Chapter 8
Tribology of Metal Matrix Composites

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Abstract Metal matrix composites (MMCs) are an important class of engineering materials that are increasingly replacing a number of conventional materials in the automotive, aerospace, marine, and sports industries due to their lightweight and superior mechanical properties. In MMCs, nonmetallic materials are embedded into the metals or the alloys as reinforcements to obtain a novel material with attractive engineering properties, such as improved ultimate tensile strength, ductility, toughness, and tribological behavior. In this chapter, an attempt has been made to summarize the tribological performance of various MMCs as a function of several relevant parameters. These parameters include material parameters (size, shape, volume fraction, and type of the reinforcements), mechanical parameters (normal load and sliding speed), and physical parameters (temperature and the environment). In general, it was shown that the wear resistance and friction coefficient of MMCs are improved by increasing the volume fraction of the reinforcements. As the normal load and sliding speed increase, the wear rate of the composites increases and the friction coefficient of the composites decreases. The wear rate and friction coefficient decrease with increasing temperature up to a critical temperature, and thereafter both wear rate and friction coefficient increase with increasing temperature. The nano-composites showed best friction and wear performance when compared to micro-composites.

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1 Introduction

Composite materials are engineered or naturally occurring materials which contain two or more distinct materials with significantly different chemical, physical, and mechanical properties. Generally, the properties of composite materials are superior to those of the monolithic constituents. There are different classifications for composites. According to the most common classification which is based on the nature of the matrix, there are three kinds of composites. These are (a) metal matrix composites (MMCs), (b) polymer matrix composites (PMCs), and (c) ceramic matrix composites (CMCs).

MMCs are promising materials for a number of specific applications in the aerospace, sports, marine, and automotive industries. MMCs filled with nonmetallic fibers, particles, or whiskers and solid lubricants may have excellent mechanical and tribological properties. MMCs must be able to support heavy loads without distortion, deformation, or fracture during performance and maintain good tribological behavior over long periods without severe surface damages such as galling, scuffing, or seizure. The MMCs have gotten significant attention worldwide because of their superior mechanical and tribological properties.

Friction and wear are universal phenomena during sliding or rolling of solid surfaces and they usually cause energy dissipation and material deterioration. In general, the extent of friction and wear dramatically decreases by the application of lubricants between the solid surfaces. Some kinds of materials have a low coefficient of friction and wear rate during applications and no external lubricant is required. These kinds of materials are known as self-lubricating materials [1]. There are distinct methods to produce self-lubricating materials. They are (a) applying coatings like diamond-like carbon (DLC) [2] to the material and (b) embedding solid lubricants such as graphite [3] and molybdenum disulfide [4] into the matrix of a composite material. MMCs produced by embedding solid lubricants possess excellent tribological properties, good corrosion resistance, and higher fatigue life than the coated materials. These advantages cause an increase in the popularity of MMCs in comparison to the coated materials.

The amount, size, shape, and distribution of fibers or hard/soft particles embedded into the matrix have some effects on the wear and friction performance of the composites. In addition, the interfacial bonding between the reinforcements and the matrices is another important factor which affects the mechanical and tribological properties of the MMCs. Generally, it is an admissible opinion that the hard particles as reinforcements in the matrix increase the strength and wear resistance of MMCs; however, it decreases the ductility of the composites. On the other hand, soft particles usually act as a solid lubricant and hence decrease the friction coefficient of the MMCs. Sometimes, the reinforcements and solid lubricants have undesirable effects on the composites and lead to unexpected properties of MMCs [5]. An approach in SiC_p/Al (SiC particles embedded in Al matrix) composite production is to incorporate graphite particles as additional reinforcement into the SiC_p/Al composites. The graphite-embedded SiC_p/Al composites showed better wear resistance and low coefficient of friction when compared to SiC_p/Al composites without graphite reinforcement [3, 6, 7].

There are three important factors which can determine the performance of MMCs: They are (1) the composition and the microstructure of MMCs; (2) the size, volume fraction, and distribution of particles in metal matrices; and (3) the properties of the interface between the metal matrices and the reinforcements. During manufacturing processes of MMCs, different types of defects including voids and porosities may form. These defects can influence the tribological properties such as friction and wear of the composite materials. It has been shown that increasing the porosity content in the composite materials leads to reduction of mechanical and tribological properties of MMCs. Additionally, tribological testing parameters such as sliding speed, applied load, sliding time, and surface roughness affect the wear and friction behavior of MMCs.

2 Wear and Friction Properties

Wear is the progressive loss of material during relative motion between a surface and the contacting substance or substances. Tribological properties of MMCs have been extensively investigated by various researchers [3, 6–14]. The results have shown that the wear performance of MMCs is higher than that of unreinforced matrices [10, 15–17] and is shown in Fig. 8.1. As an example, Al6061 MMC reinforced by SiC particles has better wear properties than Al6061 alloy [17]. However, under certain conditions, the wear resistance of MMCs is lower or comparable to that of unreinforced matrices.

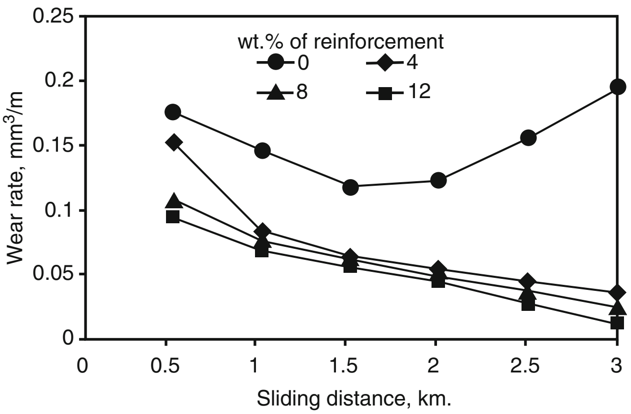


Fig. 8.1 Variations of wear rate with sliding distance for Al6061-based MMC at applied load of 10 N and sliding velocity of 1.85 m/s [17]

Different kinds of wear mechanisms may take place during the relative motion. These mechanisms include adhesive wear, abrasive wear, delamination wear, erosive wear, fretting wear, fatigue wear, and corrosive/oxidative wear. The common wear mechanisms of MMCs are adhesive wear, abrasive wear, fatigue wear, and corrosive/oxidative wear.

Adhesive wear occurs when two smooth metallic surfaces are made to slide against each other under an applied load. By applying normal pressure, the local pressure at the asperities increases to an extremely high value and often exceeds the material yield stress value. Then, the plastic deformation occurs at the asperities until the real area of contact has increased sufficiently to support the applied load. Consequently, the strong short-range forces come into action, and strong adhesive junctions may be formed at the real area of contact. During relative motion, the adhered junctions are sheared. The name "adhesive" is specified due to the formation of strong metallic bonds between the asperities on the surfaces of the contacting materials. Abrasive wear occurs when a hard rough surface slides across a softer surface. In some cases, abrasive wear occurs when hard particles trapped at the interface cause abrasive action against the surfaces in contact. Abrasive wear can be caused by both metallic and nonmetallic particles, but in most cases, the nonmetallic particles cause abrasion in MMCs. The dynamic interactions between the environment and mating material surfaces play an important role during the wear process. In corrosive wear, the contacting surfaces react with the environment and thus reaction products are formed on the surfaces at the asperities. Thus, during sliding interactions, wear of the reaction products occurs as a result of crack formation and/or abrasion. In fact, the corrosive wear occurs when reaction products on the surfaces of materials remove through physical interaction of the two surfaces in contact. Thus, corrosive wear requires corrosion and rubbing. Fatigue wear occurs at the surface of materials which experience cyclic loading. For example, the ball bearings and the gears normally experience fatigue wear due to existence of cyclic stresses during their applications.

Friction is the resistance an object encounters in moving over another. The coefficient of friction is a dimensionless scalar value which represents the ratio of the force of friction (F) between two bodies and the normal force (P) pressing them together. The symbol usually used for the coefficient of friction is μ and is expressed mathematically as follows:

$$\mu = \frac{F}{P} \tag{8.1}$$

Scientists and engineers are trying to employ an appropriate method to improve wear and friction behavior of metallic materials. One method which is used to decrease the coefficient of friction of materials is applying coating. DLC is a suitable coating which when applied to different metals such as aluminum decreases the coefficient of friction to less than 0.1 [2]. The other method to improve the tribological behavior of metals is embedding suitable reinforcements

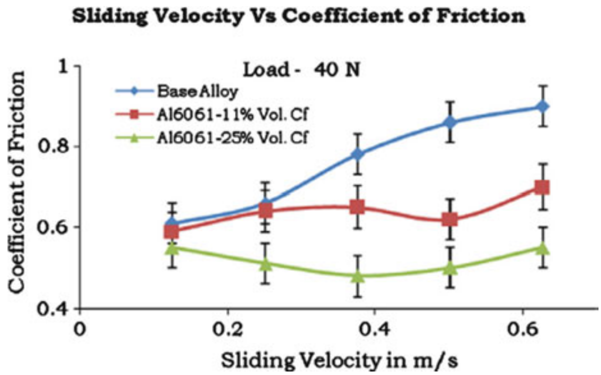


Fig. 8.2 Variation of coefficient of friction with sliding velocity for the Al6061 alloy and its carbon fiber (C_f)-reinforced composites [20]

into the metal matrices to produce composites. Different kinds of reinforcements are added to the metal matrices. Some kinds of reinforcements which are very common in MMCs are Al_2O_3, SiC, and B_4C. They are usually added to the metal to improve the mechanical properties of the composites. These kinds of reinforcements have also improved the friction coefficient and wear resistance of the composites [14, 15, 18]. There are other types of reinforcements, known as solid lubricants, such as graphite, molybdenum disulfide, and hexagonal boron nitride. These particles are embedded into the metal matrices to improve the tribological behavior of MMCs. These kinds of reinforcements usually decrease the coefficient of friction of the composites significantly [19]. In general, the reinforcement particles improve the coefficient of friction of the composites [15–17]. Figure 8.2 shows the coefficient of friction of the aluminum alloy and the aluminum matrix composite [20]. It shows that the coefficient of friction of the aluminum MMC is less than that of unreinforced aluminum alloy [17].

Different factors can affect the wear and friction behavior of MMCs. The basic tribological parameters which can control the wear and friction behavior of MMCs can be classified into three categories [8]:

1. Material factors (intrinsic to the material undergoing surface interaction), such as type of reinforcement, reinforcement size, shape of reinforcement, reinforcement volume fraction, and microstructure of matrix.
2. Mechanical factors (extrinsic to the material undergoing surface interaction), such as normal load, sliding velocity, and sliding distance.
3. Physical factors (extrinsic to the material undergoing surface interaction), such as temperature and environmental conditions.

