Chapter 11
Self-Lubricating Behavior of Graphite-Reinforced Composites

Pradeep L. Menezes, Carlton J. Reeves, Pradeep K. Rohatgi, and Michael R. Lovell

Abstract Lubricants are extensively used between contacting surfaces to reduce friction and wear. Typically, liquid lubricants are used to achieve low friction and wear. However, these lubricants are not effective in elevated temperature applications or vacuum environments. For these reasons, solid lubricants are utilized to meet these operational needs, where liquid lubrication is impractical. Solid lubricants are only effective as long as they are present in the tribo-interface. Therefore, it is desirable to provide a constant supply of solid lubricant material to the contacting surface. This is often achieved by incorporating solid lubricants as a second phase in the base material. These composite materials have the ability to achieve low friction and wear at the contact surfaces without any external supply of lubrication during sliding. Metal matrix composites reinforced with lamellar solid lubricant particles such as graphite are being used as self-lubricating materials for various engineering applications. In this chapter, the tribological behavior of metal and ceramic matrix composites reinforced with graphite particles has been reviewed. More specifically, copper–graphite, nickel–graphite, magnesium–graphite, silver–graphite, aluminum–graphite, silicon nitride–graphite, and alumina–graphite composites are studied. The influence of various environmental and mechanical parameters on the friction coefficient and wear rate is discussed. It was found that the amount of graphite released on the worn surface forms a thin transfer film on the contact surfaces. This transfer film reduces the overall friction

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coefficient and wear rate. The presence of the graphite-based transfer film increases the seizure resistance and enables the contacting surfaces to run under boundary lubrication without galling. The formation and retention of this transfer film on the sliding surface as well as its composition, area fraction, thickness, and hardness are important factors in controlling the friction and wear behavior of the material. The effectiveness of the transfer film also depends on the nature of the sliding surface, the test condition, environment, and the graphite content in the composite.

1 Introduction

A lubricant is a substance used to facilitate relative motion of solid bodies by minimizing friction and wear between contacting surfaces. A lubricant functions by introducing a layer of material between the contacting surfaces with a lower shear strength than the surfaces themselves [1]. In lubricated systems, a lubricant may either completely or partially prevent asperity contact, thus reducing the strength of the junctions formed [2]. In general, there are three categories of lubricants: liquid, solid, and gaseous.

Nearly all lubricants used in the automotive and manufacturing sectors are oil or grease based. These oils include engine oils, transmission fluids, hydraulic fluids, and gear oils. These products are not typically environmentally friendly or biodegradable and can introduce significant quantities of pollutants into the waste stream [3]. Thus, disposal of these large volumes of material obviously represents an environmental burden. Hence, it is very important to develop either green lubricants or composite materials, which have self-lubrication properties. Moreover, industrial applications are becoming more advanced with elevated temperatures or vacuum environments that are moving beyond the tolerable domain of liquid lubricants rendering liquid lubricants impractical. For these reasons, solid lubricants are utilized to meet the various extreme operational requirements of many advanced applications, where liquid lubricants are ineffective. Solid lubricants are most effective when they are continuously present in the tribo-interface; therefore, it is desirable to provide a constant supply of solid lubricant material at the contacting surface. This is often achieved by incorporating solid lubricants as a second phase material within the matrix material to create a composite.

1.1 Composite Materials

Composite materials are a special class of materials and are made from two or more constituent components with significantly different physical or chemical properties, which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. In the case of two constituent components, the material with the highest volume fraction is considered as the matrix, whereas the other is the reinforcement material that modifies the properties of the matrix. In metal matrix composites, the matrix is made of a metal and the reinforcement may be a different metal or another material, such as a ceramic or organic compound. Similarly, in ceramic matrix composites, the matrix is composed of silicon nitride, alumina, or another type of ceramic material and the reinforcement may be a different ceramic, metallic, or solid lubricant compound. When a composite has two or more second phase reinforcing materials, then it is called a hybrid composite. Composites are synthesized by dispersing a reinforcing material into a matrix. Sometimes, the reinforcement materials are coated to prevent a chemical reaction with the matrix. The matrix is the monolithic material into which the reinforcement is embedded and is completely continuous. The reinforcement material is embedded into the matrix usually in the form of particles, fibers, whiskers, or wires. The most common structurally reinforcing materials are alumina and silicon carbide, and the most common lubricating reinforcing materials are graphite and molybdenum disulfide. The reinforcement can be either continuous or discontinuous. Discontinuous matrix composites can be isotropic. The reinforcement does not always serve a purely structural task, but it is used to change physical properties such as friction coefficient, wear, or thermal conductivity. Metal and ceramic matrix composites have been used in the aerospace, aircraft, and automotive industries because they possess many potential advantages over monolithic materials, including higher specific strength and stiffness, higher wear resistance, higher thermal conductivity, and lower coefficient of thermal expansion.

1.2 Solid Lubricants

When lamellar solid lubricants such as graphite (C), molybdenum disulfide (MoS_2), boric acid (H_3BO_3), and hexagonal boron nitride (hBN) are introduced at the sliding interface, these often cause the friction and wear values to decrease. Lamellar solid lubricants are important because they have a layered structure [4]. The layers consist of flat sheets of atoms or molecules, and the structure is called a layer-lattice structure. The atoms are strongly bonded within the sheets by covalent bonds and are weakly bonded between the layers by van der Waals bonds. The importance of lamellar solid lubricants is their ability to shear more easily parallel to the layers than across them. They can therefore support relatively heavy loads at right angles to the layers while still being able to slide easily parallel to the layers in the direction of the relative motion. This property is effectively taken advantage of during the lubrication process. It is also important that the solid lubricant should adhere strongly to the contacting surface, otherwise it would be easily rubbed away which results in a short service life. Graphite, which consists of carbon atoms arranged in a layer-like structure, displays a low coefficient of friction ranging from 0.1 to 0.2 while sliding on a clean surface. With friction coefficients so low, this suggests that graphite can be used as a solid lubricant. It is reported that graphite is an effective lubricant additive for its anticorrosion, high-temperature endurance, and self-lubricating properties derived from its lamellar structure [5]. The slippage between lamellar endows the graphite excellent lubricating properties under heavy loads [6].

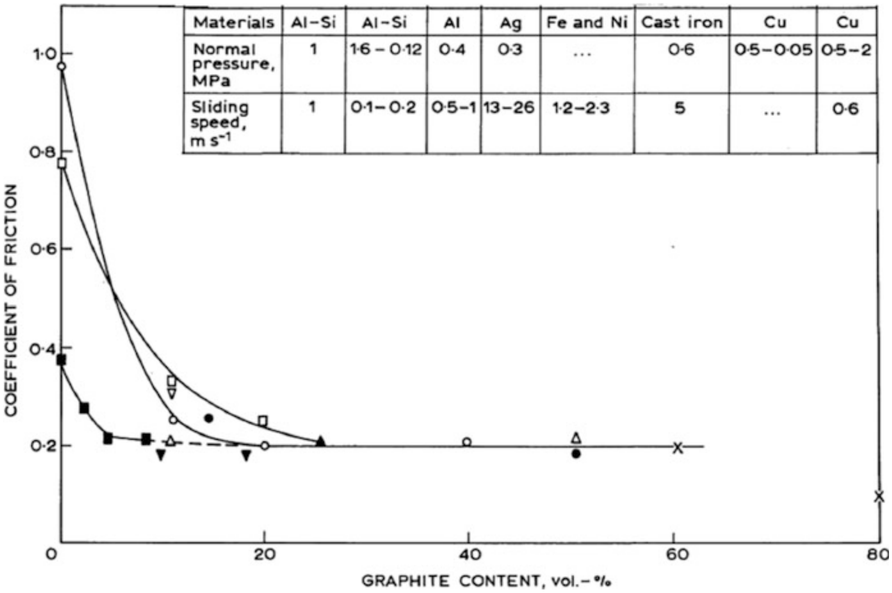
One of the major issues in using solid lubricants is maintaining a continuous supply of lubricant between two sliding surfaces. A continuous supply of lubricant is more easily maintained in the case of fluid lubricants when compared to solid lubricants. An interesting innovation to ensure a supply of solid lubricant between sliding surfaces is to incorporate the solid lubricant into the matrix of one of the sliding components by forming a matrix composite. Thus, self-lubricating matrix composites are materials in which solid lubricants such as graphite or MoS_2 are introduced as reinforcing materials into the matrix during preparation that enable the self-lubricating properties.

During sliding contact, wear particles are often produced at the interface. Sometimes these wear particles act as a third body abrasive component causing the friction and wear rates to increase with sliding distance. For this reason, lubricants are generally used to reduce the friction coefficient and wear rate. Solid lubricants have been studied in the literature as a means to lubricate metals as solid films that are adsorbed, bonded, or deposited on the contacting surfaces [7–15]. Often solid lubricants are utilized as thin films on metallic substrates by burnishing [7, 8], sputtering [11, 12], or plasma spraying [13, 14]. Although, solid lubricant films can reduce the friction coefficient and the wear rate, they are only effective as long as they are present on the surface. Therefore, it is desirable to provide a constant supply of solid lubricant material in the tribo-contact. This is often achieved by incorporating solid lubricants as a second phase in the base material. Self-lubricating composites have a unique advantage in that the wear particles formed at the interface are comprised of the solid lubricant material initially used as the reinforcement material, which helps in decreasing the friction coefficient and wear rate. Under sliding conditions the composite becomes self-lubricating. Here, the solid lubricant embedded in the metal matrix transfers to the contacting surfaces and forms a thin film solid lubricant which prevents direct contact between the mating surfaces. Thus, friction and wear are reduced and this process eliminates the use of an external lubricant supply. The success of a matrix impregnated with lamellar solid particles relies on the ability of the solid particles to emerge from their embedded state in the matrix and spread evenly in the form of a solid lubricating film over the tribological surface to provide lubrication.

1.3 Self-Lubrication

A matrix composite impregnated with a solid lubricant combines the properties of strength, hardness, and abrasion resistance of the matrix alloy with the natural lubricity of the solid lubricant. The matrix alloy may also be chosen to impart good electrical and thermal conductivity to the composite. Much of the early work on metal matrix composites utilized graphite particles using powder metallurgy, which is expensive and limited in the sizes that can be produced. Rohatgi et al. [16–19] first introduced graphite as a solid lubricant in aluminum matrices through casting routes, by mixing the molten alloy with graphite particles to make a uniform suspension that was then underwent a casting process. In many instances, the graphite is rejected by the liquid aluminum encountered in the casting due to the density differences and poor wettability between the metal matrix and the reinforcement material. These problems have been solved to a large extent at the laboratory scale by the use of metal coatings such as Ni and Cu on the particle of graphite and by the addition of reactive elements (e.g., Mg and Ti) to the melt. This work was subsequently extended to other solid lubricant dispersions but aluminum–graphite composite by far has the most potential for commercial applications. Cast aluminum–graphite composites for antifriction applications were initially developed in 1966. The cast aluminum–graphite composites have a unique structure, in which graphite particles are in the inter-dendrite regions. These composites have been reported to have superior tribological properties when compared with similar composites prepared by powder metallurgy techniques. These composites have been cast into tribological components using sand casting, pressure die casting, gravity die casting, and centrifugal casting. The particulate composites of graphite and a matrix alloy are characterized by (a) the composition and microstructure of the matrix alloy; (b) the size, volume fraction, and distribution of graphite particles; and (c) the nature of the interface between the matrix and the dispersed graphite. In addition, the composites may have defects such as voids and porosity, which, unless accounted for, will result in an erroneous estimate of area of contact and thereby influence friction and wear. Furthermore, the strength of the composite will reduce with increased porosity content, thus increasing the wear rate.

In composites, the reinforced solid lubricants enhance the tribological properties of the composite through the formation of a solid lubricant thin film on the tribo-surface [20, 21]. This lubricating film is formed as a result of shearing solid particles impregnated in the sliding surface of the composite. The solid particle-enriched lubricant film helps to reduce the magnitude of shear stress transferred to the material underneath the contact area, alleviate the plastic deformation in the subsurface region, minimize metal-to-metal contact, and act as a solid lubricant between two sliding surfaces. Therefore, it helps to reduce friction and wear and improve seizure resistance of the composite. The formation and retention of this tribo-layer on the sliding surface as well as its composition, area fraction, thickness, and hardness are important factors in controlling the wear behavior of the material and depend on the nature of the sliding surface, the test condition, environment, and solid particle content in the composite. The formation of the lubricating layer at the sliding surface becomes thicker with the addition of more solid particles to the base alloy. It is this lubricating layer that is responsible for playing an effective role for keeping the friction and wear behavior of the composite low. The formation of the solid lubricating film also depends on the matrix characteristics, for example, the deformability of matrix helps in the transfer of solid particles from the matrix to the tribo-surface. Additionally, the formation of the solid lubricating film also depends on the adhesion of the solid particle film to the matrix and the presence of



Materials	Al–Si	Al–Si	Al	Ag	Fe and Ni	Cast iron	Cu	Cu
Normal pressure, MPa	1	1·6 – 0·12	0·4	0·3	...	0·6	0·5–0·05	0·5–2
Sliding speed, m s^{-1}	1	0·1–0·2	0·5–1	13–26	1·2–2·3	5	...	0·6

Fig. 11.1 Variation of coefficient of friction with graphite content for composites with different base alloys [21]

an environment, which permits the solid particles to spread in the form of a thin film thus acting as a lubricant. Earlier works have also identified that by increasing the solid particle content, the lubricating film formed on the tribo-surface lowers the wear rate [20, 21]. Several researchers [22, 23] have also observed the solid lubricating film formed on the wearing surface and reported that a solid lubricant particularly graphite particles in the composite helps in reducing the friction coefficient and increasing the anti-seizing quality, thus improving the tribological behavior of the base alloy.

In self-lubricating composites, solid particles such as graphite and MoS_2 are embedded in the matrix. Here, the formation of a thin film will occur by transferring the solid particles from the matrix to the tribo-surface during initial periods of sliding. The observed friction and wear behavior will, therefore, have two distinct stages: (a) transient state, while the thin solid lubricant film is being established, and (b) steady state, when a stable solid lubricant film (in the dynamical sense of being continuously replenished, i.e., “self-lubricating,” to make up for the wear loss) has formed. The variation of the coefficient of friction with graphite content for composites with different base alloys (aluminum, silver, iron, nickel, and copper) is shown in Fig. 11.1 [21]. The tests were carried out with different loads and sliding velocities. All the composites, with the exception of the silver matrix, were tested against a steel counter-surface, for the conditions indicated in the figure. It can be seen that when the graphite content in the composites exceeds 20 vol.%, the friction coefficients observed in different composites are virtually independent of the metal matrix and the graphite content and appear to attain a constant value of close to 0.2.

The elemental graphite has a friction coefficient of 0.18, and this increases with the desorption of adsorbed vapors. Thus, it appears that both the mating surfaces, including the graphitic composite and the counter-surfaces like steel, become completely smeared with graphite, and a friction coefficient close to that of pure graphite against itself is observed, regardless of the matrix.

In this chapter, the self-lubricating behavior of various graphite-reinforced metal matrix and ceramic matrix composites are reviewed. More specifically, metal matrix composites in the form of copper–graphite, nickel–graphite, magnesium–graphite, silver–graphite, and aluminum–graphite as well as ceramic–graphite composites in the form of silicon nitride–graphite and alumina–graphite composites are examined along with their tribological properties.

