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Review

A Review of the Friction and Wear Behavior of Particle-Reinforced Aluminum Matrix Composites

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Abstract: Aluminum matrix composites are key materials used in the preparation of lightweight structural parts. It has the advantages of low density, high specific strength, and high specific stiffness. Additionally, its friction and wear properties are important factors that determine the material's suitability for use in a batch. Therefore, this paper systematically analyzes the current research on the friction and wear behavior of particle-reinforced aluminum matrix composites. It also discusses the effects of various internal factors, such as the microstructure characteristics of the matrix materials and the state of the reinforced particles, as well as external factors like wear pattern, applied load, sliding speed, thermal treatment, and temperature on the friction and wear properties of these composites. The applications of particle-reinforced aluminum matrix composites in the fields of transportation, aerospace, and electronics are summarized. In addition, this paper discusses the current research status and future development trends regarding the wear behavior of particle-reinforced aluminum matrix composites. Finally, this study aims to provide technical references for researching the friction and wear properties of particle-reinforced aluminum matrix composites. It is intended to benefit scientific researchers and engineering technicians and provide insights for the development of new composite materials in the future.

Keywords: wear behavior; aluminum matrix composites; influence factors; applications

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1. Introduction

With the rapid development of modern science and technology [1], traditional single-nature materials have become inadequate to meet the diverse needs of different fields. In order to adapt and meet the needs of modern science and technology, composite materials have emerged [2] and become indispensable and important components in the field of materials science and engineering. Modern composite materials are composed of two or more types of materials with different properties, which are combined using various processes such as superposition or product effects [3]. The core concept of composites is to "learn from each other", overcome the shortcomings and weaknesses of single-nature materials, and improve the comprehensive performance of materials [4]. Because of their high specific strength, specific modulus, good thermal conductivity, electrical conductivity, wear resistance, high-temperature performance, low coefficient of thermal expansion [5–8], high dimensional stability, and other excellent comprehensive properties, metal matrix composites have broad application prospects in aerospace, electronics, automobiles, and advanced weapon systems [9].

Among the various composites, the particle-reinforced aluminum matrix composite has emerged as a viable alternative to traditional wear-resistant materials. This is primarily due to its exceptional properties, including high specific strength, specific stiffness, low coefficient of thermal expansion, and excellent wear resistance. At present, the more common matrix materials are Al-Si [10], Al-Cu [11], Al-Mg, and other aluminum alloys [12]. The materials of the reinforcement are roughly divided into the following categories: oxides, such as Al_2O_3 [3,13], MgO, SiO_2 [14], etc.; carbides, such as SiC [4,15], TiC, BC, AlC, etc.; nitrides, such as Si_3N_4 [16], AlN, etc.; and other types of reinforcement, such as carbon nanotubes [17], TiB_2 [18], ZrB_2 [19], etc. Nevertheless, SiC particle-reinforced aluminum matrix composites are widely recognized as one of the most competitive types of particle-reinforced aluminum matrix composites [20]. In the past 20 years, researchers in various countries have conducted extensive research on aluminum matrix composites reinforced with SiC particles. However, compared with other friction materials, SiC particle-reinforced aluminum matrix composites not only possess the high wear resistance of ceramic and low expansion, high strength, and low density of aluminum alloys but also exhibit better thermal conductivity and other characteristics [21]. Therefore, they are considered to be excellent friction materials for high-speed trains. Additionally, due to its low cost and excellent manufacturing and processing properties, it has broad development prospects and has been highly valued by people [22]. Therefore, the wear resistance of particle-reinforced aluminum matrix composites has become the focus of researchers in various countries.

The behavior of friction and wear is a crucial performance indicator during the cyclic loading process of composite materials [23]. As we know, the wear properties of materials are typically characterized by the friction coefficient and wear rate [24]. The friction coefficient is an important parameter for measuring the friction and wear properties and studying the friction and wear mechanism of materials [25,26]. It is not only related to the process of friction but also to the properties and states of the friction pairs. The friction coefficient of the same material can vary under different experimental conditions [27]. The wear rate is a crucial indicator for measuring the wear resistance of aluminum matrix composites, and it is calculated as the reciprocal of the material's wear amount [28]. Although there are many ways to express the wear rate, it is usually expressed as the amount of wear per unit volume of the sample [29].

In this paper, the recent research progress on the wear properties of particle-reinforced aluminum matrix composites is reviewed. The common preparation techniques for aluminum matrix composites and the main parameters affecting their friction and wear behavior are briefly introduced. The effects of applied load, sliding speed, temperature, and reinforcement particles on the wear properties of aluminum matrix composites are analyzed. The wear mechanism of aluminum matrix composites under various conditions is discussed, the application fields of particle-reinforced aluminum matrix composites are summarized, and the future trends in wear property research are pointed out. This provides researchers with new research ideas for the development of new-style composite materials. In order to clearly convey the idea of this work, the framework of this review is presented in Figure 1. It mainly includes the typical preparation technology, wear mechanism, and applications of particle-reinforced aluminum matrix composites.

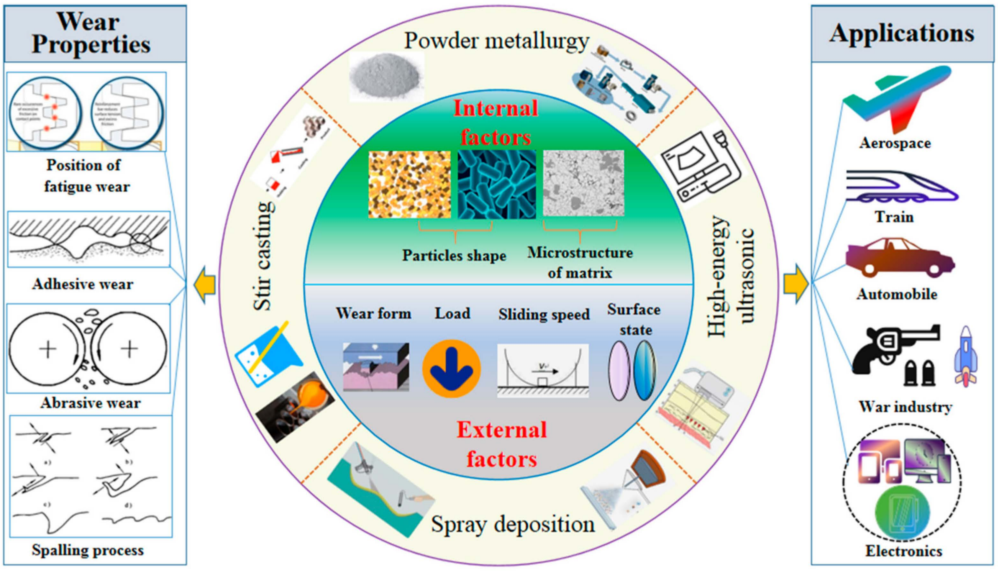

Figure 1. Framework of this review.

2. Typical Preparation Technology of Composites

2.1. Stir Casting

Stir casting is a common preparation process for particle-reinforced aluminum matrix composites. The composites obtain a uniform microstructure and exhibit excellent properties when utilizing this method. Tharanikumar et al. [30] studied the evolution of microstructure and mechanical properties in Si_3N_4-BN strengthened Al-Zn-Mg alloy hybrid nanocomposites using a vacuum-assisted stir-casting process. As shown in Figure 2, it was found that the reinforced particles were uniformly distributed in the matrix, with no residual particles along the grain boundaries. This resulted in the production of a high-quality composite material with a comprehensive strength of 79.48%.

