calcium fluoride powder as SLs, but limited studies have been reported regarding calcium fluoride. MoS_2 surpassed traditional lubricants, demonstrating exceptional lubrication performance across all sliding speeds examined. However, the method of delivering SL powder in dry form to the cutting zone remains a challenge that future research may address.

3. POWDER METALLURGY AND BALL MILLING FOR SOLID LUBRICANT DEVELOPMENT

Among the various production process routes, the mechanical alloying (MA) method is considered the most powerful tool for nanostructured materials due to its simplicity, cost-effectiveness, and scalability. Mechanical milling allows the easy production of equilibrium, non-equilibrium, and nanocomposite materials [92]. The generation of nanocrystalline materials during MA of ceramic or metallic powders is due to the significant cold work applied to the ball-milled powders, which raises the number of imperfections (such as point and lattice defects), leading to a reduction in the thermodynamic stability of the original materials. The specific type of defects present influences the different nanocrystalline materials obtained, each exhibiting distinct physical and mechanical properties. Narayanasamy and Selvakumar [93] developed Mg self-lubricating composites reinforced with graphite (Gr)/MoS_2 by employing powder metallurgy (PM). The PM method allows for the creation of composite metallic materials containing solid lubricants, with the reinforcements evenly distributed throughout the matrix. Aluminum alloy-graphite particulate composites are significant as self-lubricating materials, improving wear resistance, machinability, and postponing severe wear and seizing. MoS_2 exhibited better friction and wear properties than Gr.

Ball milling is a fundamental step employed in most PM processes. The time set for milling and the ball-to-powder ratio (BPR) are crucial factors influencing the properties of milled powder samples [94-96]. Incorporating self-lubricating properties can greatly enhance the tribological performance of various composites [97], achieved by incorporating SL during powder processing in the ball mill. Freschi et al. [98] used tungsten disulfide (WS_2), a member of TMDCs, as SL to obtain a tribologically superior copper-tungsten disulfide composite (a metal matrix composite, MMC) via ball milling through the powder metallurgical route. It was found that shorter milling durations resulted in larger WS_2 flakes within the Cu matrix, whereas extended milling times led to smaller and more dispersed particles. Work by Pethő et al. [96] showed that lower BPR resulted in homogeneously phased nanocrystallites in the powder, while higher BPR resulted in smaller nanocrystallites but at the cost of contamination from the milling equipment. MoS_2, another TMDC and SL, has gained ample attention due to its properties similar to graphene, being inexpensive, and offering additional advantages such as light weight, magnetic attributes, and superior mechanical, optical, and electronic properties [99]. Ball milling can generate nanoscale powder particles, improve inter-grain connectivity, and enhance microstructural homogeneity. This can be utilized in offbeat applications such as tuning properties like superconductivity [100], increasing the energy retaining ability of lithium iron phosphate used in lithium-ion batteries [101], and biomedical porous alloy structures for bone tissue growth [102]. The ultrafine-grained (UFG) alloys and composites produced via ball milling show enhanced microstructural and mechanical properties [103-105], with parameter optimization playing a crucial role [106]. It is important to properly and cautiously use the powder mix in the ball milling machine to prevent sudden failure of machine components [107]. Proper utilization of process control agents (PCA) also greatly influences the quality of the milled powder [108].

Two antagonistic mechanisms, particle breakage and particle agglomeration, are key in determining the minimum size of the ground product in a ball mill, especially for size reduction below 10 µm [109]. Fecht proposed a mechanism for producing nanocrystalline materials via ball milling [110], involving a three-stage phenomenon of grain size reduction. In the initial phase, slip and twinning induce plastic deformation within the crystal lattices of the ball-milled powders, generating a dense network of dislocations. During the early stages of milling, strain at the atomic level escalates owing to the buildup of dislocation density. In the subsequent phase, as dislocation density continues to accumulate, crystals that were previously separated by low-angle grain boundaries begin to break down into subgrains. This transformation into subgrains occurs as atomic-level strain is reduced. In the final phase, prolonged ball milling causes additional deformation in the shear bands of the non-strained areas of the powders, leading to a reduction in subgrain size and resulting in random crystallographic orientations among the grains. These result in varying slip directions from one grain to another.