2 Self-Lubricating Behavior of Metal Matrix Composites

2.1 Introduction

Self-lubricating metal matrix composites have been extensively used in antifriction applications where liquid lubricants are impractical. The composites illustrate the mechanism of solid lubrication by graphite. In this section, selected examples of various metal–graphite composites are analyzed for their industrial potential and current application. The influence of the metal matrix alloy composition; graphite content, shape, and size; and test variables such as contact pressure, sliding velocity, temperature, current density, counterpart materials, and environment on the tribological behavior of the composites is discussed. The process of graphite-rich film formation on the tribo-surfaces of metal–graphite composites is analyzed. The superior tribological properties of graphite-reinforced composites are strongly dependent on the formation of a graphite-rich film. The friction and wear rate in the composites are significantly reduced due to the incorporation of graphite particles when compared to similar composites without graphite reinforcement.

2.2 Self-Lubricating Behavior of Copper–Graphite Composites

Metal matrix composites have a variety of uses and practical applications. Copper metal matrix composites, for example, are being investigated for their use in electromechanical applications. Copper, which is well known for its high thermal and electrical conductivity, is currently used in metal matrix composites reinforced with graphite particles for its use in electrical sliding contact applications such as brushes in electric motors and generators [24–31]. In welding machines, low voltage, high current densities, and sliding of critical components necessitate materials

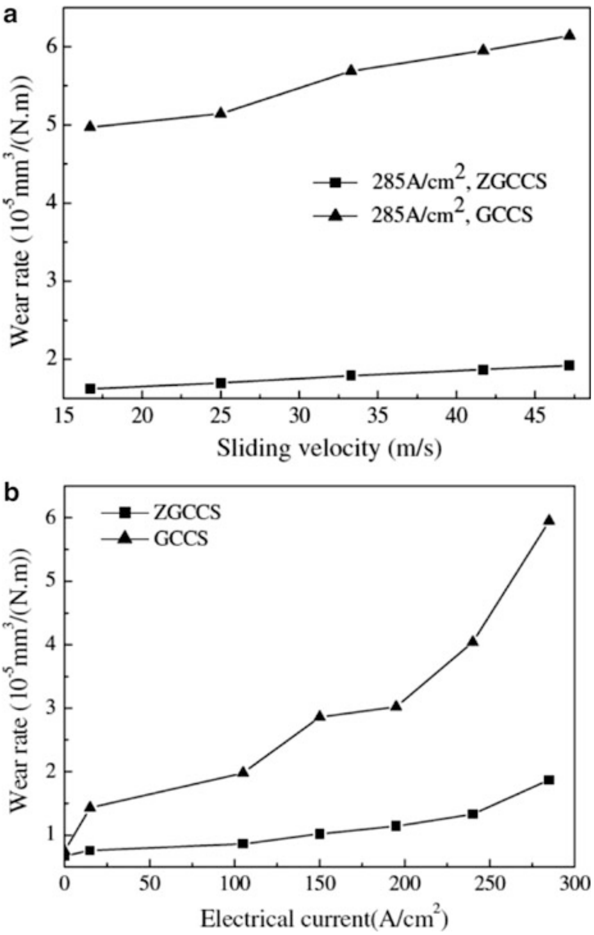


Fig. 11.2 The variation of wear rate with (**a**) sliding velocity and (**b**) electrical current [32]

with a very high specific electrical conductivity, good thermal conductivity, and low friction coefficient. Copper–graphite composite materials are some of the few materials that can fulfill such conditions. Copper–graphite composites combine the properties of copper (i.e., excellent thermal and electrical conductivities) and graphite (i.e., superior lubricity and a low thermal expansion coefficient).

Considerable efforts have been made to study the tribological performance of copper–graphite composites. Tu et al. [32] studied the tribological behavior of a zinc-coated graphite–copper contact strip (ZGCCS) and a graphite–copper contact strip (GCCS) which were both derived from a graphite–copper matrix composite with self-lubricating properties. Figure 11.2 shows the variation of wear rate with sliding velocity and electrical current. It was observed that the wear rate of both the ZGCCS and the GCCS increased with the increment of the current density and the sliding velocity. However, the ZGCCS exhibited wear resistance superior to the GCCS, indicating the positive effect that the electroplating of zinc had on the graphite.

The zinc electroplating played an important role in improving the wear resistance and the wear rate of ZGCCS. In Fig. 11.2, it can be seen that the wear rate of the ZGCCS was only one-third of the GCCS at a sliding velocity of 41.7 m/s and with a current density of 285 A/cm^2. During the investigation of the graphite–copper contact strips, arc erosion wear, oxidative wear, and adhesive wear were the dominant mechanisms during the electrical sliding process. The arc erosion of the graphite–copper composite contact strip was reduced by the electroplating of zinc on graphite since the zinc-coated graphite particles were homogeneously distributed in the copper matrix. Kováčik et al. [33] investigated the effect of graphite composition on the friction coefficient of copper–graphite composites in the range of 0–50 vol.% of graphite at constant load. The study was specifically done to determine the critical graphite content above which the coefficient of friction of the composite remains almost composition independent and constant. Hence, an uncoated copper–graphite composite in the composition range of 0–50 vol.% of graphite and coated composites with 30 and 50 vol.% of graphite were prepared, and their tribological properties were measured. Figure 11.3 shows the composition dependence of the coefficient of friction for an (a) uncoated and (b) coated copper–graphite composite. It was found that with increasing concentration of graphite, the coefficient of friction of coated and uncoated composites at first decreased until a certain critical concentration threshold of graphite was reached. Then, the coefficient of friction of the composite becomes independent of the composition and corresponds to the dynamic coefficient of friction of used graphite material (0.15–0.16 for used graphite). In regard to the wear rate, it was seen to decrease continuously without stabilizing with an increasing concentration of graphite. The results were also compared with work done by Moustafa et al. [27] on copper–graphite composites as shown in Fig. 11.3.

Efforts have also been made to study the friction and wear performance of copper–graphite composites against different counterpart materials. Ma et al. [34] investigated tribological behaviors of copper–graphite composites sliding against different counterparts, specified as 2024 aluminum alloy, AZ91D magnesium alloy, and Ti6Al4V titanium alloy. Figure 11.4 shows the variation of friction coefficient and wear rate with sliding speed. It was found that the tribological performance of copper–graphite composite was strongly dependent on its counterpart materials. Copper–graphite composite could provide friction reduction in sliding against 2024 and Ti6Al4V. The copper–graphite composite was revealed to be an excellent self-lubricating material in sliding against AZ91D at low speeds. The authors described that the transfer layer of the copper–graphite composite on the counterface is the key to friction reduction. The wear mechanism of the copper–graphite composite was related to the transfer (from copper–graphite composite to counterpart alloys) and counter-transfer (from counterpart alloys to copper–graphite composite).

Studies were also made to investigate the influence of various self-lubricating particles on tribological behavior of copper–matrix composites. Chen et al. [35] studied the tribological properties of two solid lubricants, graphite and hexagonal boron nitride (hBN) dispersed within copper-based friction composites. Copper-based friction composites containing graphite at weight fractions in the range of 0 %, 2 %, 5 %, 8 %, and 10 %, corresponding to the hexagonal boron nitride at

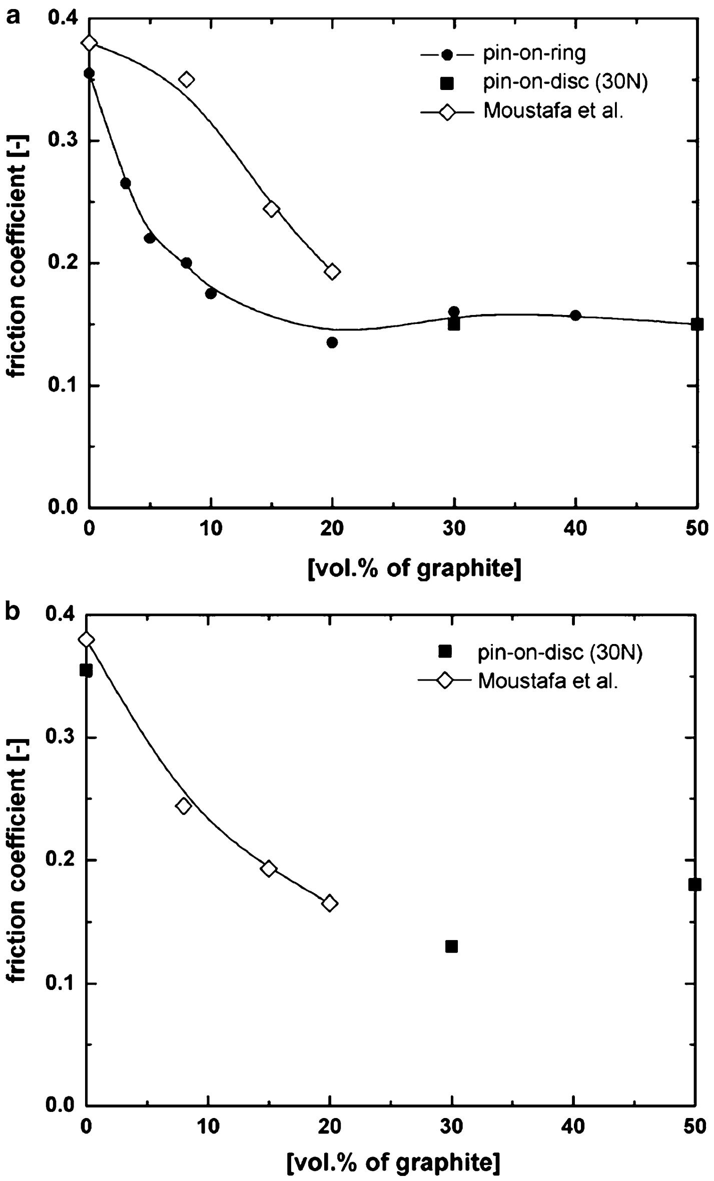


Fig. 11.3 Composition dependence of friction coefficient of (**a**) uncoated and (**b**) coated copper–graphite composites [33]

weight fractions in the range of 10 %, 8 %, 5 %, 2 %, and 0 %, were fabricated by a powder metallurgy hot press method, respectively. Figure 11.5 shows the variation of coefficient of friction and wear rates for different normal loads. The results indicate that the lubrication effects of graphite are superior to those of hBN. It was

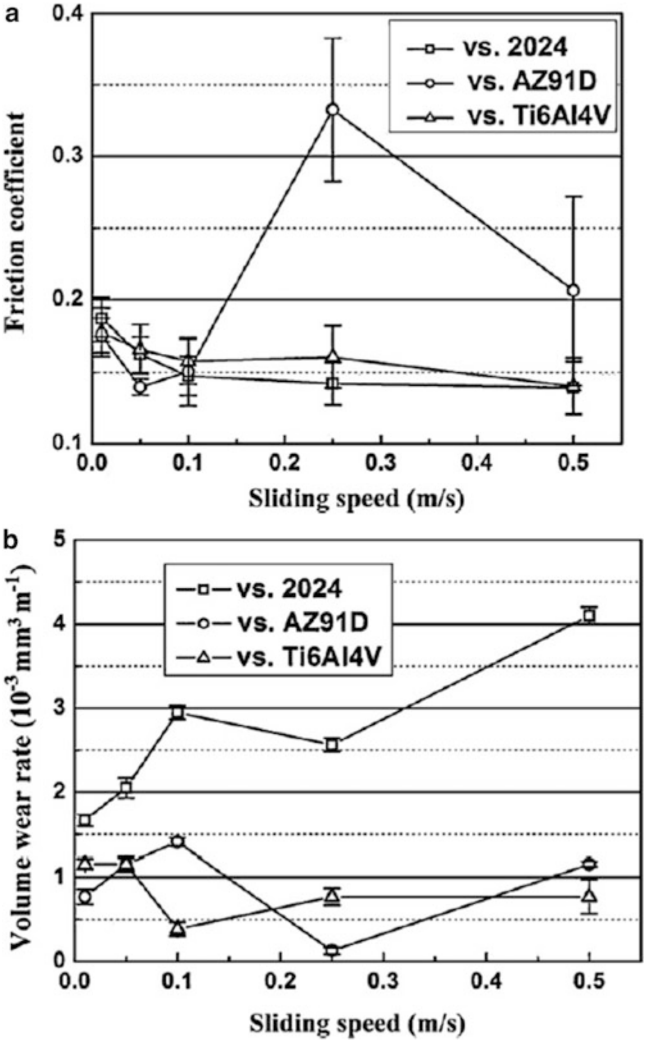


Fig. 11.4 (**a**) Friction coefficients and (**b**) wear rates of copper–graphite composite sliding against 2024 aluminum alloy, AZ91D, and Ti6Al4V [34]

also revealed that the wear rates and friction coefficients decreased with an increase in graphite content.

Different heat treatments were used to improve the tribological properties of copper–graphite composites. Rajkumar and Aravindan [36] studied friction and wear properties of microwave-heat-treated copper–5 wt% graphite composites and untreated copper–graphite composites. Figure 11.6 shows the variation of the coefficient of friction and the wear rates of untreated and microwave-heat-treated copper–graphite composites. It was found that the microwave-heat-treated

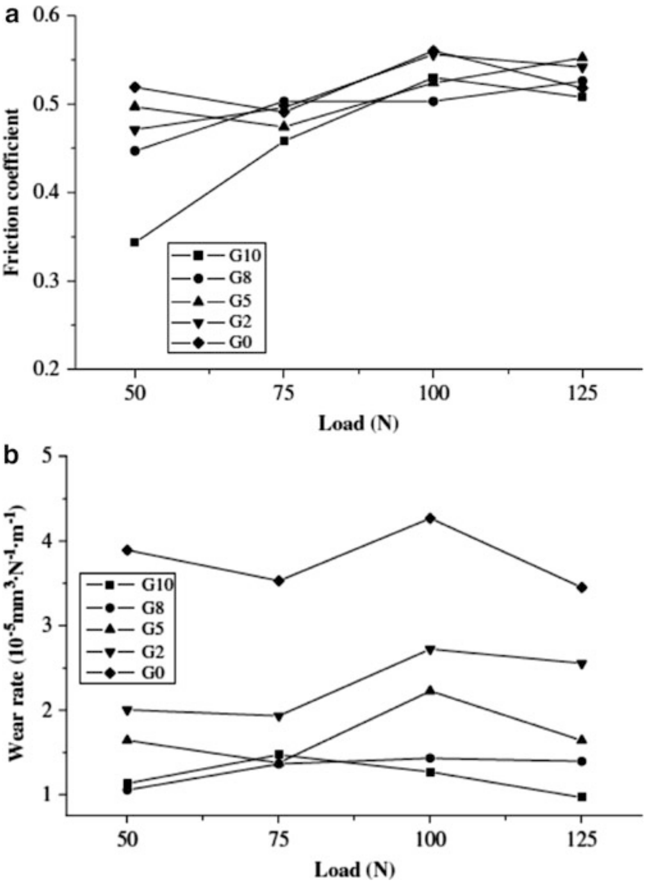


Fig. 11.5 Variation of (**a**) friction coefficient and (**b**) wear rates with loads for various copper-based composites [35]

composites exhibited a reduced coefficient of friction and specific wear rate when compared to the untreated ones. The untreated copper–graphite composites exhibited the highest coefficient of friction and specific wear rate due to weaker interface contact. Microwave-heat treating reduces the coefficient of friction and specific wear rate by facilitating the formation of a stable graphite layer at the contact region of the tribo-surface. Moreover, Rajkumar and Aravindan [37] studied the tribological performance of microwave-sintered copper–graphite hybrid composites reinforced with TiC. Figure 11.7 shows the variation of the coefficient of friction and wear rate of the hybrid composites with normal load. The coefficient of friction and wear rate of the copper–TiC–graphite hybrid composites and unreinforced copper material increased with an increase in the normal load. The coefficient of friction and the wear rate of the hybrid composites are lower than those of unreinforced copper. The wear rate of hybrid composites is reduced with an

