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ORIGINAL ARTICLE

Carbon solid lubricants: role of different dimensions

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Abstract

Over one-third of the worldwide energy production is estimated to be consumed by friction and wear. Delivering adequate lubrication between two contacting surfaces is one of the most efficient strategies to solve this issue. Over the past several decades, carbon materials have been regarded as promising lubricating materials due to their versatile structures, and superior mechanical, thermal, electrical, and chemical properties. This article provides a critical review on the lubricating performance of carbon materials with different dimensions ranging from zero (0D) to three dimensions (3D). Applications of these 0D to 3D carbon materials as lubricant coatings, additives in lubricants, and reinforcements in composites are reviewed. The mechanisms of the enhanced friction reduction and anti-wear performance based on the carbon-based lubricating materials are discussed. This review provides valuable guidelines on the selection and design of eco-friendly and nontoxic carbon-based lubricating systems.

Keywords Carbon · Solid lubricant · Friction · Wear · Lubrication

1 Introduction

Mechanical failures in machine components, such as engines, gears, bearings, piston, and cylinder liners, are mainly caused due to inefficient lubrication. Approximately one-third of the total energy loss is reported to be caused by friction and wear every year [1–3]. Furthermore, over 40% of the energy generated by consuming mined mineral is wasted to overcome friction, and about 2.7% of CO_2 emission worldwide is attributed to friction and wear [4]. Therefore, highly efficient strategies for decreasing friction and wear loss and saving energy are urgently required. As early as 4000 years ago, Egyptians had realized that lubricants such as water, gypsum, and animal fats could effectively reduce friction [5]. With the fast development of new materials, lubricants have been regarded as one of the most efficient methods to overcome friction and wear in modern tribology [6, 7].

As one of the basic elements on earth, carbon has been widely investigated regarding to its outstanding mechanical [8, 9], thermal [10, 11], electrical [12], and chemical properties [13]. Based on different types of bonding between carbon atoms, various dimensions of carbon ranging from zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures can be obtained (see Fig. 1) with various properties [14].

C_{60} is a typical 0D carbon material that consists of 12 pentagons and 20 surrounded hexagons arranged in a corannulene-like type [15], where all double bonds are conjugated [16]. It has been deemed one of the most promising materials in electronic, mechanical, and optical fields owing to the unique spherical π-electron surface and availability for chemical modifications. Following the discoveries of sp^2-bonded 1D carbon nanotubes (CNTs) and 2D graphene, carbon materials have pushed the enthusiasm of researchers around the world to a climax [17, 18]. Because of the honeycomb lattice structure, they exhibit electrical superconductivity, ultrahigh mechanical strength, and remarkable thermal conductivity, making the two carbon nanomaterials valuable candidates for diverse applications [10, 19–21]. As one of the typical 3D carbon materials, graphite has been extensively investigated as an efficient solid lubricant owing to the weak interplanar bonding by van der Waals forces [22, 23] and continues to receive significant attention as a promising additive in lubricants and self-lubricating materials in recent studies [24, 25].

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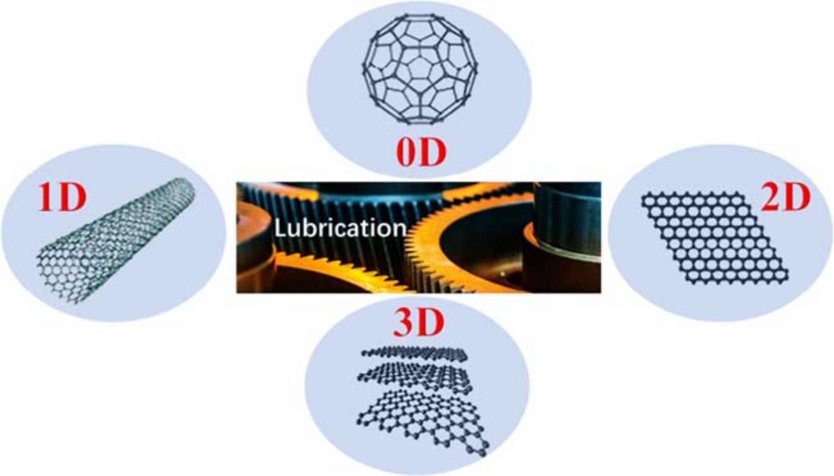

Fig. 1 Carbon materials with different dimensions for lubrication. Reprinted with permission from Ref. [14]

Numerous studies have been carried out on lubricating properties of carbon materials as solid lubricant coatings, additives in lubricants, and reinforcements in bulk composites [26–39]. Furthermore, in the past decade, a significant increase in the number of published scientific papers appears related to tribology of carbon materials [40], exhibiting a booming interest in carbon materials from tribologists. Here, we briefly review the progress in the development of lubricants using carbon materials with different dimensions and prospect the outlook of carbon materials in future tribological applications.

2 Carbon materials as lubricant coatings

Highly durable and conductive lubricant coatings have long been desired to reduce friction and wear. Extensive efforts have been made to develop conventional coatings applied in large industrial devices that are suffering from severe friction and wear [40–42]. Recently, the urgent need for decreasing friction and wear in micro/nanoscale electromechanical devices has attracted much interest in developing micro/nanoscale coatings. Carbon materials have been widely explored as solid lubricant coatings to minimize energy consumption caused by friction in the past several decades due to their outstanding mechanical and electrical properties at the micro/nanoscale. In this section, developments of carbon materials as solid lubricant coatings are briefly summarized.

2.1 Coating methods

Many coating techniques of carbon lubricants have been reported to protect substrates in corrosive or other harmful environments, among which sol–gel method, electrodeposition, thermal spray coating, physical vapor deposition (PVD), and chemical vapor deposition (CVD) have been regarded as the most effective and applicable ones [43–45]. Each method has its own pros and cons, which should be considered to meet the demands of practical applications.

Sol–gel technique is an effective method to coat substrates with complex or porous structures because of its liquid-based nature. By using a sol–gel technique, Wang et al. prepared graphene-reinforced polymer composite coatings with strong interfacial interactions between graphene and polymer [46]. They first functionalized graphene oxide by a silane coupling agent and subsequently mixed the silane-functionalized graphene and pretreated polymer in an aqueous solution. However, controlling the thickness of such coatings precisely is rather difficult, although it can be roughly manipulated by dipping coating times and velocities. Electrodeposition provides uniform and controllable coatings through a potential difference between anode and cathode, which can also be utilized in coating complex structures. It has been one of the most efficient methods for coating carbon materials, including C_{60} [47], CNTs [48] and graphene [49, 50]. A disadvantage of this technique is the requirement for an electrically conductive substrate.

Thermal spray coating includes processes using plasma, electricity, or chemical combustion to achieve high temperature, thus melting coating materials, followed by a spray process on the surface of substrates. Since carbon is difficult to melt because of its extremely high melting point, few studies have been focused on coating carbon materials by thermal spray coating. PVD and CVD are coating techniques through gaseous deposition. The former typically takes place in high vacuum, during which solid or liquid phase transforms to gas phase, followed by condensation of gas to a coating film [45]. In contrast, the latter is a chemical process. In this process, the surface of substrates is exposed to a high-vacuum environment with volatile materials acting as precursors to provide desired elements. Such techniques are widely used to prepare high-quality and high-resistance coating layers. The limitation of both methods is their relatively high cost to achieve elevated temperatures and high vacuum.

2.2 0D carbon materials

As a typical 0D carbon material, C_{60} has been regarded as an excellent solid lubricant because of its unique spherical structure, outstanding mechanical strength, low surface energy, stable chemical property, and weak intermolecular bonding [31, 51]. C_{60} was first studied as a solid lubricant by Bharat Bhushan et al. [52]. They tested friction and wear performance of C_{60} film under various environmental conditions by depositing fullerene on a polished (111) silicon wafer. The results indicated that the C_{60} film coating with a thickness from 2 to 5 μm exhibited low coefficients of friction (0.08–0.12) comparable to those of MoS_2 and graphite (~ 0.1). By optimizing the operation conditions, a lowest friction (0.08) was observed in a nitrogen environment. The authors attributed the excellent friction properties to the low surface energy as well as low adhesion to the mating surface of C_{60}. After that, Bharat Bhushan et al. [53] conducted friction and wear tests of diamond-like carbon coatings and C_{60} film on macro and microscales by sliding against an Al_2O_3-TiC head slider. The approximately 20-nm-thick C_{60} film was found to exhibit lower friction compared to that of the diamond-like carbon coating, and both coatings performed better friction properties at the microscale than macroscale.

Previous studies have also exhibited the extremely low friction coefficient of C_{60} ball bearings. For instance, Sasaki's group employed monolayer C_{60} as molecular bearings between graphite plates [54]. They found that the hexatomic-carbon-ring nanogears between C_{60} molecules and graphite helped minimize static and mean dynamical frictional forces, leading to an extremely low-friction motion. Direct molecular dynamics simulations for C_{60} molecular ball bearings were conducted by Li et al. [55]. The molecular ball bearings exhibited extremely low friction and energy dissipation because of various motion statuses in a single C_{60} molecule, including fast thermal rotation and periodic rolling. Furthermore, the friction of C_{60} molecular ball bearings could be manipulated by controlling the dispersion and rotation of C_{60} molecules. Tribological performance of other carbon materials with fullerene-like structures has also been investigated recently. For instance, Wang et al. [56] prepared fullerene-like hydrogenated carbon films and tested the friction and wear properties under different fullerene-like carbon content. Ultra-low friction coefficient and wear of 0.011 and 1.48×10^{-8} mm^3/N m were achieved, respectively, with a high fullerene-like carbon content.

Apart from acting as lubricant coating itself, C_{60} has also been added into other carbon materials such as graphene and graphite to form composite surface coatings. For instance, Wang's group [31] successfully prepared a novel graphene–C_{60} hybrid film by a multistep self-assembly process (Fig. 2). By virtue of combining the rolling effect of C_{60} molecules and excellent mechanical properties of graphene, the hybrid film exhibited fantastic synergistic effects, resulting in substantially better lubricating performance than single graphene or C_{60} films.

2.3 1D carbon materials

Since the discovery of CNTs by arc-discharge evaporation in 1991, they have aroused much interest in research due to their excellent mechanical, physical, chemical, and thermal properties [9, 57–59]. Because CNTs are rolled carbon atom sheets with the same sp^2-hybridized structure, ideal linear and rotational nano-bearings can be easily formed during nano-sliding or nano-rotating, endowing CNTs with excellent lubricating properties. Zhang et al. [1] directly prepared CNT films on 201 stainless steel by a mechanical rubbing method. Because of the sliding and densifying of CNTs at the sliding interface, friction coefficients and wear rates of CNTs/stainless steel samples were decreased to 1/5 and 1/(4.3–14.5), respectively, compared with the bare stainless steel. Vander Wal et al. [60] prepared a series of fluorinated CNT samples under direct fluorination. The type of chemical treatment was found to play an essential role in enhancing tribological properties. The fluorinated CNT samples exhibited excellent lubricating performance with friction coefficients as low as 0.002–0.07. A report found that the friction coefficients of multi-walled CNT (MWCNT) films can be easily tuned by changing the surface temperature and chemistry of either the countersurface or the nanotubes [61]. The authors argued that the variation of temperature led to changes in the interaction between the surface chemical groups on MWCNTs and rubbing countersurfaces. Tribological behavior of samples treated by plasma with various gases was tested to investigate the influence of surface chemistry on friction coefficients of MWCNT films. They found that friction coefficients varied according to the types of bonding between MWCNT films and countersurfaces, thus providing a promising strategy to tune friction coefficients by tailoring the surface chemistry of MWCNTs and countersurfaces.

CNTs have also been introduced into other materials, forming CNT-based lubricating composite coatings. Based on the number of the layers, CNTs can be divided into single-walled CNTs (SWCNTs) and MWCNTs. Satyanarayana et al. [62] investigated the influence of SWCNTs on the tribological properties of polymer films. In this study, SWCNTs were used as a filler material for polyimide films on silicon substrate. They found that the existence of SWCNTs increased the hardness and elastic modulus of pure polyimide films by 60–70% and reduced the friction of polyimide films by approximately 20%. Samad et al. [59] reinforced ultra-high molecular weight polyethylene (UHMWPE) coatings with SWCNTs to enhance the mechanical, thermal, and tribological properties. To ensure a stable adhesion between SWCNTs and the polymer, they pretreated

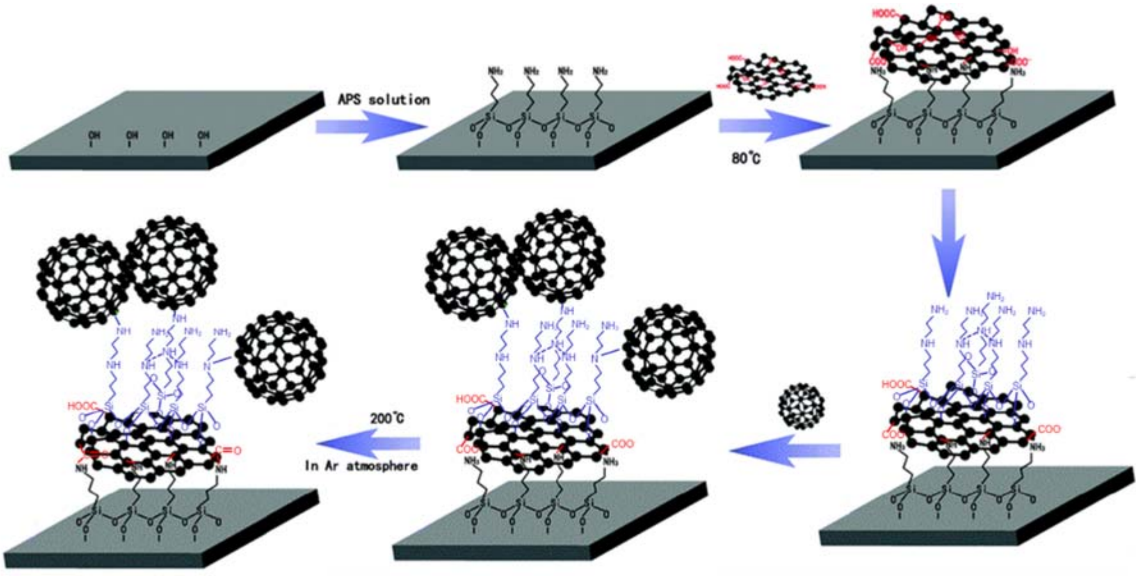

Fig. 2 The schematic diagram of the preparation process of graphene–C_{60} hybrid film. Reprinted with permission from Ref. [31]

the SWCNTs by plasma to introduce surface functional groups (e.g., carbonyl, hydroxide, and carboxyl). The enhanced bonding between SWCNTs and the UHMWPE matrix ensured the polymer intact, therefore preventing the peeling-off or delamination of the composite film. The wear resistance was significantly improved despite a slight increase in friction coefficient.