In this chapter, the influence of some of these parameters on tribological behavior of MMCs is discussed.

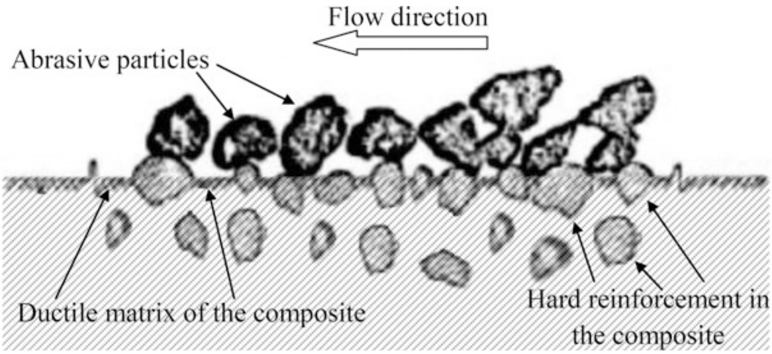


Fig. 8.3 Schematic illustration of hard second-phase particles protecting the ductile matrix from abrasion [35]

2.1 Volume Fraction

The volume fraction of particles has a strong effect on the wear resistance of MMCs [21, 22]. In general, increasing the reinforcement content enhances the wear resistance of composite materials [5, 23–30]. This is mainly due to the fact that the mechanical properties such as hardness and strength of MMCs increase with increase in the volume fraction of the reinforcements [31]. This trend was observed in different MMCs, such as Al–Fe composite [32], AZ91D–0.8 % Ce alloy reinforced by Al_2O_3 short fibers and graphite [33], nickel matrix composite reinforced by graphite and MoS_2 [19], and steel matrix composites reinforced with (W, Ti)C particles [34].

During sliding, the hard second phase particles resist the metal matrix against wear. Sometimes, these second phase particles might become dislodged from the matrix, and when this occurs the wear rate of matrix material increases due to abrasion of the second phase particles. At a certain critical volume fraction of the reinforcement, the metal matrix will be protected to a maximum extent. Figure 8.3 schematically illustrates the mechanism of protecting the ductile matrix by hard second-phase particles against abrasive particles. An increase in the volume fraction of reinforcement reduces the plastic deformation in the layer below the worn surface, which ultimately reduces the adhesive wear of the composite [35].

Figure 8.4 presents the wear rate of the aluminum MMC reinforced by micron-sized SiC particles as a function of volume fraction of SiC particles at different normal loads. It can be seen that when the volume fraction of SiC particles increases, the wear rate of the composite linearly decreases. This reveals that the volume fraction of the reinforcement is proportional to the wear resistance of the composite. The percentage improvement in the wear resistance of composites with respect to an alloy could be calculated from the measured wear rate values using the following equation [36]:

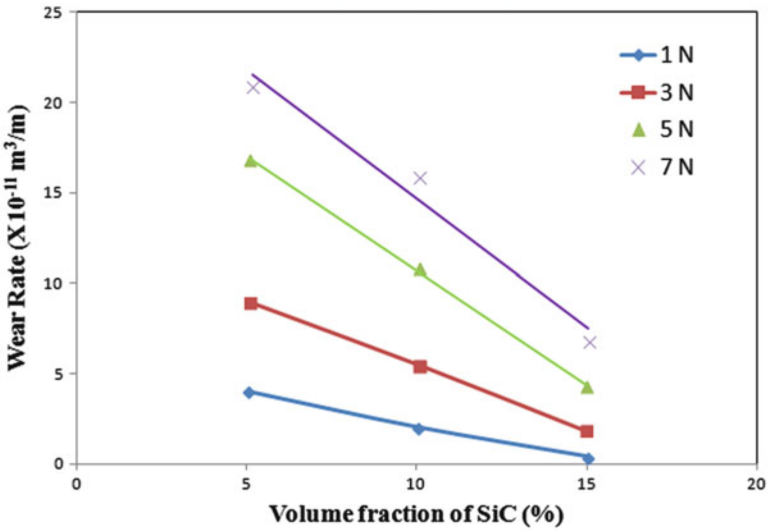


Fig. 8.4 Effect of volume fraction of SiC on the wear rate of aluminum metal matrix composite [36]

$$IWR_{ca}(\%) = \left(\frac{W_a - W_c}{W_a}\right) \times 100 \qquad (8.2)$$

where IWR_{ca} is the percentage improvement in the wear resistance of the composite with respect to an alloy, W_a is the wear rate of an alloy, and W_c is the wear rate of the composite.

It is interesting to note that the improvement in the wear rate of the composite significantly diminished by increasing the volume fraction of micron-sized reinforcements over 20 vol%. As shown in Fig. 8.5, the aluminum alloy (Al-1080) reinforced by 10–50 % volume fraction of SiC with particle size of 20 μm indicates that weight loss is decreased by increasing the volume fraction of SiC particles. Until 20 vol% of the reinforcement, the weight loss decreases significantly. However, over 20 vol%, the weight loss decreases a negligible amount with increasing volume fraction of particles [37]. This trend has also been shown by other researchers [25, 35, 38]. Besides, it is commonly recommended for MMCs reinforced by ceramic particles that the volume fraction of ceramic should not be more than 30 vol% if the composite is proposed for structural applications [39].

Similar experiments have been carried out with nano-composites. A nano-composite is a multiphase solid material where the size of one of the phases or the constituents, at least in one dimension, is less than 100 nm or has a structure included with nano grains [40]. Metal matrix nano-composites (MMNCs) usually

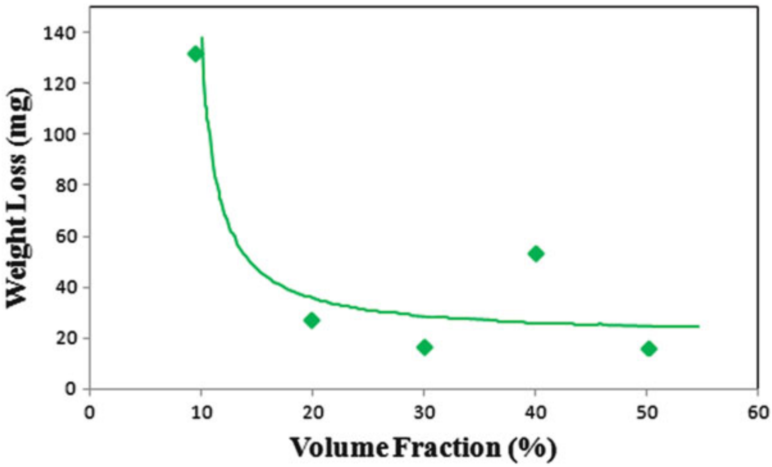


Fig. 8.5 Weight losses of the aluminum composite with vol% of SiC as reinforcement [37]

have better mechanical and tribological properties than those of MMCs reinforced by micron-sized particles [41–46].

Two factors have significant effects on the properties of MMNCs. They are (a) distribution of nanoparticles into the metal matrix and (b) deagglomeration of nanoparticles. Researchers have demonstrated that by having a good distribution of nanoparticles in the matrix [47, 48] and avoiding agglomeration of nanoparticles in the matrix [45, 49], the properties of MMNCs can be improved.

Among different nano reinforcements, such as Al_2O_3 and SiC, the recently developed nano reinforcement, such as carbon nano tubes (CNTs), has shown significant interest for researchers due to their excellent mechanical and physical properties. It is expected that the utilization of multi-wall carbon nano tubes (MWCNTs) will increase in the industrial applications due to their optimum cost. Thus, there have been many investigations to develop MMNCs reinforced with MWCNTs using various fabrication routes. One of the best methods for dispersion of CNTs in matrices is the frequently utilized powder metallurgy process [9, 19].

Some studies have explored the effect of volume fraction of CNTs as reinforcement in MMNCs on the wear rate of these composites [50–52]. The results illustrate a reduction of wear rate with an increase in the volume fraction of reinforcements up to 20 vol% as shown in Fig. 8.6. Nano-sized particles, when compared to the micron-sized particles, have more surface area than its volume. As a result, nanoparticles come together and tend to agglomerate so as to decrease their surface energy. This phenomenon has a negative effect on nano-composites and causes the properties of nano-composites to degrade. A good distribution of nanoparticles into the matrix and agglomeration prevention of nanoparticles are two important challenges during synthesizing of nano-composites. These challenges are much more difficult in larger volume fraction of nano-sized particles in the matrix. A study on aluminum matrix composites reinforced by MWCNTs has shown that the

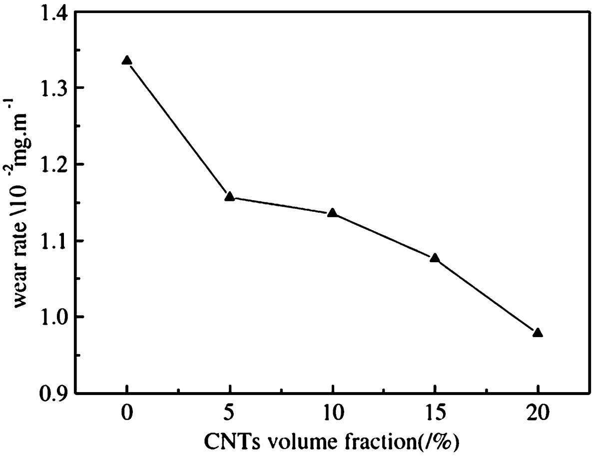


Fig. 8.6 Effects of CNT volume fraction on the wear rate of the CNT/Al composite at a sliding velocity of 0.1571 ms^{-1} under a load of 30 N [50]

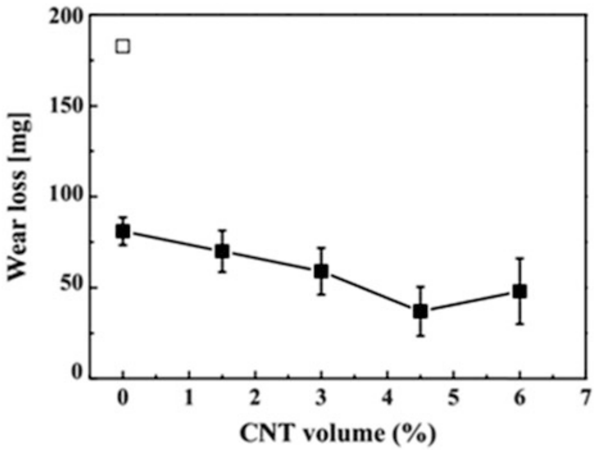


Fig. 8.7 The variation of wear rate with volume fraction of MWCNT [9]

composite with 4.5 vol% of CNTs has the minimum wear rate after 30 min of sliding at an applied load of 30 N and a sliding speed of 0.12 mm/s as shown in Fig. 8.7 [9]. According to this figure, by increasing the volume fraction of MWCNT up to 4.5 vol%, the wear loss of the composites gradually decreases and the wear resistance of the composites increases. However, when the volume fraction of the MWCNTs is more than 4.5 vol%, the wear resistance of the composite decreases. The decreasing tendency in wear resistance of the composites which contain the higher volume fraction of MWCNTs may due to the presence of voids, cracks, and agglomeration of nanoparticles. These kinds of defects could act as a source of weakening of the composites, and as a result the wear resistance of the composite decreases [9]. Moreover, many researchers [45, 53] have shown that when the volume fraction of nanoparticles in the composite is more than 4 vol%, the mechanical properties of composite decrease due to the agglomeration of nano-sized particles. It is worth mentioning that the mechanical properties of MMCs have a great influence on wear resistance of the composites. A decrease in mechanical properties of the composites may lead to a decrease in wear resistance.