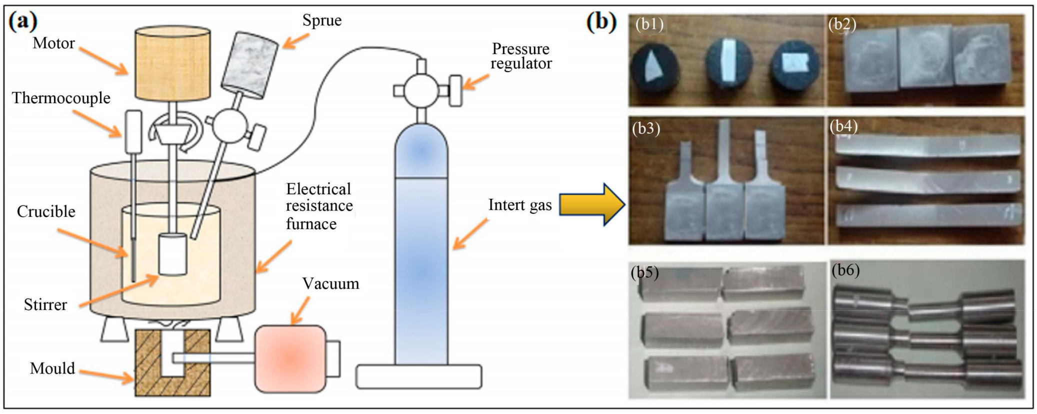

Figure 2. Preparation process of (**a**) the schematic of stir casting process for particle-reinforced aluminum matrix composites, (**b**) preparation for experimental sample, (**b1**–**b6**) six kinds of experimental samples were prepared, respectively. Reproduced with permission from Ref. [30]. Copyright 2022 The Author(s).

Usually, the large aluminum alloy is washed, dried, and melted in a medium-frequency induction furnace with a graphite agitator. It is then heated to 720 °C for refining and removing impurities. Then, the SiC particles, pretreated using a specialized process, are uniformly dispersed onto the surface of the molten liquid by an Ar airflow. They subsequently enter the molten liquid due to the combined effects of gravity and vortex forces. After adding all SiC particles, the molten liquid is cooled to 565 °C (the semi-solid temperature of the matrix aluminum alloy), and it is stirred at 690 rpm. As a commonly used preparation method, stirring casting offers several notable advantages, including low equipment requirements and a simple process. However, the disadvantage is that a harmful interfacial reaction between carbide particles and the Al matrix is prone to occur, thereby weakening the bonding strength at the interface. Due to the involvement of a large amount of gas in the stirring process [31], it is easy to form a high porosity, resulting in a decrease in density.

2.2. Powder Metallurgy

The biggest advantage of the powder metallurgy method is that the proportion of the reinforced phase can be adjusted according to needs. The volume fraction can be as high as 70%, and the particle size can be adjusted in the nano-to-micron range. Additionally, the process is simple, and the requirements are low. Lower temperatures can also reduce the interface reaction between the reinforcement and the matrix. Powder metallurgy requires the uniform mixing of the matrix alloy powder and reinforcement particles. Therefore, the particle size ratio of the particles to the alloy powder should be selected as 0.7:1. Typically, the particle size of the matrix alloy powder is chosen to be 20~40 μm. The particle size of the reinforcement particles is selected as 3~20 μm.

The limitations of powder metallurgy include restrictions on the size and shape of the parts, a complex manufacturing process, and a lengthy production cycle. When the size of the reinforced particles is small, or the volume fraction reaches a certain value, the phenomenon of particle agglomeration will become more pronounced [32]. In addition, SiC particle-reinforced Al matrix composites generally need to undergo secondary processing. Improving the distribution of SiC particles in the matrix and reducing the interfacial reaction between SiC particles and the matrix are key areas of focus for future research. These measures aim to effectively enhance the properties of composite materials.

Herzallah et al. [33] prepared SiC particles and CNT-reinforced pure aluminum composites using powder metallurgy. They studied the effects of particles with different compositions on the properties of the composites and found that as the SiC and CNT contents increased, the relative density and friction coefficient of the composites decreased. However, the hardness and compressive strength of the composites increased, as shown in Figure 3.

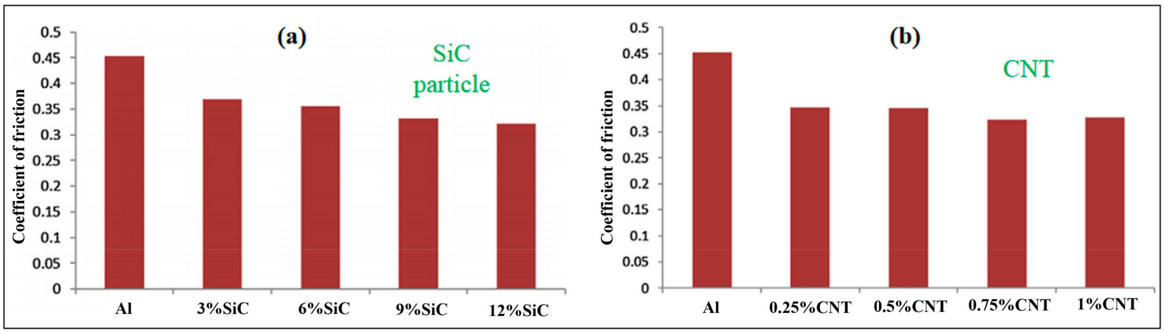

Figure 3. Friction coefficient of (**a**) Al-SiC, (**b**) Al-CNT composite. Reproduced with permission from Ref. [33]. Copyright 2019 The Authors.

2.3. Spray Deposition

The principle of the spray deposition method is to melt the matrix alloy and then atomize the metal liquid by adding protective gas through the nozzle. At the same time, the reinforcement particles are introduced into the atomizing atmosphere of the matrix. The reinforcement particles and atomized metal droplets are then deposited on the substrate simultaneously, allowing for rapid solidification and the formation of the required billet samples [34]. The reinforced phase of the composite prepared by spray deposition is evenly distributed, the solidification structure is fine, and the interface is clean.

Cheng et al. [35] used a multi-layer spray deposition device to prepare 15 vol.% SiC/6066Al composites. The difference between multi-layer spray deposition and traditional spray deposition lies in the movement of the atomizing nozzle. In traditional spray deposition, the atomizing nozzle generally remains stationary, whereas, in multi-layer spray deposition, both the heating crucible and atomizing nozzle can move. This allows for the formation of the deposited billet through multiple superpositions, resulting in a faster condensation rate than that of traditional spray deposition. The spray deposition process offers the advantages of a fast cooling rate and small grain size. However, it also leads to the formation of fine pores, resulting in low material density. In order to enhance the density and properties of composite materials, it is typically necessary to subject the prepared composite materials to hot pressing or hot isostatic pressing treatment.