MWCNTs-reinforced coatings are reported to possess better lubricating properties than SWCNTs-reinforced coatings due to their outstanding self-lubricating and load-bearing effects [40]. Numerous efforts on dispersing MWCNTs into various matrices (e.g., ceramics [63], metals [64] or polymers [65]) have been made to prepare lubricating coatings. Xu et al. [63] prepared chemically bonded phosphate ceramic coatings with modified MWCNTs as reinforcements. Although the tribological tests showed that lubricating properties of the composite film deteriorated at 500 °C due to oxidation, the introduction of MWCNTs remarkably decreased friction coefficient and improved the wear resistance of coatings under 500 °C. The authors attributed the improved properties to the enhancement of fracture toughness by MWCNTs through preventing the crack generation and forming bridges when cracks occur. Wang et al. [66] incorporated MWCNTs into plasma-sprayed TiO_2 coatings and investigated the influence of MWCNTs on tribological properties of the coatings. They claimed that although the feedstock powder underwent extreme high temperature (10,000 K) during the plasma-sprayed deposit process, MWCNTs still remained because of the short residence time in plasma and the covering by molten-TiO_2 layer. The addition of MWCNTs was found to significantly decrease the friction coefficient and wear rate of the coating by approximately 36.8% and 93.6%, respectively. During the tribological tests, the tribo-protruding, tribo-reorientation, tribo-film, and tribo-degradation of MWCNTs played essential roles in enhancing lubricating performance of the coatings (see Fig. 3).

2.4 2D carbon materials

Graphene is a single-atom sheet which consists of sp^2 hybridized carbon atoms [67]. As one of the greatest discoveries in the twenty-first century, graphene has attracted extensive attention because of its unique mechanical [68, 69], thermal [11], electrical [12], and chemical properties [13]. Graphene has also been regarded as an excellent lubricant thanks to its low surface energy. When coated on other substrates, the extremely low thickness and low surface energy provide graphene lower adhesion and friction with the coated surfaces [29, 33, 70–72]. To date, various methods have been utilized to grow graphene on different solid substrates, including epitaxial growth [73], CVD [74], self-assembly [75], and photocoupling techniques [76]. Lee's group [29] synthesized graphene on Cu and Ni substrates by CVD. After transferring the CVD-grown graphene to Si/SiO_2 substrates, they tested the tribological properties of graphene as a lubricant film between contacting surfaces. The tests showed that graphene grown on the two substrates exhibited quite different friction behavior, because of a tortoise shell-like pattern appearing during friction tests. By testing the coefficient of friction of these CVD-grown graphene sheets, they found that the as-grown graphene on Ni exhibited excellent tribological properties that are comparable to bulk graphite. These results indicate that graphene exhibits great potential as an ultrathin lubricating film. Mi et al. [70] designed a novel self-assembling route to grow graphene films on various substrates by introducing a thin transition layer of polydopamine (Fig. 4). The

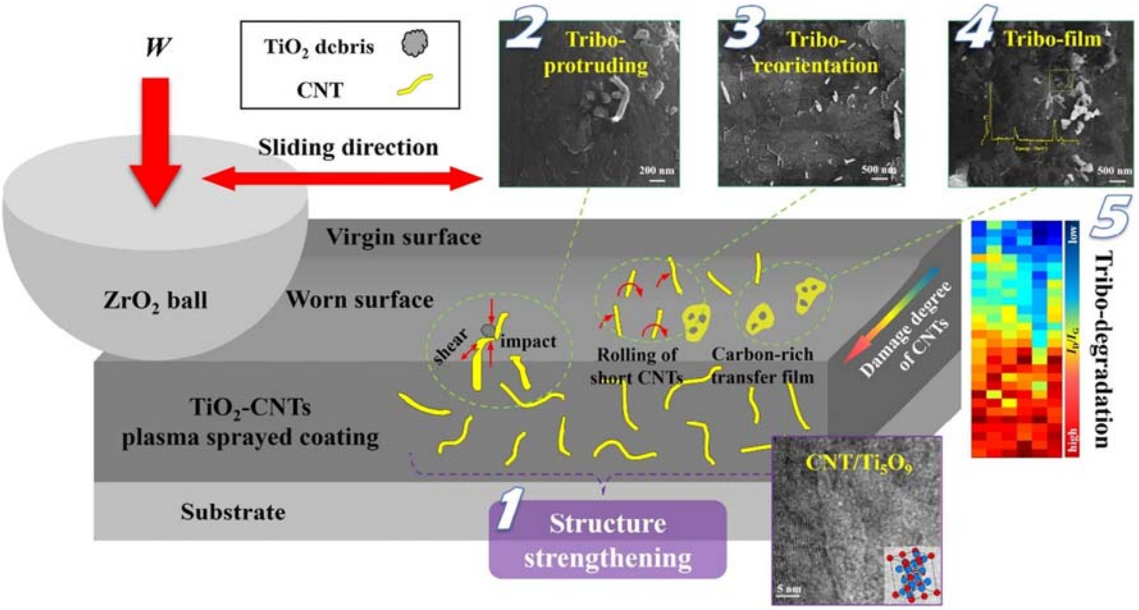

Fig. 3 Schematic of the enhancing mechanism induced by MWCNTs for plasma-sprayed TiO_2 coatings. Reprinted with permission from Ref. [66]

morphology showed that the graphene layer had been successfully embedded into substrates by the self-assembling route, and such an in situ graphene film exhibited impressive friction and wear resistance.

Recently, several papers reported direct coatings of graphene on microspheres to reduce friction and wear resistance [77–79]. For instance, Liu et al. deposited a graphene film on SiO2 microspheres by a metal-catalyst-free CVD method and investigated tribological performance of such graphene-coated microspheres [78]. Because of the multi-asperity contact by randomly oriented graphene nanograins, an ultra-low friction coefficient of 0.003 was achieved under a contact pressure up to 1 GPa. Moreover, the superlubricity was independent of relative surface rotation angles because

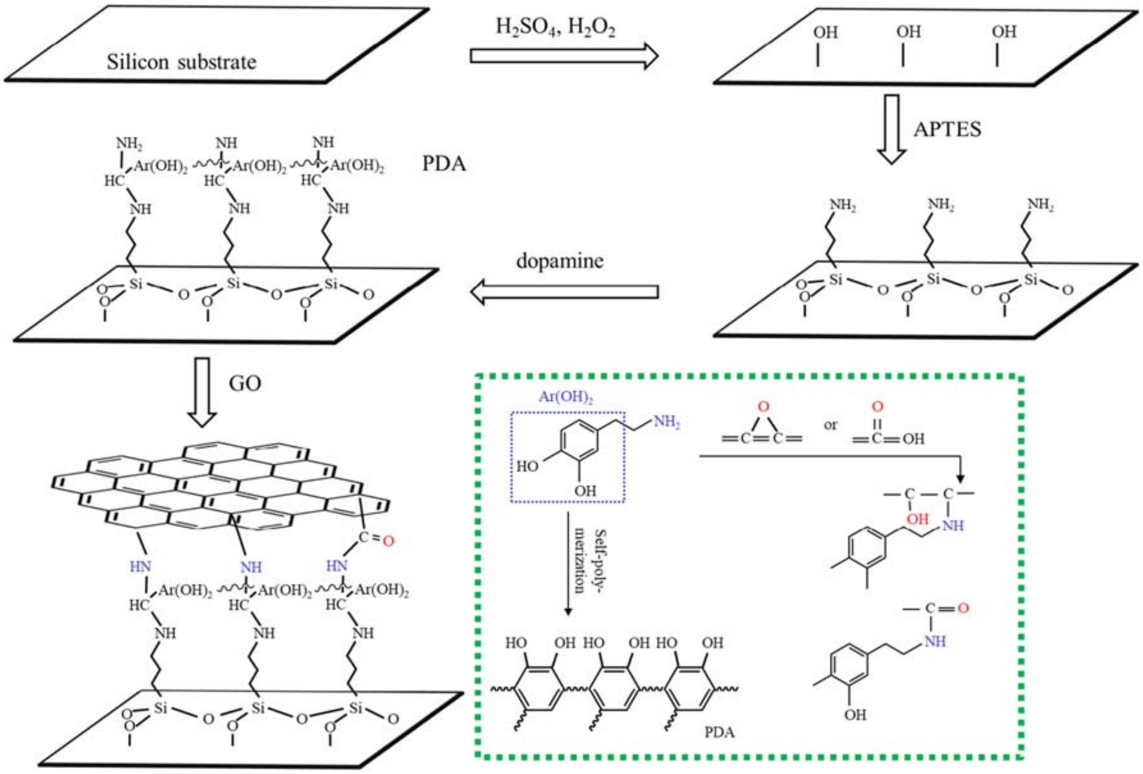

Fig. 4 Self-assembled route of 3-aminopropyl triethoxysilane-polydopamine-graphene film on a silicon wafer. Reprinted with permission from Ref. [70]

of the spherical shape of graphene-coated microspheres. This novel technique can also be employed to coat other 2D materials such as MoS_2 to achieve microscale superlubricity.

Graphene is also used as a reinforcement in composite coatings. Through a pulse electrodeposition technique, Algul et al. [80] prepared nickel–graphene metal matrix composite coatings and studied the influence of graphene loading on the tribological behavior of the obtained nanocomposite coatings. They found that when the content of graphene in electrolytes increased from 100 to 500 mg/L, the microhardness and wear resistance increased significantly while the friction coefficient decreased substantially, indicating that the addition of graphene successfully improved the tribological properties of the nickel matrix. Menezes's group [81] studied the surface energy and tribological properties of electrodeposited Ni and Ni/graphene coatings on steel. They found that the low surface energy of Ni/graphene coating decreases the adhesive forces leading to low friction and wear compared to Ni coating. In another research, Menezes's group studied the wear-corrosion synergism behavior of Ni-graphene coating and steel [82]. The wear-corrosion was substantially evident in steel as compared to Ni/graphene. This behavior of Ni/graphene was attributed to a compact, refined-grain structure leading to minimal-grain pull-out during wear.

In addition to graphene sheets, derivatives of graphene such as graphene oxide (GO) and reduced graphene oxide (rGO) are also capable of acting as promising lubricants. Via a novel electrophoretic deposition approach, Liang et al. [83] successfully introduced GO films with various thicknesses onto a nanoscale silicon wafer and studied morphology, friction properties, and wear properties of the obtained samples. They found that the existence of GO films on the wafer surface significantly reduced the friction coefficient and wear volume of the silicon wafer by 5/6 and 23/24, respectively.

In addition, simulation studies on the tribological properties of graphene have also been conducted to facilitate the understanding of its tribological behavior. Terrell's group [84] studied graphene's abrasive wear and failure and compared the properties with those of diamond-like-carbon coatings. Their simulation results indicated that graphene could perform as an excellent nanoscale lubricating coating because of its ultra-low thickness and high load-carrying capacity.

2.5 3D carbon materials

As a typical 3D solid lubricant, graphite has been widely used in industry for years. Graphite is reported to exhibit better lubricating properties in humid environments than dry or vacuum environments [85]. In a humid environment, water molecules can penetrate into the space between graphite layers, therefore rendering graphite easy shearing and low friction. Moreover, during the tribological process, graphite scrolls can be formed to reduce the surface energy and thus decrease friction in the sliding interfaces [33]. Berman et al. [33] compared the tribological properties of graphite with their prior studies of graphene [71, 86]. The tribological tests of graphite and graphene were conducted in humid air and dry nitrogen under the same test conditions. Their results showed that graphite powder exhibited high friction and high wear losses in a dry nitrogen atmosphere while the wear of graphene was significantly reduced in both humid air and dry nitrogen environments (Fig. 5).

Graphite has also been incorporated into metals to form composite coatings. Chen et al. [87] incorporated Cu-coated graphite into Cu-10 wt% Al_2O_3 spray powder to prepare Cu-Al_2O_3-graphite solid-lubricating coatings. Compared with pure graphite, stable adhesion between Cu-coated graphite and Cu powder enabled the superior tribological performance of the coatings. Because of a combined effect of hard reinforcement (i.e., Al_2O_3) and solid lubricant (i.e., graphite), the composite coating exhibited a relatively low friction coefficient (0.29).

Diamond-like carbon (DLC) is another important 3D allotrope of carbon materials, which is characterized by sp^3 bonds between carbon atoms. DLC has attracted tremendous attention because of its wide bandgap, high hardness, and excellent chemical stability [88, 89]. Binu et al. deposited multilayer Ti, TiN, and DLC coatings on standard tool substrates at varying sputtering parameters and conditions, such as power density, partial pressure, substrate temperature, and reactive gases [88]. After testing the tribological properties of such samples by a pin-on-disc setup, they found that bombarding during the sputtering process led to strong adhesion between DLC and substrates, while the formed DLC coating significantly strengthened the micro hardness and reduced the coefficient of friction of substrates. Another research on DLC coating [89] showed that the top part of sp^3-bonded DLC coating was transformed into sp^2-bonded graphene-like structures during the running-in period, leading to superlubricity performance with a friction coefficient below 0.01.

Carbon coating has also been utilized in other applications such as improving the electrical conductivities of substrates [90, 91]. Recently, Liu et al. observed an interesting phenomenon when preparing carbon coating on lithium iron phosphate particles by a spray–pyrolysis system [90]. A highly reducing atmosphere during carbon coating processes resulted in the formation of secondary phases. The electrical conductivities of the phases were dependent on size, temperature, and annealing atmosphere. Such controllable secondary phases may have promising potential in tribological applications.

Recent studies on the tribological performance of carbon materials with different dimensions and related composites as lubricant coatings are summarized in Table 1. Lubricant coatings containing carbon materials from 0D to 3D behave quite differently because of dispersion uniformity, various structures, and hybridizations of carbon

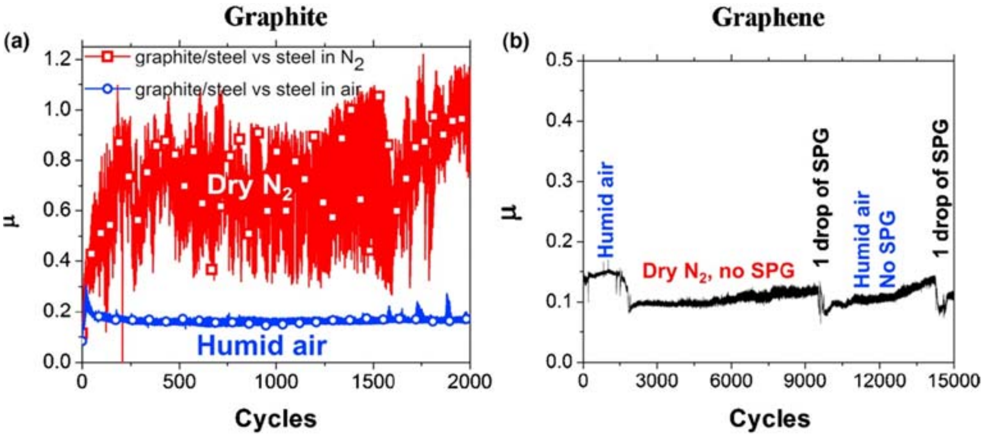

Fig. 5 Coefficient of friction of graphite (**a**) and graphene (**b**) in different atmospheres. Reprinted with permission from Ref. [33]

atoms. From Table 1, we can infer that C_{60}, CNTs, and graphene work well both at the micro- and nanoscale, while 3D graphite works well as lubricant coatings mainly at the microscale. Among them, graphene is expected to perform as a promising candidate for nanoscale electromechanical devices. A low friction of 0.12 could be achieved by adding graphene even with a thickness of only 1 to 10 nm [29]. Nonetheless, some issues associated with carbon lubricant coatings still exist. For example, a dry environment is not suitable for graphite [33], and graphene-based nanoscale lubricant coatings require sophisticated technologies to make the films continuous with high quality.