In recent years, various Ni-alloy-based solid-lubricating composites have been developed using PM techniques. These include PM212, PM300, Ni alloy-graphite-Ag, Ni-alloy -WC-Co-Mo-PbO, Ni-alloy -Ag-CeF_3, Ni-alloy -graphite-CeF_3, NiCr-Al_2O_3-$SrSO_4$-Ag, Ni-alloy -MoS_2-graphite, among others. PM212 exhibits potential for application across a broad temperature range from room temperature to 900°C, while PM300 shows favorable tribological performance from room temperature to 650°C [21]. PM methods are also used to manufacture aluminum carbon nanotube (Al/CNT) nanocomposites with varying raw material properties under optimized conditions. Jargalsaikhan et al. [111] successfully produced samples of un-milled Al, un-milled Al with CNT, and milled Al with CNT nanocomposites. Scanning electron microscopy indicated that CNTs were more effectively dispersed on the surface of the fabricated milled Al with CNT nanocomposites than in un-milled Al with CNT nanocomposites. Liu et al. [112] created CNT-reinforced pure Al (CNT/Al) composites using ball-milling and powder metallurgy. Observations revealed that as the ball-milling time increased, CNTs became increasingly well dispersed within the Al matrix, achieving a uniform distribution after 6 hours of ball-milling.

High-energy ball milling is common in different mechanical processes for particle fabrication, such as grinding, alloying, and mechanochemical reactions [113]. This technique utilizes planetary ball mills, vibratory mills, and stirring mills (attritors). Planetary ball milling is particularly effective for producing nanostructured powders and is frequently applied in PM [92]. Nanostructured WC and WC-Co alloys exhibit exceptional hardness and wear resistance due to the tiny size of the WC grains [114]. Nanocomposed inorganic materials have various applications, including sensors, photocatalysts, and quantum dots [115-118]. The BPR greatly affects the particles' energy dissipation, which indicates the amount of powdered particles and milling balls placed in the mill jar. Planetary ball mills are easily operable and structurally simple, making them the most popular high-energy mills. In high-energy ball mills, the dissipated energy received by the particles during collisions generally changes due to the breakage or aggregation of the particles, leading to changes in particle size. Hirosawa and Iwasaki studied the behavior of particles and balls in a planetary ball mill to explore energy variations, taking into account diverse sizes and quantities of particles and balls. The contact forces, types of collisions among particles, and their collision frequency are influenced by the varying sizes and amounts of balls and particles. Even with a constant BPR, changes in the distribution of dissipated energy and specific dissipated power were seen [119]. The primary parameters in mechanical milling using a planetary ball mill include milling time, BPR, process control agent (PCA), and milling speed. Canakci et al. [120] optimized these process parameters while milling nanocrystalline Al 2024 powder. The application of the Taguchi method for optimization showed that PCA had a considerable impact, accounting for 84% of the variance in mean particle size (d50). The remaining parameters contributed less, with a total of 16%. Shin et al. [121] identified that there is an optimal ball size for effective milling at a specific rotation speed. Additionally, the influence of powder loading on particle size reduction under specific conditions of ball size and rotation speed was studied through the wet milling of alumina powder using zirconia balls of different diameters at various rotation speeds. The analysis of the resulting particle size indicated that increasing the rotation speed elevates the kinetic energy of the balls, thereby shifting the optimal ball size towards a smaller dimension.

WC-Co-based cutting tools are popular for machining of various materials, including carbon fiber reinforced plastics (CFRP) [122,123]. Researchers have used ball milling to produce nanostructured WC-Co powder for cemented carbide tools used in cutting, machining, wear, and bearing applications [124,125]. Traditionally, uncoated tools were used, where achieving good tool life was always a decisive criterion. To increase tool life, machining quality, and overall tribological performance, researchers have tried nano-polishing of cemented carbide tool inserts [126]. Self-lubricating cutting tools have also been reported as an alternate promising method, but they still remain underexplored [127]. A typical laboratory-scale twin bowl type planetary ball mill apparatus by Insmart Systems is shown in Figure 7.

```
SET VALUES
PLATE RPM:   125 RPM
BOWL RPM:    250 RPM
ON TIME:  0:25: 0H:M:S
OFFTIME:  0:10: 0H:M:S
TOTAL TIME:   0:35: 0
NO OF CYLES:   4
```

(a) (b)

(c) (d)

Figure 7. (a) A view of the planetary ball mill in closed position, (b) running screen/programming screen of the planetary ball mill, (c) inside view of the planetary ball mill showing plate and bowl, and (d) a milling chamber/bowl with the lid open and balls inside