2.4. High-Energy Ultrasound Assisted

In recent years, numerous studies have discovered that the application of an ultrasonic external field to the melt during the preparation of particle-reinforced aluminum matrix composites can effectively enhance the wetting and dispersion of the reinforced particles in the matrix alloy [36]. Compared with the mechanical stirring method [30,37], the composite prepared by the high-energy ultrasonic method has a more even distribution of reinforcement phase particles. This is attributed to the generation of acoustic cavitation and acoustic flow effects in the melt by high-energy ultrasound. The particles are more evenly dispersed throughout the matrix.

Venkatesh et al. [38] prepared nano-SiC reinforced aluminum matrix composites using ultrasonic-assisted agitation, as shown in Figure 4. They found that by applying ultrasonic treatment to the composite material melt, the grains can be refined, and uniform dispersion of nano-SiC in the aluminum matrix can be achieved. The addition of SiC can significantly enhance the overall mechanical properties of the composite. When the SiC particle content is 1.5 wt.%, the maximum hardness is 163 BHN, and the ultimate tensile strength is 431 MPa. When the SiC particle content continues to increase to 2.0 wt.%, brittle agglomeration occurs in the reinforced phase, resulting in a decline in mechanical properties. Li et al. [39] used a 20 kHz, 600 W ultrasonic generator to prepare Mg-based (AZ91D) and Al-based (A356) block metal matrix nanocomposites. These composites were strengthened by the addition of nano-SiC particles (30 nm) using a high-energy ultrasound casting process. The SiC nanoparticles are added to the melt aggregate to form clusters and coalesce at the solidified grain boundaries. When the ultrasonic power reaches 80 W, cyclic high-energy ultrasound generates numerous tiny bubble nuclei and holes in the melt. These bubbles grow and expand under cyclic negative pressure and collapse under subsequent cyclic positive pressure, completing a cavitation cycle. This process occurs within a very short time frame (approximately 100 ms) and repeats cyclically. At the end of a cavitation cycle, the cavitation bubble collapses, resulting in the formation of transient high temperatures (>5000 K) and high pressures ($>5 \times 10^7$ Pa). These phenomena create so-called micro-hotspots. The shock wave formed by the transient space-time and the resulting high temperature in the micro-region not only improves the wettability of the nanoparticles and the melt but also gradually disperses the nanoparticles in the melt. This process continues until the nanoparticles are evenly distributed in the melt, ultimately achieving a dispersed distribution of the nanoparticles in the solidified structure.

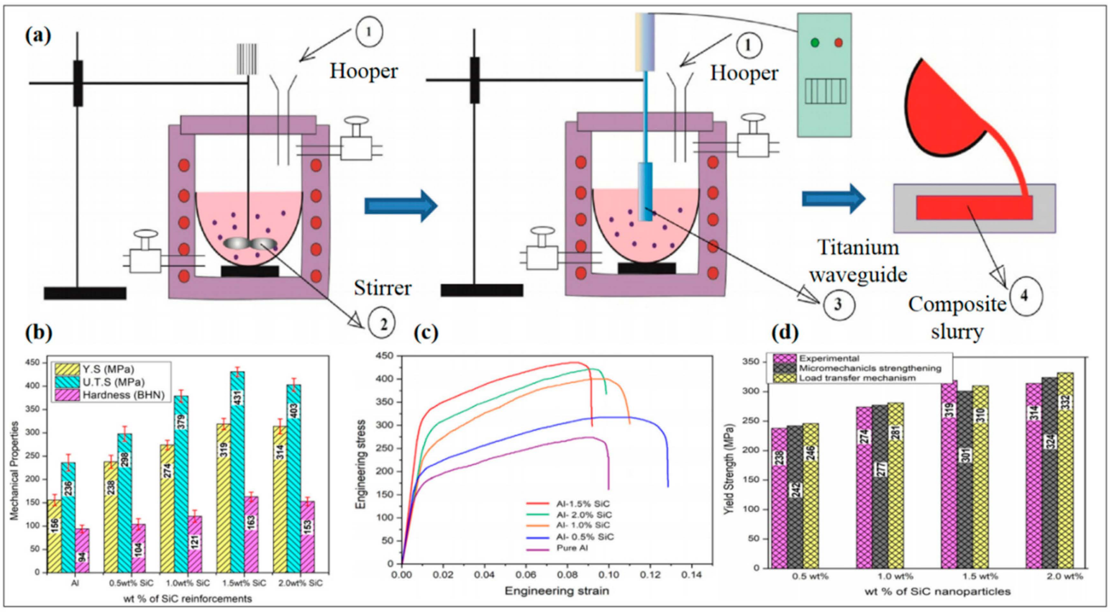

Figure 4. (**a**) schematic diagram for ultrasonically assisted stir casting, (**b**) mechanical properties of the as-cast Al-SiC nanocomposites, (**c**) stress–strain curves for the as-cast Al-SiC nanocomposites, (**d**) yield strength due to experimentally predicted and strengthening mechanisms. Reproduced with permission from Ref. [38]. Copyright 2023 The Author(s).

3. Friction and Wear Behavior of Composites

Particle-reinforced aluminum matrix composites are primarily utilized in the manufacturing of automobile brake disc components [40,41]. In addition to meeting the conventional physical and mechanical performance requirements, the factors that must be considered are the friction coefficient and wear amount. Since the 20th century, numerous institutions, both domestically and internationally, have conducted extensive research on the friction and wear properties of aluminum matrix composites [25,42,43]. The majority of these studies focus on investigating the frictional behavior between aluminum alloys and steel materials. The friction pair formed by resin-based brake pads and brake discs used in automobiles is very different from other friction pairs. However, the friction and wear properties of the friction pair formed by resin-based brake pads and aluminum composite materials have been relatively less studied. The friction and wear performance of the brake disc and brake pads mainly refers to the friction coefficient and wear characteristics. This includes the wear of the brake disc and brake pads and is influenced by the materials used and the working conditions [44].

3.1. Friction Coefficient

The friction coefficient is an important parameter for measuring the friction and wear properties of materials and studying the mechanisms behind friction and wear. It is not only related to the process of friction but also to the nature and state of the friction pair. The friction coefficient of the same material can vary under different experimental conditions. Bowden et al. [45] proposed that three processes can influence the friction coefficient of materials, namely, the adhesion of the sliding surface area, the plowing caused by reinforcing particles and rough surfaces, and the deformation of rough surfaces due to friction. In general, the influence of plowing and rough surface deformation on the friction coefficient of a material is greater under different sliding conditions, friction pair materials, and service conditions.

However, some scholars also believe that during the stable friction stage [46,47], the addition of highly hard reinforced particles will decrease the friction coefficient of the composite material. Furthermore, as the amount of addition increases, the reduction in the friction coefficient becomes more pronounced. This is because the addition of reinforced particles to the matrix reduces the contact area between the matrix material and the friction pair material during the friction process. This effectively distributes the applied load and reduces the wear of the friction pair on the matrix material. Uyyuru et al. [48] believe that the external load has little influence on the friction coefficient of the composite under a low external load state. However, the friction coefficient of the composites shows an increasing trend under higher load conditions. This is because the effect of friction leads to small scraps on the surface of the friction pair, and a transfer layer is also generated. This transfer layer effectively enhances the wear resistance of the composite material during the friction process, resulting in a stable friction state. As the load continues to increase, the temperature of the contact surface rises. This causes the enhanced particles to break or even fracture, resulting in the loss of their protective effect on the matrix. The wear mechanism also changes, which affects the surface finish of the contact surface of the material. This can lead to severe adhesive wear, causing an increase in the friction coefficient.