3 Carbon materials as additives in lubricants

Studies on controlling the friction and wear in industrial component contacting surfaces by lubricants have lasted over one hundred years. As one of the crucial factors impacting the performance of lubricants, lubricant additives can efficiently decrease friction and wear. Modern lubricants typically comprise two components: base oil and additive [92]. The base oil determines the primary properties of lubricant, eliminating excess heat and reducing wear/friction, while additives are utilized to further improve lubricating properties such as oxidative stability, anti-corrosion, viscosity modification, and resistance to biodegradation [93, 94]. In this section, we will

Table 1 Tribological performance of carbon materials as lubricant coatings

	Coatings	Operating conditions	Thickness (μm)	Friction coefficient	Wear rate (mm^3/N m)	Ref.
0D	C_{60}	1 N, 2.4 mm/s, 20 °C	2–5	0.18–0.12	–	[52]
	C_{60}	1 N, 2.4 mm/s, 100 °C	2–5	0.08	–	[52]
	C_{60}	0.1 N, 10 mm/s, 20 °C	0.02	0.12	–	[53]
1D	0.1 wt% MWCNTs/polyimide	3 N, 0.16 m/s	100	0.26	2.0×10^{-4}	[39]
	0.7 wt% MWCNTs/polyimide	3 N, 0.16 m/s	100	0.18	6.5×10^{-4}	[39]
	0.75 wt% MWCNTs/phosphate ceramic	10 N, 100 rpm, 100 °C	200 ± 10	0.39	8.0×10^{-3}	[63]
	0.75 wt% MWCNTs/phosphate ceramic	10 N, 100 rpm, 300 °C	200 ± 10	0.28	13×10^{-3}	[63]
	3 wt% MWCNTs/TiO_2	20 N	250–280	0.50–0.55	–	[66]
2D	Cu-grown graphene on SiO_2	5–70 mN, 50 μm/s	0.001–0.01	0.22	–	[29]
	Ni-grown graphene on SiO_2	5–70 mN, 50 μm/s	0.001–0.01	0.12	–	[29]
	APTES-PDA-rGO	0.1 N–0.2 N	0.012	0.13	–	[70]
	250 mg/L graphene/Ni	1 N, 150 mm/s	–	0.20	9.3×10^{-4}	[80]
	500 mg/L graphene/Ni	1 N, 150 mm/s	–	0.10	8.6×10^{-4}	[80]
	GO on silicon wafer	400 mN, 25 mm/s	0.05	0.05	–	[83]
	GO on silicon wafer	400 mN, 25 mm/s	0.09	0.067	–	[83]
3D	Graphite/steel	1 N, dry N_2	–	0.6–0.8	–	[33]
	Graphite/steel	1 N, humid air	–	0.18	–	[33]
	10 wt% Cu-coated graphite/10 wt%Al_2O_3/Cu	5 N, 360 rpm	365 ± 16	0.29	2.2×10^{-4}	[87]
	20 wt% Cu-coated graphite/10 wt%Al_2O_3/Cu	5 N, 360 rpm	365 ± 16	0.34	1.2×10^{-4}	[87]

review the state-of-the-art literature on carbon additives with different dimensions in lubricants.

3.1 0D carbon additives

Because of the unique spherical shape, C_{60} has been widely used as an additive in various lubricants [26, 37]. Hwang's group [37] studied the change of tribological performance in mineral oil with different viscosities after adding C_{60} nanoparticles. By testing the raw oil and fullerene-added oil, they found that with low-viscosity raw oil and high normal load conditions, the addition of fullerene additives exhibited a noticeable difference in friction coefficient of mineral oil. Yu's group [26] introduced C_{60} into mineral oil to obtain a promising lubricant used in refrigerator compressors. With the addition of C_{60} into mineral oil, the friction coefficients decreased by 12.9–19.6%, and the coefficient of performance (COP) of compressors was improved by 5.6%. The performance of lubricants added with other 0D carbon materials has also been studied [95, 96]. Abdullah et al. [95] prepared ultrasmooth carbon spheres with diameters ranging from 100 to 500 nm by an ultrasound-assisted process. By adding them as additives into lubricating oils, friction and wear decreased by 10–25%. They claimed that carbon spheres could perfectly fill the gap between interfaces due to their spherical shape and could act as a nanoscale ball bearing during sliding and reduce friction and wear.

3.2 1D carbon additives

The high aspect ratio and remarkable mechanical properties of CNTs make them promising as lubricant additives [34, 97–103]. Outstanding chemical resistance is one of the exotic properties of CNTs; however, this is accompanied by an issue: CNTs, because of their high surface area, are extremely difficult to disperse homogeneously in solvents, therefore limiting their application as nano-additives in liquid lubricants such as oil. Therefore, to utilize CNTs as additives, the issue of CNT dispersion needs to be addressed. Chen's group [97] successfully modified MWCNTs by sulfuric, nitric acids or stearic acid, and obtained CNTs/oil suspension (Fig. 6) which could be stable up to 6 months. They claimed that the tribological properties of the nano-lubricant depended on both the tribological behavior of CNTs and the dispersion of CNTs in oil. Francisco et al. [100] added 0.5 wt% single-walled CNTs into an ionic liquid, 1-octyl, 3-methylimidazolium chloride. Due to the capability of separating the sliding surfaces by interactions between the single-walled CNTs and ionic liquid molecules, the obtained composite exhibited excellent tribological properties (ultra-low friction and preventing wear) for polycarbonate sliding against stainless steel.

However, SWCNTs are rather difficult to prepare, and the high cost also hinders further application of CNT-added lubricants. MWCNTs, with simpler fabrication processes and lower cost than SWCNTs, are attracting much attention recently. Chauveau et al. [98] dispersed MWCNTs with various concentrations in oil and studied lubricant mechanisms of the MWCNT-added oil by a tribometer. The results showed that the coefficient of friction was apparently reduced with the addition of MWCNTs. They also found that both the entrainment velocity and the content of MWCNTs were crucial to the lubricant film-forming capability of oil. Bo et al. [34] first treated MWCNTs by imidazolium-based ionic liquids, 1-hydroxyethyl-3-hexyl imidazolium tetrafluoroborate, and then added the ionic liquid-treated MWCNTs into a base lubricant, 1-methyl-3-butylimidazolium tetrafluoroborate. The results showed that because of the unique cylindrical shape of such ionic liquid-treated MWCNTs, they exhibited excellent anti-wear performance as an additive in 1-methyl-3-butylimidazolium tetrafluoroborate at relatively low concentrations under different conditions. Menezes's group [104] studied the effect of the particulate mixture on friction and wear performance. The particular mixture was prepared by adding graphite or MWCNTs in the base oil. In was found that MWCNTs-based particulate mixture increased both friction and wear when compared to graphite-based particulate mixture. This is because the MWCNT particulate mixtures witnessed capillary effects that absorbed the base oil, creating a highly viscous slurry rendering the particulate mixture useless as a lubricant.

3.3 2D carbon additives

Graphene can also act as an effective additive to improve the tribological properties of base oil. However, graphene faces the same issue as CNTs: graphene is extremely difficult to disperse homogeneously in water-based lubricants or oil because of its high surface area. Thus, modifications to graphene become to be an appropriate approach to improve its dispersion in the base oil. Zhang et al. [105] modified graphene sheets by oleic acid and dispersed them in gear oil uniformly via a 15-min ultrasonication process. Compared to the pristine gear oil, the addition of graphene with low concentrations (0.02–0.06 wt%) decreased friction coefficient and diameter of wear scar by 17% and 14%, respectively.

In addition, the derivatives of graphene have also been frequently used as additives [106–108]. Song el, al. [32] prepared GO nanosheets by an improved Hummer's method and then distributed such GO nanosheets into water-based lubricants. Using the same process, they also introduced oxidized MWCNTs separately into the same water-based lubricant. The tribological results on a UMT-2 ball-plate tribotester showed that the GO nanosheet-added water-based lubricant possessed less friction coefficient and wear than the oxidized MWCNT-added water-based lubricant. Kinoshita et al. [109] prepared GO by an improved Hummer's method and introduced GO

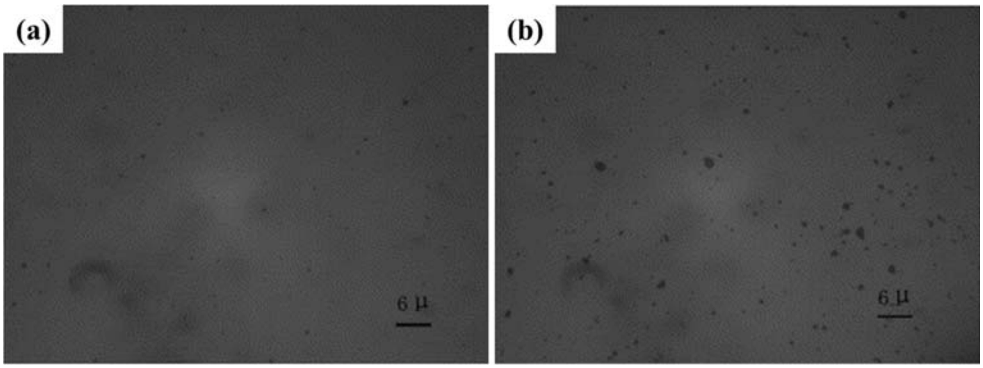

Fig. 6 Micrographs of CNTs in lubricants: (a) after modification with stearic acid; (b) before modification. Reprinted with permission from Ref. [97]

into water-based lubricants. They found that the friction coefficient of such water-based lubricant was reduced to a low value of approximately 0.05 after adding GO, and even after 60,000 cycles of friction testing, no obvious surface wear was observed.

Eswaraiah et al. [110] used a novel solar exfoliation to exfoliate GO, therefore obtaining ultrathin graphene. After preparing GO by Hummer's method, they spread GO over a Petri dish and kept the sample under sunlight. Under the illumination of the sun, different carbon atom layers were separated and formed ultrathin graphene layers. They mixed such obtained ultrathin graphene with commercial engine oil and tested the tribological properties of the mixed engine oil. The results showed that compared to the pristine engine oil, the ultrathin graphene-added engine oil decreased friction and wear by 80% and 33%, respectively.

Gupta et al. [30] studied the mechanisms of how rGO improves the lubrication and anti-wear properties as an additive. They investigated the role of rGO concentration in the lubrication of solid body contacts and found that when the concentration of rGO was relatively low, the lubrication was dominated by base oil; while at higher concentration, rGO aggregated seriously in the base oil, therefore deteriorating interlayer sliding. Only at an optimized concentration can rGO play a role as an effective additive in the base oil, and such concentration of rGO reduced the friction coefficient and wear by 30% and 50%, respectively. Based on the Fourier-transform infrared spectroscopy (FTIR) analysis and wear track, they proposed a new model where rGO sheets and polyethylene glycol (PEG) molecules were linked through hydrogen bonding (Fig. 7). When the contact pressure was relatively low, rGO sheets could align between PEG molecules. The parallel arrangement between graphene and PEG molecules provided less shear strength, therefore effective lubrication. While under higher contact pressures, shear mobility occurring in graphene started dominating lubrication behavior, thus reduced the friction more significantly while deformation of the wear tracks became negligible. They also investigated the influence of oxygen functional groups in rGO on lubricating properties [111]. Two different rGO decorated by hydroxyl and epoxy-hydroxyl groups were fabricated and blended with two different molecular weights of PEG, respectively. After that, they tested the tribological properties and found that compared to rGO terminated by epoxy-hydroxyl groups, the ones terminated by hydroxyl exhibits reduced wear due to fewer defects on hydroxyl functionalized graphene planes, but increased friction because of the lower friction energy caused by intercalation of PEG in epoxy-hydroxyl-functionalized rGO.

Menezes's group [112] studied the effect of graphene and graphite as additives in canola oil. These additives in oil showed a lower coefficient of friction and wear rate compared with bare canola oil. The graphene sheets were more effective than graphite in terms of reducing friction and wear. The optimal concentration of the additive in canola oil was approximately 0.7 wt%. Moreover, the worn surface of the contacting materials was smoother in the presence of solid lubricant rather than bare oil. In another work, Menezes's group [113] studied the effect of multiphase lubricants on friction and transfer layer formation during sliding against various surface textures. The sliding tests were conducted in multiphase lubricants that consist of canola oil and graphene at different concentrations. A minimum friction coefficient of 0.05 was achieved for various surface textures by adopting a specific concentration of graphene. The amount of graphene required to achieve the minimum friction coefficient is attributed to the variations in asperity and graphene additive interaction when sliding against different surface textures.