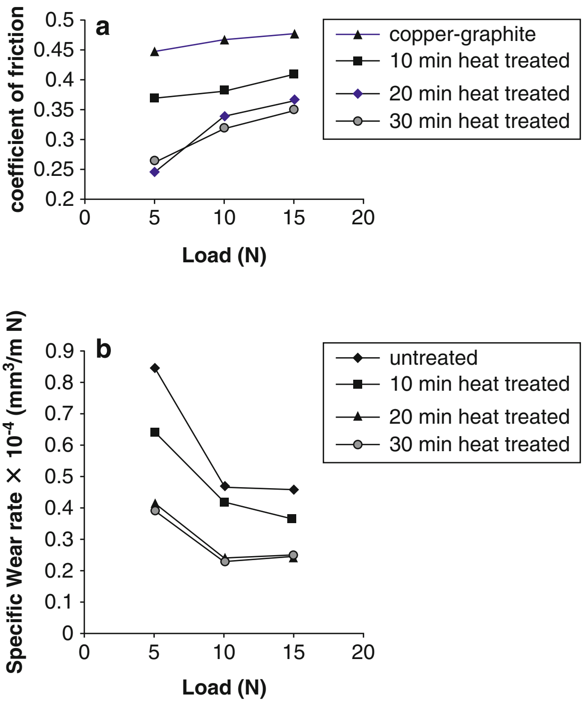


Fig. 11.6 Variation of (**a**) coefficient of friction and (**b**) wear rates of untreated and microwave-treated copper–graphite composites [36]

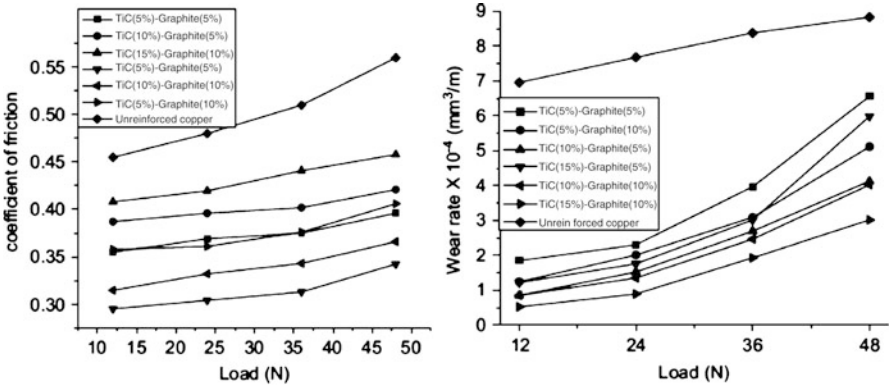


Fig. 11.7 Variation of friction coefficient and wear rate of hybrid composite with normal load [37]

increase in both the percentage of TiC and graphite, due to the cooperative effect offered by both reinforcement materials. An increased content of the TiC reinforcement for a given volume fraction of graphite leads to a higher coefficient of friction. The coefficient of friction of the hybrid composites decreases with an increase in the percentage of graphite reinforcement. The presence of a mixed layer particularly in higher content graphite hybrid composites was found to influence the tribological properties. Increasing sliding velocity increased the coefficient of friction and wear rate of the hybrid composites. The wear mechanism involved in the copper–TiC–graphite hybrid composites for a given volume fraction of graphite and 5 % TiC was oxidative wear with plastic deformation. The wear mechanism occurring in the hybrid composites with 15 % TiC and the 5 % graphite hybrid composites were oxidative wear with high strained delamination. The wear mechanism involved in the 15 % TiC and 10 % graphite composite was oxidative wear with delamination. In another study, Ramesh et al. [38] analyzed the tribological performance of novel cast copper–SiC–graphite hybrid composites. The coefficient of friction of hybrid composites was higher than that of copper, and the wear rates of the hybrid composites were lower when compared to copper. These results revealed that an increased content of hard reinforcement material (SiC) for a given volume fraction of soft reinforcement material (graphite) in a metal matrix composite leads to a higher coefficient of friction and lower wear rate of the composite.

The influence of sliding speed on the tribological performance of copper–graphite composites was studied by Ma and Lu [39] to establish the effect of sliding speed on surface modification and tribological behavior of a copper–graphite composite. Figure 11.8 shows the variation of the coefficient of friction and wear rates for different sliding speeds. The results showed that the friction coefficient and wear rate of copper–graphite composites were largely dependent on sliding speed. When the speed exceeds the critical value, a transition of the friction and wear regime occurred. The formation of a lubricant layer on the contact surface is regarded as an important characteristic for enhanced tribological performance of copper–graphite composites. Due to a large strain gradient in the subsurface deformation zone, the graphite-rich lubricant layer can easily form on the sliding surface when the speed is lower than the critical value. At speeds exceeding the critical value, the formation of the lubricant layer is difficult due to the effects of delamination wear caused by the high strain rate. At speeds less than the critical value, the wear mechanism occurring tends to be mild wear caused by ratcheting, and at speeds exceeding the critical value, the wear mechanism is more severe induced by delamination wear. Ma and Lu [40] also studied the effect of surface texture on the transfer layer formation and tribological behavior of copper–graphite composites. Three kinds of texture were prepared on the surface of steel discs: parallel grooves (PG), random grooves (RG), and polished surfaces (PS). The influence of surface texture on the friction and wear behavior of copper–graphite composites was investigated under both low and high load conditions at a fixed speed. It was found that the textures had different ratcheting effects on the contact surface of the copper–graphite composite and thus influenced the friction and wear behaviors as shown in the Fig. 11.9.

Efforts have also been made to study the tribological performance of copper–graphite composites at high temperatures. Zhan and Zhang [41] studied the effect of graphite particles in a copper hybrid composite sliding against steel at high temperatures. Dry sliding wear properties of copper matrix composites

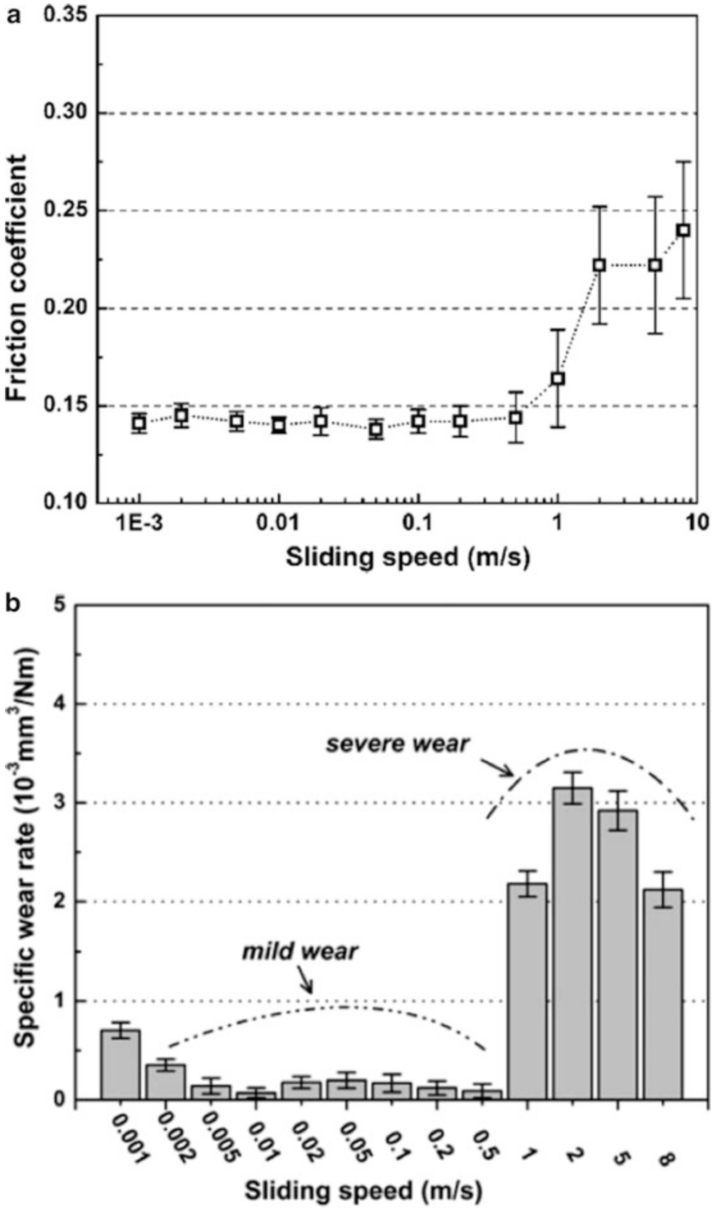


Fig. 11.8 Variation of (**a**) average friction coefficient and (**b**) wear rate of copper–graphite composites at different sliding speeds [39]

reinforced with SiC and graphite particles were tested at elevated temperatures ranging between 373 and 723 K. Figure 11.10 shows the variation of the coefficient of friction and wear rate for the two composites. It was found that the addition of graphite particles simultaneously decreased the wear rates of the composite and

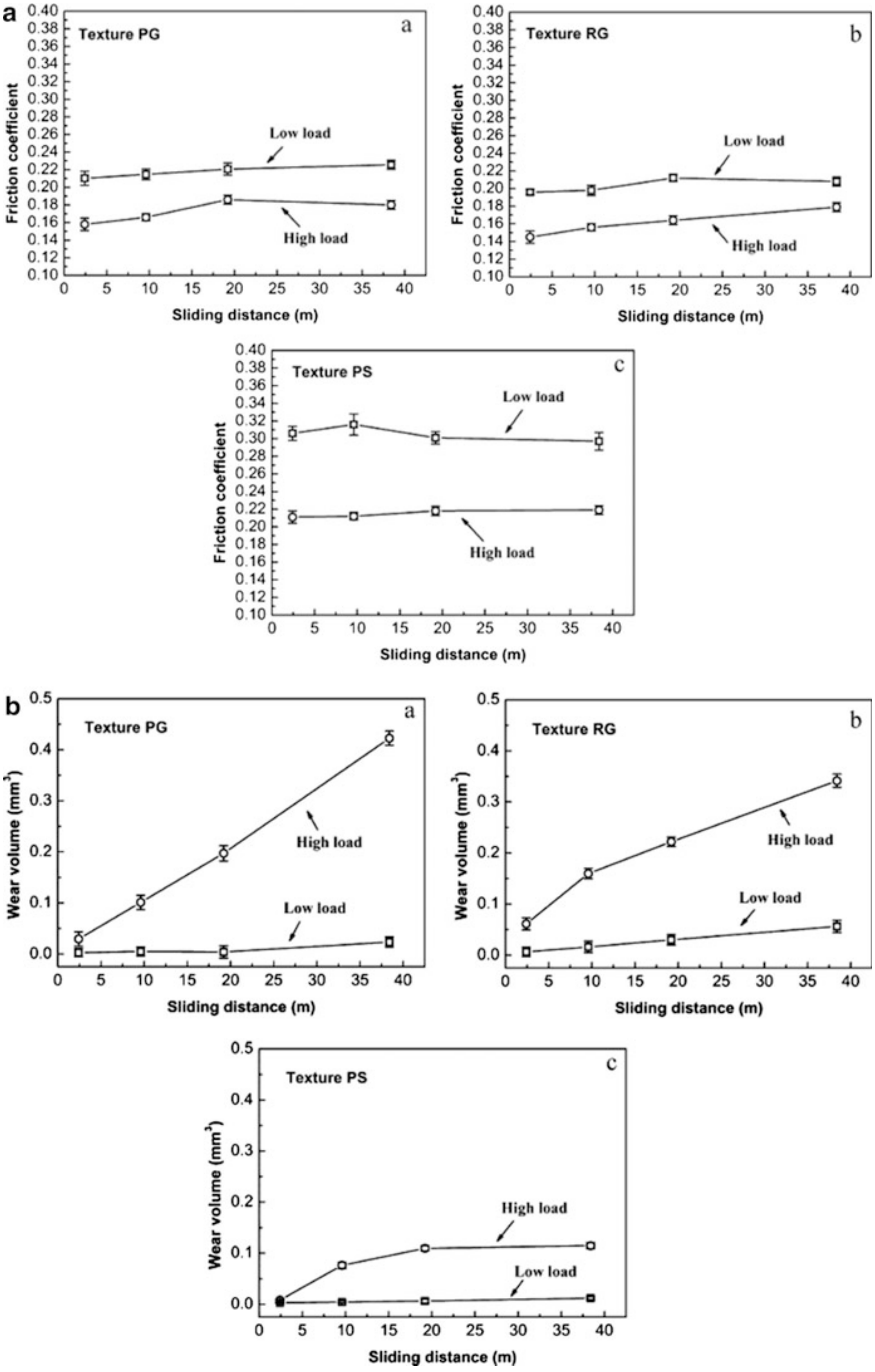
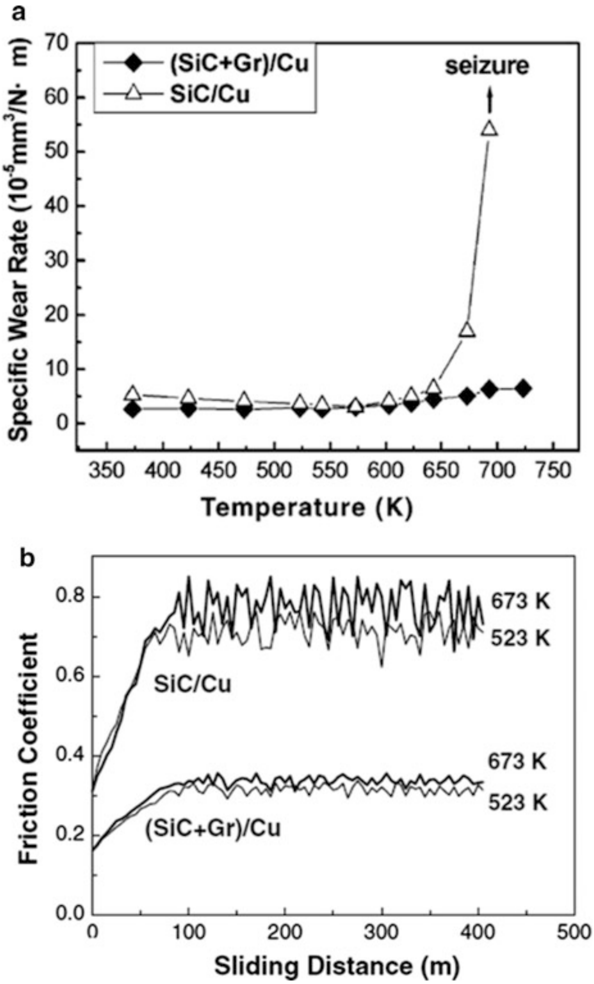


Fig. 11.9 Variation of average friction coefficient and wear rates with sliding distance for the pin sliding against various surface textures [40]

Fig. 11.10 (**a**) Variation of specific wear rate with temperature (**b**) variation of friction coefficient with sliding distance for various temperatures [41]



effectively avoided the occurrence of severe wear up to 723 K. The coefficient of friction of copper hybrid composites was more stable and lower than that of the SiC–copper composite. It was concluded that the graphite particles were an effective reinforcement material for copper matrix composites when subjected to high-temperature sliding wear conditions.