Hybrid metal matrix composites (HMMCs) are engineering materials reinforced with a combination of two or more different types of reinforcements. These composites have combined the properties of each reinforcement and exhibited an improvement in physical, mechanical, and tribological properties of the composites [54]. It has been reported that the hybrid composites have a lower wear rate than the composites which are reinforced by only one type of reinforcements. In general, the tribological properties of HMMCs are also increased by increasing the amount of reinforcements in the composites [55, 56].

As mentioned earlier, graphite is a solid lubricant which is used as reinforcement in metal matrices. Graphite usually increases the wear resistance of the composites by forming a protective layer between two contact surfaces of materials during sliding [7, 57]. In addition, it has been reported that by adding a hard ceramic particle like Al_2O_3 or SiC to the matrix the mechanical properties of the composites increase [45, 46]. Moreover, it has been shown that synthesizing an HMMC reinforced with hard ceramic particle and graphite at the same time increases the mechanical properties and also the wear resistance of the composite simultaneously [25]. In this regard, efforts have been made to study the mechanical behavior and wear resistance of two aluminum matrix composites. The results showed that hybrid aluminum alloy matrix composite reinforced by SiC and graphite (20 % SiC–3 % and 10 % Gr-Al) has a better mechanical properties and wear resistance than aluminum alloy matrix composite reinforced by SiC (20% SiC–A356) [6].

The wear behavior of a hybrid aluminum matrix composite reinforced by SiC and Al_2O_3 is also investigated. The results showed that the wear resistance of the hybrid composites reinforced by SiC and Al_2O_3 is higher than that of the aluminum matrix composite reinforced by SiC or Al_2O_3 alone [5, 54, 58–60]. Similar results are also observed in magnesium alloy hybrid composites. The magnesium alloy hybrid composite reinforced by Saffil short fibers and SiC particles has lower wear rate than magnesium alloy reinforced only with Saffil short fibers. In the hybrid composite, the SiC particles remain intact while retaining their load bearing capacity. The SiC particles also delay the fracturing of saffil short fibers at higher loads and cause an increase to the wear resistance of the hybrid composites [61].

Figure 8.8 shows a general variation of wear rate with volume fraction of reinforcement in the composites. The data for this plot was obtained from different references [22, 38, 62–66]. As indicated earlier, the wear rate of the composite decreases with increasing volume fraction of the reinforcement particles.

It has been indicated that the coefficient of friction of the composites decreased with increase in the volume fraction of reinforcements [25, 26, 50, 67, 68]. The coefficient of friction of aluminum matrix composite reinforced with CNTs decreases with increasing volume fraction of CNTs in the composite as shown in Fig. 8.9. It has been indicated that an increasing volume fraction of CNTs at the contact surfaces reduces the direct contact between the metal matrix and the

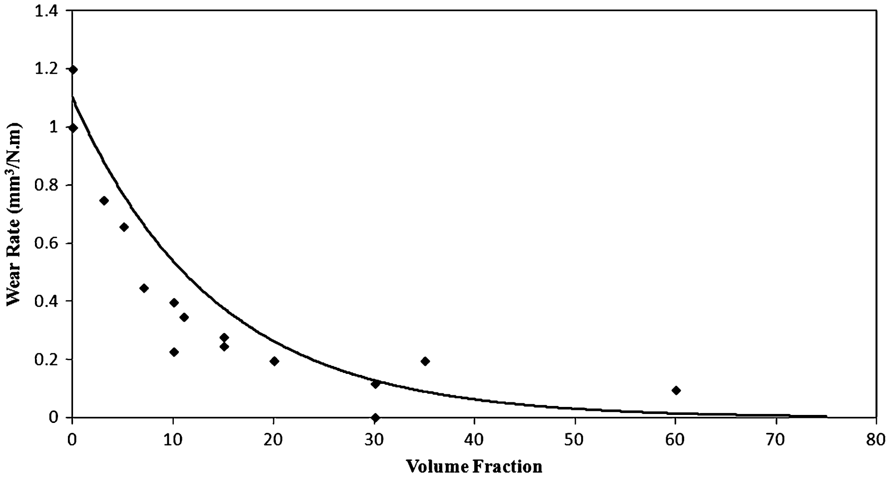
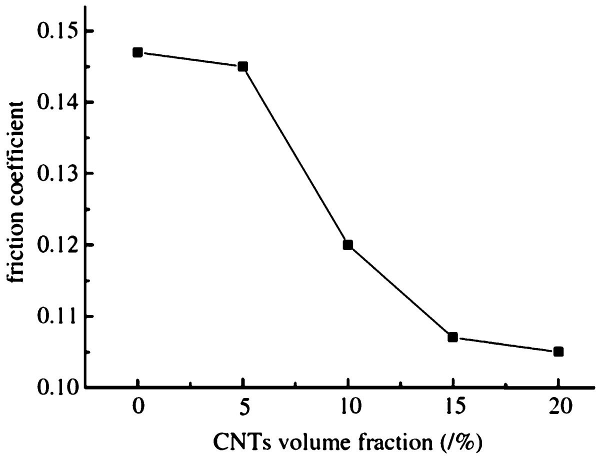


Fig. 8.8 Effect of volume fraction of reinforcement on wear rate of composites [22, 38, 62–66]

Fig. 8.9 Effects of CNT volume fraction on the friction coefficient of the CNT/Al composite at a sliding velocity of 0.15 ms^{-1} under a load of 30 N [50]



counterface [50, 52]. The CNTs have tube shape and also have the self-lubricating properties. Due to these characteristics, the CNTs can slide or roll easily between the mating metal surfaces; consequently, the coefficient of friction of the MMCs reinforced by CNTs decreases.

The coefficient of friction values of pure aluminum and aluminum matrix composite reinforced by MWCNTs with varying volume fraction is presented in Fig. 8.10. The coefficient of friction of the composite dramatically decreases with increasing volume fraction of MWCNTs up to 4.5 vol% because of the lubricating

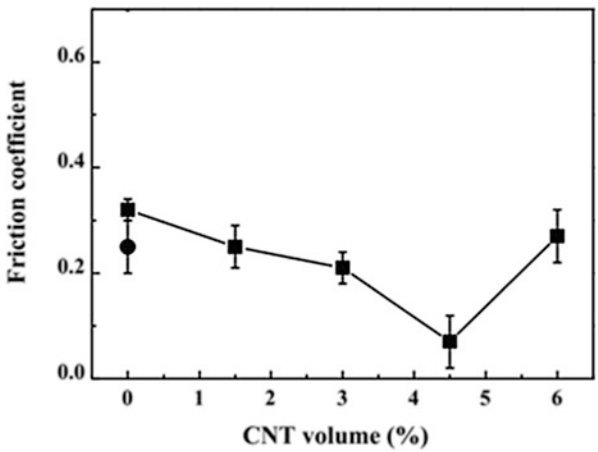


Fig. 8.10 Variation of coefficient of friction with MWCNT volume fraction in the composite [9]

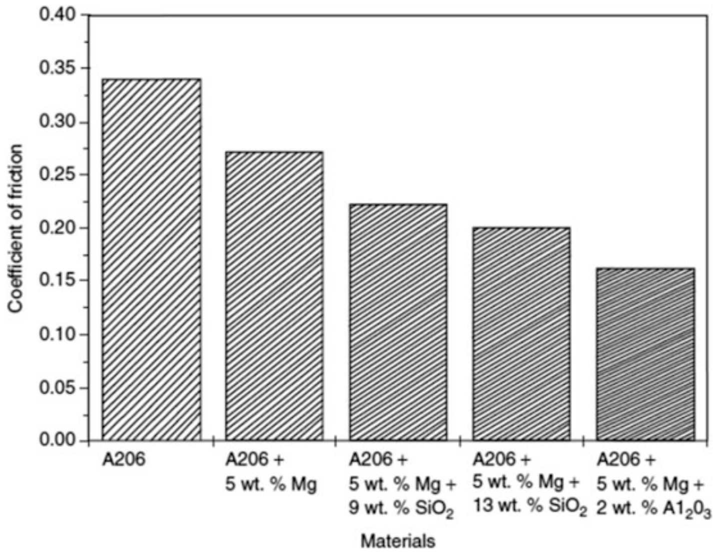


Fig. 8.11 Coefficient of friction values for various metal matrix composites reinforced by micron and nanoparticles [69]

effect of MWCNTs. Later on, the coefficient of friction of the composite increases with increasing volume fraction of MWCNTs. The composite that contains 4.5 vol % MWCNTs has the lowest coefficient of friction (about 0.1) [9].