3.4 3D carbon additives

Graphite has also been used as additives in lubricants. Su et al. [114] studied the lubricating properties and lubrication mechanisms of graphite oil-based nanofluids by adding graphite nanoparticles into vegetable-based oil. They found that

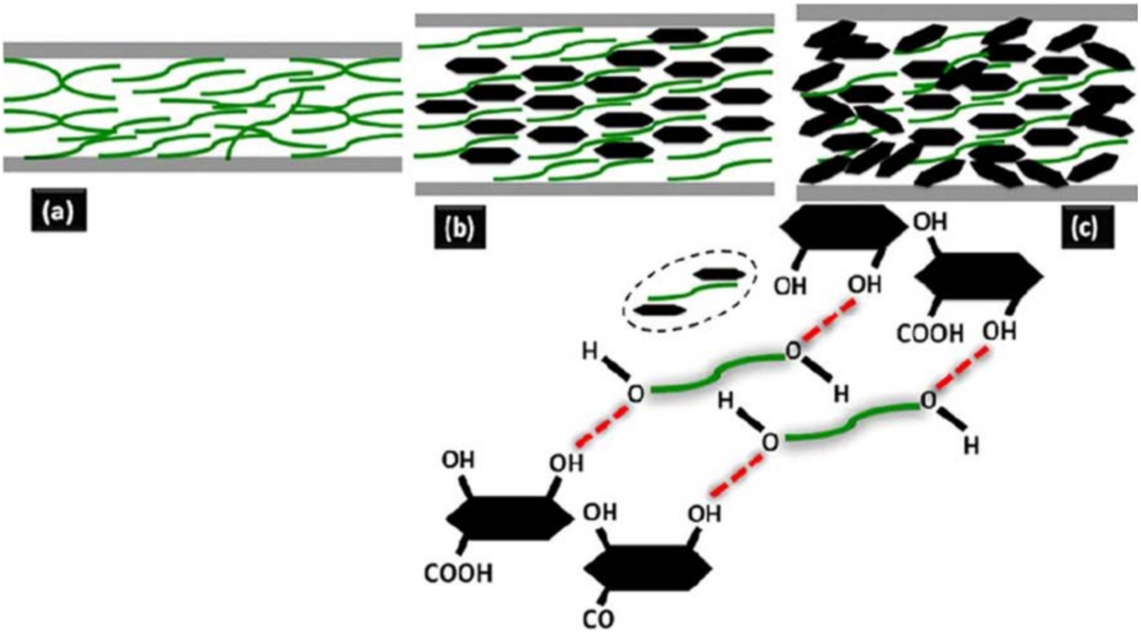

Fig. 7 Lubrication mechanisms in (a) PEG steel-steel contact (b) 0.2 mg mL^{-1} rGO-PEG-lubricated contact and (c) 1.0 mg mL^{-1} rGO-PEG-lubricated contact. Reprinted with permission from Ref. [30]

friction and wear were significantly reduced as the volume fraction of graphite nanoparticles increased. Due to the small size and high surface energy of graphite nanoparticles, a physical deposition film was formed during the test, therefore reducing friction and wear. Lee et al. [115] introduced graphite nanoparticles as an additive into industrial gear oil and investigated the tribological properties of the formed lubricants. It was found that graphite nanoparticles could significantly reduce the contact between the plates by acting as ball-bearing spacers, therefore improving lubricating properties compared to pristine gear oil. Martorana et al. [116] formed colloidal suspensions by dispersing fine graphite flakes and carbon nanofibers in ethanol; then they tested the effect of such carbon additives in a closed hydraulic loop. They found that the addition of graphite particles could form thin lubricating layers at the surface of gears, causing a significant reduction in friction.

Recent studies on the tribological performance of carbon materials with different dimensions as additives in lubricants are summarized in Table 2. Carbon materials with different dimensions can perform as excellent additives in lubricants such as mineral oil, engine oil, and vegetable oil. The addition of carbon materials can substantially reduce friction coefficient and wear rate even with an extremely low loading content. From Table 2, one can see that SWCNTs perform better than MWCNTs. However, employing SWCNTs as an additive also results in extra costs. Moreover, increasing content of carbon materials to an appropriate extent can improve tribological performance, while at a higher concentration, the dispersion issue of the carbon nanomaterials needs to be addressed.

4 Improving lubricating properties of bulk composites

Apart from being acting as lubricant coatings and additive in lubricants, carbon materials have also been utilized to improve tribological properties of bulk materials [120, 121]. This section will discuss the latest research on using carbon materials with different dimensions as reinforcements for ceramics, metals, and polymers to enhance their lubricating performance.

4.1 0D carbon materials

Only a few studies are reported on enhancing lubricating properties by employing C_{60} as reinforcement for bulk materials. Wang et al. [122] prepared aligned CNT/C_{60}-epoxy nanocomposites and conducted tribological tests. It is found that the friction coefficients of C_{60}-epoxy composite and aligned CNT-epoxy composites were 26.2% and 38.1%, respectively, lower than that of pure epoxy. Yoshimoto et al. [123] synthesized C_{60}/expanded graphite composites and studied the synergistic effects via a combination of C_{60} and graphite. The results showed that C_{60} played an essential role in enhancing lubricating performance, and the C_{60}/expanded graphite composites could be further used as a promising antiwear additive in lubricants. Their earlier work also showed that superlubricity and ultra-low spatial-average friction could be achieved using graphite-confined C_{60} monolayer systems [54, 124].

Table 2 Tribological performance of carbon materials as additives in lubricants

	Additive	Base stock	Operating conditions	Friction coefficient	Reduction ratio of friction (%)	Wear rate (mm^3/N m)	Reduction ratio of wear (%)	Ref.
0D	3 g/L C_{60}	Mineral oil	981 N, 600 rpm, 75 °C ± 2 °C	–	19.6	–	–	[26]
	5% C_{60}	I-40A industrial oil	800–1200 N	0.02	–	–	–	[117]
	0.5 vol% C_{60}	Mineral oil	1000 N, 1000 rpm	0.02	84.6	–	–	[118]
	0.1 vol% C_{60}	Mineral oil	1200 N, 1000 rpm	0.01	90	–	–	[119]
	3 wt% Carbon sphere	SAE 5W30 engine oil	22.2 N, 0.3 m/s	0.087	15.5	1.5×10^{-4}	66	[95]
1D	0.5 wt% SWCNTs	[OMIM]Cl	0.49 N, 0.1 m/s	0.023	66	–	–	[100]
	1 wt% MWCNTs	Mobil gear 627	800 N, 1200 rom	0.058	57	–	68	[101]
	1 wt% MWCNTs	Paraffinic Mineral oils	800 N, 1200 rpm	0.076	49	–	39	[101]
	0.06 wt% functionalized MWCNTs	[Bmim][PF6]	800 N, 0.05 m/s	0.088	7.4	–	–	[103]
2D	0.02 wt% graphene	PAO9	400 N, 1450 rpm	0.042	17	–	8.3	[105]
	0.02 mg/ml alkylated graphene	10W-40 commercial engine oil	100 mN, 1 cm/s	0.11	25	–	–	[107]
	0.02 mg/mL alkylated graphene	10W-40 commercial engine oil	3 N, 3 cm/s	0.105	16	–	25	[107]
	0.01 wt% GO	SN 150 mineral oil	60 N, 0.22 m/s	0.118	16.9	–	30	[108]
	0.025 mg/mL graphene	Engine oil	392 N, 600 rpm	0.02	80	–	33	[110]
	0.2 mg/mL rGO	PEG	50 mN to 500 mN, 0.5 cm/s	0.06	78	–	50	[30]
3D	0.25 vol% graphite (35 nm)	Vegetable-based oil	2 N	0.123	53.2	4.8×10^{-4}	11.1	[114]
	0.25 vol% graphite (35 nm)	Vegetable-based oil	10 N	0.288	20	4.4×10^{-4}	15.4	[114]
	0.5 vol% graphite	Supergear EP 220	3000 N, 500 rpm	0.01	24	–	–	[115]

4.2 1D carbon materials

Numerous studies have shown that CNTs can act as a perfect reinforcement in composites [28, 125–127]. Moghadam et al. [57] proved that the stress transferred to the nanotube (σ_f) through the interface could also be described by the shear lag models used in fiber-reinforced composites:

$$\frac{l_f}{D_f} = \frac{\sigma_f}{2\tau_{mf}} \tag{1}$$

where τ_{mf} is the shear stress between CNTs and matrix; l_f and D_f are the length and the diameter of the CNT, respectively. From the model, one can see that more load can be transferred to CNTs as the aspect ratio of CNTs increases.

Puchy et al. [128] described tribological properties of Al_2O_3-CNT composites prepared by spark plasma sintering. With a low loading content of CNTs, the composite exhibited reduced friction and depth penetration, which can be attributed to the grain size effect and reinforcement effect of CNTs. Bastwros et al. [129] mixed CNTs with aluminum particles by high-energy ball milling, followed by cold compaction and hot extrusion to prepare composite samples. They systematically investigated how the wear performance changed with the loading content of CNTs, sliding velocity, and applied load (Fig. 8). As the loading content of CNTs increased, both coefficient of friction and wear rate significantly decreased. An addition of 5 wt% CNTs could reduce the coefficient of friction and wear rate of composites by 55.6% and 78.8%, respectively. From SEM micrographs of worn surfaces in Fig. 8c–e, the dominant wear mechanism changed from adhesion to abrasion as the CNTs content increased. Due to the self-lubricating properties of CNTs, they formed a carbon coating on the contacting surfaces during the test and acted as a solid lubricant, therefore decreasing friction and wear.

Zhang et al. [28] synthesized vertically oriented CNTs on inconel substrates by CVD, after which they electrodeposited MoS_2 on the surface of the vertically oriented CNTs. This novel composite showed excellent tribological properties at both room and elevated temperatures. Hereafter, Wang's group [126] prepared continuously aligned CNTs by CVD and produced aligned CNTs-reinforced epoxy composites by the capillary-induced moistening method under vacuum condition for 2 h. When sliding both pure epoxy samples and the aligned CNTs- reinforced epoxy samples, the results showed that increasing sliding velocity led to decreased wear rates and friction coefficients. With a test condition of 1.2 MPa and 0.69 m/s, the wear of CNTs-reinforced epoxy composites was decreased by up to 219 times compared to pure epoxy. Golchin's group [127] utilized MWCNTs as a reinforcement to enhance the tribological properties of UHMWPE. The results of the water-lubricated sliding test showed that the obtained MWCNTs-reinforced UHMWPE exhibited a lower friction and higher wear resistance compared to the pure UHMWPE.

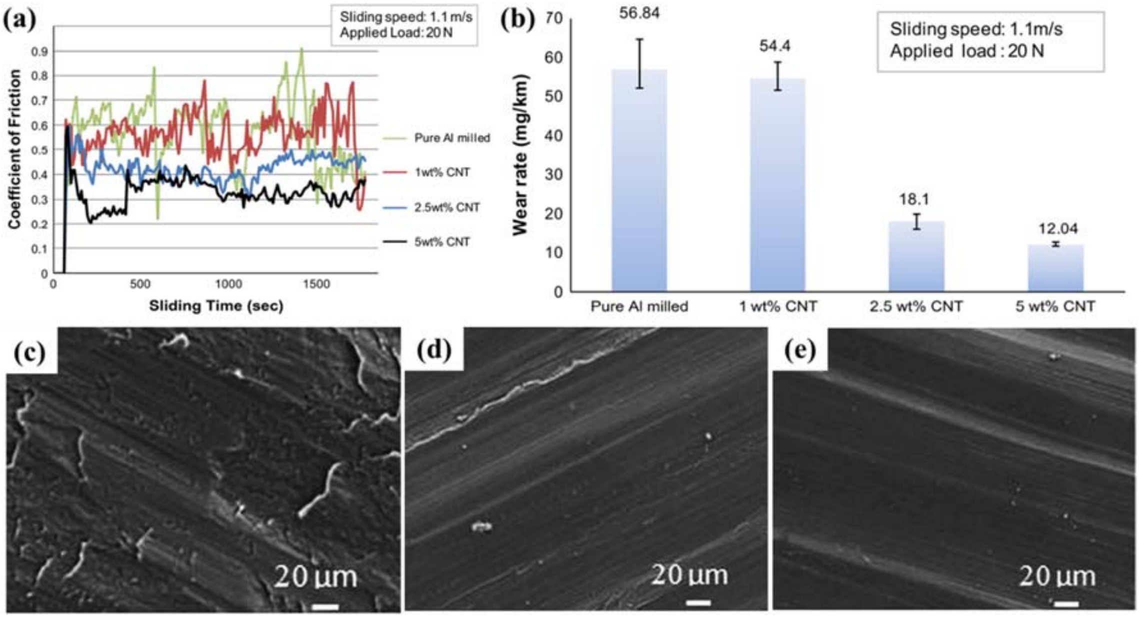

Fig. 8 Coefficient of friction (**a**) and wear rate (**b**) of Al and Al-CNT samples. **c**–**e** SEM micrographs of worn surfaces of Al-CNT samples: (**c**) 1 wt%, (**d**) 2.5 wt%, (**e**) 5 wt%. Reprinted with permission from Ref. [129]

4.3 2D carbon materials

The outstanding mechanical properties, large surface area, and low density make graphene an ideal reinforcement for composites [130, 131]. Single-layer graphene is difficult to be used in large-scale applications because of its high cost; instead, multilayer graphene with a lower cost contains 10–30 layers of graphene and possesses properties similar to those of single-layer graphene. Xu et al. [132] prepared multilayer graphene-reinforced TiAl matrix composites by spark plasma sintering. They mixed multilayer graphene powder with commercial powders of Ti, Al, B, Nb, and Cr in a molar ratio of 48:47:2:2:1 by ball milling at vacuum and then put the mixed powder in a mold for the spark plasma sintering process. The tribological results showed that the multilayer graphene reinforcement reduced the friction coefficients to 1/5 and decreased wear by a factor of nearly 4–9 times, indicating that multilayer graphene acted as an excellent reinforcement to enhance the tribological properties of the matrices.

However, like CNTs, the severe aggregation of graphene in the matrix can inhibit further promotion of tribological properties and limit the loading content of graphene added into the matrix. Tremendous efforts have been made to tackle this issue. As a typical example, Hwang et al. [130] fabricated rGO/Cu composites by a novel molecular-level mixing method and a following spark plasma sintering process (see Fig. 9). They prepared GO first and then mixed them with Cu salts in aqueous solution during which GO assembled with Cu ions. After that, they reduced the obtained GO/Cu to rGO/Cu powders with a subsequent spark plasma sintering process to prepare rGO/Cu composite. Through such a novel method, they successfully realized a homogenous dispersion of graphene in the copper matrix, and such structure exhibited extremely high adhesion energy between sintered graphene and Cu (164 J m^{-2}) compared to that (0.72 J m^{-2}) between graphene grown on a Cu substrate. Using a similar method, Gao et al. [38] prepared graphene-reinforced copper matrix composites through fabricating GO/Cu powder by electrostatic self-assembly and subsequent sintering process by powder metallurgy. They achieved a 65% decrease in friction coefficient compared to pure copper. Menezes's group [133] synthesized aluminum matrix composites reinforced by graphene nanoplatelets by a powder metallurgy method. The graphene nanoplatelets-reinforced composites showed outstanding tribological properties and demonstrated the self-lubricating nature of the composite during tribological conditions.