Various novel composites were developed to enhance self-lubricating properties of copper-based metal matrix composites for specific applications. Chen et al. [42] developed new composites with 1 and 2 wt% graphite for the use in frictional bearings under high speed and low-load sliding conditions. New copper-based self-lubricating composites with 1 and 2 wt% graphite were prepared using atomized Cu–10Ni–3Sn–3Pb (wt%) powder as the matrix alloy with 0.5 wt% Y_2O_3 as the matrix. Figure 11.11 shows the variation of friction and wear rate. It was found that

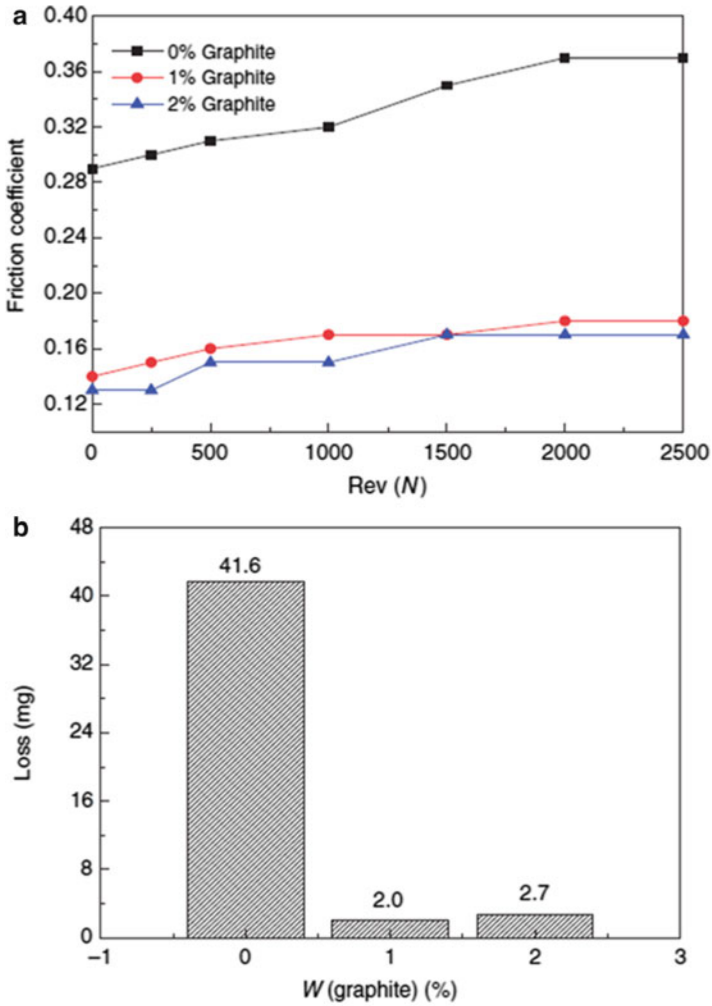


Fig. 11.11 (**a**) Friction coefficient and (**b**) wear loss of the composites with different graphite contents [42]

the composite with 1 wt% of graphite demonstrated improved mechanical and frictional properties, while the composite with a 2 wt% of graphite possessed better self-lubricating properties.

In another application of copper-based metal matrix composites, Ma et al. [43] studied the sliding wear behavior of copper–graphite composite material using a specially designed sliding wear apparatus. Here, the apparatus simulated the tribological conditions of sliding current collectors in a magnetic levitation (maglev) transportation system. The material was slid against a stainless steel band under unlubricated conditions. The investigation revealed that the wear loss increased

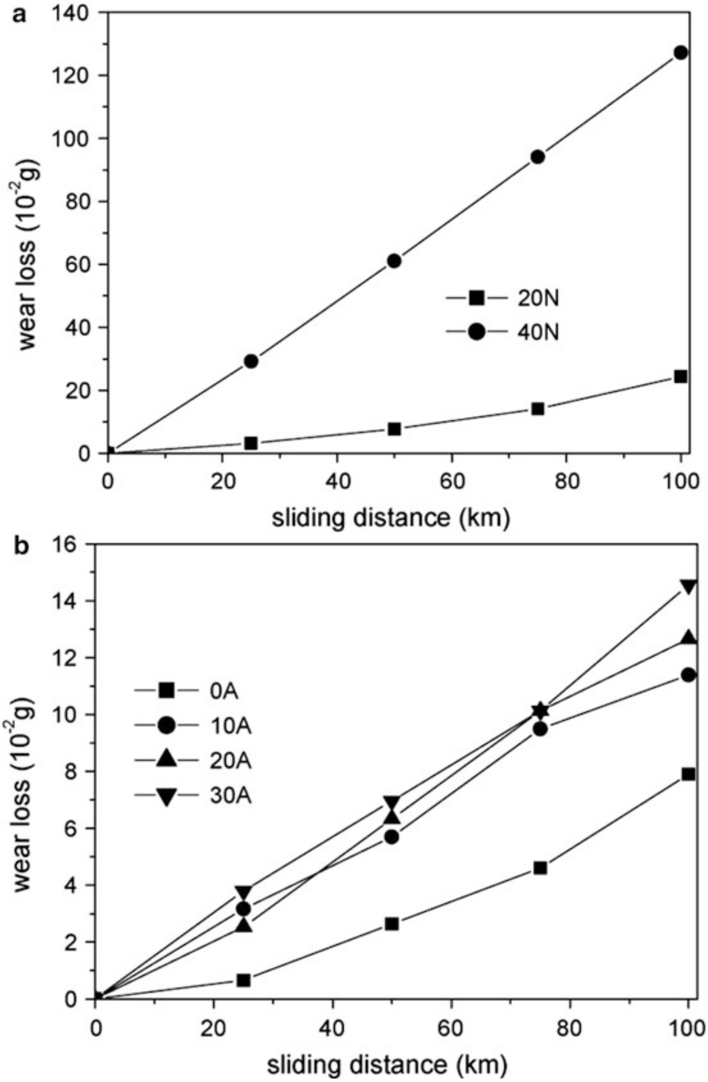


Fig. 11.12 Variation of wear loss with sliding distance as function of (**a**) normal load (**b**) current [43]

with the increasing normal pressure and electrical current. More specifically, at a sliding speed of 50 km/h and a cumulative sliding distance of 100 km without electrical current, the wear loss under a stress of 40 N is about five times to that with 20 N as shown in Fig. 11.12a. The wear loss almost doubled under electrical current, compared to the case without electrical current at an applied stress of 20 N and a sliding speed of 25 km/h as illustrated in Fig. 11.12b. Adhesive wear, abrasive wear, and electrical erosion wear are the dominant wear mechanisms during the electrical sliding wear processes. The authors concluded that the results provide insight into understanding the governing principles that can add value to the design of sliding counterparts in the current collection device in magnetic levitation systems.

Copper–graphite composites have found use in various other applications such as in plane bearings for trucks, cranes, bulldozers, and automobiles; drive shafts and roller bearings for stoker chain feeds in boiler furnaces; screw conveyors; roller conveyors; spherical bushings for automotive transmissions; sliders for electric cars; overhead railways for dams and flood gates; slide bushings for discharge valves in hydraulic turbines; and electrical contacts and brushes. The complexity of each application of copper-based composites warrants unique and useful reinforcement materials that aid in achieving varying degrees of friction and wear necessary for system operation. As described these reinforcement materials can range from graphite particles dispersed in the metal matrix composite to zinc-coated graphite, hBN, TiC, and SiC.

2.3 *Self-Lubricating Behavior of Nickel–Graphite Composites*

Nickel–graphite composites are widely used in high-efficiency engines due to their excellent high-temperature performance. Considerable efforts have been made to study the effect of various operating parameters on the tribological behavior of nickel–graphite composites. Li and Xiong [44] studied the tribological performance of graphite-containing nickel-based composite as functions of temperature, load, speed, and counterface material. Figure 11.13 shows the variation of friction coefficients and wear rates for different graphite content, load, speed, and counterpart materials. It was observed that the friction and wear properties are significantly improved by adding graphite in a nickel-based alloy. The optimum addition of graphite is 6–12 wt% of the nickel-based alloy. The coefficient of friction of the nickel–graphite composite decreased with an increase of load and sliding speed. It was also revealed that the wear rates of the nickel–graphite composites increased with an increase of temperature and sliding speed. The lower friction coefficients and wear rates were obtained when the composites rubbed against nickel-based alloy containing molybdenum disulfide when compared to alumina and silicon nitride counterpart materials. Further, Li and Xiong [45] studied the tribological properties of nickel-based composites at various temperature conditions. More specifically nickel-based self-lubricating composites consisting of nickel (Ni), chromium (Cr), tungsten (W), and iron (Fe) with graphite and molybdenum disulfide as solid lubricant reinforcement materials were prepared. It was found that chromium sulfide and tungsten carbide were formed in the composite by adding molybdenum disulfide and graphite, which were responsible for low friction and

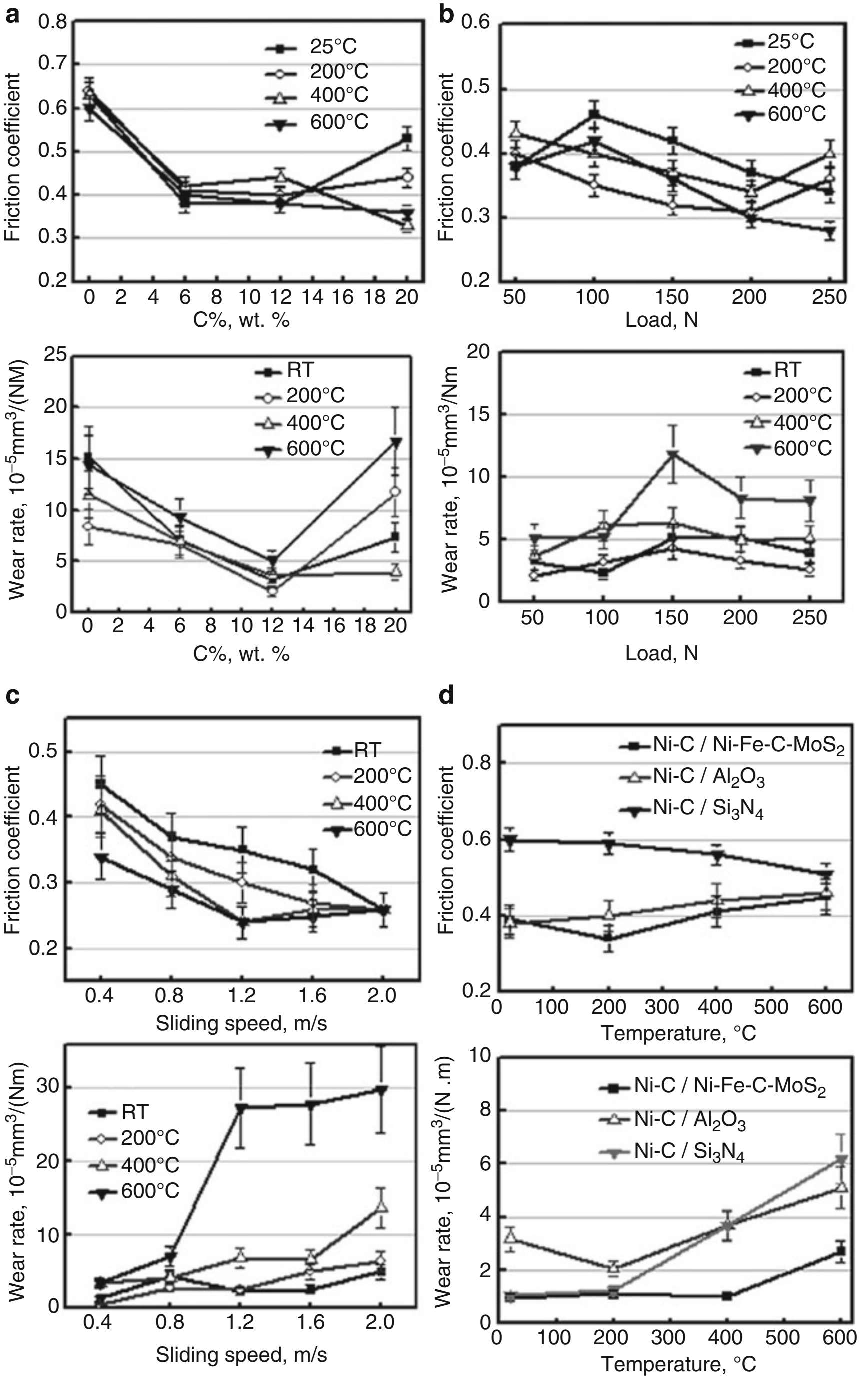


Fig. 11.13 Variation of friction coefficients and wear rates for different (**a**) graphite content, (**b**) load, (**c**) speed, and (**d**) counterpart materials [44]

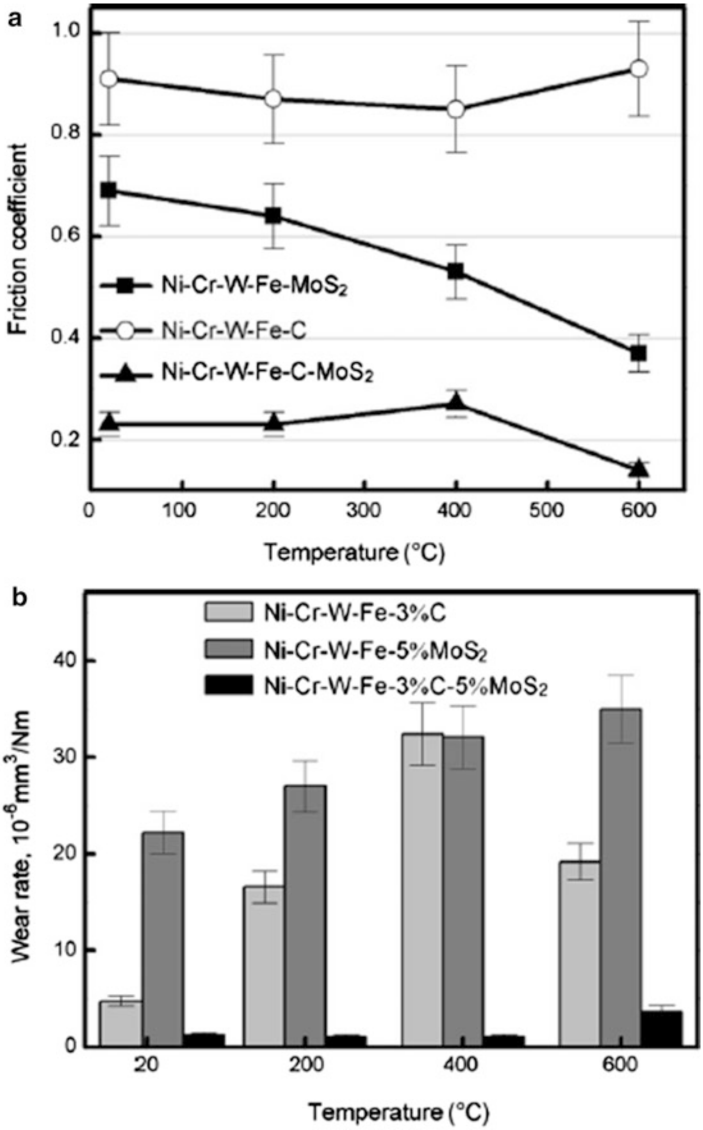


Fig. 11.14 Variation of (**a**) friction coefficients and (**b**) wear rates in the composites containing graphite and MoS_2 as lubricants [45]

high wear resistance at elevated temperatures, respectively. Figure 11.14 shows the variation of friction and wear rate for different composites containing graphite and MoS_2 as lubricants. The Ni–Cr–W–Fe–C–MoS_2 composite possessed excellent self-lubricating properties over a wide range of temperatures as a result of synergistic lubricating effect of graphite (C) and molybdenum disulfide (MoS_2). The graphite contributed to the dominant role of lubrication at room temperature, while