As indicated earlier, the MMCs reinforced by nano-sized reinforcements usually have better wear resistance than the MMCs reinforced by micron-sized particles. Likewise, the MMNCs usually have lower coefficient of friction than the micron composites. Figure 8.11 shows the coefficient of friction values for aluminum

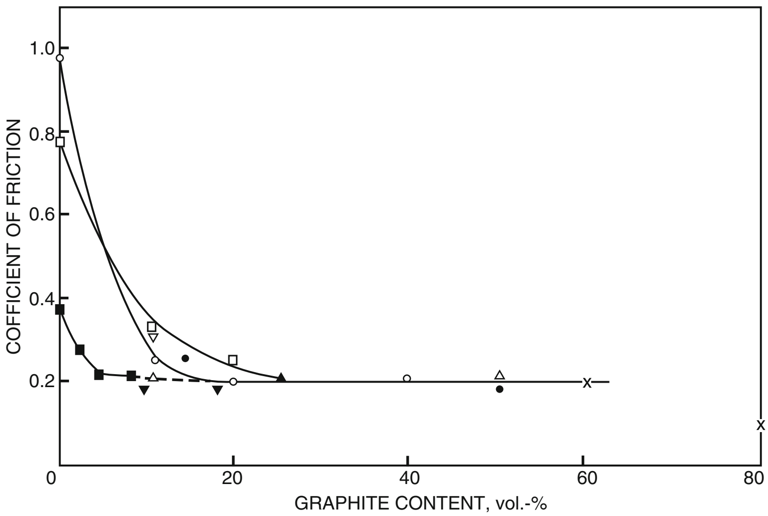


Fig. 8.12 Variation of coefficient of friction with graphite content for composites with different base alloys [70]

alloys and its composites. It can be observed that the A206 alloy shows the highest coefficient of friction values among other materials. Adding of 5 wt% magnesium to the A206 alloy decreased the coefficient of friction to a lower value. It can also be observed that the coefficient of friction values of the micro-composites is lower than that of aluminum alloys. The results show that by increasing the amount of reinforcement (SiO_2) from 9 to 13 wt% in the micro-composites, the coefficient of friction of the composites decreases. Moreover, it has been shown that by using 2 wt % nano-alumina instead of the micro-SiO_2 in the composite, the coefficient of friction of the nano-composite decreases to the lowest values among the materials tested. It is important to be mentioned again that the nano-composite showed the lowest coefficient of friction compared to that of the other micro-composites and unreinforced matrix materials [69].

Figure 8.12 presents the variation of friction coefficient with graphite volume fraction in the composites prepared using different base alloys. This figure shows that the coefficient of friction attains a constant value of close to 0.2 by increasing the amount of graphite in the composites over 20 vol%, and this is true for different composites. This means that the coefficient of friction is almost independent of the matrix and the graphite content over 20 vol%. The coefficient of friction of elemental graphite is about 0.18 and it increases with desorption of adsorbed vapors. Thus, when the content of graphite in the composites exceeds 20 vol%, both of the mating surfaces, including the composite reinforced by graphite and the counterface material like steel, are completely covered with the graphite, and a coefficient of friction value of 0.2, which is close to that of pure graphite against itself (i.e., 0.18), is observed regardless of the matrix material [70].

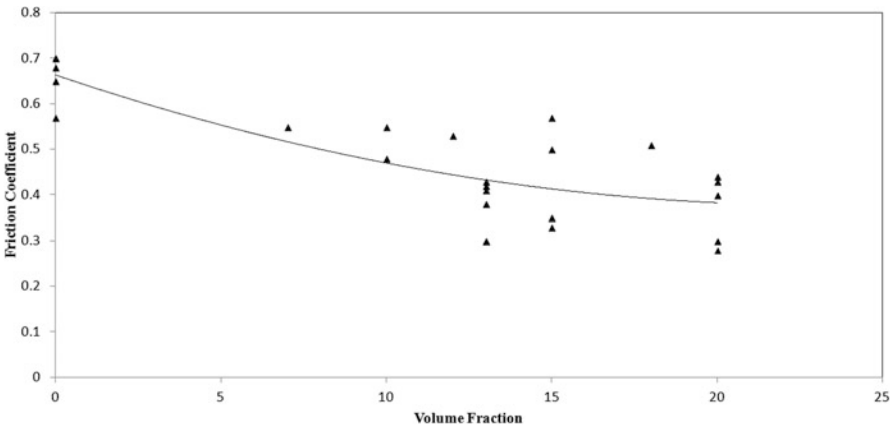


Fig. 8.13 Effect of volume fraction of reinforcements on friction coefficient of composites [13, 15, 38, 65, 71–78]

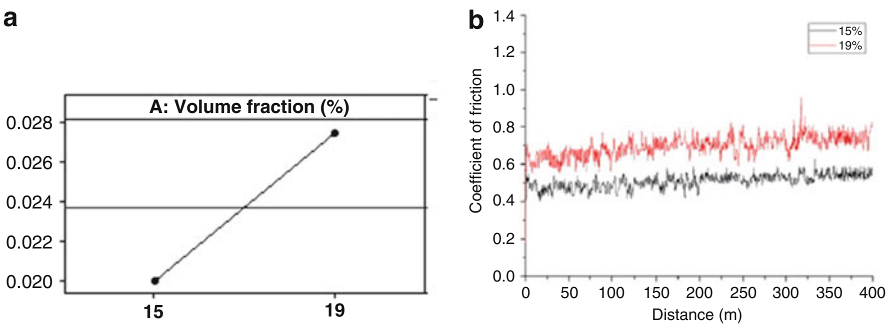


Fig. 8.14 The effect of increasing vol% of B_4C_p on (**a**) wear rate and (**b**) the friction coefficient of Al metal matrix composite [13]

Figure 8.13 shows the variation of the coefficient of friction with volume fraction of the reinforcements of composite materials. The data here is obtained from various research works [13, 15, 38, 65, 71–78]. The result shows that the coefficient of friction decreases with increasing volume fraction of the reinforcement in the composites.

It has been shown earlier that the wear rate of the composites generally decreases with increasing reinforcement volume fraction in the MMCs. However, the tribological behavior of the aluminum matrix composites reinforced by B_4C_p has showed different results [13]. It is important to note that the B_4C_p is an extremely hard particle when compared to other reinforcements, such as SiC or Al_2O_3. The research results indicate that there is an increase in the values of the wear rate (see Fig. 8.14a) and the coefficient of friction (see Fig. 8.14b) of the composites with increasing volume fraction of B_4C particles from 15 to 19 vol%. The amount of

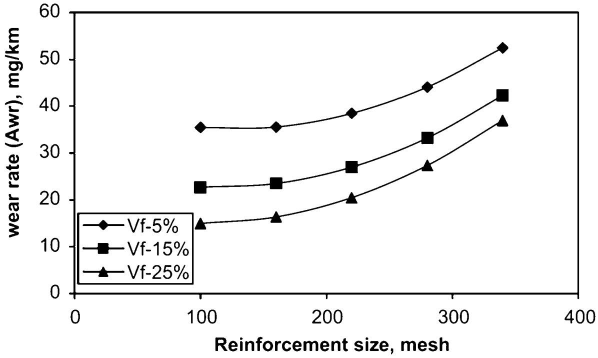


Fig. 8.15 The effect of reinforcement mesh size on the wear rate of MMCs [89]

abraded out B_4C particles at the interface between the counterface and the composite with 19 vol% B_4C in the wear test is higher than that at the interface between the counterface and the composite with 15 vol% B_4C. Consequently, the presence of higher amount of B_4C hard particles between two surfaces causes an increase in the wear rate and the coefficient of friction of the composite. This type of variations is very rare.

2.2 *Particle Size*

The mechanical and tribological properties of MMCs, such as hardness [79], ultimate tensile strength (UTS) [80], ductility [81], toughness [82], wear resistance [83], and coefficient of friction [84] depend strongly on the size of the reinforcement particles. The reinforcement which can affect the wear resistance of MMCs is an important parameter provided that a good interfacial bonding between the reinforcement and the matrix occurs.

MMC materials usually show a lower wear rate than the unreinforced alloys mainly due to the strength improvement of the composites caused by embedding the particles into the matrices. The particles act as load-bearing constituents in the composite materials and lead to an increase in the wear resistance of the metal matrices reinforced by particles in comparison with the unreinforced alloys [85].

It is well known that the nanoparticle-reinforced MMCs showed better wear resistance than the micro-particle-reinforced MMCs. Within the micro-composites, the effect of the particle size on the wear rate of the MMCs is not clear. Some researchers have indicated a decrease in the wear rate of the MMCs with an increase in the particle size of the reinforcements [6, 23, 86–88]. Efforts have been made to study the wear rate of 2014 Al matrix composite reinforced by SiC with different particle sizes. The results showed that the Al matrix composite reinforced by 15.8 μm SiC particle size has a superior wear resistance than the composite with the same volume fraction of 2.4 μm SiC particle size [23]. Figure 8.15 shows the wear rate of AA7075 Al matrix composite reinforced by SiC particles. The figure

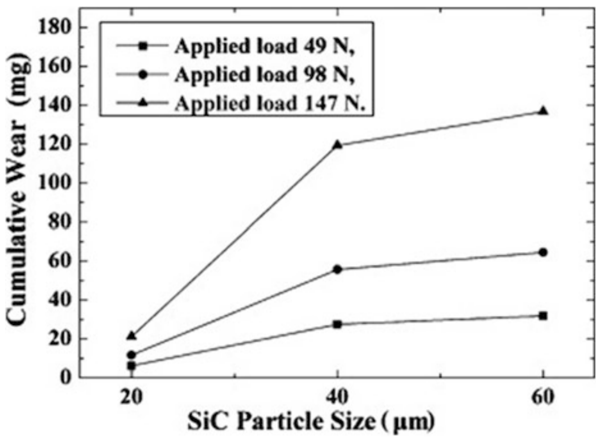


Fig. 8.16 Effect of various SiC particle size (volume fraction of 12 %) on the wear rate of magnesium metal matrix composite [91]

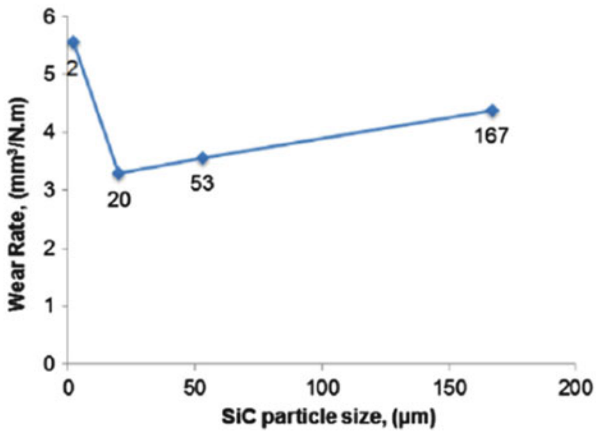


Fig. 8.17 The effect of particle size of reinforcement on the wear rate of the composite [66]

shows an increase in the wear rate of the MMCs with an increase in the mesh size of the reinforcements (increasing the mesh size means decreasing the particle size) [89]. However, other investigations have shown an increase in the wear rate of the MMCs by an increase in the size of the reinforcements [89, 90]. Figure 8.16 shows the wear rate of magnesium matrix composite reinforced by SiC particles. The figure shows an increase in wear rate of the MMCs with an increase in the size of the reinforcements [91]. Nevertheless, some studies show a critical particle size of reinforcements at which the wear rate of the composites changes considerably [66, 90]. Figure 8.17 shows the wear rate of the aluminum matrix composites reinforced by SiC particles (2–167 μm). The wear rate of the composites decreases with particle size up to 20 μm and later it increases with increasing particle size up to 167 μm. It has been observed that a critical particle size is important to determine the wear behavior of the composites. The 20 μm SiC particle size is the critical size for this composite at which the minimum wear rate is obtained [66].