Kim et al. [49] prepared a composite material of AlSi10Mg reinforced with TiH_2@ZrH_2 and conducted a friction and wear test. The wear test results show that AlSi10Mg prepared with ZrH_2 exhibits the highest wear resistance. Additionally, the sample's surface friction fluctuation is the largest, which can be attributed to the presence of numerous pores on its surface. However, these pores are filled with debris from wear, which flattens the surface and reduces the coefficient of friction. Figure 5 shows the friction coefficient, wear rate, and friction fluctuation of the wear test results. Because the hardness of the reinforcement phase is higher than that of the AlSi10Mg substrate, the greater the hardness, the smaller the actual contact area between the corresponding material and the sample surface. Therefore, due to the energy required to wear the surface during the sliding process [50], the wear resistance exhibited is high. With the progression of friction, the contact interface exhibits repeated adhesion and shear, leading to significant fluctuations in the friction coefficient. The analysis also indicates that the fluctuation of the high friction coefficient is associated with the pore structure.

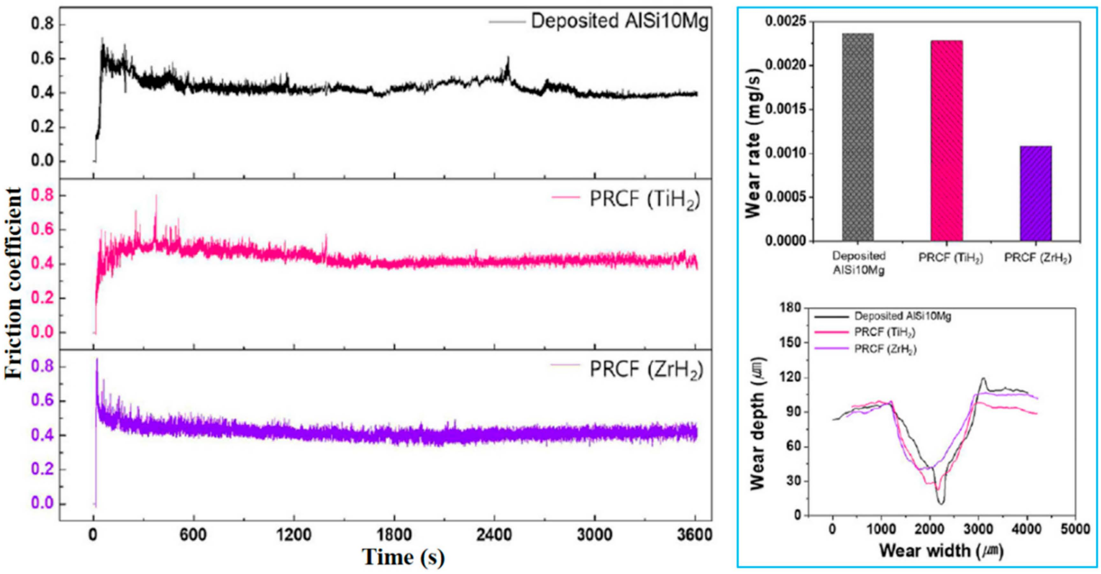

Figure 5. Friction coefficient, wear rate, and wear depth of TiH_2@ZrH_2 reinforced aluminum matrix composites. Reproduced with permission from Ref. [49]. Copyright 2023 The Author(s).

3.2. Wear Rate

As we know, the wear rate is a key indicator used to measure the wear resistance of aluminum matrix composites. It is calculated as the reciprocal of the material's wear amount. Although there are many ways to express the wear rate, it is typically measured as the amount of wear per unit volume of the sample. Devaraju et al. [51] showed that the friction and wear properties of SiC_p and Al_2O_{3p} reinforced 6061 aluminum matrix composites are within the range of 0~20%. They were studied using a scraping test under the experimental conditions of a scraping speed of 6 mm·s^{-1}, grinding range of 6 mm, and load of 10 N. When larger-sized reinforced particles were used, a study was conducted on the friction and wear properties of 6061 aluminum matrix composites through a scraping test. At this time, the wear rate is not high, which is not only related to the hardness of the reinforcing particles but also to the volume fraction of the reinforcing particles. In the case of smaller sizes of reinforced particles, the hardness of the composite is related to its wear rate [52].

Ma et al. [53] used 40Cr as the friction pair material on a self-made pin–disk friction and wear test machine to investigate the friction and wear properties of aluminum matrix composites reinforced with 10% particles. The results show that the wear rate of the composite decreases with an increase in sliding speed, and the average wear rate of the composite is lower than that of the matrix. It is crucial to properly maintain automotive brake components. This not only extends the service life of the brake components but also increases the stability of the brake system and reduces the noise it generates.

The effect of the size and distribution of reinforcement particles on the wear properties of aluminum matrix composites has been widely discussed [54,55]. Some researchers [56] believe that when the size of the reinforcement particles is too small, it becomes difficult to enhance the wear resistance of aluminum matrix composites. This directly impacts the performance of aluminum matrix composites. However, if the size of the reinforcement particles is too large, the number of grain boundaries will increase, leading to stress concentration. This can shorten the service life of aluminum matrix composites. However, some researchers [57] believe that increasing the particle size in the case of low load can provide more effective protection to the matrix and prevent scratching of the friction pair. This, in turn, improves the wear resistance of the entire composite material. Other researchers [58] believe that a narrower particle size distribution range of the reinforcement leads to better wear resistance of the material and a stable friction coefficient.

Singhal et al. [59] studied the dry sliding wear behavior of aluminum matrix composites reinforced with silicomanite (shown in Figure 6). Under the applied load of 9.81~68.67 N and sliding distance of 3000 m, the wear behavior of Al_2SiO_5-reinforced aluminum matrix composites was studied using a 3 wt.% solid lubricant. Because the sample cannot withstand sudden shear stress, it becomes unstable and experiences maximum wear loss when sliding distances reach up to 250 m. Due to the continuous sliding motion, the pin body deforms, which leads to the formation of abrasive grooves on the surface of the specimen pin. The run-in wear rate of 3T10 and 3G10 is greater than the run-in wear rate. This can be attributed to the presence of Al_2SiO_5 particles and a single solid lubricant. In aluminum matrix composites, these mineral particles act as load-bearing components, minimizing losses due to dry slip wear. In addition, the surface of the dowel is oxidized due to the constant sliding motion between the dowel and counter surfaces, resulting in the formation of an oxide layer on the surface. The protective coating reduces the contact between the sample and the steel plate, thereby preventing further wear. In addition, at 1000 m (3T10, 3G10) and 750 m (3TG10), the sliding distance wear rate tends to stabilize, indicating a steady state of wear.

3.3. Aluminum Matrix Surface

The morphology and condition of the aluminum matrix surface have a significant impact on the friction and wear characteristics of the composites, and they also determine the friction and wear properties of the composites. During the study of the friction and wear behavior of composites [49,53], it has been found that surface roughness is one of the primary parameters that affect the friction and wear properties of these composites. The surface roughness of the matrix affects the density of the composites' nucleation. When the roughness is small, there are fewer surface defects, which increases the nucleation barrier on the surface. As a result, the nucleation density of the particle on the matrix surface is smaller. The main reason is that as the roughness of the matrix increases, the mechanical interaction between the two surfaces is enhanced, leading to intensified composite wear.