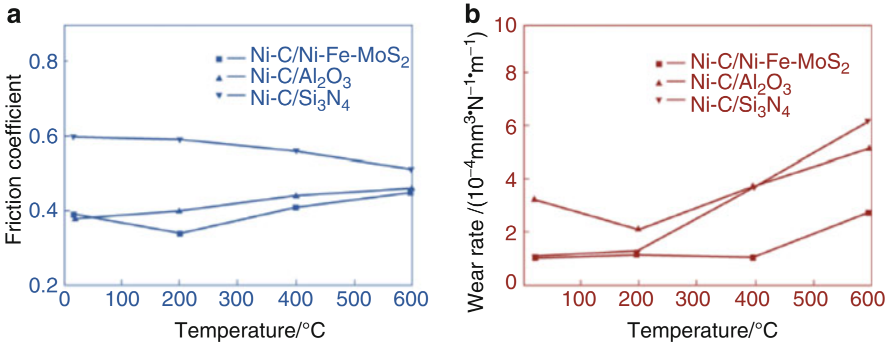


Fig. 11.15 Variation of (**a**) friction coefficient and (**b**) wear rate with temperature against different counterfaces [46]

the sulfides were responsible for low friction at high temperatures. Li et al. [46] studied the tribological properties of nickel–graphite composites against different counterfaces at elevated temperatures. Figure 11.15 shows the variation of coefficients of friction and wear rates of a 12 wt% graphite–nickel composite over various temperatures when rubbing against alumina (Al_2O_3) ceramic, silicon nitride (Si_3N_4) ceramic, and Ni–Fe–C–MoS_2 alloy under a load of 50 N and a velocity of 0.8 m/s. Compared with the counterface of alumina and silicon nitride, the friction coefficients and wear rates are lower when the composite rubs against the nickel-based alloy containing molybdenum disulfide. Wu et al. [47] studied the dry friction and wear behavior of Ni–P matrix composites with graphite (abbreviated Gr) and SiC particles. Figure 11.16 shows the variation of friction for the three composites. It was found that the Ni–P–Gr matrix composite had the lowest friction coefficient. The wear rates of the composites were found to be 0.5447, 0.0015, and 0.0152 (10^{-3} mm^3/m) for Ni–P–Gr, Ni–P–SiC, and Ni–P–Gr–SiC, respectively. These results indicate that the Ni–P–SiC had the lowest wear rate. By comparison with Ni–P–Gr and Ni–P–SiC, the overall results indicate that the hybrid Ni–P–Gr–SiC composite had superior antifriction and wear resistance which is a result of the graphite-rich mechanical mixed layer (GRMML) formed on the contact surface. The graphite-rich mechanical mixed layer formed on the worn surface was responsible for enhanced lubricity, which allowed even the Ni–P–SiC to see improved results when graphite was added to the composite. When the SiC particles mixed with the graphite in the transfer layer, the SiC particles acted as a load-bearing support in protecting the graphite-rich mechanical mixed layer from easily shearing, thus maintaining improved friction reduction capabilities.

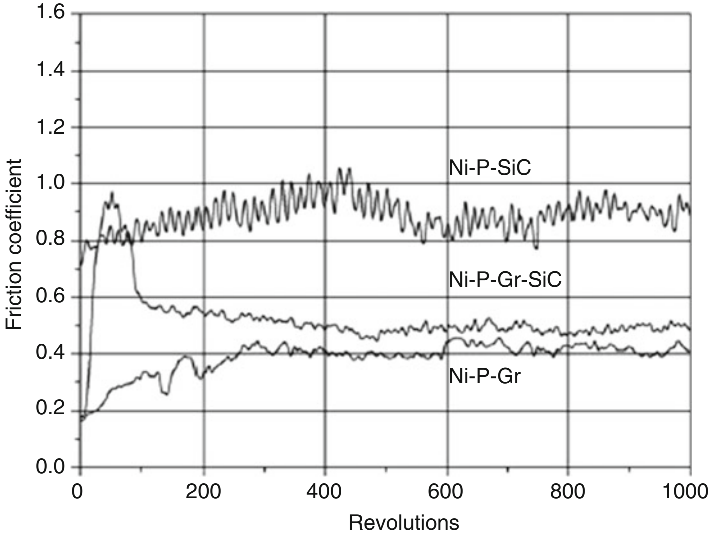


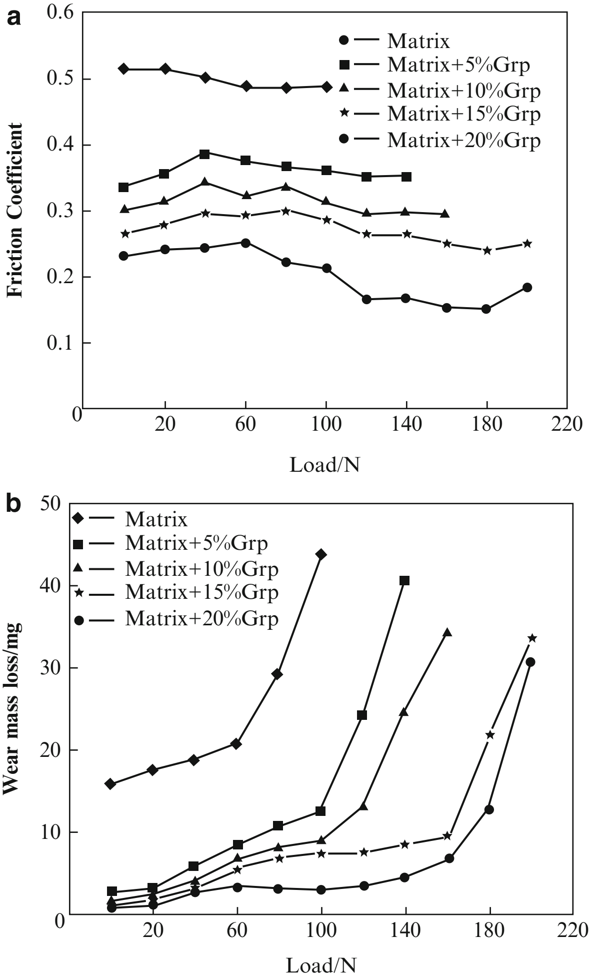
Fig. 11.16 The variation of friction coefficient of the Ni–P and Ni–P composites [47]

2.4 Self-Lubricating Behavior of Magnesium–Graphite Composites

Magnesium alloys are used in automobile and aerospace industries due to their low density, high specific strength, stiffness, good damping characteristic, excellent machinability, and ease of casting. Additionally, the poor corrosion and wear resistance of magnesium is a drawback that facilitates its primary use as an alloying agent to make aluminum–magnesium alloys. The most commonly used magnesium alloy is AZ91 alloy (consisting of 90 % magnesium, 9 % aluminum, and 1 % zinc). Magnesium alloy–graphite composites have found applications in pistons and space structural applications, thus expanding their versatility and use as self-lubricating metal matrix composites.

Attempts have been made to study the tribological performance of magnesium–graphite composites. Qi [48] studied the influence of graphite particle content on the friction and wear characteristics of an AZ91 magnesium alloy matrix composite. The variation of the friction coefficient of the composites normalized with respect to the base alloy as a function of the applied load against the hardened steel is shown in Fig. 11.17a. It can be seen that the coefficient of friction of the composites was much lower than that of the matrix alloy. The graphite content affects the friction coefficient of the composites, and the friction coefficients were revealed to reduce with increasing graphite content. In regard to the wear rate, the wear behavior of composites containing different contents of graphite particles has been determined and compared with that observed in the base alloy. Figure 11.17b shows the wear mass loss of the composites as well as the base alloy specimens as a

Fig. 11.17 Variation between (**a**) friction coefficient and (**b**) wear mass loss with load [48]



function of the applied load. The results showed that under similar testing conditions, the wear resistances of the graphite-containing composites are improved when compared to the based alloys that do not have graphite. The wear mass loss of each composite specimen reduces with the increase in graphite content. The investigations revealed that a continuous black lubricating film forms progressively on the worn surface during sliding, which effectively limits the direct interaction between the composite tribo-surface and the counterpart, and also remarkably delays the transition from mild wear to severe wear for the magnesium alloy graphite composites.

In regard to the influence of particle size on the tribological performance, Zhang et al. [49] studied the effect of graphite particle size on wear property of graphite

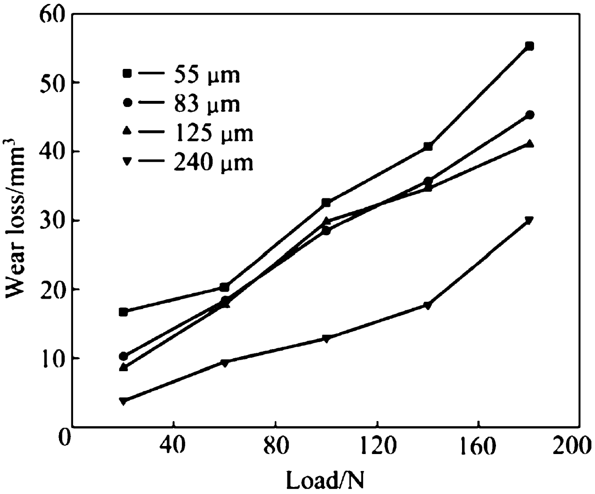


Fig. 11.18 Variations of wear loss with load of composites [49]

and alumina (Al_2O_3) ceramic-reinforced AZ91D–0.8 %Ce composite. Figure 11.18 shows the variation of wear loss with load. It was observed that the embedded graphite in the matrix acts as lubricant and decreases the wear loss. The wear resistance of the composite increased as the graphite particle size increased. At low loads, the composites have a low variation of wear loss; however, at high loads, the variations of wear loss of the composite are significant. It can be seen in the figure that the composite with the largest graphite particle size demonstrated superior wear resistance. The wear mechanism of all the composites at low load is abrasive wear and oxidation wear, and at high load, the wear mechanisms of the composites changed to delamination wear. In another study, Zhang et al. [50] investigated the effect of graphite content on the wear property of graphite/Al_2O_3/Mg–9Al–1Zn–0.8Ce composites. More specifically, the composites were studied for the influence of graphite content of 5, 10, 15, and 20 %. It was found that the wear resistance of the composites increased with increasing graphite content. Again, the wear mechanisms of the composites at low load were abrasive and oxidation wear, and at high loads the wear mechanism was delamination wear. Cerium (Ce) was found to play an important role in the magnesium–graphite composite. Zhang et al. [51] further investigated wear properties of graphite and Al_2O_3-reinforced AZ91D–Ce*x* composites. It was found that the wear resistance of the composites increased with an increasing Ce content as shown in the Fig. 11.19.

2.5 Self-Lubricating Behavior of Silver–Graphite Composites

Several metal matrix composites have been specifically designed for the use in electromechanical applications combining materials with excellent wear resistance and high electrical conductivity. These metal matrix composites are often

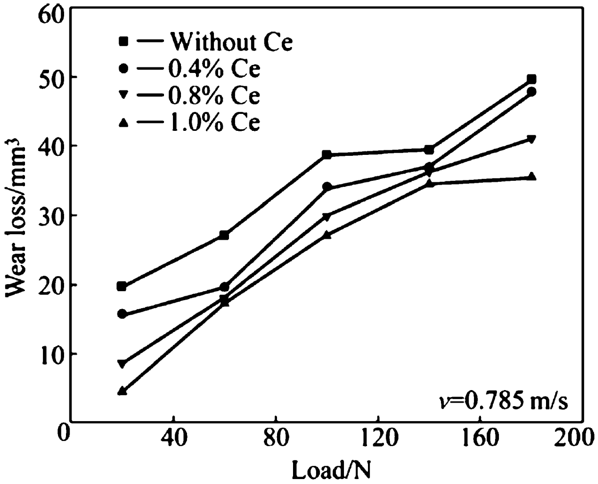
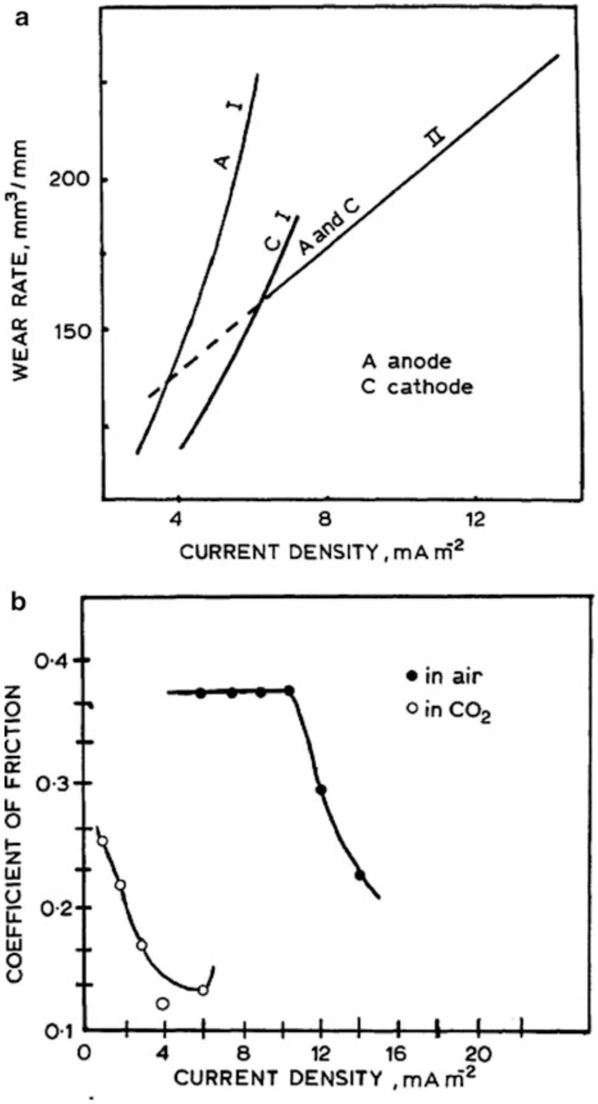


Fig. 11.19 Variations of wear loss of the composites with loads as a function of Ce content in the magnesium–graphite composite [51]

composed of copper-based metal matrices; however, in some applications, a silver based-graphite composite is used, especially for use in various electrical contacts. In electrical contact applications, the friction and wear behavior under sliding with electrical current flow can become quite complex when compared to that under purely mechanical sliding conditions. The amount of materials removed under sliding electrical contact is the sum of the contributions from purely mechanical wear in the absence of electrical current flow, arc erosion, and mechanical wear resulting from softening of the matrix by local heating caused by the electrical arcing. As reported in the literature [21, 52], in silver–graphite systems, the wear rate of composites increased with an increase of current density at both low and high temperatures, as shown in Fig. 11.20a. The figure shows that when there is a transition in the mode of sliding wear with temperature, the current density for the same wear is considerably higher while sliding at higher temperatures, compared with that observed during sliding at ambient temperature. The coefficient of friction decreased with the current density, as shown in Fig. 11.20b, both in air and in a CO_2 atmosphere.

The influence of pressure on the tribological behavior of the silver–graphite composites has been studied by Feng et al. [53] who investigated the effect of pressure on the friction and wear properties of carbon nanotube-silver–graphite composites with and without 10 A/cm^2 of current. The results showed that the mechanical wear of composites increased with an increase of pressure, but the electrical wear of composites varied in the shape of U with an increase of pressure (Fig. 11.21a). The electrical wear is shown to be significantly higher than mechanical wear by a factor of 6–20. The differences between the with-current electrical wear and without-current mechanical wear are due to the Joule heat released in the friction zone which leads to breakdown of the lubricating film, roughening of the surface, and intensification of the adhesive interaction at the contact spots. The coefficient of friction of metal matrix composites with electrical current is greater than metal matrix composite without electrical current as shown in Fig. 11.21b.