4.4 3D carbon materials

Graphite can also serve as a promising reinforcement in bulk composites [134–136]. Ravindran's group [36] prepared Al 2024-SiC-graphite hybrid composites by a powder metallurgy method. The prepared composites with 5 wt% graphite as reinforcement exhibited significantly decreased friction and wear because of the self-lubricating effect of graphite. Ma et al. [137] investigated how the tribological behavior of Cu/graphite composites changed depending on sliding speed and found that the friction and wear regimes of the composite changed at a critical speed (Fig. 10). At speeds below this critical speed, a graphite-rich lubricant layer formed at the contact interface due to the large strain gradient in the subsurface

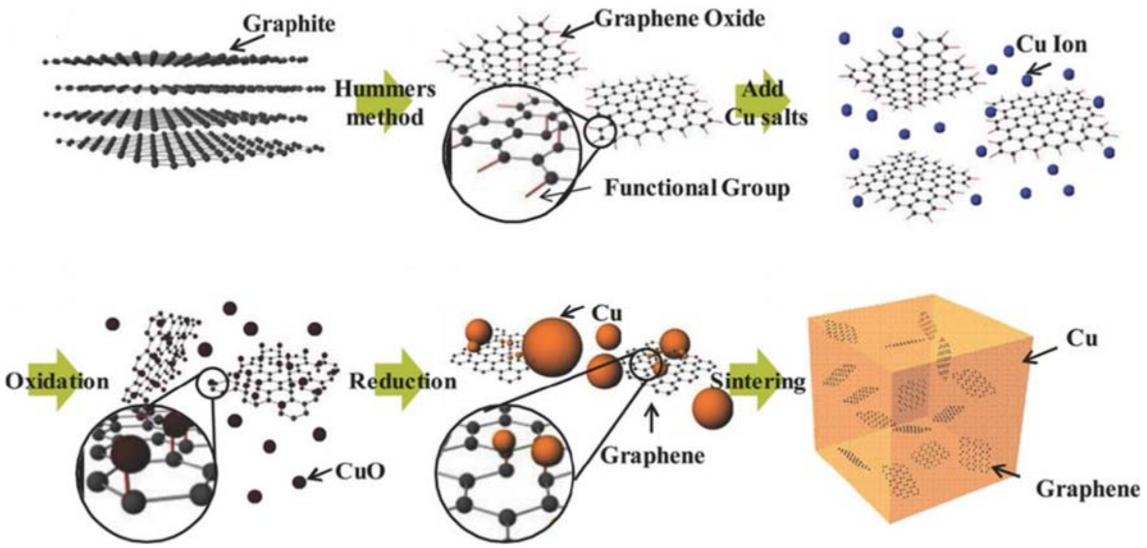

Fig. 9 Schematic of the fabrication process of rGO/Cu nanocomposites by molecular-level mixing method. Reprinted with permission from Ref. [130]

deformation zone, therefore greatly improving the tribological properties of the composite. While at speeds higher than this critical speed, delamination wear caused by high sliding speed inhibited the formation of such a graphite-rich lubricant layer, resulting in severe wear.

Additionally, they also investigated the effect of surface texture on the tribological behavior of Cu/graphite composites [138]. At the beginning, they prepared Cu/graphite composites by a powder metallurgy method and tested the tribological properties on the surfaces of several annealed 1045 steel discs with different predisposed surface types: parallel grooves texture (PG) generated by unidirectionally grinding, random grooves texture (RG) generated by "8" shape grinding and polished surface texture (PS) generated by polishing. Based on the friction and wear behavior of Cu/graphite on different textures, they proposed a formation process of a transfer layer (Fig. 11). These three textures exhibited different ratcheting effect. The PG and RG textures produced more severe deformation on composite compared to PS texture resulted in the accumulation of large size slivers, which would break to large flakes in the following sliding process. These large flakes gradually turned to continuous transfer layers under continuous rolling and shearing during sliding, leading to lower friction coefficients. On the contrary, sliding against PS texture gave rise to the formation of small fragments which were difficult to adhere to surfaces. Therefore, continuous transfer layers could hardly appear on PS texture. Menezes's group [139] synthesized Al-16Si-5Ni-5Graphite composite to substitute steel in piston ring materials. They found that the Al-16Si-5Ni-5Graphite composite showed better tribological performance than steel under limited or boundary lubrication conditions. The superior tribological behavior is attributed to the presence of graphite in the composites acting as a solid lubricant on worn surfaces reducing friction and wear.

Recent studies on the tribological performance of carbon materials with different dimensions acting as improving lubricating properties of bulk composites are summarized in Table 3. Few studies are reported on investigating tribological properties of fullerene-reinforced bulk composites. CNTs and graphene have been widely regarded as excellent reinforcements to enhance mechanical properties of bulk matrices [19, 57]. From Table 3, one can see that CNTs and graphene are outstanding candidates to improve tribological properties of composites. Ideal dispersion and strong bonding between CNTs/graphene and matrix are known to be the two key factors determining the performance of composites [57]. Therefore, pretreatments of carbon materials such as surface functionalization and surfactant introduction can be quite helpful. New pretreatment strategies under the guidance of both experiments and computational modeling are still urgently needed to effectively address the foregoing two issues.

5 Applications of carbon solid lubricants

5.1 As lubricant coatings

Because of their prominent friction reduction and wear resistance performance, carbon solid lubricants with different dimensions have been widely employed in vast applications, such as lubrication in industrial machines [116, 144–146] and electromechanical devices [147–149], acting as lubricant coatings, additives in lubricants, or reinforcements in bulk lubricating composites. Particularly, solid lubricant coatings are often applied to reduce friction and wear in sliding motions when liquid lubricants tend to be squeezed out [7]. Moreover,

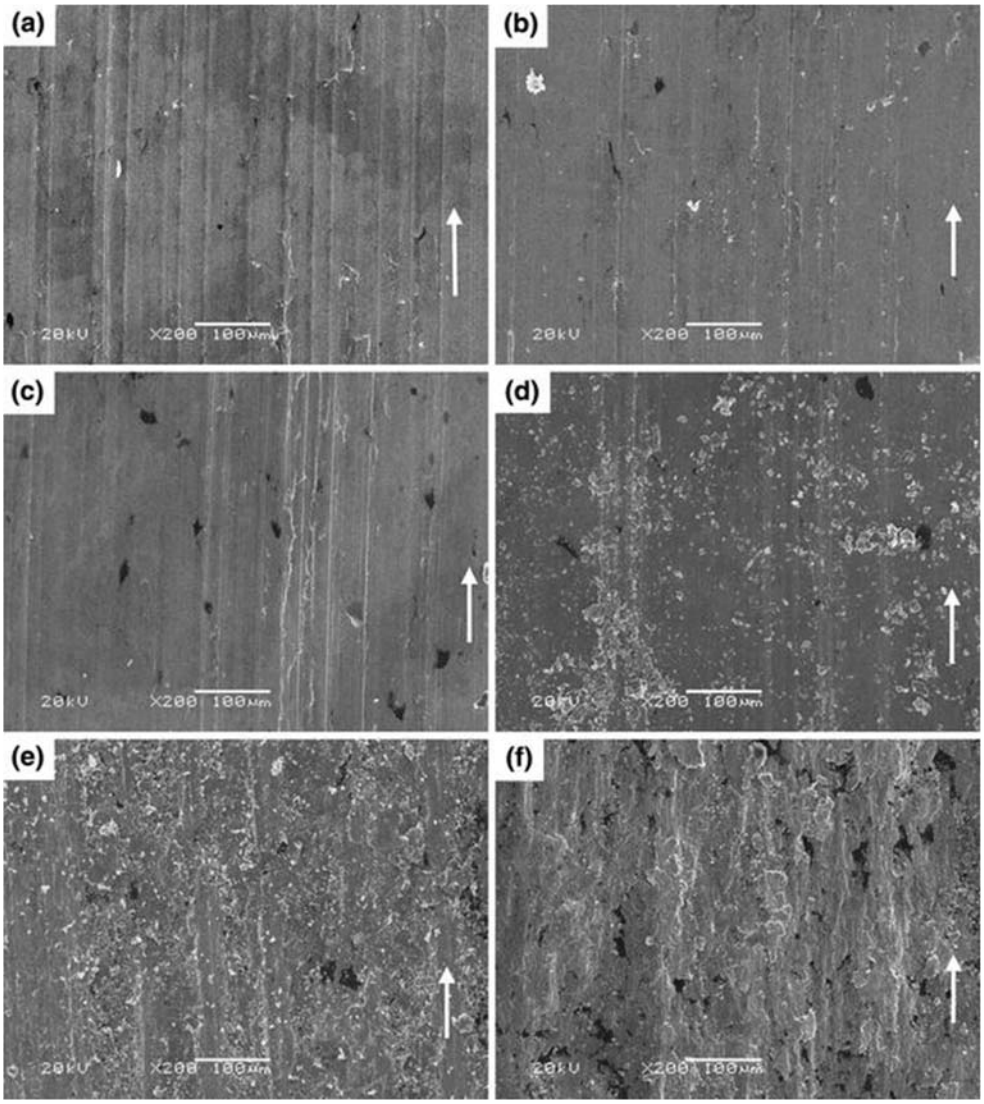

Fig. 10 SEM micrographs of worn surfaces at different speeds: (**a**) 0.001 m/s, (**b**) 0.01 m/s, (**c**) 0.1 m/s, (**d**) 0.5 m/s, (**e**) 1 m/s, (**f**) 8 m/s. Arrows are the sliding direction of the pin. Reprinted with permission from Ref. [137]

carbon coatings are better choices in extreme environments such as ultra-high or ultra-low temperatures, where liquid lubricants do not survive [7]. Wang's group [150] prepared diamond-like carbon/ionic liquid/graphene composite coatings and investigated lubricating performance towards space applications, which require excellent stability and high bearing capacity of the coatings. They conducted tribological tests under high vacuum and radiations to simulate space environment. They found that the diamond-like carbon/ionic liquid/graphene coating exhibited long-term, stable tribological properties even under strong radiations, suggesting that such a carbon-based coating could be utilized as a space lubricant. By virtue of their superior electrical conductivity and good chemical stability, carbon lubricant coatings also exhibit substantial potential in the application of electrical contacts compared to traditional metal materials (e.g., Ag), which suffer from high material loss during sliding electrical contacts [147–149].

5.2 As additives in lubricants

Carbon materials with different dimensions have been introduced into base lubricants to further improve their performance in practical applications. For instance, Yu's group added a 0D carbon material, C_{60}, into pure mineral oil to enhance lubrication in domestic refrigerator compressors [26]. They found the COP of the compressor was improved by 5.6% with the addition of C_{60}. Cornelio et al. [145] conducted rolling-sliding tests for both CNT-added oil and water. Their test results showed that CNTs acted as an excellent additive in base lubricants for applications in a wheel-rail system. Singh et al. [146] employed graphene nanoparticle as an additive in base lubricant and applied the hybrid lubricant in turning operation. By using graphene-added lubricant, the tool flank wear and nodal temperature were decreased by 12.29% and 5.79%, respectively. Bayer's group [116] found that the addition of 3D graphite particles in ethanol could form thin

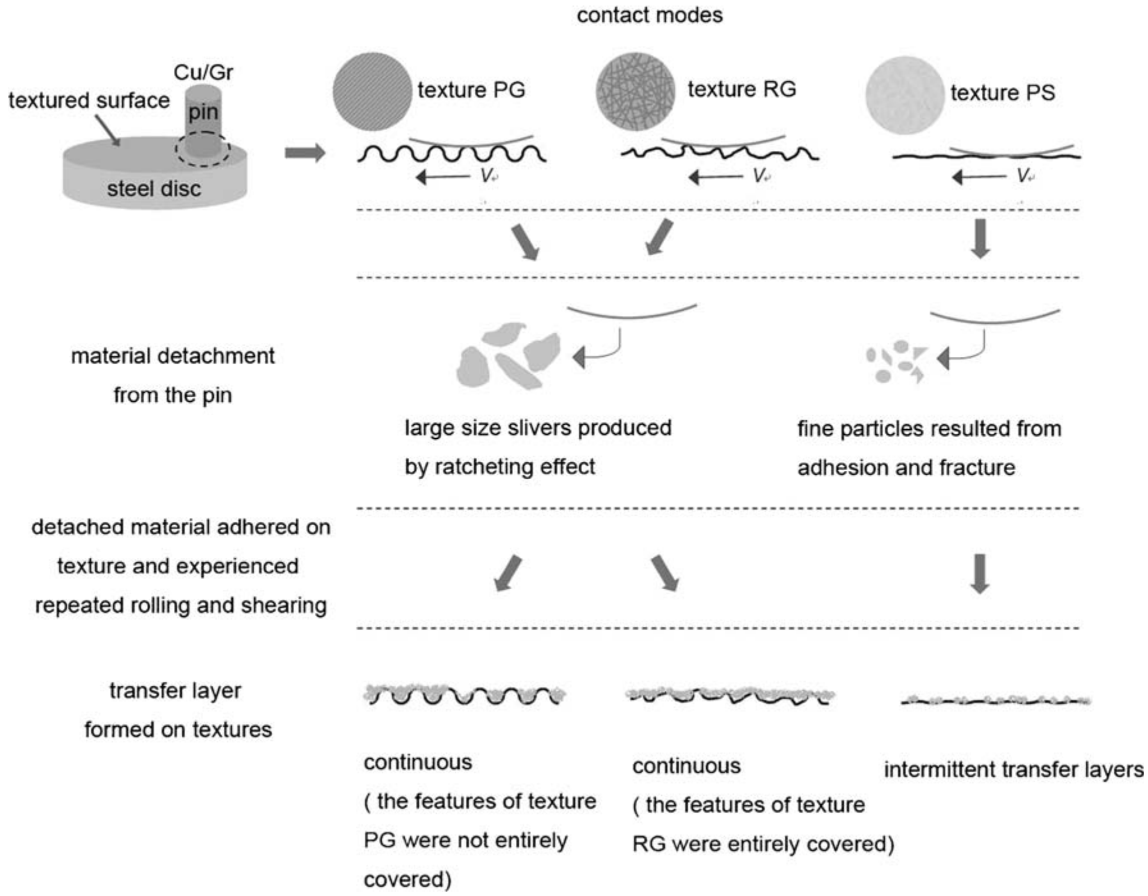

Fig. 11 Schematic of transfer layer formation. Reprinted with permission from Ref. [138]

lubricating layers at the surface of gears, causing a significant reduction in friction, which could be used to improve the efficiency of a gear pump–driven hydraulic circuit.

5.3 As reinforcements in bulk lubricating composites

Tribological contacts in practical applications such as aerospace, automotive, marine and other sectors require not only low friction and wear but also outstanding mechanical properties [151]. When acting as reinforcements in bulk lubricating composites, carbon materials can simultaneously enhance mechanical strength [57] and lubricating properties [120, 121], and therefore can meet the demanding requirements for various practical applications. For instance, Sinha's group [152] reported a self-lubricating nanocomposite towards microelectromechanical system applications. In the nanocomposite, CNTs or graphite was added as a reinforcement to improve the poor mechanical and tribological properties of SU-8 matrix. Pang et al. [144] fabricated GO-reinforced UHMWPE composites, which exhibited excellent wear and corrosion resistance under a seawater environment. The authors claimed that such composites could be suitable candidates for marine applications. In addition, along with their non-toxicity and outstanding biocompatibility, carbon materials have been considered as promising modifiers in bio-tribological systems. Recent studies have confirmed the significant improvement of both tribological and mechanical properties of the UHMWPE matrix for joint replacement by employing various carbon materials as reinforcements [153–155].