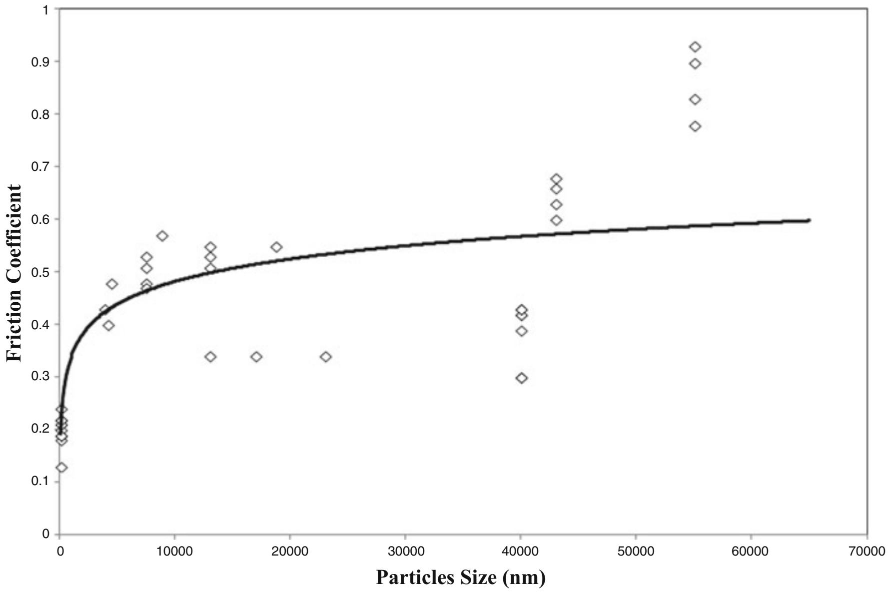


Fig. 8.18 The effect of particle size on coefficient of friction of the composites [14, 65, 72–75, 78, 85, 92, 93]

The effect of reinforcement particle size on the coefficient of friction has been studied. Figure 8.18 shows the variation of the coefficient of friction with particle size. The data presented here is considered from different references [14, 65, 72–75, 78, 85, 92, 93]. The results show that the friction coefficient increases with increasing particle size of the reinforcements.

Based on the above discussion, it is difficult to predict the wear behavior of the micro-composite reinforced by micron-size particles of varying sizes. However, a clear trend was observed when comparing the tribological properties between micron- and nano-composites. Figure 8.19a, b shows the wear rate and coefficient of friction of aluminum matrix composite reinforced by 15 vol% nano and micron Al_2O_3 particles. The results show a significant drop in the friction coefficient and wear rate of aluminum composites when the particle size is reduced below 1 μm [94].

2.3 Shape of Particle

Shape of the reinforcements is another factor that may affect the tribological behavior of MMCs. The wear resistance of (a) hybrid aluminum matrix composites reinforced by 10 % Saffil fibers and 5 % graphite fibers, (b) hybrid aluminum matrix composites reinforced by 10 % Saffil fibers and 5 % graphite flake, (c) aluminum

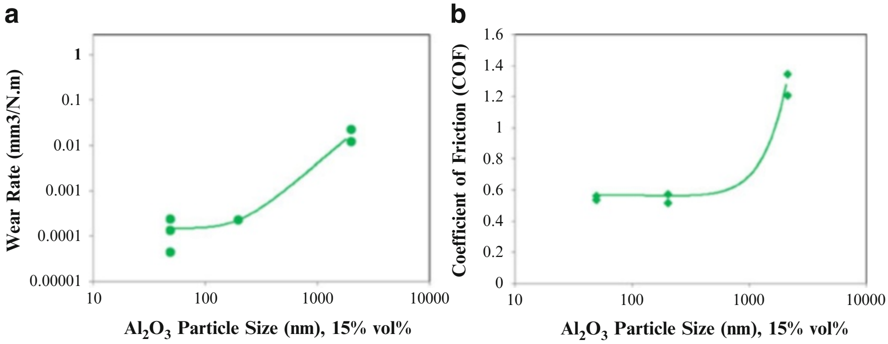


Fig. 8.19 Effect of particle size on (**a**) wear rate and (**b**) coefficient of friction of Al–15 vol% Al_2O_3 metal matrix composites [94]

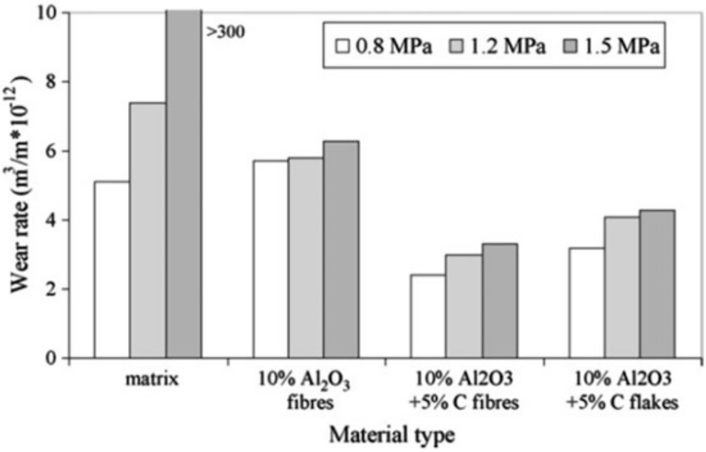


Fig. 8.20 The effect of normal load and graphite shape on the wear behavior of the composite at 0.8, 1.2, and 1.5 MPa contact pressures [10]

matrix composite reinforced by 10 % Saffil fibers, and (d) unreinforced aluminum alloy are compared in Fig. 8.20 [10]. The results showed that aluminum matrix composites reinforced by alumina fibers only prevent adhesion and seizure, especially under higher pressures, greater than 1 MPa. The aluminum matrix composites reinforced by alumina fibers and graphite (hybrid composites) showed a reduction in the wear rate when compared to Al/Saffil composites. Also, the shape of the graphite has an effect on the wear rate of the hybrid composites. The experimental results have indicated that the graphite fibers are more effective than the graphite flakes. This difference is much clear at low volume fraction of alumina fiber in the composites and at high pressure. In addition, the orientation of the alumina fibers affects the wear behavior of the composites, specifically at higher pressure. Parallel

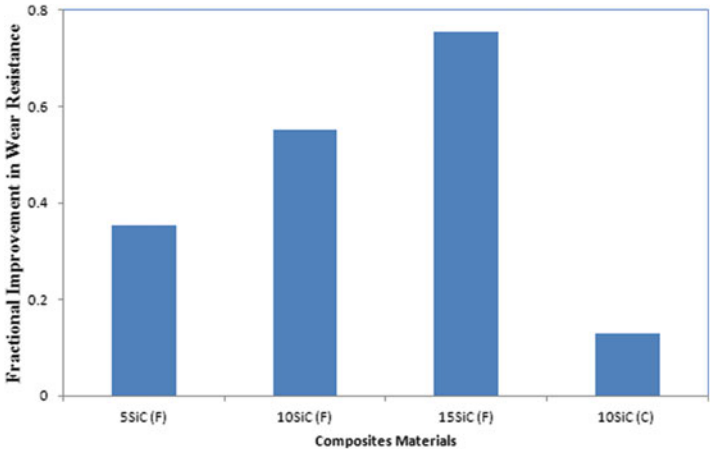


Fig. 8.21 Bar chart showing improvement in wear resistance of metal matrix composites reinforced by fine particles (F) and coarse particles (C) [36]

arrangement of the fibers to the friction surface has lower wear rate than the perpendicular arrangement [10].

Figure 8.21 compares the wear resistance of three different composites reinforced by fine particles and a composite reinforced by coarse particles. It was found that the percentage improvement in the wear resistance of the composites with respect to that of an alloy is 26, 55, and 75 % for 5, 10, and 15 vol% fine SiC reinforcements, respectively. On the other hand, the percentage improvement in the wear resistance of 10 vol% coarse SiC particle-reinforced composite is around 15 % as compared to 55 % improvement in 10 vol% fine SiC particle-reinforced composite [36].