4. ADVANCED SOLID LUBRICANT MATERIALS

Expectations from SLs include a low value of COF in both atmospheric and vacuum conditions, low shear strength coupled with high thermal stability at elevated temperatures. DLC, MoS_2, Graphite, PTFE, metal borides and nitrides, and soft metals (e.g., copper, lead) are extensively utilized as SLs. To improve the performance of SLs, the nanoparticle addition strategy is commonly used. Considerable advancements have been achieved with the application of nanoparticles composed of metal, carbon compounds, metal oxides, metal carbonates, metal sulfides, metal borates, rare earth compounds, and SiO_2 as effective friction modifiers in lubricants. CuO and CuS coatings were applied to AISI 4140 steel samples by Kovacı et al. [128] utilizing Successive Ionic Layer Adsorption and Reaction (SILAR) to evaluate their potential as solid lubricants. Tests indicated that CuO films demonstrated superior wear resistance compared to CuS films in both dry and lubricated conditions. Both CuO and CuS films generated through SILAR have shown potential as alternatives to traditional SLs.

Recently, a new category of 2D materials known as MXenes, specifically $Ti_3C_2T_x$ nanoparticles, has attracted significant attention in the fields of energy storage and catalysis. This material features a relatively loose multi-layered structure with inherent self-lubricating properties. However, their application for tribological purposes remains surprisingly limited, indicating substantial research opportunities. Rosenkranz et al. [129] conducted tribological tests combined with comprehensive material characterization to precisely evaluate the friction and wear mechanisms of $Ti_3C_2T_x$ nanoparticles as a solid lubricant in dry conditions. Their findings underscore $Ti_3C_2T_x$ nanoparticles as exceptional candidates for next-generation solid lubricants in nano- and microscale systems. Battez et al. [130] investigated the effects of CuO, ZnO, and ZrO_2 nanoparticles as additives in oil lubricants under extreme pressure scenarios (boundary lubrication). Additionally, research has been conducted on bio-inspired self-sharpening cutting tool surfaces designed for high-quality hard turning of steel. The coating design, inspired by the structures of sea urchins and shark teeth, provides serrated cutting edges along with self-sharpening capabilities [131].

4.1 Carbon Nanotube

Carbon Nanotubes (CNTs) were discovered in 1991. They may be single-walled (SWCNT) or multi-walled (MWCNT). CNTs have a unique 1D hollow cylindrical structure and are essentially formed of a rolled-up graphene sheet [132]. CNTs have gained widespread attention and popularity owing to their all-around nature of superior thermal, mechanical, chemical, optical, and electrical properties [132,133]. E.g., Young's modulus of SWCNT is ~ 1 TPa and maximum tensile stress is ~ 30 GPa [134]. For tribological applications, they are utilized in various forms like additives in oil/lubricants, coatings, and bulk reinforced SLs.

For instruments undergoing a harsh frictional wear environment, their life span drastically increases by the application of SLs having low frictional coefficients and wear rates. However, the performance of SLs drastically reduces under extreme service conditions like elevated temperatures and high humidity, e.g., graphite, WS_2, sputtered or nanoparticulate MoS_2. To mitigate this problem, Zhang et al. [135] produced composites of CNTs and MoS_2, which showed better tribological properties compared to nanoparticulate MoS_2-based coatings. Reinert et al. [136] attempted to understand the tribo-mechanism and the tribological influence of CNTs. The study found various underlying conditions, behaviors, and performance of CNTs as SL under their investigated conditions.

In some tribological systems, unfavorable environmental conditions like high operational temperature or operation under vacuum demand the replacement of liquid with SLs. In this regard, MWCNTs are found to be very effective SL [137,138]. Reinert et al. [138] deposited MWCNT via electrophoretic deposition onto sample surfaces textured by laser. This approach combines the advantages of solid lubricants while improving tribological performance through the creation of precisely defined surface topographies using laser surface texturing. The resulting integrated method demonstrated a minimum fivefold increase in lubrication longevity, significantly reducing wear on the laser textures. MWCNTs can provide very good solid lubrication in air as well as in vacuum due to the very low level of COF associated, and hence they are very much suitable for space and aeronautics applications [139].

4.2 Hexagonal Boron Nitride

hBN is an inorganic SL having a lamellar structure. This category also encompasses graphite, MoS_2, and other sulfides, as well as chalcogenides like tungsten, niobium, molybdenum, tantalum, and titanium selenides and tellurides. Boron nitride forms a lubrication film that strongly adheres to the substrate surface, providing excellent wear and seizure resistance. Likewise, MoS_2, boron nitride, too, does not require a moist atmosphere for lubrication. It exhibits low friction characteristics both in a dry atmosphere and in a vacuum. The main advantage of hBN over graphite and MoS_2 is its thermal stability. In an inert or reducing environment, hBN retains its lubrication properties up to 2760°C, and in an oxidizing atmosphere, it is retained up to 870°C [140].