6 Summary and prospects

Because of the multifarious structures and outstanding mechanical, chemical, electrical, and thermal properties, carbon materials have been extensively studied in versatile applications. Furthermore, as one of the basic elements in human bodies, carbon is absolutely eco-friendly and nontoxic. This article reviews the lubricating performance and applications of carbon materials with different dimensions ranging from 0D to 3D, acting as lubricant coatings, additives in lubricants and reinforcements in bulk lubricating composites.

Despite the remarkable achievements in lubrication, carbon materials are still facing many open challenges: (1) more stable adhesion between coatings and substrates, thereby contributing to better friction and wear performance. For most carbon-based tribological systems, they are connected by

Table 3 Tribological performance of carbon materials as reinforcements for bulk composites

	Material	Operating condition	Friction coefficient	Reduction ratio of friction (%)	Wear rate	Reduction ratio of wear (%)	Ref.
0D	10 wt% mixed fullerene/epoxy	50 μN, 5 μm/s	0.408	26.2	–	–	[122]
1D	5 wt% MWCNTs/Al	20 N, 1.1 m/s	0.3	53.8	12.04 mg/km	78.8	[129]
	1.1 vol% CNTs/epoxy	1.2 MPa, 0.69 m/s	0.44	51.1	1×10^{-6} mm^3/N m	99.5	[126]
	0.5 wt% MWCNTs/UHMWPE	80 N, 0.13 m/s	0.18	14.3	2.5×10^{-6} mm^3/N m	87.5	[127]
	1 wt% MWCNTs/Ni	0.1 N, 1 mm/s	0.08	80.9	–	–	[140]
	10 wt% MWCNTs/Al_2O_3	14 N, 10 mm/s	0.11	80	–	–	[141]
2D	0.5 wt% GO/UHMWPE	80 N, 0.13 m/s	0.19	9.5	5×10^{-6} mm^3/N m	75	[127]
	0.3 wt% graphene/Cu	10 N, 120 rpm	0.26	65	–	–	[38]
	3.5 wt% multilayer graphene/TiAl	10 N, 0.2 m/s	0.33	40	3.3×10^{-6} mm^3/N m	89.4	[132]
	1 wt% graphene/UHMWPE	300 μN, 0.333 μm/s	0.24	68	–	77.8	[142]
	1.08 wt% graphene/poly (vinyl chloride)	30 N, 0.5 m/s	0.44	15.4	7.4×10^{-6} mm^3/N m	53.8	[143]
3D	20 vol% graphite/Cu on PS texture	10 N, 5 mm/s	0.21	–	5.5×10^{-4} mm^3/N m	–	[138]
	20 vol% graphite/Cu on RG texture	10 N, 5 mm/s	0.15	–	1.1×10^{-3} mm^3/N m	–	[138]
	20 vol% graphite/Cu on PG texture	10 N, 5 mm/s	0.15	–	1×10^{-3} mm^3/N m	–	[138]
	5 wt% graphite/5 wt% SiC/Al 2024	10 N, 1 m/s	0.144	64.6	–	56.54	[36]
	5 wt% graphite/Cu	10 N, 0.01 m/s	0.14	–	7.5×10^{-5} mm^3/N m	–	[137]

weak van der Waals forces, which deteriorate the tribological performance and lifetime of lubricating coatings. Forming stable and strong covalent bonds between coatings and substrates by introducing surface functional groups might be an efficient way to solve this issue. (2) Efforts to achieve homogeneous dispersion of carbon nanomaterials both in lubricant and bulk materials, which is essential to maximize the enhancement effect of these nanomaterials. Currently, researchers improve the dispersion of carbon lubricants in base oil or bulk matrices mainly by adding dispersants or surface functionalizations. Such methods improve the dispersibility to a certain extent while introducing impurities simultaneously, which can deteriorate the tribological performance of intrinsic carbon lubricants. Developing and optimizing reliable homogeneous dispersions without introducing impurities is always one of the most promising ways to achieve outstanding tribological properties. (3) Further understanding of friction and wear mechanisms under various conditions and environments to help better select and design appropriate lubricating systems. Although various mechanisms have been proposed to help understand the process of friction and wear reduction. However, in practical cases, such reduction is attributed to synergic effects of more than one mechanism. Figuring out how different mechanisms work together would help better elucidate lubricating behavior of carbon materials, thus providing efficient guidelines for further development of carbon lubricants such as controllable modification and functionalization. Future work addressing such challenges will tap the full potential of the excellent lubricating properties of carbon materials.

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References

1. Zhang B, Xue Y, Qiang L, Gao K, Liu Q, Yang B, Liang A, Zhang J (2017) Assembling of carbon nanotubes film responding to significant reduction wear and friction on steel surface. Appl Nanosci 7(8):835–842. https://doi.org/10.1007/s13204-017-0622-7
2. Holmberg K, Erdemir A (2017) Influence of tribology on global energy consumption, costs and emissions. Friction 5(3):263–284. https://doi.org/10.1007/s40544-017-0183-5
3. Sayfidinov K, Cezan SD, Baytekin B, Baytekin HT (2018) Minimizing friction, wear, and energy losses by eliminating contact charging. Sci Adv 4(11):eaau3808. https://doi.org/10.1126/sciadv.aau3808
4. Holmberg K, Kivikytö-Reponen P, Härkisaari P, Valtonen K, Erdemir A (2017) Global energy consumption due to friction

and wear in the mining industry. Tribol Int 115:116–139. https://doi.org/10.1016/j.triboint.2017.05.010

5. Nosonovsky M (2007) Oil as a lubricant in the ancient middle east. Tribol Online 2(2):44–49. https://doi.org/10.2474/trol.2.44
6. Reeves CJ, Menezes PL, Lovell MR, Jen T-C (2013) Tribology of solid lubricants. In: Menezes PL, Nosonovsky M, Ingole SP, Kailas SV, Lovell MR (eds) Tribology for scientists and engineers: from basics to advanced concepts. Springer New York, New York, pp 447–494. https://doi.org/10.1007/978-1-4614-1945-7_13
7. Prajapati AK, Omrani E, Menezes PL, Rohatgi PK (2018) Fundamentals of solid lubricants. In: Menezes PL, Rohatgi PK, Omrani E (eds) Self-lubricating composites. Springer, Berlin Heidelberg, pp 1–32. https://doi.org/10.1007/978-3-662-56528-5_1
8. Hsieh TH, Huang YS (2017) The mechanical properties and delamination of carbon fiber-reinforced polymer laminates modified with carbon aerogel. J Mater Sci 52(6):3520–3534. https://doi.org/10.1007/s10853-016-0646-5
9. Okoro AM, Lephuthing SS, Oke SR, Falodun OE, Awotunde MA, Olubambi PA (2019) A review of spark plasma sintering of carbon nanotubes reinforced titanium-based nanocomposites: fabrication, densification, and mechanical properties. JOM 71(2):567–584. https://doi.org/10.1007/s11837-018-3277-2
10. Gspann TS, Juckes SM, Niven JF, Johnson MB, Elliott JA, White MA, Windle AH (2017) High thermal conductivities of carbon nanotube films and micro-fibres and their dependence on morphology. Carbon 114:160–168. https://doi.org/10.1016/j.carbon.2016.12.006
11. Muley SV, Ravindra NM (2016) Thermoelectric properties of pristine and doped graphene nanosheets and graphene nanoribbons: part I. JOM 68(6):1653–1659. https://doi.org/10.1007/s11837-016-1871-8
12. Xiong G, Meng C, Reifenberger RG, Irazoqui PP, Fisher TS (2014) A review of graphene-based electrochemical microsupercapacitors. Electroanalysis 26(1):30–51. https://doi.org/10.1002/elan.201300238
13. Torres T (2017) Graphene chemistry. Chem Soc Rev 46(15):4385–4386. https://doi.org/10.1039/C7CS90061A
14. Dang VT, Nguyen DD, Cao TT, Le PH, Tran DL, Phan NM, Nguyen VC (2016) Recent trends in preparation and application of carbon nanotube–graphene hybrid thin films. Adv Nat Sci 7(3):033002. https://doi.org/10.1088/2043-6262/7/3/033002
15. Diederich F, Thilgen C (1996) Covalent fullerene chemistry. Science 271(5247):317–324. https://doi.org/10.1126/science.271.5247.317
16. Prato M (1997) [60]fullerene chemistry for materials science applications. J Mater Chem 7(7):1097–1109. https://doi.org/10.1039/A700080D
17. Novoselov KS, Geim AK, Morozov SV, Jiang D, Zhang Y, Dubonos SV, Grigorieva IV, Firsov AA (2004) Electric field effect in atomically thin carbon films. Science 306(5696):666–669. https://doi.org/10.1126/science.1102896
18. Iijima S (1991) Helical microtubules of graphitic carbon. Nature 354(6348):56–58. https://doi.org/10.1038/354056a0
19. Kasar AK, Xiong G, Menezes PL (2018) Graphene-reinforced metal and polymer matrix composites. JOM 70(6):829–836. https://doi.org/10.1007/s11837-018-2823-2
20. Xin G, Yao T, Sun H, Scott SM, Shao D, Wang G, Lian J (2015) Highly thermally conductive and mechanically strong graphene fibers. Science 349(6252):1083–1087. https://doi.org/10.1126/science.aaa6502
21. Kasar AK, Menezes PL (2018) Synthesis and recent advances in tribological applications of graphene. Int J Adv Manuf Technol 97(9):3999–4019. https://doi.org/10.1007/s00170-018-2019-5
22. Teobaldi G, Ohnishi H, Tanimura K, Shluger AL (2010) The effect of van der Waals interactions on the properties of intrinsic defects in graphite. Carbon 48(14):4145–4161. https://doi.org/10.1016/j.carbon.2010.07.029
23. Chen B, Bi Q, Yang J, Xia Y, Hao J (2008) Tribological properties of solid lubricants (graphite, h-BN) for cu-based P/M friction composites. Tribol Int 41(12):1145–1152. https://doi.org/10.1016/j.triboint.2008.02.014
24. Jiang X, Song J, Su Y, Zhang Y, Hu L (2018) Novel design of copper–graphite self-lubricating composites for reliability improvement based on 3d network structures of copper matrix. Tribol Lett 66(4):143–111. https://doi.org/10.1007/s11249-018-1098-7
25. Niu M, Qu J (2018) Tribological properties of nano-graphite as an additive in mixed oil-based titanium complex grease. RSC Adv 8(73):42133–42144. https://doi.org/10.1039/C8RA08109C
26. Xing M, Wang R, Yu J (2014) Application of fullerene C_{60} nano-oil for performance enhancement of domestic refrigerator compressors. Int J Refrig 40:398–403. https://doi.org/10.1016/j.ijrefrig.2013.12.004
27. Miura K, Ishikawa M (2010) C_{60} intercalated graphite as nanolubricants. Materials 3(9):4510–4517. https://doi.org/10.3390/ma3094510
28. Zhang X, Luster B, Church A, Muratore C, Voevodin AA, Kohli P, Aouadi S, Talapatra S (2009) Carbon nanotube−MoS_2 composites as solid lubricants. ACS Appl Mater Interfaces 1(3):735–739. https://doi.org/10.1021/am800240e
29. Kim KS, Lee HJ, Lee C, Lee SK, Jang H, Ahn JH, Kim JH, Lee HJ (2011) Chemical vapor deposition-grown graphene: the thinnest solid lubricant. ACS Nano 5(6):5107–5114. https://doi.org/10.1021/nn2011865
30. Gupta B, Kumar N, Panda K, Dash S, Tyagi AK (2016) Energy efficient reduced graphene oxide additives: mechanism of effective lubrication and antiwear properties. Sci Rep 6:18372. https://doi.org/10.1038/srep18372
31. Pu J, Mo Y, Wan S, Wang L (2014) Fabrication of novel graphene–fullerene hybrid lubricating films based on self-assembly for MEMS applications. Chem Commun 50(4):469–471. https://doi.org/10.1039/C3CC47486K
32. Song HJ, Li N (2011) Frictional behavior of oxide graphene nanosheets as water-base lubricant additive. Appl Phys A Mater Sci Process 105(4):827–832. https://doi.org/10.1007/s00339-011-6636-1
33. Berman D, Erdemir A, Sumant AV (2014) Graphene: a new emerging lubricant. Mater Today 17(1):31–42. https://doi.org/10.1016/j.mattod.2013.12.003
34. Yu B, Liu Z, Ma C, Sun J, Liu W, Zhou F (2015) Ionic liquid modified multi-walled carbon nanotubes as lubricant additive. Tribol Int 81:38–42. https://doi.org/10.1016/j.triboint.2014.07.019
35. Khun NW, Zhang H, Yang J, Liu E (2013) Mechanical and tribological properties of epoxy matrix composites modified with microencapsulated mixture of wax lubricant and multi-walled carbon nanotubes. Friction 1(4):341–349. https://doi.org/10.1007/s40544-013-0028-9
36. Ravindran P, Manisekar K, Narayanasamy R, Narayanasamy P (2013) Tribological behaviour of powder metallurgy-processed aluminium hybrid composites with the addition of graphite solid lubricant. Ceram Int 39(2):1169–1182. https://doi.org/10.1016/j.ceramint.2012.07.041
37. Ku BC, Han YC, Lee JE, Lee JK, Park SH, Hwang Y-J (2010) Tribological effects of fullerene (C_{60}) nanoparticles added in mineral lubricants according to its viscosity. Int J Precis Eng Manf 11(4):607–611. https://doi.org/10.1007/s12541-010-0070-8
38. Gao X, Yue H, Guo E, Zhang S, Yao L, Lin X, Wang B, Guan E (2018) Tribological properties of copper matrix composites reinforced with homogeneously dispersed graphene nanosheets. J