Fig. 11.20 (**a**) Variation of wear rate with current density at ambient and elevated temperatures; I is observed below 100 °C, but II is observed at elevated temperatures, above 100 °C. (**b**) Reduction in coefficient of friction of Ag-25 vol.% graphite composite with current density in air and CO_2 atmosphere [21]



Silver–graphite composite brushes are known for their low noise level, low and stable contact resistance, low friction, and high conductivity. In modern inertial energy storage devices (e.g., homopolar motor generators), a large amount of energy is stored and the energy is delivered in the form of low voltage, high current pulses. Silver–graphite brushes are suitable for such systems. Silver–graphite brushes suppress radio interference noise level and are useful for slip rings, segmented rings, and other applications where similar requirements justify the

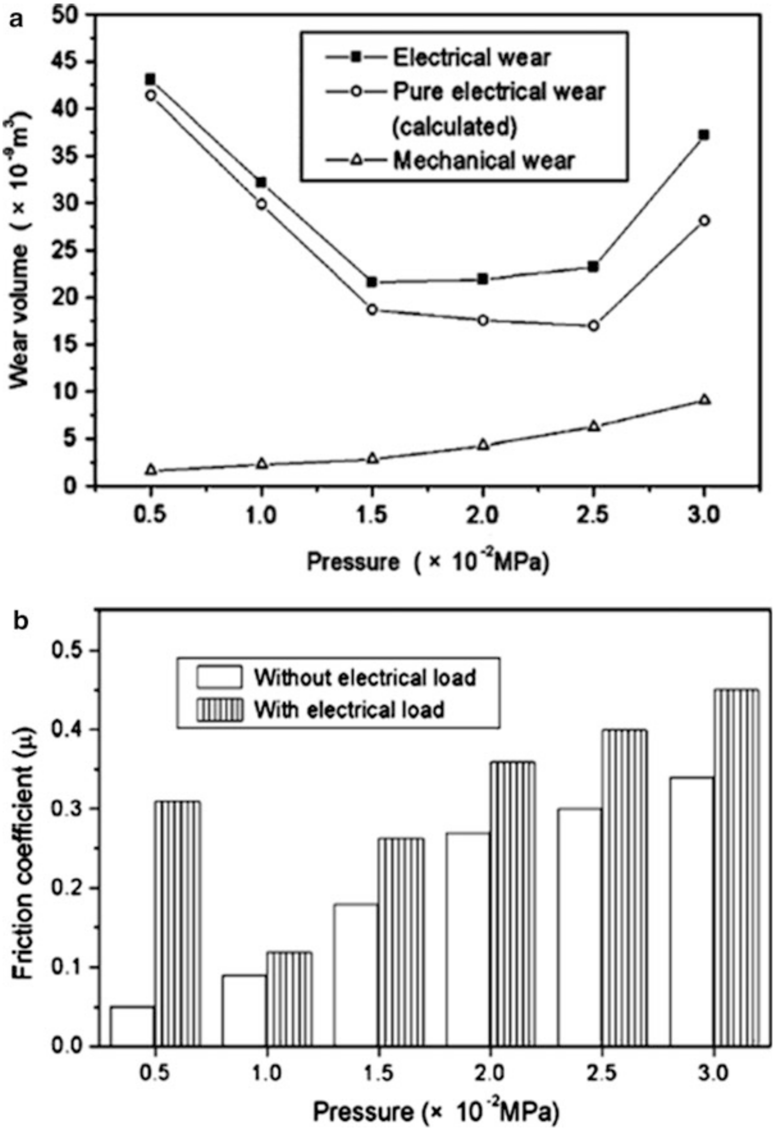


Fig. 11.21 Effect of pressure on (**a**) wear rate and (**b**) friction coefficient of carbon nanotube-reinforced silver–graphite composite under mechanical and electrical wear [53]

high material cost. Often silver–graphite composites are used in electromechanical applications that encounter severe detrimental effects caused by current erosion or electrical heating. Silver-based metal matrix composites can often minimize the effects of electrical current and maintain desirable tribological properties.

2.6 Self-Lubricating Behavior of Aluminum–Graphite Composites

Aluminum alloys are promising materials in high-technology automotive fields due to their excellent specific mechanical and physical properties such as low density, good resistance to corrosion, and low thermal expansion. However, their low resistance to wear under poor lubricating conditions and their severe seizure and galling under boundary lubrication conditions are major concerns for their use in high-performance tribological applications. With solid lubricant particle dispersion in the matrix of an aluminum alloy, this material can exhibit improved wear resistance and consequently become more suitable for high-performance tribological applications [54, 55].

Considerable efforts have focused on incorporating solid lubricating particles in aluminum alloy matrices to improve friction, wear, and anti-seizing properties. Researchers have identified graphite as a suitable solid lubricating material for the preferred applications. These self-lubricating aluminum alloy–graphite particulate composites have received attention because of their low friction and wear, reduced temperature rise in the tribo-interface, improved machinability, excellent anti-seizure effects, low thermal expansion, and high damping capacity. The variation of the coefficient of friction with graphite content for an Al–SiC–graphite composite is shown in Fig. 11.1. Figure 11.22 shows the variation of wear rate with graphite content for different Al–Si alloys reinforced with graphite. It can be seen that the coefficient of friction and the wear rate decrease with increasing graphite content as seen in Figs. 11.1 and 11.22, respectively. As the graphite content continues to increase, the friction and wear values plateau once the graphite film completely covers the sliding surface. It is speculated that the wear rate may increase when graphite content in the matrix exceeds a critically high value that can cause a decrease in the strength of the matrix. This scenario can lead to the formation of a thick graphite film, which in itself can wear by delamination within the film in a manner similar to that of bulk graphite. It is interesting to observe in Fig. 11.22 that for the case of 6061 alloy prepared by powder metallurgy method, a phenomenon occurs where the wear rate increases with increasing graphite content. Recently, Baradeswaran and Elayaperumal [56] studied this phenomenon by investigating the effect of graphite content on tribological behavior of aluminum alloy–graphite composites. The 6061 aluminum alloy–graphite composite with graphite particle dispersions up to 20 % was used. Here, the composites were prepared by a casting method. As illustrated in Fig. 11.23a, the wear rate of the composites decreased with an increasing graphite content which is in contrast to the result presented by the previous authors in Fig. 11.22 [21].

The coefficient of friction of 6061 aluminum alloy–graphite composite was also found to decrease with the addition of graphite particles as a reinforcement material and recorded a 2.5 times lower friction value than the base alloy (Fig. 11.23b). It was also revealed that the wear loss was found to decrease with increasing sliding speed. Like other Al–SiC alloy–graphite composites, the 6061 aluminum alloy

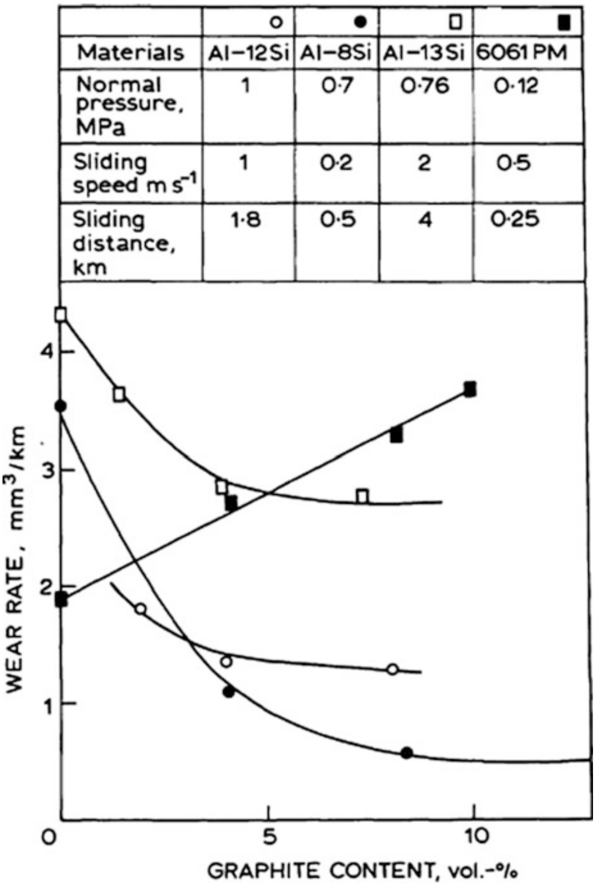


Fig. 11.22 Variation of wear rate with graphite content in aluminum alloy matrix [21]

exhibits its potential to act effectively as a matrix material for a self-lubricating composite under dry sliding conditions, due to the formation of the graphite-based transfer film.

It is reported earlier that the wear rate is also a function of sliding velocity in composites. Figure 11.24 shows the variation of wear rate with sliding velocity in Al–Si alloy–graphite composite and compares it with that of the respective base alloys without the presence of graphite. As the sliding speed increases, the interface temperature also increases resulting in (a) the formation of oxides on the sliding surface and (b) a decrease in the flow stress. In addition, there may be microstructural changes such as dissolution of precipitates, which would also be reflected in the wear behavior. In Fig. 11.24, it is interesting to note that the composite with only 5 vol.% of graphite retains relatively the same trend of wear rate with sliding speed as that of the base alloys. Conversely, the composite with 15 vol.% of graphite shows a drastically different trend to that of the base alloys. This trend is an indication that the sliding surface might have been largely covered by graphite film so that the wear rate

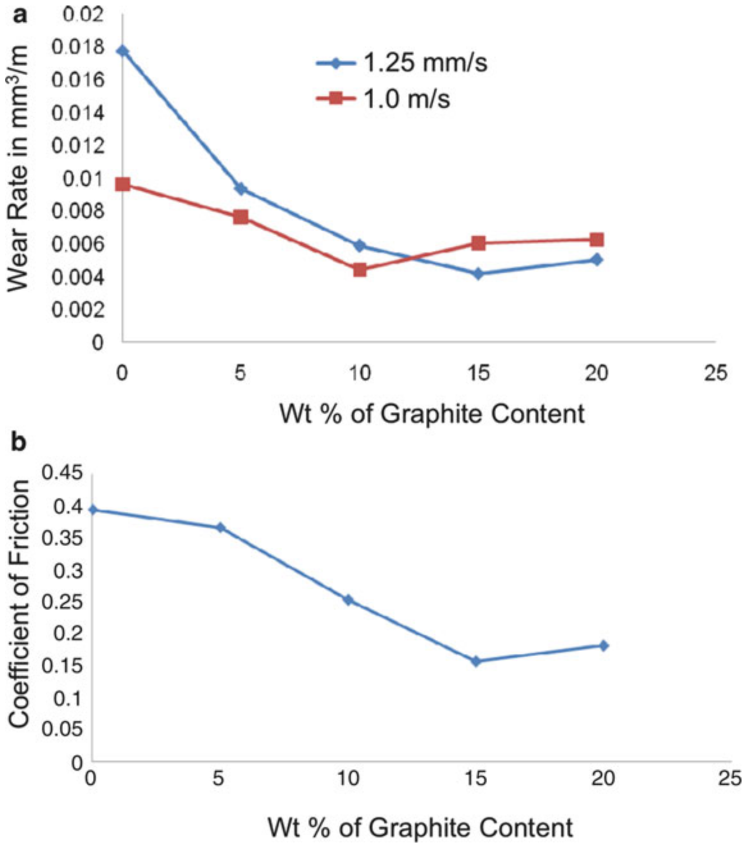


Fig. 11.23 Variation of (**a**) wear rate and (**b**) friction coefficient with graphite content [56]

becomes almost unaffected by changes in sliding speed under the given test conditions. When the graphite content is low, the sliding interface is insufficiently covered by the graphite-rich film, and the wear characteristics are similar to that of the matrix. Normal load is another important parameter that influences the wear rate of composites. The variation of wear rate with normal load in Al–Si alloys composites is shown in Fig. 11.25. Results demonstrated that the wear rate increases with increasing normal loads for all materials.

Efforts have been made to study various aluminum–graphite composites using different testing variables and conditions. For example, Akhlaghi and Zare-Bidaki [20] studied the influence of graphite content on wear behavior of Al 2024–graphite composites during dry sliding and oil-impregnated sliding. The variation in the measured coefficient of friction and wear rate with the weight percent of graphite in the composites for both dry sliding and oil-impregnated sliding are shown in Fig. 11.26. It was found that an increase in graphite content reduced the coefficient of friction for both dry and oil-impregnated sliding, but this effect was more

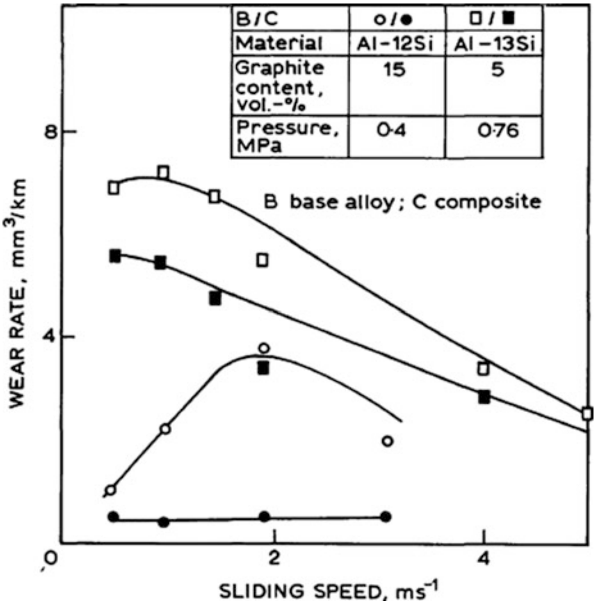


Fig. 11.24 Variation of wear rate with sliding speed for Al–Si alloy–graphite particle composites and corresponding base alloys [21]

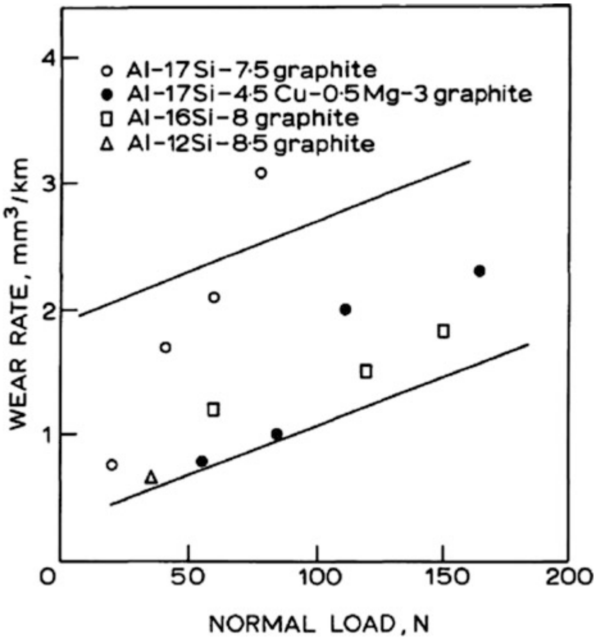


Fig. 11.25 Variation of wear rate with normal load for Al–Si alloy–graphite particle composites [21]

pronounced in dry sliding. Under dry sliding, the wear rate of the Al 2024–5 wt% graphite is about ten times lower than that for the base alloy. However, for composites with 10 wt% or more of graphite particle reinforcement material, the wear rate increased. The change in the wear rate for specific amounts of graphite