2.4 Normal Load

Normal load is an important mechanical factor which affects the wear rate and friction coefficient of MMCs. With increasing applied normal load, especially at higher normal loads, fracture of the reinforcement particles in the matrix may occur. As a result, the mechanical properties of the composite decrease and hence the wear rate of the composites increases to the levels comparable to those of the unreinforced metallic matrix. It is generally accepted that the wear rate of MMCs increases with increasing normal loads during sliding [13, 14, 18, 26, 34–36, 89, 95, 96] as shown in Fig. 8.22. This type of trend has been observed in Al–Fe composite [32], Mg alloy matrix hybrid composite reinforced by Saffil short fibers (diameter 3–8 µm and length 200 µm) and SiC particles (40 µm) [61], AZ91D–0.8 % Ce alloy matrix hybrid composite reinforced by Al_2O_3 short fibers and graphite [86], and Cu/WC composites [97]. In addition to the increase of wear

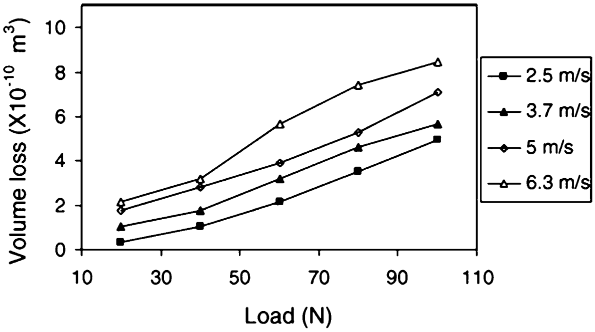


Fig. 8.22 Variation of wear rate of MMCs with applied normal loads [14]

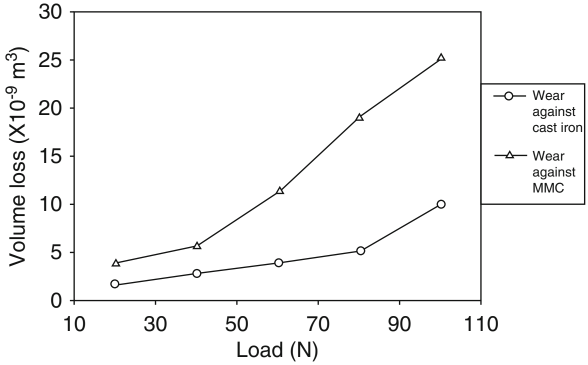
rate with increasing normal load, the wear mechanism of the composites changes with normal loads. It has been reported that the wear mechanism of the composites is usually by oxidation at lower normal loads. However, the wear mechanism of the composite materials at higher normal load is changed to adhesive wear and delamination wear [24]. It has been reported that a critical normal load would exist during wear test of MMCs [76]. Below this critical normal load, the wear rate is usually mild and steady. However, the wear rate increases and a severe wear occurs above this critical normal load during sliding. It has also been demonstrated that the temperature of the contact surfaces can influence the amount of the critical normal load, and at higher temperature the critical normal load decreases [98].

All flat surfaces and even those polished to a mirror finish are not perfectly flat on an atomic scale. Asperities or surface projections exist on all flat surfaces. When two flat surfaces come into contact, these two surfaces touch only at tops of highest asperity points. As a result, the contacts can be defined by (a) apparent area of contact (AAC) and (b) real area of contact (RAC). The RAC is the total area of asperities of two surfaces which are actually in contact. As a result, the RAC is always less than the AAC. When the surfaces are subjected to a normal load, the contacting asperities are plastically deformed and the RAC increases with increasing normal load and moves towards the amount of AAC. As a result of increasing RAC between two surfaces, the wear rate and also the temperature between these two surfaces usually increase during sliding.

As mentioned earlier, there is a critical normal load above which severe wear occurs and this is because of the increase in the RAC. When the RAC increases and reaches to an amount very close to AAC, it is very difficult for two contacting surfaces to slide over each other. This situation in tribology is referred to as seizure. The seizure occurs for both the unreinforced and reinforced composites. The seizure event is usually accompanied by a sudden increase in wear rate, heavy noise, and vibration [99].

Some studies [14, 33] have shown that at lower normal loads, the wear rates of the composite materials with different volume fraction of the reinforcement and the unreinforced matrices are comparable to each other. The reinforced and unreinforced matrices can tolerate the lower normal loads, and consequently the wear rate is low. However, the difference between the wear rates of the composites and the

Fig. 8.23 The variation of wear rate at low and high loads [14]



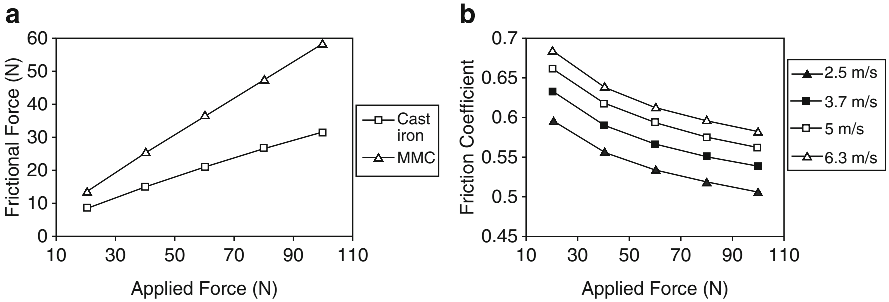


Fig. 8.24 Variation of (**a**) frictional force and (**b**) friction coefficient with different applied force [14]

unreinforced matrices is considerable at higher normal loads as shown in Fig. 8.23 [14]. At higher normal loads, the asperities of the unreinforced matrices plastically deform and the RAC increases; accordingly the wear rate also increases. The mechanical properties of the reinforced matrices are usually higher than the unreinforced one, and some amount of normal load is carried by the reinforcements during the wear tests. Thus, the plastic deformation of the asperities of reinforced matrices is delayed longer than the unreinforced one, and hence the reinforced matrices cause a lower wear rate. For example, as shown in Fig. 8.20, the wear rate of the unreinforced aluminum alloy was too high at a high contact pressure of 1.5 MPa, and the test was interrupted because of seizure. But, the wear rate of the composites at that contact pressure is much lower than the unreinforced one [10].

In general, an increment in the applied normal force increases the frictional force (see Fig. 8.24a). It has been reported that the coefficient of friction of MMCs decreases by increasing the normal load as shown in Fig. 8.24b [14, 18, 28, 57, 84, 95]. As an example, the tribological behavior of nickel matrix composites reinforced by graphite illustrates that the friction coefficient of the composites containing graphite decreases to about 0.3 by increasing the normal load [100].

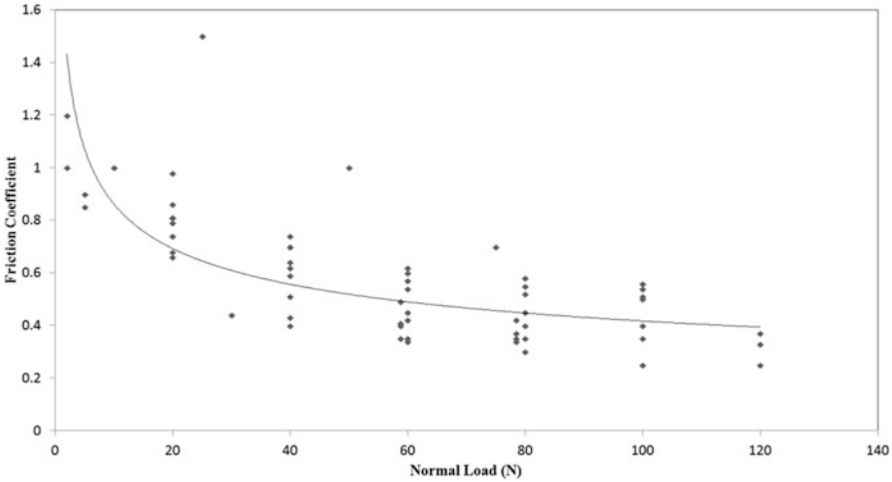


Fig. 8.25 The effect of normal load on friction coefficient [13, 14, 71, 101–104]

This is due to the formation of a transfer film during sliding, and this transfer film is found to be stable for longer duration and a broad range of normal loads. However, at very high normal loads, the transfer film may destroy [14], and as a result, the coefficient of friction may increase.

Figure 8.25 shows the results obtained from different resources demonstrating the effect of normal load on coefficient of friction of MMCs [13, 14, 71, 101–104].

2.5 Sliding Speed

Sliding speed is another important parameter which affects the tribological behavior of MMCs. It has been reported that an increase in the sliding speed causes an increase in the wear rate and decrease in the wear resistance of the MMCs [14, 26, 96, 105], and the variation between the wear rate and sliding speed is usually linear [106, 107]. As the sliding speed increases, the interface temperature also increases resulting in (a) the microthermal softening of matrix material [108], (b) oxide formation on the contact area [109], and (c) decrease in flow stress of the material [109]. In addition, there may be some changes in the microstructure, such as dissolution of precipitates which will also be reflected in the wear behavior. Since the physical and mechanical properties of different matrices in different composites are not the same, the microthermal softening, oxidation, and flow stress for different materials occur at distinct temperatures. As a result, the sliding speed may have different effects on the composites with different matrices.

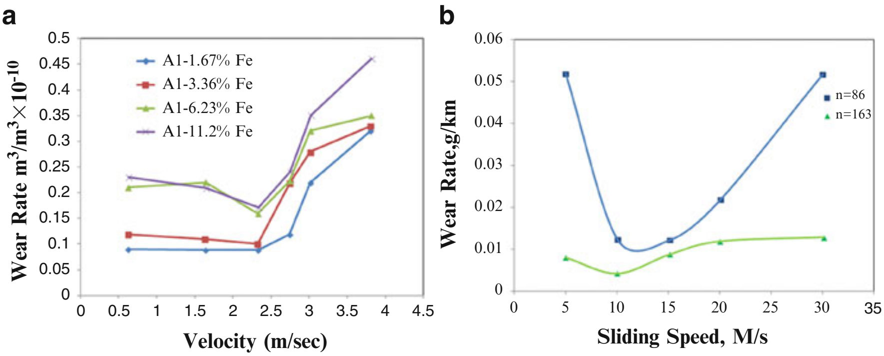


Fig. 8.26 Variation of the wear rate with sliding speed for (**a**) Al–Fe composites [32] and (**b**) aluminum matrix composite [5]

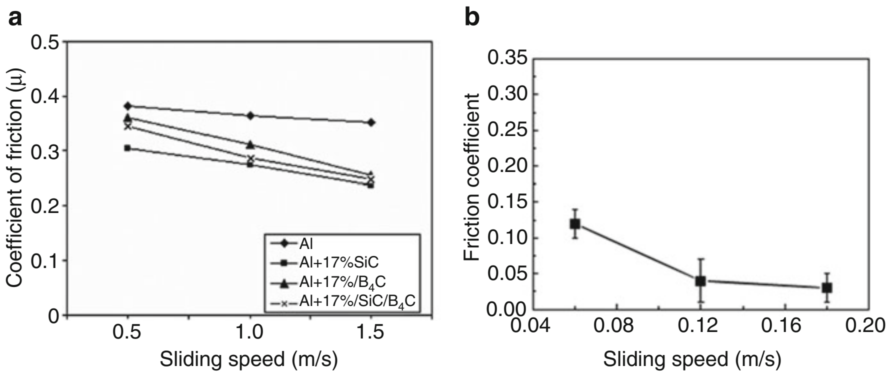


Fig. 8.27 Variation of coefficient of friction with sliding speed for (**a**) aluminum metal matrix composite reinforced by SiC and B_4C [110] and (**b**) aluminum metal matrix composite reinforced by CNT [9]

Several studies have shown that an increase in sliding speed leads to an increase in wear rate, especially at higher sliding speed ranges. For instance, Al–Fe and Al–SiC composite illustrate an initial decrease in the wear rate at lower sliding speeds; however, these composites showed a sharp increase in the wear rate at higher sliding speeds (see Fig. 8.26) [5, 32].