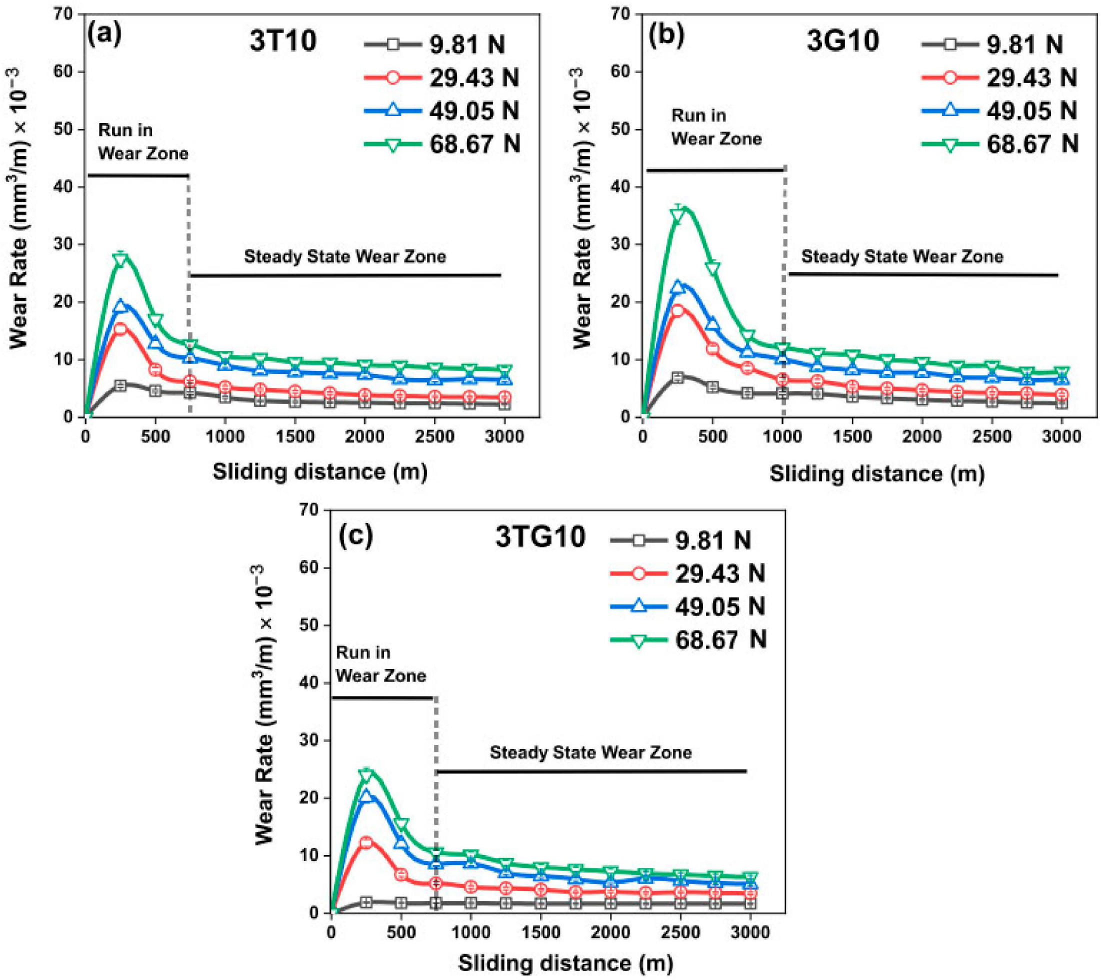

Figure 6. Wear rate analysis of (**a**) 3T10, (**b**) 3G10, (**c**) 3TG10. Reproduced with permission from Ref. [59]. Copyright 2023 Elsevier Ltd.

4. Effect of Factors on Friction and Wear Behavior of Composites

4.1. Internal Factors

4.1.1. Microstructure Characteristics of Matrix Materials

The type and content of the matrix, as well as the bonding interface between the matrix and reinforcement particles, have significant effects on friction and wear behavior. The higher the metallurgical compatibility between friction surfaces, the greater the wear. The higher the hardness, the lower the adhesion and furrowing on the friction surface, resulting in reduced wear. When the composite has a good metallurgical bonding interface, it exhibits high wear resistance [60].

According to a multifaceted analysis of the wear mechanism, the wear performance of the composite depends on the interaction between the matrix and the reinforced particles. As the hardness of the composite matrix increases, the reinforced particles are supported more firmly by the matrix [61]. Instead, the substrate wears out preferentially due to a lack of protection. Similarly, the structural morphology of the matrix material is related to its properties, which largely determines its specific characteristics and has a significant impact on its friction and wear properties.

4.1.2. State of Reinforced Particles

The premise of enhancing the wear resistance of the composite is that the reinforcement particles are uniformly distributed in the matrix and form a strong bonding interface. Once the reinforcement particles detach from the friction surface of the composite, three-body wear particles are formed, which can decrease the wear resistance of the composite [62]. The addition of hard ceramic particles enhances the mechanical properties of the composite material and improves its thermal stability. In general, under dry friction conditions, the wear resistance of the composite material improves with a higher particle content of the reinforcement.

The influence of particle content on the wear properties of aluminum matrix composites is significant. Umanath et al. [63] studied the friction and wear behavior of Al6061 composites reinforced with particles. The results showed that composites with 15% particle content exhibited better wear performance compared to composites with 5% particle content. Among these four factors—particle content, load, speed, and hardness—all of them will affect the wear properties of composite materials to some extent. However, the particle content is the most important factor.

Kang et al. [64] studied particle-reinforced aluminum matrix composites and found that the microstructure of the reinforced particles has a significant influence on the wear performance. They believe that spherical or ellipsoidal particles have the best anti-wear performance, followed by polygonal particles, short bars, and fibers. Analysis of the reasons shows that the stress concentration between the spherical and ellipsoidal reinforced particles and the matrix is lower. As a result, the bonding is stronger, and it can effectively prevent the expansion of cracks. The other reinforced particles, whether polygonal, dendritic, or short fibers, experience significant stress concentration with the matrix. As a result, cracks easily form during the wear process, leading to the loss of the reinforced particles and a decrease in wear resistance.

However, the particle size also affects the wear performance of the composites. In aluminum matrix composites, the average diameter of SiC particles is too small (less than 10 μm), resulting in a limited strengthening effect and a limited improvement in wear resistance. However, if the SiC particles are too large (greater than 100 μm), there will be excessive stress concentration in the matrix, which will have a negative impact on the wear performance. Shao et al. [65] prepared a composite material consisting of SiC particles reinforced in an aluminum matrix, using A356 aluminum alloy as the matrix. They then used this material to create a friction pair with an HFM605 friction plate, which was used in the Santana 2000 car. The research found that the friction coefficient had little relationship with the SiC content and particle size in the composite material. However, as the SiC particle size decreases and the SiC content increases, the wear resistance of SiC particle-reinforced aluminum matrix composites gradually improves.