Mater Sci Technol 34(10):1925–1931. https://doi.org/10.1016/j.jmst.2018.02.010

39. Nie P, Min C, Song HJ, Chen X, Zhang Z, Zhao K (2015) Preparation and tribological properties of polyimide/carboxyl-functionalized multi-walled carbon nanotube nanocomposite films under seawater lubrication. Tribol Lett 58(1):7–12. https://doi.org/10.1007/s11249-015-0476-7
40. Zhai W, Srikanth N, Kong LB, Zhou K (2017) Carbon nanomaterials in tribology. Carbon 119:150–171. https://doi.org/10.1016/j.carbon.2017.04.027
41. Donnet C, Erdemir A (2004) Historical developments and new trends in tribological and solid lubricant coatings. Surf Coat Technol 180-181:76–84. https://doi.org/10.1016/j.surfcoat.2003.10.022
42. Renevier NM, Lobiondo N, Fox VC, Teer DG, Hampshire J (2000) Performance of MoS_2/metal composite coatings used for dry machining and other industrial applications. Surf Coat Technol 123(1):84–91. https://doi.org/10.1016/S0257-8972(99)00424-7
43. Piri-Moghadam H, Alam MN, Pawliszyn J (2017) Review of geometries and coating materials in solid phase microextraction: opportunities, limitations, and future perspectives. Anal Chim Acta 984:42–65. https://doi.org/10.1016/j.aca.2017.05.035
44. Dehghanghadikolaei A, Fotovvati B (2019) Coating techniques for functional enhancement of metal implants for bone replacement: a review. Materials 12(11):1795
45. Fotovvati B, Namdari N, Dehghanghadikolaei A (2019) On coating techniques for surface protection: a review. J Manuf Mater Process 3(1):28
46. Wang X, Xing W, Song L, Yang H, Hu Y, Yeoh GH (2012) Fabrication and characterization of graphene-reinforced waterborne polyurethane nanocomposite coatings by the sol–gel method. Surf Coat Technol 206(23):4778–4784. https://doi.org/10.1016/j.surfcoat.2012.03.077
47. Echegoyen L, Echegoyen LE (1998) Electrochemistry of fullerenes and their derivatives. Acc Chem Res 31(9):593–601. https://doi.org/10.1021/ar970138v
48. Arai S, Endo M, Kaneko N (2004) Ni-deposited multi-walled carbon nanotubes by electrodeposition. Carbon 42(3):641–644. https://doi.org/10.1016/j.carbon.2003.12.084
49. Hilder M, Winther-Jensen B, Li D, Forsyth M, MacFarlane DR (2011) Direct electro-deposition of graphene from aqueous suspensions. Phys Chem Chem Phys 13(20):9187–9193. https://doi.org/10.1039/C1CP20173E
50. Liu C, Wang K, Luo S, Tang Y, Chen L (2011) Direct electrodeposition of graphene enabling the one-step synthesis of graphene–metal nanocomposite films. Small 7(9):1203–1206. https://doi.org/10.1002/smll.201002340
51. Lüthi R, Meyer E, Haefke H, Howald L, Gutmannsbauer W, Güntherodt H-J (1994) Sled-type motion on the nanometer scale: determination of dissipation and cohesive energies of C_{60}. Science 266(5193):1979–1981. https://doi.org/10.1126/science.266.5193.1979
52. Bhushan B, Gupta BK, Van Cleef GW, Capp C, Coe JV (1993) Fullerene (C_{60}) films for solid lubrication. Tribol Trans 36(4):573–580. https://doi.org/10.1080/10402009308983197
53. Bhushan B, Gupta BK (1994) Friction and wear of ion-implanted diamondlike carbon and fullerene films for thin-film rigid disks. J Appl Phys 75(10):6156–6158. https://doi.org/10.1063/1.355440
54. Miura K, Kamiya S, Sasaki N (2003) C_{60} molecular bearings. Phys Rev Lett 90(5):055509. https://doi.org/10.1103/PhysRevLett.90.055509
55. Li X, Yang W (2007) Simulating fullerene ball bearings of ultra-low friction. Nanotechnology 18(11):115718. https://doi.org/10.1088/0957-4484/18/11/115718
56. Wang Y, Guo J, Gao K, Zhang B, Liang A, Zhang J (2014) Understanding the ultra-low friction behavior of hydrogenated fullerene-like carbon films grown with different flow rates of hydrogen gas. Carbon 77:518–524. https://doi.org/10.1016/j.carbon.2014.05.057
57. Dorri Moghadam A, Omrani E, Menezes PL, Rohatgi PK (2015) Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene – a review. Compos Part B 77:402–420. https://doi.org/10.1016/j.compositesb.2015.03.014
58. Xiong G, He P, Lyu Z, Chen T, Huang B, Chen L, Fisher TS (2018) Bioinspired leaves-on-branchlet hybrid carbon nanostructure for supercapacitors. Nat Commun 9(1):790. https://doi.org/10.1038/s41467-018-03112-3
59. Samad MA, Sinha SK (2011) Mechanical, thermal and tribological characterization of a UHMWPE film reinforced with carbon nanotubes coated on steel. Tribol Int 44(12):1932–1941. https://doi.org/10.1016/j.triboint.2011.08.001
60. Vander Wal RL, Miyoshi K, Street KW, Tomasek AJ, Peng H, Liu Y, Margrave JL, Khabashesku VN (2005) Friction properties of surface-fluorinated carbon nanotubes. Wear 259(1):738–743. https://doi.org/10.1016/j.wear.2005.02.082
61. Dickrell PL, Pal SK, Bourne GR, Muratore C, Voevodin AA, Ajayan PM, Schadler LS, Sawyer WG (2006) Tunable friction behavior of oriented carbon nanotube films. Tribol Lett 24(1):85–90. https://doi.org/10.1007/s11249-006-9162-0
62. Satyanarayana N, Rajan KSS, Sinha SK, Shen L (2007) Carbon nanotube reinforced polyimide thin-film for high wear durability. Tribol Lett 27(2):181–188. https://doi.org/10.1007/s11249-007-9219-8
63. Xu R, Bian D, Zhao Y, Xu X, Liu Y, Zhou W (2019) Tribological behavior studies of chemically bonded phosphate ceramic coatings reinforced with modified multi-walled carbon nanotubes (MWCNTs). Int J Appl Ceram Technol. https://doi.org/10.1111/ijac.13386
64. Kang K, Park H, Kim J, Lee C (2015) Role of spray processes on microstructural evolution, and physical and mechanical properties of multi-walled carbon nanotube reinforced cu composite coatings. Appl Surf Sci 356:1039–1051. https://doi.org/10.1016/j.apsusc.2015.08.158
65. Song H, Qi H, Li N, Zhang X (2011) Tribological behaviour of carbon nanotubes/polyurethane nanocomposite coatings. Micro Nano Lett 6(1):48–51. https://doi.org/10.1049/mnl.2010.0167
66. Wang HD, He PF, Ma GZ, Xu BS, Xing ZG, Chen SY, Liu Z, Wang YW (2018) Tribological behavior of plasma sprayed carbon nanotubes reinforced TiO_2 coatings. J Eur Ceram Soc 38(10):3660–3672. https://doi.org/10.1016/j.jeurceramsoc.2018.04.019
67. Geim AK, Novoselov KS (2007) The rise of graphene. Nat Mater 6:183–191. https://doi.org/10.1038/nmat1849
68. Lee C, Wei X, Kysar JW, Hone J (2008) Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science 321(5887):385–388. https://doi.org/10.1126/science.1157996
69. Suk JW, Piner RD, An J, Ruoff RS (2010) Mechanical properties of monolayer graphene oxide. ACS Nano 4(11):6557–6564. https://doi.org/10.1021/nn101781v
70. Mi Y, Wang Z, Liu X, Yang S, Wang H, Ou J, Li Z, Wang J (2012) A simple and feasible in-situ reduction route for preparation of graphene lubricant films applied to a variety of substrates. J Mater Chem 22(16):8036–8042. https://doi.org/10.1039/C2JM16656A
71. Berman D, Erdemir A, Sumant AV (2013) Few layer graphene to reduce wear and friction on sliding steel surfaces. Carbon 54:454–459. https://doi.org/10.1016/j.carbon.2012.11.061

72. Feng X, Kwon S, Park JY, Salmeron M (2013) Superlubric sliding of graphene nanoflakes on graphene. ACS Nano 7(2):1718–1724. https://doi.org/10.1021/nn305722d
73. Mishra N, Boeckl J, Motta N, Iacopi F (2016) Graphene growth on silicon carbide: a review. Phys Status Solidi A 213(9):2277–2289. https://doi.org/10.1002/pssa.201600091
74. Deokar G, Avila J, Razado-Colambo I, Codron JL, Boyaval C, Galopin E, Asensio MC, Vignaud D (2015) Towards high quality CVD graphene growth and transfer. Carbon 89:82–92. https://doi.org/10.1016/j.carbon.2015.03.017
75. Shen J, Hu Y, Li C, Qin C, Shi M, Ye M (2009) Layer-by-layer self-assembly of graphene nanoplatelets. Langmuir 25(11):6122–6128. https://doi.org/10.1021/la900126g
76. Liu LH, Zorn G, Castner DG, Solanki R, Lerner MM, Yan M (2010) A simple and scalable route to wafer-size patterned graphene. J Mater Chem 20(24):5041–5046. https://doi.org/10.1039/C0JM00509F
77. Huang Y, Yao Q, Qi Y, Cheng Y, Wang H, Li Q, Meng Y (2017) Wear evolution of monolayer graphene at the macroscale. Carbon 115:600–607. https://doi.org/10.1016/j.carbon.2017.01.056
78. Liu SW, Wang HP, Xu Q, Ma TB, Yu G, Zhang C, Geng D, Yu Z, Zhang S, Wang W, Hu YZ, Wang H, Luo J (2017) Robust microscale superlubricity under high contact pressure enabled by graphene-coated microsphere. Nat Commun 8(1):14029. https://doi.org/10.1038/ncomms14029
79. Wu P, Li X, Zhang C, Chen X, Lin S, Sun H, Lin CT, Zhu H, Luo J (2017) Self-assembled graphene film as low friction solid lubricant in macroscale contact. ACS Appl Mater Interfaces 9(25):21554–21562. https://doi.org/10.1021/acsami.7b04599
80. Algul H, Tokur M, Ozcan S, Uysal M, Cetinkaya T, Akbulut H, Alp A (2015) The effect of graphene content and sliding speed on the wear mechanism of nickel–graphene nanocomposites. Appl Surf Sci 359:340–348. https://doi.org/10.1016/j.apsusc.2015.10.139
81. Siddaiah A, Kumar P, Henderson A, Misra M, Menezes PL (2019) Surface energy and tribology of electrodeposited Ni and Ni–graphene coatings on steel. Lubricants 7(10):87. https://doi.org/10.3390/lubricants7100087
82. Nazir MH, Khan ZA, Saeed A, Siddaiah A, Menezes PL (2018) Synergistic wear-corrosion analysis and modelling of nanocomposite coatings. Tribol Int 121:30–44. https://doi.org/10.1016/j.triboint.2018.01.027
83. Liang H, Bu Y, Zhang J, Cao Z, Liang A (2013) Graphene oxide film as solid lubricant. ACS Appl Mater Interfaces 5(13):6369–6375. https://doi.org/10.1021/am401495y
84. Sandoz-Rosado EJ, Tertuliano OA, Terrell EJ (2012) An atomistic study of the abrasive wear and failure of graphene sheets when used as a solid lubricant and a comparison to diamond-like-carbon coatings. Carbon 50(11):4078–4084. https://doi.org/10.1016/j.carbon.2012.04.055
85. Bryant PJ, Gutshall PL, Taylor LH (1964) A study of mechanisms of graphite friction and wear. Wear 7(1):118–126. https://doi.org/10.1016/0043-1648(64)90083-3
86. Berman D, Erdemir A, Sumant AV (2013) Reduced wear and friction enabled by graphene layers on sliding steel surfaces in dry nitrogen. Carbon 59:167–175. https://doi.org/10.1016/j.carbon.2013.03.006
87. Chen W, Yu Y, Cheng J, Wang S, Zhu S, Liu W, Yang J (2018) Microstructure, mechanical properties and dry sliding wear behavior of cu-Al_2O_3-graphite solid-lubricating coatings deposited by low-pressure cold spraying. J Therm Spray Technol 27(8):1652–1663. https://doi.org/10.1007/s11666-018-0773-4
88. Yeldose BC, Ramamoorthy B (2008) Characterization of DC magnetron sputtered diamond-like carbon (DLC) nano coating. Int J Adv Manuf Technol 38(7):705–717. https://doi.org/10.1007/s00170-007-1131-8
89. De Barros Bouchet MI, Martin JM, Avila J, Kano M, Yoshida K, Tsuruda T, Bai S, Higuchi Y, Ozawa N, Kubo M, Asensio MC (2017) Diamond-like carbon coating under oleic acid lubrication: evidence for graphene oxide formation in superlow friction. Sci Rep 7(1):46394. https://doi.org/10.1038/srep46394
90. Liu Y, Liu J, Wang J, Banis MN, Xiao B, Lushington A, Xiao W, Li R, Sham T-K, Liang G, Sun X (2018) Formation of size-dependent and conductive phase on lithium iron phosphate during carbon coating. Nat Commun 9(1):929. https://doi.org/10.1038/s41467-018-03324-7
91. Bernard P, Alper JP, Haon C, Herlin-Boime N, Chandesris M (2019) Electrochemical analysis of silicon nanoparticle lithiation – effect of crystallinity and carbon coating quantity. J Power Sources 435:226769. https://doi.org/10.1016/j.jpowsour.2019.226769
92. Menezes PL, Reeves CJ, Lovell MR (2013) Fundamentals of lubrication. In: Menezes PL, Nosonovsky M, Ingole SP, Kailas SV, Lovell MR (eds) Tribology for scientists and engineers: from basics to advanced concepts. Springer New York, New York, pp 295–340. https://doi.org/10.1007/978-1-4614-1945-7_10
93. Ali I, Basheer AA, Kucherova A, Memetov N, Pasko T, Ovchinnikov K, Pershin V, Kuznetsov D, Galunin E, Grachev V, Tkachev A (2019) Advances in carbon nanomaterials as lubricants modifiers. J Mol Liq 279:251–266. https://doi.org/10.1016/j.molliq.2019.01.113
94. Reeves CJ, Siddaiah A, Menezes PL (2017) A review on the science and technology of natural and synthetic biolubricants. J Bio- Tribo-Corros 3(1):11–27. https://doi.org/10.1007/s40735-016-0069-5
95. Alazemi AA, Etacheri V, Dysart AD, Stacke L-E, Pol VG, Sadeghi F (2015) Ultrasmooth submicrometer carbon spheres as lubricant additives for friction and wear reduction. ACS Appl Mater Interfaces 7(9):5514–5521. https://doi.org/10.1021/acsami.5b00099
96. St.Dennis JE, Jin K, John VT, Pesika NS (2011) Carbon microspheres as ball bearings in aqueous-based lubrication. ACS Appl Mater Interfaces 3(7):2215–2218. https://doi.org/10.1021/am200581q
97. Chen CS, Chen XH, Xu LS, Yang Z, Li WH (2005) Modification of multi-walled carbon nanotubes with fatty acid and their tribological properties as lubricant additive. Carbon 43(8):1660–1666. https://doi.org/10.1016/j.carbon.2005.01.044
98. Chauveau V, Mazuyer D, Dassenoy F, Cayer-Barrioz J (2012) In situ film-forming and friction-reduction mechanisms for carbon-nanotube dispersions in lubrication. Tribol Lett 47(3):467–480. https://doi.org/10.1007/s11249-012-0006-9
99. Kałużny J, Merkisz-Guranowska A, Giersig M, Kempa K (2017) Lubricating performance of carbon nanotubes in internal combustion engines – engine test results for CNT enriched oil. Int J Automot Technol 18(6):1047–1059. https://doi.org/10.1007/s12239-017-0102-9
100. Carrión FJ, Sanes J, Bermúdez M-D, Arribas A (2011) New single-walled carbon nanotubes–ionic liquid lubricant. Application to polycarbonate–stainless steel sliding contact. Tribol Lett 41(1):199–207. https://doi.org/10.1007/s11249-010-9700-7
101. Khalil W, Mohamed A, Bayoumi M, Osman TA (2016) Tribological properties of dispersed carbon nanotubes in lubricant. Fullerenes, Nanotubes, Carbon Nanostruct 24(7):479–485. https://doi.org/10.1080/1536383X.2016.1188804
102. E-o-l E, Ahmadi H, Rashidi A, Nouralishahi A, Mohtasebi SS (2013) Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. Int Commun Heat Mass 46:142–147. https://doi.org/10.1016/j.icheatmasstransfer.2013.05.003