Generally, the friction coefficient of MMCs decreases with increasing sliding velocity [9, 13, 14, 18, 84, 110]. Figure 8.27a, b shows the dependency of the coefficient of friction of aluminum matrix composites reinforced by 17 % SiC and B_4C [110] and also 4.5 vol% CNTs [9] at different sliding speeds. It is obvious that the coefficient of friction decreases with increasing sliding speed. It can be observed in Fig. 8.27b that the coefficient of friction attains less than 0.05 with increasing sliding speed for the aluminum matrix nano-composite reinforced by CNTs.

2.6 Temperature

Temperature is another key parameter which affects the wear behavior of MMCs. The effect of temperature on tribological behavior of MMCs due to change in the normal loads and sliding speeds has been discussed in the previous sections. Investigations have demonstrated that the wear rate of MMCs initially decreases with increasing temperature and then increases with increasing temperature [19, 111, 112]. The thermal properties, such as thermal conductivity of the matrices and the reinforcements in the composites, may affect the wear resistance of MMCs at different temperatures. It has been reported that the higher thermal conductivity of the reinforcements in a composite can lead to an improvement in the wear resistance of the composites [113].

In general, there is a significant variation in the wear rate and coefficient of friction of MMCs by varying the temperature. These variations depend on the types of materials in the composites. Some studies have reported that a critical temperature exists which changes the wear rate and coefficient of friction of the MMCs [114, 115]. Below this critical temperature, the wear rate and coefficient of friction are either more or less constant or in some cases decrease inconsiderably with increasing temperature. Above this critical temperature, the wear rate and coefficient of friction increase significantly with increasing temperature. These variations are due to the change of mechanical properties of materials, such as hardness, at high temperatures. The critical temperature is generally higher for the MMCs when compared to the monolithic alloys. Figure 8.28 shows the variation of the wear rate and coefficient of friction with temperature for different aluminum matrix composites and monolithic aluminum alloys [114, 115]. In some composites a significant decrease in the wear rate and coefficient of friction with temperature below the critical temperature has been reported (Fig. 8.29) [116]. Hence, it can be inferred that the variation in tribological behavior of MMCs with temperature depends on the properties of the materials, such as mechanical properties of the materials at high temperatures.

The self-lubricating composites, such as Ni–Cr–W–Fe–C–MoS_2 composites, have excellent self-lubricating properties over a wide range of temperature due to the lubricating effect of graphite and molybdenum disulfide. The friction coefficient values of this composite are in the range of 0.14–0.27, and the wear rates are 1.0×10^{-6}–3.5×10^{-6} $mm^3/(Nm)$ from room temperature to 600 °C (see Fig. 8.30). The results have shown that the wear rate of the composite varied slightly by increasing the amount of MoS_2 in the composite at low temperatures; however, at elevated temperatures, the wear rate and the coefficient of friction of the composite decreased by increasing the amount of MoS_2 in the composite. At temperature above 400 °C, graphite oxidation occurs, and the graphite oxide does not act as a good lubricant at that temperature. As a result, the MoS_2 is responsible for reduction of coefficient of friction and wear rate at elevated temperature [19]. The effect of temperature on the friction coefficient of self-lubricating MMCs is not the same as the effect of temperature on the wear rate of these

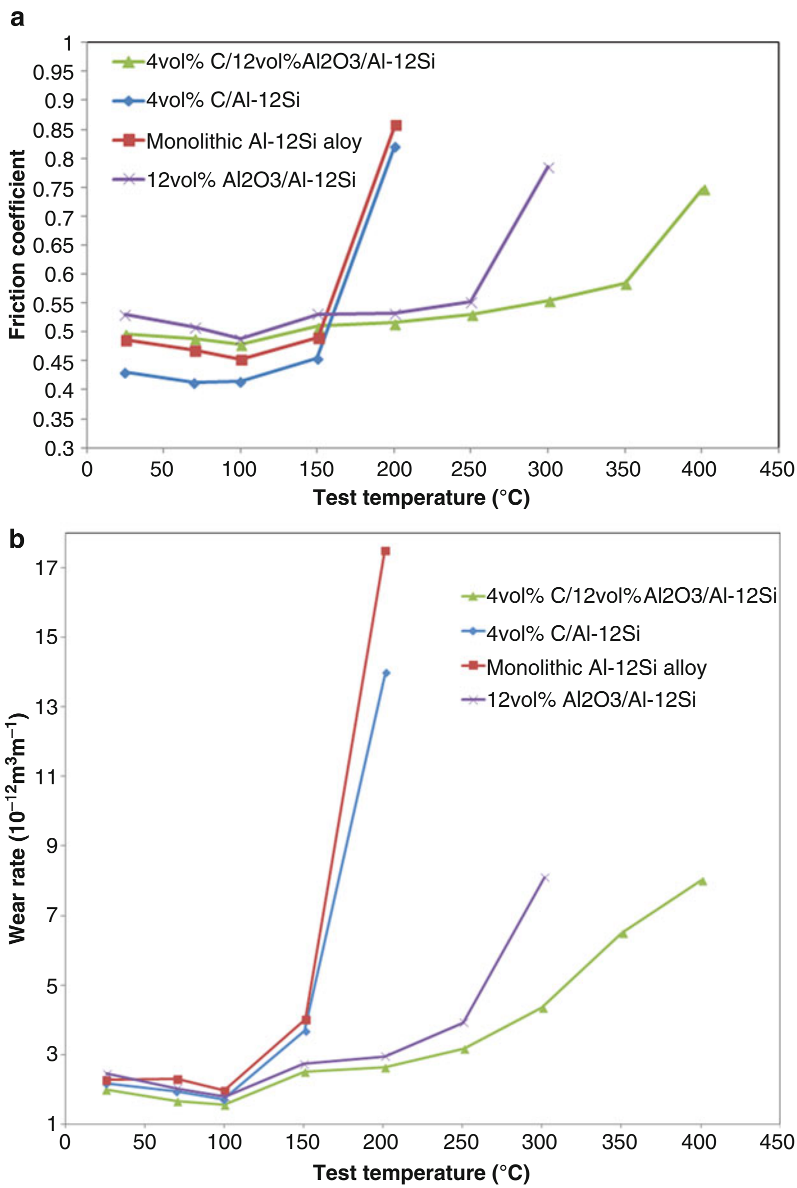


Fig. 8.28 Variations of (**a**) friction coefficient and (**b**) wear rate with test temperature for monolithic Al–12Si alloy, 4 vol% C/Al–12Si, 12 vol% Al_2O_3/Al–12Si composites, and 4 vol% C/12 vol% Al_2O_3/Al–12Si hybrid composites [114]

composites. Generally, increase in the temperature leads to a decrease in the coefficient of friction of the MMCs. Figure 8.30b shows the effect of temperature (from room temperature to 600 °C) on the coefficient of friction of nickel-based MMCs. In nickel-based MMCs reinforced by graphite, the friction coefficient in

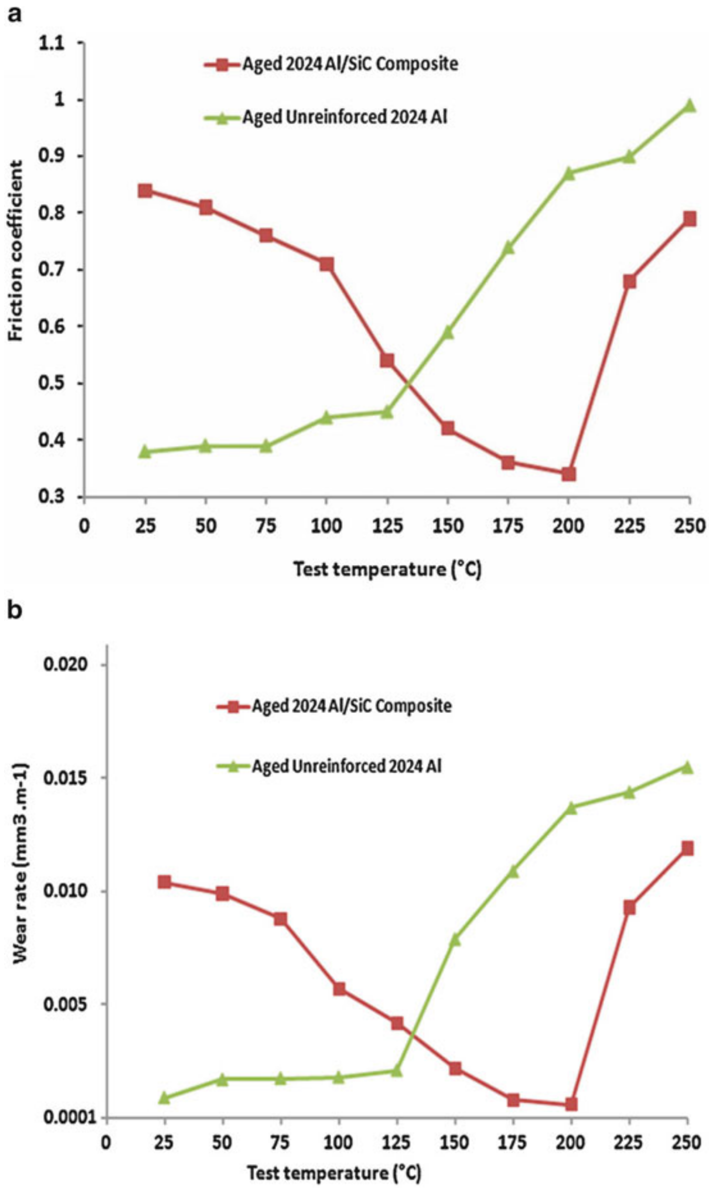


Fig. 8.29 Variations of (**a**) friction coefficient and (**b**) wear rate with test temperatures for aged 2024 Al/20 vol% SiC composite and aged unreinforced 2024 Al at the applied load of 20 N [116]

this range of temperature is about 0.8–1.0, while it is about 0.4–0.7 for nickel-based matrix composites reinforced by molybdenum disulfide. When graphite and MoS_2 are combined and used as reinforcement for nickel-based matrix, both the friction coefficient and the wear rate are reduced significantly. For instance, the coefficient