4.2. External Factors

4.2.1. Wear Pattern

In the dry friction process of particle-reinforced aluminum matrix composites, there are mainly adhesive wear, abrasive wear, and spalling wear [66]. The wear mechanism of different wear patterns is different, and the wear behavior of composites will also vary. The friction and wear process of composites is very complicated, and there are many factors that can influence it. Adhesive wear occurs when two surfaces slide relative to each other, and the pressure between the contact surfaces is high enough to cause local plastic deformation [67]. The hardness of the material determines the actual contact area of the contact surface, making the surface hardness of the material more crucial for friction behavior than the overall hardness. When abrasive wear occurs, two friction pairs slide against each other. This can be due to the presence of rough micro-convex bodies on the hard surface or the presence of hard particles between the sliding friction surfaces, which cause damage to the softer surface. Wear chips generated by other wear forms, such as adhesive wear particles, are retained between the friction surfaces. They gather and grow, eventually becoming hard particles due to work hardening. This process also contributes to abrasive wear. According to the spalling wear theory [68], when two sliding surfaces come into contact, the normal load and tangential load are transferred through the contact point. The micro-convex body on the softer surface is prone to deformation or breakage under repeated loads, resulting in the formation of a smooth surface. At this time, the contact is not exactly between the micro-convexities but rather between the micro-convexity and the plane. This means that when the micro-convexity on the harder surface experiences relative friction with the plane, each contact point on the softer surface has to bear a periodic load.

4.2.2. Applied Load

The effect of the applied load on the wear properties of aluminum matrix composites is primarily observed in the alteration of the wear mechanism during the wear process [28,69]. As we know, the load affects the friction and wear characteristics by influencing the size of the contact area and the degree of deformation. With an increase in load, the contact surface's actual contact area also increases. This leads to a higher degree of deformation and an increase in wear due to the accumulation of abrasive particles in the contact area.

Ma et al. [70] conducted friction and wear experiments on SiC/ZL102 using a self-made pin–disk friction and wear testing machine. The research shows that the friction coefficient of SiC-reinforced aluminum matrix composite increases with increasing pressure under the conditions of a linear friction velocity of 0.24~5.45 m/s and a load of 0.3~0.9 MPa, while the matrix material fluctuates greatly. The wear rate of the composite is approximately 1/7 lower than that of the matrix alloy. The primary wear form of the composite is abrasive wear, while the main wear form of the matrix is adhesive wear. The wear layer softens and undergoes plastic rheology, but the change in the composite is not significant. Singhal et al. [59] studied the dry sliding wear behavior of aluminum matrix composites reinforced with silicomanite under an applied load of 9.81~68.67 N (as shown in Figure 7) and found that the various applied loads had distinct effects on the wear properties of the composites. This indicates that the wear strength and wear resistance varied.

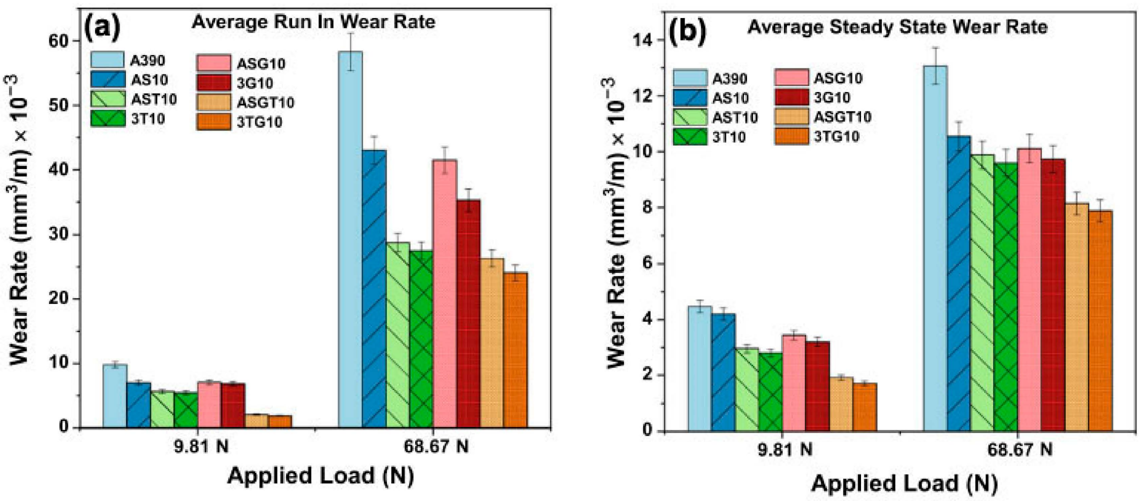

Figure 7. Effect of applied load on wear behavior (**a**) average run in wear rate, (**b**) average steady state wear rate. Reproduced with permission from Ref. [59]. Copyright 2023 Elsevier Ltd.

The wear properties of an Al-Mg alloy and a SiO_2 particle-reinforced aluminum matrix composite were studied under different load conditions. The sliding speed was 0.6 m·s^{-1}, the dry grinding time was 40 min, and the friction pair material used was GGr15 steel [71]. The results showed that within the load range of 200 N, the volume wear of both the matrix alloy and the composite material increased with the increase in load. However, the volume wear of the composite material was lower than that of the matrix alloy, indicating that the composite material had better wear resistance compared to the matrix alloy. However, when the applied load exceeded 200 N, the wear rate of both the matrix alloy and the composite material increased significantly. Therefore, the load range for using the composite material in a dry friction wear state is limited to less than 200 N.

4.2.3. Sliding Speed

The influence of sliding velocity on the friction and wear properties of the composite is primarily observed through the impact on the deformation rate of the subsurface layer and the temperature changes resulting from frictional heat. According to the literature [72], at higher sliding speeds (above 3 m/s^{-1}), the material exhibits improved wear performance, and the friction system remains more stable. Li et al. [73] investigated the relationship between wear amount and sliding speed in pin–disk dry sliding friction. They specifically studied flyash particle-reinforced aluminum matrix composites with varying volume content (5–30%). The study found that there was a relationship between the wear amount and friction coefficient of the aluminum matrix and the sliding speed. It was observed that as the sliding speed increased, the wear amount and friction coefficient tended to initially increase and then decrease. However, the relationship between the amount of wear and the friction coefficient of the composite material and the sliding speed initially increased, then decreased, and then increased again. In general, as the sliding speed increases, the wear rate of the two materials also increases. However, the friction coefficient of the composite material shows little correlation with the change in sliding speed.

Wang et al. [74] investigated the dry sliding friction and wear behavior of composites reinforced with 20 vol.% SiC particles (SiC_p) and made a close comparison with unreinforced Al7091. They found that at speeds less than 1.2 m/s, the wear mechanism is characterized by fatigue wear. Fatigue cracks are present on the wear surface, and the wear fragments are very small, typically consisting of metal fragments. Additionally, the friction surface is covered with a layer of friction material. At such a low speed, the wear rate of the composite is similar to that of the matrix alloy, and the impact of particle reinforcement is not significant. At high sliding speeds, the wear process changes. In the initial stage of the friction process, both the composite and matrix alloy experience a rapid increase in wear rate. As the sliding distance increases, the wear rate tends to stabilize. However, the wear rate of the matrix alloy continues to increase linearly, while the wear rate of the composite is significantly lower. This is because it is difficult to form a complete friction layer on the friction surface of the matrix alloy at high speeds. The friction process is primarily controlled by subsurface crack propagation and adhesive wear.