103. Wang B, Wang X, Lou W, Hao J (2010) Rheological and tribological properties of ionic liquid-based nanofluids containing functionalized multi-walled carbon nanotubes. J Phys Chem C 114(19):8749–8754. https://doi.org/10.1021/jp1005346
104. Reeves C, Menezes P, Lovell MR, Jen TC (2014) the effect of particulate additives on the tribological performance of bio-based and ionic liquid-based lubricants for energy conservation and sustainability. STLE Annual Meeting & Exhibition 2:834–836
105. Zhang W, Zhou M, Zhu H, Tian Y, Wang K, Wei J, Ji F, Li X, Li Z, Zhang P, Wu D (2011) Tribological properties of oleic acid-modified graphene as lubricant oil additives. J Phys D Appl Phys 44(20):205303. https://doi.org/10.1088/0022-3727/44/20/205303
106. Lin J, Wang L, Chen G (2011) Modification of graphene platelets and their tribological properties as a lubricant additive. Tribol Lett 41(1):209–215. https://doi.org/10.1007/s11249-010-9702-5
107. Mungse HP, Kumar N, Khatri OP (2015) Synthesis, dispersion and lubrication potential of basal plane functionalized alkylated graphene nanosheets. RSC Adv 5(32):25565–25571. https://doi.org/10.1039/C4RA16975A
108. Sarno M, Senatore A, Cirillo C, Petrone V, Ciambelli P (2014) Oil lubricant tribological behaviour improvement through dispersion of few layer graphene oxide. J Nanosci Nanotechnol 14(7):4960–4968. https://doi.org/10.1166/jnn.2014.8673
109. Kinoshita H, Nishina Y, Alias AA, Fujii M (2014) Tribological properties of monolayer graphene oxide sheets as water-based lubricant additives. Carbon 66:720–723. https://doi.org/10.1016/j.carbon.2013.08.045
110. Eswaraiah V, Sankaranarayanan V, Ramaprabhu S (2011) Graphene-based engine oil nanofluids for tribological applications. ACS Appl Mater Interfaces 3(11):4221–4227. https://doi.org/10.1021/am200851z
111. Gupta B, Kumar N, Panda K, Kanan V, Joshi S, Visoly-Fisher I (2017) Role of oxygen functional groups in reduced graphene oxide for lubrication. Sci Rep 7:45030. https://doi.org/10.1038/srep45030
112. Omrani E, Menezes PL, Rohatgi PK (2019) Effect of micro- and nano-sized carbonous solid lubricants as oil additives in nanofluid on tribological properties. Lubricants 7(3):25. https://doi.org/10.3390/lubricants7030025
113. Siddaiah A, Kasar AK, Manoj A, Menezes PL (2019) Influence of environmental friendly multiphase lubricants on the friction and transfer layer formation during sliding against textured surfaces. J Clean Prod 209:1245–1251. https://doi.org/10.1016/j.jclepro.2018.10.322
114. Su Y, Gong L, Chen D (2015) An investigation on tribological properties and lubrication mechanism of graphite nanoparticles as vegetable based oil additive. J Nanomater 2015:7. https://doi.org/10.1155/2015/276753
115. Lee CG, Hwang YJ, Choi YM, Lee JK, Choi C, Oh JM (2009) A study on the tribological characteristics of graphite nano lubricants. Int J Precis Eng Manuf 10(1):85–90. https://doi.org/10.1007/s12541-009-0013-4
116. Martorana P, Bayer IS, Steele A, Loth E (2010) Effect of graphite and carbon nanofiber additives on the performance efficiency of a gear pump driven hydraulic circuit using ethanol. Ind Eng Chem Res 49(22):11363–11368. https://doi.org/10.1021/ie100872g
117. Ginzburg BM, Shibaev LA, Kireenko OF, Shepelevskii AA, Baidakova MV, Sitnikova AA (2002) Antiwear effect of fullerene C_{60} additives to lubricating oils. Russ J Appl Chem 75(8):1330–1335. https://doi.org/10.1023/A:1020929515246
118. Lee J, Cho S, Hwang Y, Lee C, Kim SH (2007) Enhancement of lubrication properties of nano-oil by controlling the amount of fullerene nanoparticle additives. Tribol Lett 28(2):203–208. https://doi.org/10.1007/s11249-007-9265-2
119. Lee K, Hwang Y, Cheong S, Kwon L, Kim S, Lee J (2009) Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. Curr Appl Phys 9(2, supplement): e128–e131. https://doi.org/10.1016/j.cap.2008.12.054
120. Omrani E, Rohatgi P, Menezes P (2017) Tribology and applications of self-lubricating materials. https://doi.org/10.1201/9781315154077
121. de Mello JDB, Binder C, Probst SMH, Klein AN (2018) In situ generated turbostratic 2D graphite: a new way to obtain high-performance self-lubricating iron-based composites. In: Menezes PL, Rohatgi PK, Omrani E (eds) Self-lubricating composites. Springer, Berlin Heidelberg, pp 181–230. https://doi.org/10.1007/978-3-662-56528-5_7
122. Wang H, Feng J, Hu X, Ng KM (2008) Tribological behaviors of aligned carbon nanotube/fullerene-epoxy nanocomposites. Polym Eng Sci 48(8):1467–1475. https://doi.org/10.1002/pen.21068
123. Yoshimoto S, Amano J, Miura K (2010) Synthesis of a fullerene/expanded graphite composite and its lubricating properties. J Mater Sci 45(7):1955–1962. https://doi.org/10.1007/s10853-009-4187-z
124. Miura K, Tsuda D, Itamura N, Sasaki N (2007) Superlubricity of fullerene intercalated graphite composite. Jpn J Appl Phys 46(8A):5269–5274. https://doi.org/10.1143/jjap.46.5269
125. Arai S, Fujimori A, Murai M, Endo M (2008) Excellent solid lubrication of electrodeposited nickel-multiwalled carbon nanotube composite films. Mater Lett 62(20):3545–3548. https://doi.org/10.1016/j.matlet.2008.03.047
126. Yan L, Wang H, Wang C, Sun L, Liu D, Zhu Y (2013) Friction and wear properties of aligned carbon nanotubes reinforced epoxy composites under water lubricated condition. Wear 308(1):105–112. https://doi.org/10.1016/j.wear.2013.10.007
127. Golchin A, Wikner A, Emami N (2016) An investigation into tribological behaviour of multi-walled carbon nanotube/graphene oxide reinforced UHMWPE in water lubricated contacts. Tribol Int 95:156–161. https://doi.org/10.1016/j.triboint.2015.11.023
128. Puchy V, Hvizdos P, Dusza J, Kovac F, Inam F, Reece MJ (2013) Wear resistance of Al_2O_3–CNT ceramic nanocomposites at room and high temperatures. Ceram Int 39(5):5821–5826. https://doi.org/10.1016/j.ceramint.2012.12.100
129. Bastwros MMH, Esawi AMK, Wifi A (2013) Friction and wear behavior of Al–CNT composites. Wear 307(1):164–173. https://doi.org/10.1016/j.wear.2013.08.021
130. Hwang J, Yoon T, Jin SH, Lee J, Kim TS, Hong SH, Jeon S (2013) Enhanced mechanical properties of graphene/copper nanocomposites using a molecular-level mixing process. Adv Mater 25(46):6724–6729. https://doi.org/10.1002/adma.201302495
131. Wang J, Li Z, Fan G, Pan H, Chen Z, Zhang D (2012) Reinforcement with graphene nanosheets in aluminum matrix composites. Scr Mater 66(8):594–597. https://doi.org/10.1016/j.scriptamat.2012.01.012
132. Xu Z, Shi X, Zhai W, Yao J, Song S, Zhang Q (2014) Preparation and tribological properties of TiAl matrix composites reinforced by multilayer graphene. Carbon 67:168–177. https://doi.org/10.1016/j.carbon.2013.09.077
133. Tabandeh-Khorshid M, Omrani E, Menezes PL, Rohatgi PK (2016) Tribological performance of self-lubricating aluminum matrix nanocomposites: role of graphene nanoplatelets. Eng Sci Technol Int J 19(1):463–469. https://doi.org/10.1016/j.jestch.2015.09.005
134. Menezes PL, Rohatgi PK, Lovell MR (2012) Self-lubricating behavior of graphite reinforced metal matrix composites. In: Nosonovsky M, Bhushan B (eds) Green tribology: Biomimetics, Energy Conservation and Sustainability. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 445–480. https://doi.org/10.1007/978-3-642-23681-5_17

135. Menezes PL, Reeves CJ, Rohatgi PK, Lovell MR (2013) Self-lubricating behavior of graphite-reinforced composites. In: Menezes PL, Nosonovsky M, Ingole SP, Kailas SV, Lovell MR (eds) Tribology for scientists and engineers: from basics to advanced concepts. Springer New York, New York, pp 341–389. https://doi.org/10.1007/978-1-4614-1945-7_11
136. Omrani E, Moghadam AD, Menezes PL, Rohatgi PK (2016) Influences of graphite reinforcement on the tribological properties of self-lubricating aluminum matrix composites for green tribology, sustainability, and energy efficiency—a review. Int J Adv Manuf Technol 83(1):325–346. https://doi.org/10.1007/s00170-015-7528-x
137. Ma W, Lu J (2011) Effect of sliding speed on surface modification and tribological behavior of copper–graphite composite. Tribol Lett 41(2):363–370. https://doi.org/10.1007/s11249-010-9718-x
138. Ma W, Lu J (2011) Effect of surface texture on transfer layer formation and tribological behaviour of copper–graphite composite. Wear 270(3):218–229. https://doi.org/10.1016/j.wear.2010.10.062
139. Omrani E, Moghadam AD, Algazzar M, Menezes PL, Rohatgi PK (2016) Effect of graphite particles on improving tribological properties Al-16Si-5Ni-5Graphite self-lubricating composite under fully flooded and starved lubrication conditions for transportation applications. Int J Adv Manuf Technol 87(1):929–939. https://doi.org/10.1007/s00170-016-8531-6
140. Suárez S, Rosenkranz A, Gachot C, Mücklich F (2014) Enhanced tribological properties of MWCNT/Ni bulk composites – influence of processing on friction and wear behaviour. Carbon 66: 164–171. https://doi.org/10.1016/j.carbon.2013.08.054
141. Ahmad I, Kennedy A, Zhu YQ (2010) Wear resistant properties of multi-walled carbon nanotubes reinforced Al2O3 nanocomposites. Wear 269(1):71–78. https://doi.org/10.1016/j.wear.2010.03.009
142. Lahiri D, Hec F, Thiesse M, Durygin A, Zhang C, Agarwal A (2014) Nanotribological behavior of graphene nanoplatelet reinforced ultra high molecular weight polyethylene composites. Tribol Int 70:165–169. https://doi.org/10.1016/j.triboint.2013.10.012
143. Wang H, Xie G, Zhu Z, Ying Z, Zeng Y (2014) Enhanced tribological performance of the multi-layer graphene filled poly(vinyl chloride) composites. Compos A: Appl Sci Manuf 67:268–273. https://doi.org/10.1016/j.compositesa.2014.09.011
144. Pang W, Ni Z, Wu J, Zhao Y (2018) Investigation of tribological properties of graphene oxide reinforced ultrahigh molecular weight polyethylene under artificial seawater lubricating condition. Appl Surf Sci 434:273–282. https://doi.org/10.1016/j.apsusc.2017.10.115
145. Cornelio JAC, Cuervo PA, Hoyos-Palacio LM, Lara-Romero J, Toro A (2016) Tribological properties of carbon nanotubes as lubricant additive in oil and water for a wheel–rail system. J Mater Res Technol 5(1):68–76. https://doi.org/10.1016/j.jmrt.2015.10.006
146. Sharma AK, Tiwari AK, Dixit AR, Singh RK, Singh M (2018) Novel uses of alumina/graphene hybrid nanoparticle additives for improved tribological properties of lubricant in turning operation. Tribol Int 119:99–111. https://doi.org/10.1016/j.triboint.2017.10.036
147. Xie G, Forslund M, Pan J (2014) Direct electrochemical synthesis of reduced graphene oxide (rGO)/copper composite films and their electrical/electroactive properties. ACS Appl Mater Interfaces 6(10):7444–7455. https://doi.org/10.1021/am500768g
148. Jang I, Joo HG, Jang YH (2016) Effects of carbon nanotubes on electrical contact resistance of a conductive Velcro system under low frequency vibration. Tribol Int 104:45–56. https://doi.org/10.1016/j.triboint.2016.08.019
149. Mao F, Wiklund U, Andersson AM, Jansson U (2015) Graphene as a lubricant on Ag for electrical contact applications. J Mater Sci 50(19):6518–6525. https://doi.org/10.1007/s10853-015-9212-9
150. Liu X, Pu J, Wang L, Xue Q (2013) Novel DLC/ionic liquid/graphene nanocomposite coatings towards high-vacuum related space applications. J Mater Chem A 1(11):3797–3809. https://doi.org/10.1039/C3TA00764B
151. Zhang Y, Chromik RR (2018) Tribology of self-lubricating metal matrix composites. In: Menezes PL, Rohatgi PK, Omrani E (eds) Self-lubricating composites. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 33–73. https://doi.org/10.1007/978-3-662-56528-5_2
152. Saravanan P, Satyanarayana N, Sinha SK (2013) Self-lubricating SU-8 nanocomposites for microelectromechanical systems applications. Tribol Lett 49(1):169–178. https://doi.org/10.1007/s11249-012-0055-0
153. Li J, Zeng X, Ren T, Van der Heide E (2014) The preparation of graphene oxide and its derivatives and their application in bio-tribological systems. Lubricants 2(3):137–161. https://doi.org/10.3390/lubricants2030137
154. Yousef S, Visco A, Galtieri G, Nocita D, Espro C (2017) Wear behaviour of UHMWPE reinforced by carbon nanofiller and paraffin oil for joint replacement. Mater Sci Eng C 73:234–244. https://doi.org/10.1016/j.msec.2016.11.088
155. Meng Y, Ye L, Coates P, Twigg P (2018) In situ cross-linking of poly(vinyl alcohol)/graphene oxide–polyethylene glycol nanocomposite hydrogels as artificial cartilage replacement: intercalation structure, unconfined compressive behavior, and biotribological behaviors. J Phys Chem C 122(5):3157–3167. https://doi.org/10.1021/acs.jpcc.7b12465