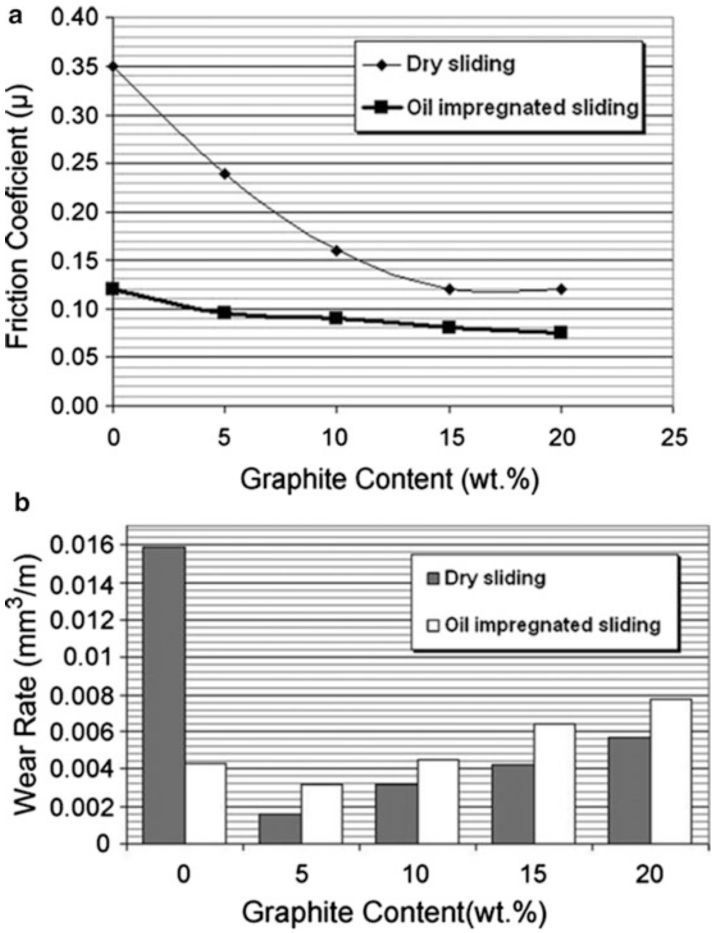
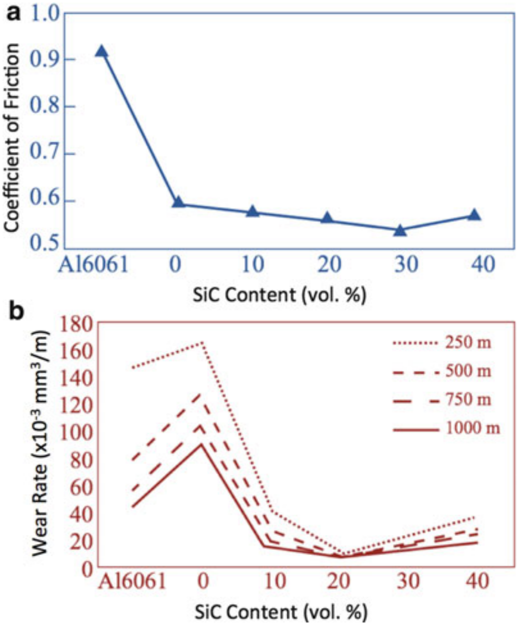


Fig. 11.26 The variation of (**a**) friction and (**b**) wear rate with the graphite content in the composites for both dry sliding and oil-impregnated sliding [20]

particle reinforcement material was caused by the following two competing factors: first, the beneficial effect of the graphite in reducing the wear of the composites due to formation of a thin lubricating graphite-rich film on the tribo-surface and second, the adverse effects of graphite in the formation of porosity and cracks as well as the deterioration of mechanical properties resulting in enhanced delamination. As shown in Fig. 11.26, for dry sliding, the coefficient of friction begins at 0.35 for the base alloy and decreases with an increasing graphite content reaching a final value of about 0.12 for composites containing 15 wt% graphite which is about one-third that of the base alloy. Additionally, the figure also shows that there is no significant difference in the friction coefficient between composites with 15 wt% and those with 20 wt% graphite content. The reason for this reduction in the coefficient of friction is attributed to the presence of the smeared graphite layer at the sliding

Fig. 11.27 Dependence between content of SiC in Al/SiC/Gr hybrid composites with 9 % graphite and (**a**) friction coefficient and (**b**) wear rate [59]



surface of the wear sample, which acts as a solid lubricant. This lubricant film prevents direct contact of the two surfaces.

Studies were also made to investigate the tribological behavior of hybrid aluminum–graphite composites. Suresha and Sridhara [57, 58] studied wear characteristics of hybrid aluminum matrix composites reinforced with graphite and silicon carbide particulates. In tribological applications demanding similar strength requirements, the authors [57, 58] reported that Al–SiC–graphite hybrid composites are better substitutes to Al–graphite or Al–SiC composites owing to an improved wear resistance and coefficient of friction as a result of the combined reinforcement of SiC and graphite particulates. Recently, Stojanovic et al. [59] investigated the tribological properties of aluminum matrices reinforced with SiC and graphite (Gr). In these studies, the hybrid composites showed that the friction coefficient and wear rate of the composite decreased with an increase in SiC and graphite content. Figure 11.27 shows the influence on the coefficient of friction and wear rate of the SiC content in the Al–SiC–Gr hybrid composite with 9 % of graphite. A maximum amount of SiC and graphite was permissible up to 20–30 %, before the effects of the reinforcement material became detrimental to the composite causing the coefficient of friction and wear rate to increase.

In another study, in contrast to previous research, Babic et al. [60] investigated the tribological characteristics of hybrid composites with aluminum-based A356 reinforced with silicon carbide and graphite material. Here, the hybrid composites consisted of 10 % SiC and 1 % graphite were subjected to various normal loads, speeds, and sliding distances to characterize their tribological performance. The results of this study revealed that the influence of the SiC and graphite

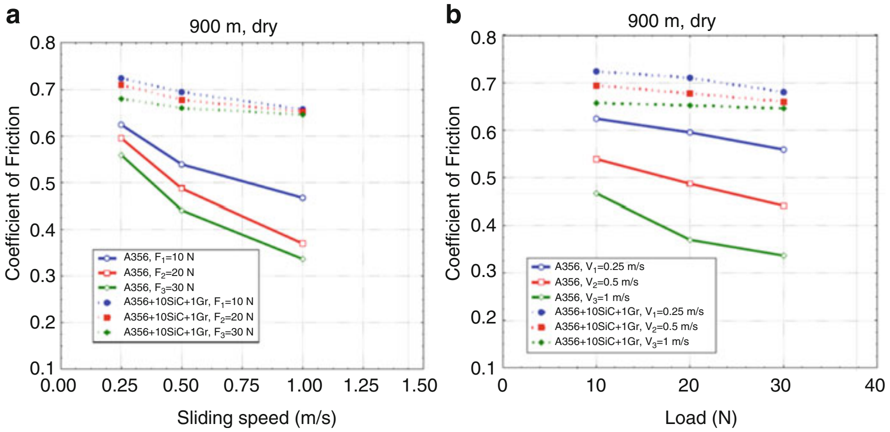


Fig. 11.28 Coefficient of friction dependence of sliding speed for different conditions of dry friction, (**a**) sliding speed and (**b**) normal load [60]

reinforcement material did not improve the coefficient of friction as seen in Fig. 11.28. In fact, the hybrid composites performed worse than the original matrix causing the friction values to increase with the addition of the reinforcement material. When a lubricious reinforcement material such as graphite is mixed with SiC, it can cause the coefficient of friction to increase for some aluminum matrices. These results could be due to the low quantity of graphite reinforcement material, the development of a poor graphite transfer layer, or the effects of wear debris.

Attempts were made to study the tribological behavior of the composites with higher graphite content under various environments. Goto and Uchijo [61] conducted wear tests of an Al–Si alloy impregnated with a high content (56 vol.%) of graphite reinforcement material. These Al–Si alloy matrix composites containing graphite were slid against bearing steel in various gas environments to investigate the wear mechanisms. The composites exhibited a decrease in wear at high loads in moist air. The wear rate was initially high at a low relative humidity (RH). The wear rate then decreased with an increasing RH to a minimum value at the median of the RH, and lastly, the wear rate increased slightly at a higher RH value. The wear rate in moist argon is approximately equal to one-third of the wear rate in moist oxygen. At the RH for the minimum wear, wide compacted transfer films consisting of graphite and metallic wear particles were formed on the disk sliding surface due to smearing of the graphite particles. These films prevent the sliding surfaces from metal-to-metal contact. The entrance of wear particles onto the contact surfaces causes the pin lifting, leading to an apparent decrease in wear.

The influence of graphite particle size on the tribological performance of the composites was also investigated. Jinfeng et al. [62] studied the effect of graphite (abbreviated Gr) particle reinforcement on dry sliding wear of SiC–Gr–Al composites. The aluminum alloy matrix composites composed of 40 % SiC, 5 % graphite, and 55 % Al with various sizes of graphite particles were fabricated by squeeze casting technology. The friction and wear properties of these aluminum matrix composites were investigated as well. Results showed that after the addition of graphite, the coefficient of friction of the composites decreased and the wear resistance increased by 170–340 times. In addition, wear resistance was improved by increasing the graphite particle size, which is attributed to the enhancement of integrity of the lubrication tribo-layer composed of a complex mixture of iron oxides, graphite as well as fractured SiC particles and some fine particles containing aluminum.

It is well known that there have been a number of publications in the literature on the sliding wear and friction of aluminum alloy–graphite composites. Unfortunately, different researchers have used different experimental parameters for hardness and roughness of the counterface, sliding speed, normal load, and the test environment, making it difficult to quantify the effect of graphite content on the tribological performance of the composites. In addition, comparing empirical wear data to theoretical generalizations of wear behavior is often difficult because of the widely different test conditions employed by various researchers to characterize the tribological properties of the composites. Despite the lack of universal testing procedure, useful generalizations concerning wear behavior of different materials including composites have been applied by constructing wear mechanism maps. Wear maps serve as predictive tools to draw meaningful conclusions relative to wear behavior under different test conditions. Specifically, some of the variations between different studies can be overcome by utilizing normalized test parameters such as nondimensional wear rate, load, and sliding velocity. Hence, normalized wear rates (i.e., composite to the base matrix alloy) were introduced to analyze the data from different studies. Figure 11.29 is a compilation of the normalized friction coefficient and wear rate data of aluminum alloy–graphite composite showing the reduction in friction and wear volume due to graphite particle dispersion [63]. As shown in the figure, the aluminum alloy–graphite composites typically exhibit a much lower friction coefficient when compared with that of the matrix alloy. The coefficient of friction decreases considerably, up to about 3 % by weight of graphite, and thereafter remains constant at about 0.2 (0.5 on a normalized scale).

Although aluminum graphite composites possess a number of superior tribological properties, there are some drawbacks. For instance, graphite loses its lubricity in dry environments. In many aerospace applications where the tribo-components are expected to perform in a vacuum, this could be a limitation. Despite the few deficiencies of graphite, aluminum alloy composites reinforced with graphite have applications in cylinder blocks, journal bearings, connecting rods and pins, fan bushings, and internal combustion engines. Aluminum–silicon composites are used in pistons and liners in two stroke and four stroke engines in passenger cars as well as in race cars.

2.7 Conclusion

The self-lubricating behavior of various graphite-reinforced metal matrix composites was reviewed. The variety of applications and use of metal matrix composites stems from the variety of composite materials in the form of copper–graphite,

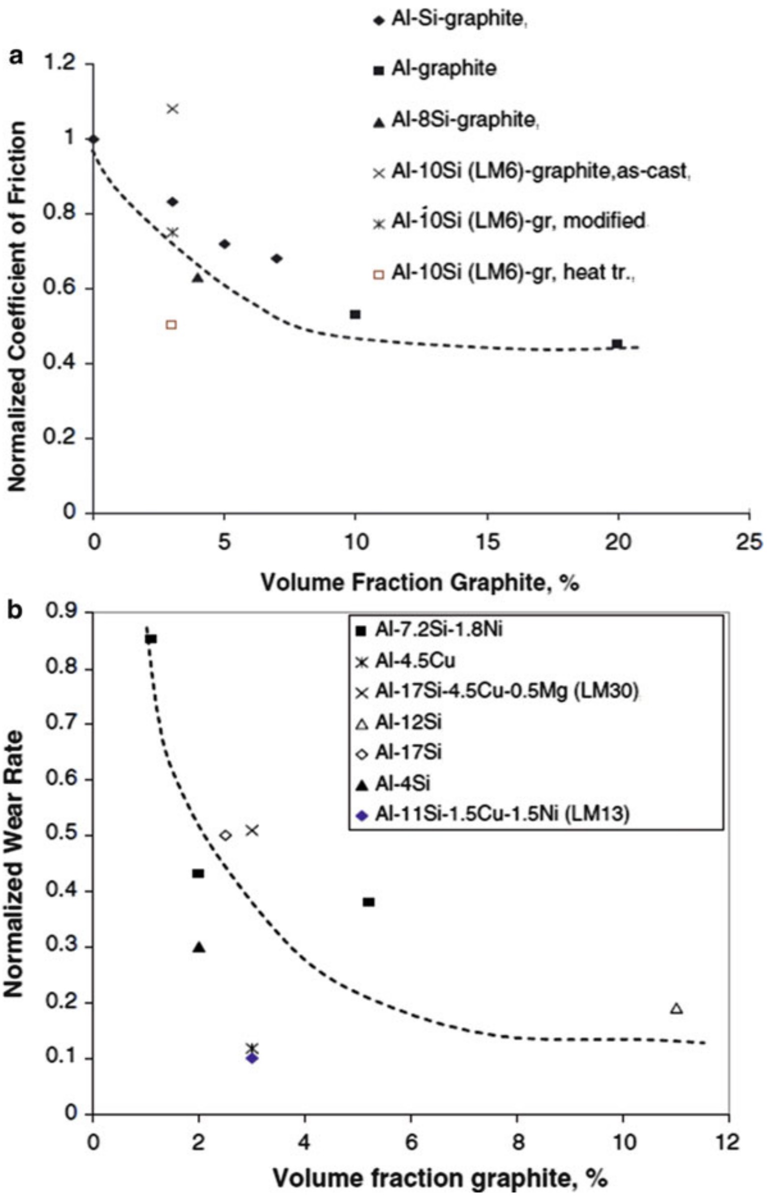


Fig. 11.29 Normalized (**a**) friction coefficient and (**b**) wear rate of aluminum–graphite composites [63]

nickel–graphite, magnesium–graphite, silver–graphite, and aluminum–graphite. Each of these composite materials presents a unique set of tribological properties and offers a unique application to take advantage of the self-lubricating properties of metal matrix composite. The complexities of each metal matrix composite achieve varying degrees of friction and wear necessary for different systems to operate in environments where liquid lubricants are impractical. As described, the reinforcement materials can range from graphite particles dispersed in the metal matrix composite to zinc-coated graphite, hBN, TiC, alumina, and SiC. Ultimately, the incorporation of graphite-based reinforcement materials allowed the metal matrices to overcome friction and wear while achieving successful operation in the desired environments.

3 Self-Lubricating Behavior of Ceramic–Graphite Composites

3.1 Introduction

Self-lubricating composites are not only derived from metal matrices, but they can also be fabricated from ceramic matrices to produce self-lubricating ceramic composites reinforced with solid lubricant additives. Ceramic composites composed of silicon nitride and alumina are the most common of ceramic matrix materials and are used in a variety of specialized applications. Ceramics are often considered for engineering applications that require the use of advanced structural materials undergoing sliding or rolling behavior at elevated temperatures or in severe environments. Ceramics offer unique physical and mechanical properties such as low density, high hardness, high wear resistance, ability to retain strength and hardness at high temperatures, and corrosion resistance [64]. Investigations into the tribological performance of ceramic materials have shown that they exhibit high coefficients of friction between 0.5 and 0.8 in unlubricated sliding conditions [65–69]. In liquid lubricated conditions, ceramic materials have shown reductions in the coefficient of friction to significantly lower values of approximately 0.1 [70–75]. Many of the applications that require the use of ceramics (i.e., elevated temperatures or vacuum environments) are beyond the tolerable domain of liquid lubricants. For this reason, to achieve the desired levels of friction, solid lubricants are often utilized to meet the operational needs. The use of solid lubricants with metals is quite detailed in the literature through various applications as thin films on substrates by burnishing [7, 9], sputtering [11, 12], or plasma spraying [13, 14]. More recently, the use of solid lubricants with ceramic materials has garnered interest [76–79].