The same conclusion is also reached by Lee et al. [75], but their results show that the critical velocity is 0.37 m/s. In addition, they also noted that the initial and stable wear rates of unreinforced aluminum alloys increase with increasing sliding velocity. However, for the reinforced composites, the initial wear rate increases correspondingly with increasing speed. On the contrary, the wear rate decreases in a steady state. Experimental results differ from those reported by Wang [74], possibly due to variations in experimental conditions such as grinding and load.

4.2.4. Thermal Treatment

The effect of heat treatment on the friction and wear properties of a material is primarily determined by its impact on the material's microstructure. Heat treatment can alter the microstructure of a material, which in turn, affects its friction and wear properties. The change in wear rate of SiC/6061Al was studied by Paladugu et al. [76]. They examined two types of materials under three heat treatment conditions: under-aging, peak aging, and over-aging. The study found that the best wear resistance was observed in materials aged around 200 °C (peak aging). On the other hand, both under-aging at temperatures below 200 °C and over-aging at temperatures above 200 °C resulted in material deterioration and reduced wear resistance.

In addition, peak aging improves the interface between particles and matrix, making it more perfect. In the friction process, the probability of particles falling off due to load, shear force, and matrix deformation decreases, resulting in a lower wear rate for composite materials. However, the probability of particles falling off and forming abrasive particles between the friction interface decreases. As a result, the likelihood of severe abrasive wear is reduced, leading to a decrease in the wear rate of materials.

4.2.5. Temperature

In the process of friction and wear, temperature change primarily affects the friction and wear of materials in the following ways: it alters the performance of the friction pair material, influences the formation of the oxide film on the friction surface, and modifies the performance of the lubricant between the friction surfaces.

Under dry friction conditions, the heat generated by friction will alter the temperature of the contact surface, leading to modifications in the wear mechanism of the contact surface. The temperature change of the contact surface depends on the thermophysical properties of the friction pair, the operating conditions, and the heat dissipation conditions. In the field of applications, the working temperature of aluminum matrix composites and various friction pairs is significantly higher than room temperature. The friction and wear properties at room temperature differ greatly from those at high temperatures. Therefore, it is essential to study the impact of temperature on the friction and wear properties of composite materials.

Zhang et al. [77] observed that during the friction process of Al_2O_3 particle-reinforced and unreinforced Al alloys, the transition from slight to severe wear occurs in alloys when the temperature exceeds the critical transition temperature. This transition is caused by the heat generated on the sliding contact surface. For the composite, the critical temperature for bite death is higher than that of the unreinforced A1 alloy, and the critical load is also higher.

During the friction process, when the ambient temperature reaches a certain value, the wear mechanism of the composite material changes, and the material transitions from the stable wear stage to its instability stage. This temperature range is referred to as the critical transition temperature. When the SiC-reinforced aluminum matrix composite and A390 alloy are friction at a speed of 6 $m \cdot s^{-1}$ [78], the critical transition temperature increases with the increase in SiC content. The critical transition temperature for a SiC content of 20% is 400 °C, and for a SiC content of 50%, it is 500 °C. The temperature exceeds 500 °C, and the alloy is sintered onto the contact surface. This demonstrates that the composition of reinforcement particles plays a crucial role in determining the high-temperature wear performance of aluminum matrix composites. Furthermore, it is observed that the higher the content of reinforcement particles, the greater the material's resistance to high temperatures.

Weng et al. [79] studied the friction and wear behavior of a 15% SiC_p/2009Al aluminum matrix composite under low-temperature sliding (as shown in Figure 8). They found that the deformation behavior of the composite during the sliding wear process is closely linked to the temperature response. Additionally, temperature has a significant impact on the plastic deformation and wear behavior of the subsurface. When sliding at room temperature, the increase in contact temperature softens the subsurface layer through heat conduction, thereby reducing the material's resistance to deformation during shear sliding. In addition, at higher contact temperatures, the material also undergoes a recovery process. This process can release the internal stress between the SiC particles and the aluminum alloy matrix, thereby reducing the dislocation density after sliding wear [50,80]. The high contact temperature has little effect on the stable SiC particles, so these particles are not completely broken when sliding at room temperature. This is because the softened aluminum alloy is easily removed beforehand. Therefore, under the given conditions, the surface of the sample is rapidly destroyed due to the cutting action of spalling coarse SiC particles and other debris. As a result, the wear surface becomes rough, stratification becomes evident, and the wear rate of the sample increases.

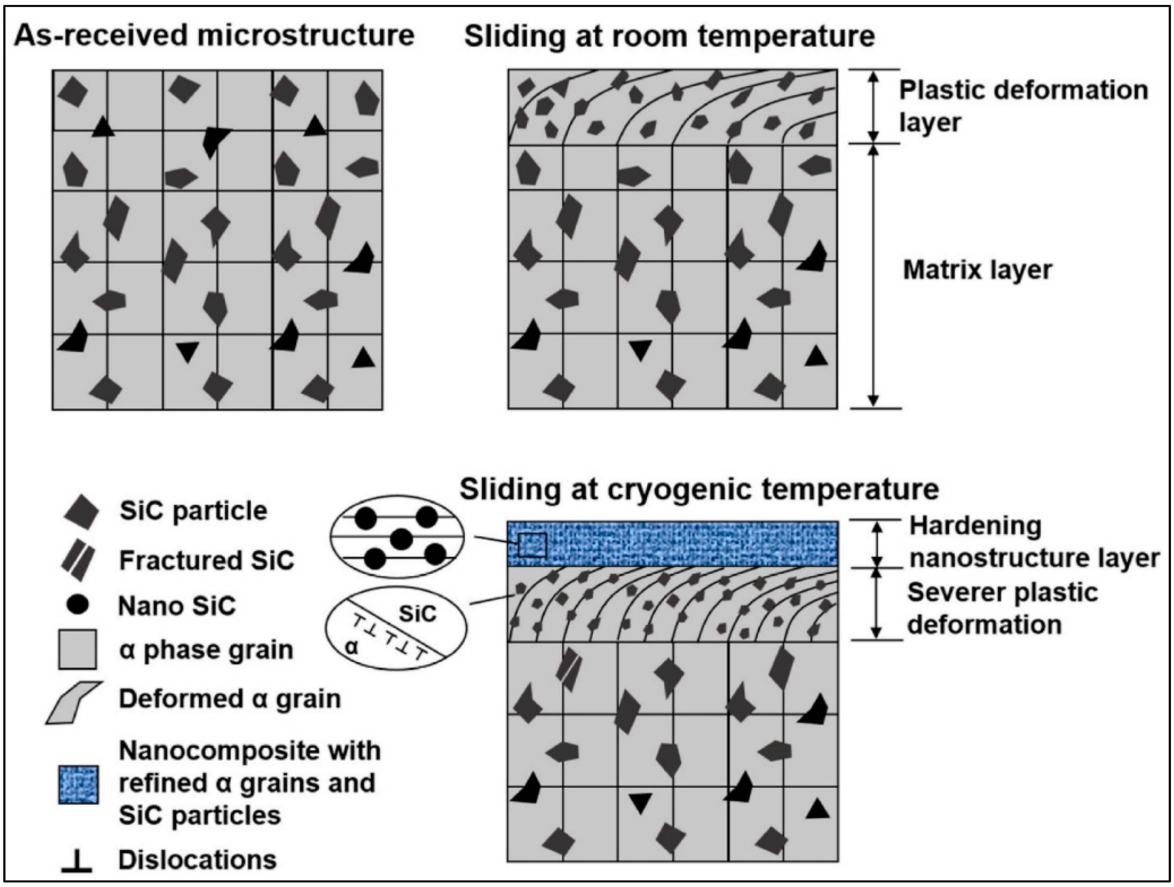

Figure 8. Diagram of the microstructure evolution of aluminum matrix composite samples under sliding wear at different temperatures. Reproduced with permission from Ref. [79]. Copyright 2023 Elsevier Ltd and Techna Group S.r.l.