Water mixed hBN powder at varying concentrations (5, 10, 15 wt%) was utilized as a lubricant by Santosh et al. [141]. Turning experiments were conducted using a TiAlN-coated tungsten carbide insert under constant speed and variable feed rate conditions. To provide a baseline, dry machining was also performed, revealing a significant temperature reduction in the cutting zone upon adding hBN solid lubricant with water. MQL conditions demonstrated a multiple decrease in cutting zone temperature compared to dry machining. Çelik et al. [142] similarly employed nano hBN particles as an oil additive and examined the tribo-characteristics of AISI 4140 steel under these circumstances. These particles were dispersed in SAE10 W engine oil in an attempt to enhance lubrication. Experiments showed an improvement of 14.4% in the friction coefficient and a decrease of 65% in the wear rate by the use of nano hBN as an oil additive.

Hammes et al. [143] (2017) worked in the direction of achieving composites with self-lubrication property, to be used for friction and wear controlling in modern systems demanding high energy efficiency. They used 5, 7.5, and 10 volume % of hBN mixed with graphite SLs for producing the samples via the PM route. The tribological investigation of the composite showed that greater contents of total SL significantly improved its scuffing resistance but diminished the mechanical properties. Investigation revealed a reduction in both properties with increasing hBN content. Zhang et al. [144] applied hBN for lubricating the sliding interface of die steel H13 against ceramic Si_3N_4, conducting experiments at 800 °C. These hot-working die steels are utilized during the hot stamping of high-strength steels to produce car bodies and various components.

4.3 Graphene

Graphene is a fascinating allotrope of carbon. It is a 2D substance made up of a single layer of atoms arranged in a honeycomb-like nanostructure. It has similarity with CNTs in terms of the bonding [145]. Graphene, from its emergence in 2004, gained much attention and applicability due to its peculiar characteristics owing to its 2D nature. Liu et al. [146] reviewed the lubrication and frictional properties of 2D materials with an emphasis on graphene. These 2D materials possess a layered architecture consisting of a monolayer or multiple layers with atomic thickness, which exhibit extremely low shear strength, along with remarkably low friction and excellent wear resistance. The fundamental nanoscale friction mechanisms of 2D, including surface friction mechanisms and interfacial friction, have been introduced.

Liang et al. [147] showed the potential of using graphene oxide (GO) as an anti-friction and anti-wear candidate. GO films have been deposited on Si-based MEMS devices to minimize friction and wear. Results revealed that using GO film as SL lowered the COF of the Si wafer to 1/6 its value, while the wear volume decreased to 1/24. Even graphene-based SLs have been studied as a replacement for oils, and promising results were obtained [148]. Xie et al. [149] analyzed the tribological performance of GO and graphene as additives in a water-based lubricant. It was found that the addition of an optimal amount of graphene or GO can significantly enhance the tribological behavior of water, with GO nanofluids demonstrating superior effectiveness.

Ren *et al.* [150] utilized graphene nanoplatelets (GNPs) as an SL for fabricating micro channels on Cu/SS304L composite via micro rolling. Various microchannels are an integral part of different microfluidic components [151-153], and there exist various other processes for microchannel fabrication on different materials [153-155]. Researchers even used graphene-based SLs by biofunctionalizing them with hyaluronic acid and deposited them on CoCr surfaces for better tribocorrosion behavior [156]. A study on biodegradable acid oil based on graphene as a possible green alternative for cutting fluids showed promising results for its usefulness [23]. Hard-to-machine nickel-based superalloy Inconel 713C has been machined with comparative ease and reduced heat generation via combining the dual advantage of a novel honeycomb tool texture with graphene SL deposited on it [157].