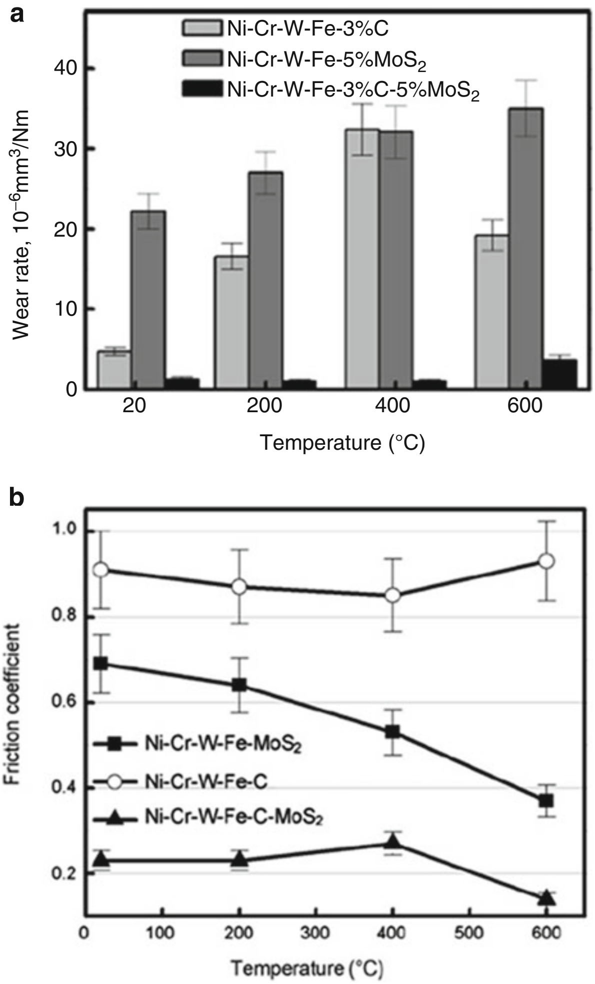


Fig. 8.30 The effect of temperature on the (**a**) wear rates and (**b**) friction coefficients of Ni matrix composite reinforced with graphite and MoS_2 lubricants [19]

of friction is reduced to about 0.2. In addition, the results have shown that at temperatures above 400 °C the oxidation of graphite occurs. At this temperature, the oxide layers form, and these layers play a key role of lubricant in the composites instead of graphite [19].

3 Summary

This chapter highlights the important parameters that affect wear and friction behavior of MMCs. More specifically, the influences of reinforcement size, volume fraction of reinforcement, shape of particles, normal load, sliding speed, and temperature on wear and friction behavior of MMCs have been discussed. As the tribological parameters, such as normal load, sliding speed, and temperature, vary on a wide range and also the counterface materials differ in different experimental tests, comparing the results of tribological behavior of different composites is extremely difficult. Composite materials usually demonstrate enhanced tribological behavior such as wear rate and coefficient of friction than unreinforced alloys, and this is mainly due to the strength improvement of the composites achieved by adding the particles as reinforcement into the matrix. Moreover, hybrid MMCs demonstrate better tribological properties than the MMCs. The reinforcement has a significant effect on wear and friction behavior of MMCs than other parameters such as the normal load and the sliding speed.

The volume fraction, size, and shape of reinforcements are the material factors which affect the tribological behavior of the composites. The effect of volume fraction of reinforcements is that the wear resistance of composite materials is enhanced and the friction coefficient of composites decreased by increasing the micron- and nano-size reinforcement content in the composite. However, an increase in the volume fraction of micron-size reinforcements over 20 vol% has no significant improvement on the wear rate. It is commonly suggested that the volume fraction of reinforcements should not be more than 30 vol% if the composite is proposed for structural applications. Deagglomeration and distribution of nano-size particles in the composites are two key challenges during production of nano-composites. These challenges can restrict the usage of high volume fraction of nano-sized particles in the composite. Among micro-composites, the reinforcement particle size has no clear effect on the wear and friction behavior of the composites. Some studies have shown a decrease in the wear rate of the MMCs with an increase in the particle size of the reinforcements, and on the other hand, other studies have shown an increase in the wear rate of the MMCs with an increase in the particle size of the reinforcements. When comparing micro- and nano-composites, the MMNCs usually show lower coefficient of friction and wear rate than the micro-composites.

Normal load is an important mechanical factor that affects the tribological behavior of the composites. The results have shown that the wear rate increases and friction coefficient of MMCs decreases with increasing the normal load. Similar to the normal load, sliding speed also influences friction and wear performance. An increase in the wear rate and a decrease in the friction coefficient of the MMCs occur when sliding speed increases during the wear test. The relationship between the wear rate with the normal load and the sliding velocity is almost linear. Temperature is another important parameter that affects the tribological behavior of MMCs. The wear rate and friction coefficient decrease with increasing temperature up to a critical temperature, and thereafter both wear rate and friction coefficient increase with increasing temperature.

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Problems

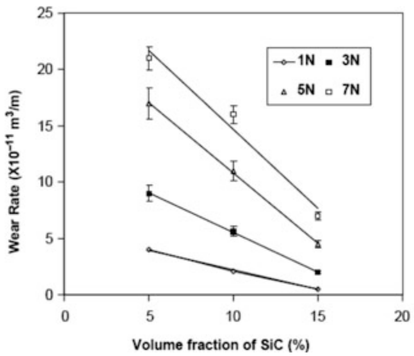
1. Mention the parameters which affect the wear and friction behavior of MMCs.
2. Explain the effect of the volume fraction of reinforcements on tribological behavior of MMCs and MMNCs with schematic diagrams.
3. How may the normal load affect the tribological (wear and friction) behavior of MMCs?
4. How can the interface temperature affect the tribological behavior of materials?
5. Different wear mechanisms occur during sliding of MMCs. Explain some of these mechanisms.
6. Tribological behavior of Al6061 and its composites reinforced by different weight percent of reinforcements have been investigated. The results are shown in Fig. 8.2. Calculate the percentage improvement in the wear resistance of composite reinforced by 12 wt% particles compared with Al6061 after 1 km sliding distance.
7. What is HMMC? Compare the tribological behavior of HMMC with MMC.

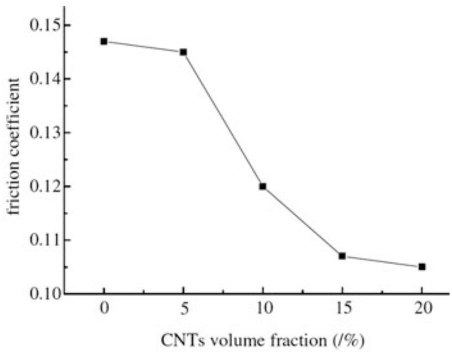
Answers

1. Different factors can affect the wear and friction behavior of MMCs. The basic tribological parameters which can control the wear and friction behavior of MMCs can be classified into three categories:

   - Mechanical factors (extrinsic to the material undergoing surface interaction), such as normal load, sliding velocity, and sliding distance.
   - Physical factors (extrinsic to the material undergoing surface interaction), such as temperature and environmental conditions.
   - Material factors (intrinsic to the material undergoing surface interaction), such as type of reinforcement, reinforcement size, shape of reinforcement, reinforcement volume fraction, and microstructure of matrix.

2. Tribology is a field of science and engineering which concentrates on interaction between surfaces of different materials in relative motion. This area of science includes the investigation and application of the principles of wear and friction. In general, increasing the reinforcement content enhances the wear resistance and the coefficient of friction of the composites of composite materials.
3. Normal load is another factor which affects wear rate and friction coefficient of MMCs. With increasing the applied load, especially in a high normal load, fracture of the reinforcement particles in the matrix may occur. As a result, the mechanical properties of the composite decrease and also wear rate of the composites increases to the levels comparable to those of unreinforced matrix alloys. It is generally accepted that when normal load increases, the wear rate also increases and the coefficient of friction of MMCs decreases during sliding.





4. The effect of temperature changes on tribological behavior of MMCs as a result of changing the normal load and the sliding. The wear rate of MMCs increases with increasing temperature, and increase in the temperature leads to a decrease in the coefficient of friction of the MMCs.
5. Different kinds of wear mechanisms may take place during the relative motion. These mechanisms include adhesive wear, abrasive wear, delamination wear, erosive wear, fretting wear, fatigue wear, and corrosive/oxidative wear. The common wear mechanisms of MMCs are adhesive wear, abrasive wear, fatigue wear, and corrosive/oxidative wear.

   Abrasive wear occurs when a hard rough surface slides against a softer surface. Abrasive wear also occurs by abrading action of hard particles that are available as debris at the interface. Abrasive wear can be caused by both metallic and nonmetallic particles, but mostly nonmetallic particles cause abrasion. Adhesive wear is caused between two metallic components which are sliding against each other under an applied load and in an environment where no abrasive particles are present at the interface. By applying the normal pressure, local pressure at the asperities increases to an extremely high value and often the yield stress is exceeded. Then, the plastic deformation occurs in asperities until the RAC has increased sufficiently to support the applied load. Consequently, the strong short-range forces come into action, and strong adhesive junctions may be formed at the RAC. During relative motion the adhered junctions are sheared. The name “adhesive” is given due to the forming of a strong metallic bond between the asperities on the surface of the contacting materials. The dynamic interactions between the environment and mating material surfaces play an important role in corrosive wear. In corrosive wear, the contacting surfaces react with the environment, and reaction products are formed on the surface of asperities. In the contact interactions of materials during sliding, wear of the reaction products occurs as a result of crack formation and/or abrasion. Specifically, corrosive wear occurs when reaction products on the surfaces of materials are removed through physical interaction of the two surfaces in contact. Fatigue wear can occur at the surface of materials which are cyclically stressed. For example, the ball bearings and the gears normally experience the fatigue wear due to the existence of cyclic stresses during their applications.

6. At first, according to Fig. 8.2, the wear rates of Al6061 and composites with 12 wt% particles are 0.15 and 0.07, respectively. So, the percentage improvement, according to (8.2), is

$$\mathrm{IWR_{ca}}(\%) = \left(\frac{0.15 - 0.07}{0.07}\right) \times 100 \approx 115\%$$

7. HMMCs are engineering materials reinforced by a combination of two or more different types of reinforcements. These composites have combined the properties of each reinforcement and exhibited an improvement in physical, mechanical, and tribological properties of the composites. It has been reported in some studies that the hybrid composites have a lower wear rate than the composites which are reinforced by only one type of particles. In general, the tribological properties of HMMCs are also increased by increasing the amount of reinforcements in the composites.