3.2 Self-Lubricating Behavior of Alumina–Graphite Composites

The study of friction and wear behavior of α-alumina coated with a thin film of silver by ion-assisted deposition techniques was investigated by Erdemir et al. [76]. This research demonstrated significant improvements in the wear

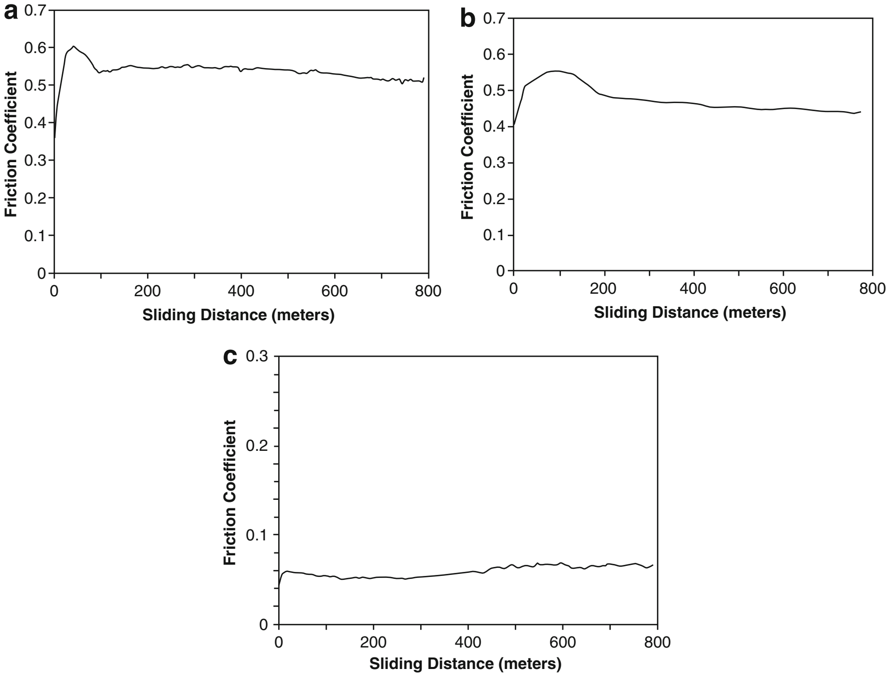


Fig. 11.30 Friction traces of (**a**) alumina, (**b**) alumina–graphite composite, and (**c**) graphite [64]

resistance for the silver-coated alumina but not for the steady-state coefficient of friction, which remained to be high, approximately 0.4. Although there was a slight improvement in the coefficient of friction when compared to the uncoated alumina material, the friction was still too high for practical applications. The tribological behavior of a glass–ceramic matrix reinforced with graphite fibers was studied [79]. It was revealed that the addition of the graphite fibers to the ceramic matrix did not provide adequate lubrication due to the high elastic modulus of the graphite fibers. Tests of alumina–graphite composites sliding on a 52100 steel ring revealed that the coefficient of friction was marginally reduced by the presence of the graphite reinforcement material as well. To further study the effects of graphite in alumina, another study by Gangopadhyay and Jahanmir [64] investigated the friction and wear characteristics of alumina–graphite matrix composites. In this study, alumina matrices were fabricated with small holes that were then mechanically filled with $NiCl_2$ intercalated graphite powder under high pressure to produce a self-lubricating composite. Friction tests were conducted and it was determined that the addition of graphite to the alumina matrix composite marginal reduced the coefficient of friction as seen in Fig. 11.30a, b. It can be seen in Fig. 11.30c, that graphite by itself has an extremely low coefficient of friction under similar conditions, illustrating the lubricious nature of the solid lubricant. The lack of a decrease in the coefficient of friction for the alumina–graphite composite can be explained by the presence of steel wear particles that inhibited the formation of the graphite transfer layer. The steel wear debris physically covered the graphite regions within the composite thus retarding the lubricating properties of the graphite.

3.3 Self-Lubricating Behavior of Silicon Nitride–Graphite Composites

Wedeven et al. [77] and Pallini et al. [78] investigated the frictional behavior of solid lubricated silicon nitride balls sliding against silicon nitride disks. Here, solid lubrication was maintained by burnishing graphite-impregnated phosphate salts on both silicon nitride surfaces prior to testing. These studies have shown the success of deposited solid lubricant films on ceramics to minimize friction and wear. However, these lubricious protective films are only effective as long as they remain in the tribo-interface. For this reason, researchers have begun studying the effects of utilizing graphite reinforcement materials in ceramic matrices to establish a continuous supply of solid lubricant material at the tribo-interface [79–81]. Gangopadhyay et al. [80] investigated the use of a silicon nitride matrix reinforced with $NiCl_2$-intercalated graphite pins pressed into the matrix to create a ceramic–graphite composite with improved lubricity. Tests of the silicon nitride–graphite composite sliding on a 52100 steel ring counter-surface revealed that the coefficient of friction of the silicon nitride–graphite matrix composite had a reduction from 0.45 to 0.17. Here, the presence of silicates was found in the transfer film. Unlike alumina–graphite composites that showed negligible improvements due to the presence of graphite, tests involving silicon nitride composite showed dramatic improvements due to the graphite reinforcement material being able to establish a transfer film. The highly lubricious graphite-based transfer films that developed were determined to be the underlying cause for the reduction of friction in the silicon nitride composites. To further study the effects of graphite in ceramics, another study by Gangopadhyay and Jahanmir [64] investigated the friction and wear characteristics of silicon nitride–graphite composites. In this study, silicon nitride was again reinforced with a $NiCl_2$-intercalated graphite powder reinforcement material under high contact pressure from a tool steel die to produce a self-lubricating composite. Here, the $NiCl_2$-intercalated graphite was pressed into two, three, and four predrilled holes on the contact surface of the silicon nitride matrix. Friction tests were conducted, and it was determined that the addition of graphite to the silicon nitride matrix composite drastically reduced the coefficient of friction as seen in Fig. 11.31a, b from 0.43 to 0.17. The decrease in the coefficient of friction for the silicon nitride–graphite composite is a result of the formation of the lubricious graphite transfer layer consisting of materials from both contacting surfaces (i.e., consisting of graphite, iron oxide, and the silicates).

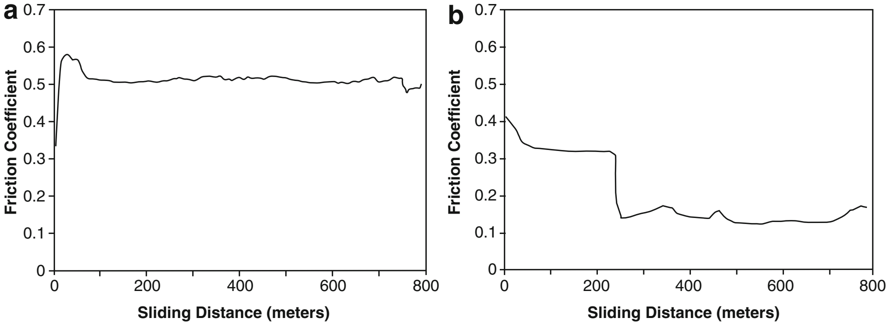


Fig. 11.31 Friction traces of (**a**) silicon nitride and (**b**) silicon nitride–graphite composite [64]

3.4 Conclusions

Research into the use of self-lubricating ceramic matrix composites has revealed that the selection of the ceramic matrix and the counterface material are as important as the selection of the solid lubricant reinforcement material. Selection of proper materials is important to (1) ensure the solid lubricant regions do not become covered by wear debris and (2) allow the formation of the lubricating transfer films in the tribo-interface. Ultimately, the advantage of self-lubricating composites over the deposition of thin solid lubricating films on ceramic substrates is the ability to have a constant supply of solid lubricant that is maintained as the matrix material wears. Self-lubricating matrix composites minimize the possibility of failure when compared to the material deposited by solid lubricant films that fail after the film has worn away.

4 Conclusions

Self-lubricating composite materials have the ability to sustain low friction and wear without any external supply of lubricants. The lubricants that are used for the tribological applications in automotive and manufacturing sectors are oil or grease based. These lubricants can introduce significant quantities of pollutants into the environment. In addition, friction and wear often lead to heat and chemical contamination to the environment. The development of self-lubricating composite materials is very important for green or environment-friendly tribology. Additionally, the use of self-lubricating composite materials allows for a practical lubrication mechanism in advanced application at elevated temperatures or vacuum environments that are beyond the tolerable domain of liquid or grease-type lubricants.

The tribological behavior of metal and ceramic matrix composites reinforced with graphite particles has been reviewed. More specifically, the tribological properties of copper–graphite, nickel–graphite, magnesium–graphite, silver–graphite, aluminum–graphite, silicon nitride–graphite, and alumina–graphite composites have been discussed. The influence of various parameters such as graphite content, particle size, normal pressure, sliding speed, sliding distance, surface texture, temperature, current density, environment, and counterpart materials on the friction coefficient and wear rate is discussed. The friction and wear rate in the metal and ceramic matrix graphite particle composites are significantly reduced when compared to similarly unreinforced material as a result of the incorporation of graphite particles. As the size of the particles increase, the friction and wear decrease in the composites. The friction and wear rate of the matrix composite decreases with an increasing graphite particle content. The graphite particles were found to be superior to other lubricant particles, and they provided effective lubrication when operating at elevated temperature. Additionally, heat treatment can improve the tribological performance of metal matrix graphite composites.

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Questions

1. What is a composite and describe two types of composites?
2. How does a self-lubricating matrix composite operate and what are the two stages?
3. Why is copper–graphite used as a self-lubricating metal matrix composite and what are some of its applications?
4. What are the dominant wear mechanisms during copper–graphite contact strip applications?
5. What is the effect of sliding speed on copper–graphite composites and how does this influence friction and wear?
6. What are the dominant wear mechanisms in the magnetic levitation transportation system?
7. In nickel–graphite composites, what compounds form to enhance the tribological properties when combining Ni, Cr, W, and Fe with graphite and molybdenum disulfide at high temperatures?
8. What contributed to the low- and high-temperature performance of the nickel alloy-based graphite–MoS_2-reinforced composite?
9. What are the mechanical properties that make magnesium alloys attractive? What are some of the drawbacks? What applications are magnesium alloys primarily used in? Provide an example of a magnesium alloy.
10. When using silver–graphite composites in electrical contact applications, the friction and wear behavior under sliding with electrical current flow can become quite complex when compared to that under purely mechanical sliding conditions. Briefly explain this behavior.
11. What are the drawbacks to aluminum matrix composites and what is the benefit to adding graphite to these composites?
12. What is the effect on the coefficient of friction when adding intercalated $NiCl_2$ graphite to silicon nitride and alumina ceramic matrices and what causes these phenomena?

Answers

1. Composite materials are a special class of materials and are made from two or more constituent components with significantly different physical or chemical properties, which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. In the case of two constituent components, the material with the highest volume fraction is considered as the matrix, whereas the other is the reinforcement material that modifies the properties of the matrix. In metal matrix composites, the matrix is made of a metal and the reinforcement may be a different metal or another material, such as a ceramic or organic compound. Similarly, in ceramic matrix composites, the matrix is composed of silicon nitride, alumina, or another type of ceramic material, and the reinforcement may be a different ceramic, metallic, or solid lubricant compound.
2. In self-lubricating matrix composites, solid particle such as graphite and MoS_2 are embedded in the matrix. Here, the formation of a thin film will occur by transferring the solid particles from the matrix to the tribo-surface during initial periods of sliding. The observed friction and wear behavior will, therefore, have two distinct stages: (a) transient state, while the thin solid lubricant film is being established, and (b) steady state, when a stable solid lubricant film (in the dynamical sense of being continuously replenished, i.e., "self-lubricating," to make up for the wear loss) has formed.
3. Copper–graphite is used as a metal matrix composite because it combines the properties of copper (i.e., excellent thermal and electrical conductivities) and graphite (i.e., superior lubricity and a low thermal expansion coefficient). These matrix composites are optimal for electromechanical applications such as in electrical sliding contact applications use in brushes in electric motors and generators. In welding machines, the low voltage, high current densities, and sliding of critical components necessitate copper–graphite metal matrix composites with a very high specific electrical conductivity, good thermal conductivity, and low friction coefficient.
4. In the copper–graphite contact strips, arc erosion wear, oxidative wear, and adhesive wear were the dominant mechanisms during the electrical sliding process.
5. When the sliding speed exceeds a critical value, a transition of the friction and wear regime occurs. The formation of a lubricant layer on the contact surface is regarded as an important characteristic for enhanced tribological performance of copper–graphite composites. Due to a large strain gradient in the subsurface deformation zone, the graphite-rich lubricant layer can easily form on the sliding surface when the speed is lower than the critical value. At speeds exceeding the critical value, the formation of the lubricant layer is difficult due to the effects of delamination wear caused by the high strain rate. At speeds less than the critical value, the wear mechanism occurring tends to be mild wear caused by ratcheting, and at speeds exceeding the critical value, the wear mechanism is more severe induced by delamination wear.

6. Adhesive wear, abrasive wear, and electrical erosion wear are the dominant wear mechanisms during the electrical sliding wear processes in the magnetic levitation transportation system.
7. Chromium sulfide and tungsten carbide were formed in the composite, and they were responsible for lowering the friction and improving the wear resistance at elevated temperatures.
8. The Ni–Cr–W–Fe–C–MoS_2 composite possessed excellent self-lubricating properties over a wide range of temperatures as a result of synergistic lubricating effect of graphite (C) and molybdenum disulfide (MoS_2). The graphite contributed to the dominant role of lubrication at room temperature, while the sulfides were responsible for low friction at high temperatures.
9. Magnesium alloys are used in automobile and aerospace industries due to their low density, high specific strength, stiffness, good damping characteristic, excellent machinability, and ease of casting. Additionally, the poor corrosion and wear resistance of magnesium is a drawback that facilitates its primary use as an alloying agent to make aluminum–magnesium alloys. The most commonly used magnesium alloy is AZ91 alloy (consisting of 90 % magnesium, 9 % aluminum, and 1 % zinc). Magnesium alloy–graphite composites have found applications in pistons and space structural applications, thus expanding their versatility and use as self-lubricating metal matrix composites.
10. In electrical contact applications, the amount of material removed under sliding electrical contact is the sum of the contributions from purely mechanical wear in the absence of electrical current flow, arc erosion, and mechanical wear resulting from softening of the matrix by local heating caused by the electrical arcing. In a purely mechanical sliding condition without current flow, only mechanical wear would result.
11. Aluminum alloys suffer from low resistance to wear under poor lubricating conditions, and their severe seizure and galling under boundary lubrication conditions are major concerns for their use in high-performance tribological applications. With solid lubricant particle dispersion in the matrix of an aluminum alloy, this material can exhibit improved wear resistance and consequently become more suitable for high-performance tribological applications. The inclusion of solid lubricating particles in aluminum alloy matrices improves friction, wear, and anti-seizing properties. Self-lubricating aluminum alloy–graphite particulate composites have received attention because of their low friction and wear, reduced temperature rise in the tribo-interface, improved machinability, excellent anti-seizure effects, low thermal expansion, and high damping capacity.
12. In silicon nitride–graphite composites, the decrease in the coefficient of friction is a result of the formation of a graphite transfer layer consisting of materials from both contacting surfaces (i.e., consisting of graphite, iron oxide, and the silicates). The lack of a decrease in the coefficient of friction for the alumina–graphite composite can be explained by the presence of steel wear particles that inhibited the formation of the graphite transfer layer. The steel wear debris physically covered the graphite regions within the composite thus retarding the lubricating properties of the graphite.