Table 3. Comparison of characteristics of solid and liquid/ semi-SLs [41, 158-159]

Variables	Liquid/semi-solid lubrication	Solid lubricants
Temperature	Clouding at LT Vaporizes at HT	Works well at HT ranges (400°-2000°F)
Pressure	Functionality decreases at high range (can be somewhat remedied with additives)	Can operate in both low and high pressures without additives.
Heat Generation	Viscosity and temperature-dependent	Lesser heat generation
Tribological Analysis	COF depends upon viscosity, temperature gradient, etc.	Lower values of COF at lower speeds and lower wear rate
Thermal and electrical conductivity	High thermal conductivity and low electrical conductivity	Outstanding electrical and thermal conductivity
Heavy Loading	Thins out as load increases	Lamellar crystal structure helps in heavy loads and extreme pressure
Storage	May spill, leak, or evaporate.	No risk of spillage and long shelf life
Sliding velocity	Heavy loads at low speeds lower resilience and lubricant performance	Resilient performance even at slow speeds
COF	Hydrodynamic films provide COF~ 0.001 – 0.003	Low COF~ 0.04-0.25
Application areas	Excel at higher speeds but at lower loads. Base oil laced with additives.	Used in fine particle form, i.e., on surface metallic contact, anti-friction lining, in spacecrafts and heavy race equipment

To further comprehend and leverage the capabilities of graphene as a prominent solid lubricant, Wu et al. [160] invented an innovative lubricating system characterized by graphene sliding against graphene, achieving low friction in macroscale contact, with a COF of approximately 0.05. A self-assembly method inspired by the Marangoni effect was utilized to create the graphene film. Wang et al. [161] assessed the interfacial friction properties of graphene-coated and hydrogen-terminated diamond surfaces. Their research revealed that, under heavier loads, the graphene-covered interface yields lower friction compared to others. Therefore, graphene stands out as a strong potential solid lubricant for diamond films. Table 3 summarizes a comparison of characteristics of solid and liquid/semi-SL based on various attributes. Meanwhile, Figure 8 shows a graphical representation of the approximation of the operating temperature of various SLs. An overall comparison between green lubricants (SLs) and conventional lubricants (petroleum-based oils and greases) has been tabulated in Table 4.

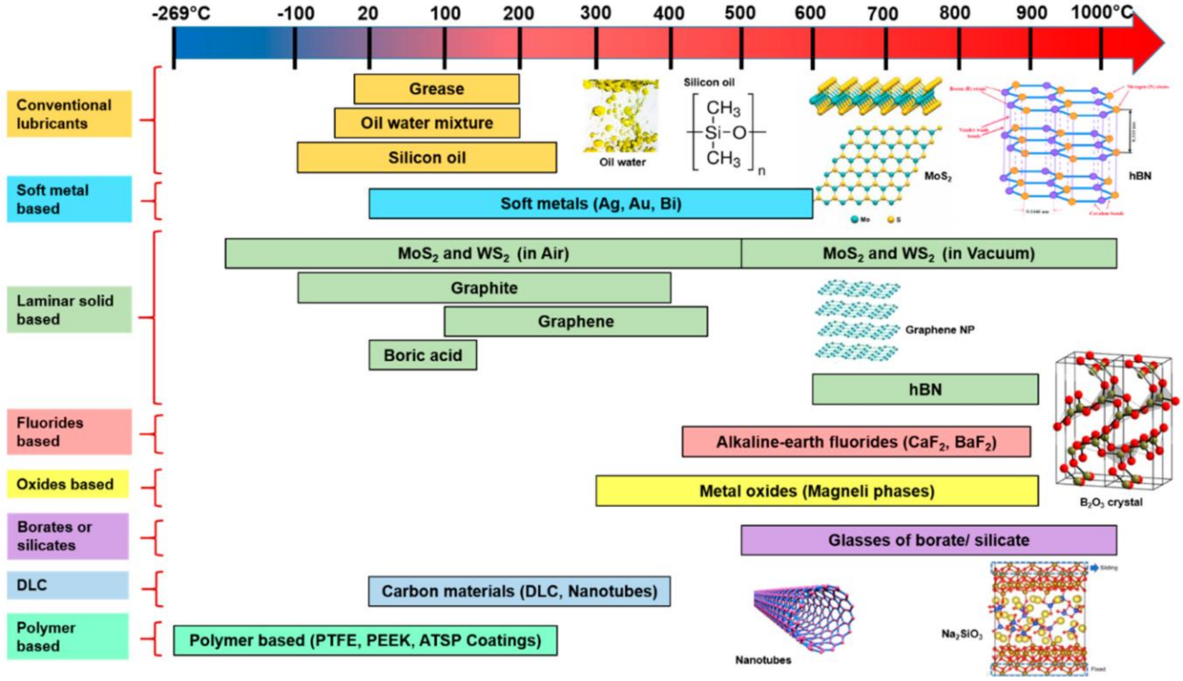

Figure 8. Range of temperature for various solid-lubricating materials (SLs) [52]

Table 4. Comparison of Green Lubricants (SLs) and Conventional Lubricants **(**petroleum-based oils and greases**)**

Aspect	Green Lubricants	Conventional Lubricants
Environmental Impact	Eco-friendly, biodegradable, and non-toxic	Potentially hazardous and polluting
Health & Safety	Generally safer for human contact, making them ideal for food-grade or medical applications. But Fine powders can pose an inhalation risk if not handled properly	Well-understood handling procedures exist. But very prone to cause skin irritation. Vapors and mists can be a respiratory hazard. Flammability can be a significant risk
Performance in Extreme Conditions	Effective in high-temperature and vacuum environments	May degrade or evaporate in extreme conditions
Application Complexity	Requires precise surface treatment for effectiveness (e.g., requires surface bonding or application as a coating)	Easy to apply with conventional methods
Replenishment Requirement	Longer-lasting, minimal need for reapplication	Requires periodic replacement due to degradation
Cost Considerations	Initial cost may be higher, but offers long-term savings	Generally lower upfront cost but ongoing expenses
Compatibility with Machinery	Suitable for specialized applications; may need modifications	Compatible with most existing systems
Energy Efficiency	Reduces friction efficiently, leading to energy savings	Performance varies based on formulation and additives

5. CONCLUSION AND FUTURE TRENDS

In modern industrialized civilization, environmental and ecological degradation due to rapid industrialization is of paramount concern. Strict environmental rules and regulations are already in place in many developed countries. India, now officially recognized as the world's most populous nation, has surpassed China according to the 2023 State of World Population report by the United Nations Population Fund [162], and is a rapidly advancing country. Under flagship government initiatives such as Make in India and the Pradhan Mantri MUDRA Yojana (PMMY), many new small- and medium-scale industries are emerging in India [163,164]. A large number of these enterprises are fabrication-based, where machining plays a key role. Various cutting fluids are frequently used in machining operations, yet these traditional cutting fluids pose risks to both operator health and environmental safety. Semi-skilled, and less educated/trained operators, who are widely employed in these sectors, are unaware of proper handling and disposal of hazardous cutting fluids, contributing to environmental harm. Strict environmental laws are expected to be introduced in India soon, highlighting the urgent need to shift to cleaner, greener, and more sustainable alternatives. This is a wakeup call not only for one country but for the entire world.

Based on a review of the literature, it can be concluded that solid-state lubrication in various forms is a green and sustainable alternative to conventional lubrication methods during machining. The tribological properties of manufactured products and the service life of SL-coated elements are greatly enhanced, which is a demanding requirement nowadays. The field of SL application has been expanding, ranging from critical high-temperature applications to vacuum environments, with machining and allied fields being dominant areas of application. Surface texturing has proven to improve the functionality and effectiveness of tools, especially when lubricants are present. Ball milling is widely used in PM methods to fabricate SL-infused tools and parts (including samples for tribological studies) and has been discussed in depth. Various prominent SL candidates, ranging from traditional graphite and MoS_2 to novel 2D materials like graphene, have been reported. Advanced materials such as CNT, hBN, and graphene have superior tribological properties and can be used in ways previously considered impossible, opening new avenues in solid-state lubrication for machining and other tribological applications.

SL has the potential to significantly regulate temperature in the machining zone, thereby directly affecting the surface and tribological characteristics of the manufactured components. Nonetheless, the challenge remains in delivering solid lubricant powder in a dry form to the cutting zone. Dry machining with SL can greatly improve product quality and process economics, apart from being environmentally and operator-friendly. Future work could focus on achieving sustainability in manufacturing through the strategic use of advanced and novel SLs. Exploring self-healing, self-adaptive, and other smart materials as candidates for SL is bound to open new possibilities. Self-adaptive and tunable smart lubricants that function effectively across a wide range of environments, from low room temperature to extreme temperatures up to 1500°C or beyond, represent the future of space and production technology. The peculiar nature and advancements of SL and lubrication will be beneficial for sustaining human life in exoplanet colonization. With the advancement and extensive use of artificial intelligence, the creation and application of 'intelligent' and 'extremely environment-friendly' solid lubricating materials is only a matter of time.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

P. Sarma (Conceptualization; Data curation; Visualization; Writing - original draft; reviewing)

A. Borah (Writing - review & editing; Funding acquisition; Supervision)

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