5. Wear Mechanisms

Particle-reinforced aluminum matrix composites have significantly improved wear resistance compared to matrix alloys. However, in certain specific cases, they may exhibit similar or even lower wear resistance than the matrix alloys [81]. In addition, the wear resistance of composite materials is influenced by friction parameters. Sometimes, these parameters can have different effects, which is attributed to the interaction between them. As a result, the wear performance of the material differs from that of a single parameter. Figure 9 illustrates a typical schematic diagram of pin–disk friction and wear, as well as the grinding surface morphology.

It has been pointed out that the main characteristics of oxidative wear are reflected in the friction process [82]. The micro-protrusions on the friction surface cause three-body wear as they scrape against each other and shed particles from the friction surface. The macroscopic mechanism involves fine abrasive chips along with a significant quantity of oxides. The mechanism of peeling wear is based on the theory of subsurface crack propagation in composite materials [83]. The result of peeling wear is a large sheet accompanied by a metallic luster. When the load, sliding speed, and temperature continue to increase, the friction generates heat that raises the temperature of the composite material to a critical value, causing the material to soften. With the occurrence of plastic deformation, the material is eventually separated from the matrix and transferred to the surface of the friction pair, leading to adhesive wear.

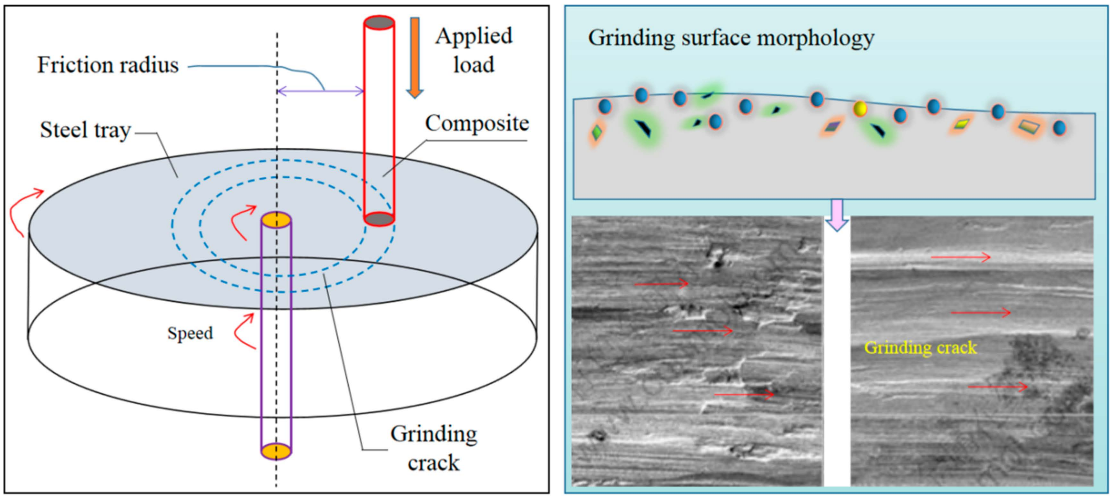

Figure 9. Schematic diagram of pin–disk friction and wear and the grinding surface morphology.

Li et al. [73] studied the friction and wear characteristics of an aluminum matrix composite reinforced with Al_2O_3@SiO_2 particles. The study was conducted under a loading range of 20–80 N and a sliding speed of 0.5–2.0 m·s^{-1}. The pin–disc dry sliding friction test was conducted using the friction form, and the friction pair material used was 5CrNiMo steel. It was found that after the onset of sliding friction, the friction and wear characteristics of the Al_2O_3@SiO_2 particle-reinforced aluminum matrix composite were reduced. The fly ash particles embedded on the surface of the matrix come into direct contact with the surface of the friction pair, bearing the load and preventing direct contact between the surface of the friction pair and the surface of the matrix. At this time, under low load and sliding speed conditions, the wear mechanism of the composite material is primarily manifested through oxidative wear, adhesive wear, and abrasive wear. With an increase in load, the binding force between the substrate surface and fly ash particles becomes less capable of resisting the friction force acting upon it. As a result, some fly ash particles detach from the substrate surface. When a specific threshold is reached, it creates a protective effect on the surface that is subject to wear [84], thereby reducing both wear and the friction coefficient. When the load continues to increase to the point where the fly ash particles fracture or break, they lose their ability to protect the surface of the matrix. This leads to significant plastic deformation of the composite material's matrix and the formation and expansion of cracks around the second phase particles in the deformation area. As a result, the material experiences subsurface stripping and the formation of flaking chips. At this time, the wear mechanism changes to peeling wear and abrasive wear.

6. Conclusions and Outlook

This comprehensive review describes the friction and wear properties of particle-reinforced aluminum matrix composites. Several typical preparation methods for particle-reinforced composites are listed, and the related mechanisms of friction and wear are introduced. The internal and external factors that influence the friction and wear properties of composites are analyzed and summarized. These general knowledge summaries are convenient for readers or researchers to quickly grasp the wear behavior characteristics of particle-reinforced aluminum matrix composites during the friction and wear process. They also provide research ideas for engineers and technicians to conduct friction and wear experiments under specific circumstances.

Particle-reinforced aluminum matrix composites, which are excellent wear-resistant materials [85,86], have broad application prospects in aerospace, military, electronics, the automobile industry, transportation, and other fields [87]. After years of effort, the United States, Germany, and other countries have achieved large-scale production of particle-reinforced aluminum matrix composites [88]. For example, automobile brake pads made of aluminum composite materials greatly reduce the weight of the pads while also minimizing brake noise, resulting in positive outcomes. Japan installed a brake disc made of SiC aluminum matrix composite material on a high-speed train [89]. According to wear conditions, its service life is expected to be more than 15 years. In addition, it also has broad development prospects in molds, tank tracks, engine pistons, engine cylinder liners, bicycle chains, and medical equipment.

China initiated research on the friction and wear properties of aluminum matrix composites in the twentieth century. This research was supported and driven by major national projects, and it laid the foundation for future practical applications [90]. In the late twenty-first century, domestic research in this field has progressed from the laboratory research stage to the application development research stage. A national pilot base and laboratory have been established, with a focus on studying particle-reinforced aluminum matrix composite industrial preparation technology. The current research on the material structure and properties of composite materials interfaces has reached a level close to that of the rest of the world.

As we know, particle-reinforced aluminum matrix composites are widely used in automotive engine components and braking systems. Friction and wear performance are important indices in service and bearing processes. It is challenging for particle-reinforced aluminum matrix composites to mitigate the impact of temperature rise during service. Therefore, there is an urgent need to investigate particle-reinforced composites that exhibit exceptional friction and wear properties, particularly at high temperatures.

The research on the friction and wear properties of particle-reinforced aluminum matrix composites is an interdisciplinary subject with multi-disciplinary implications. Its fundamental theory and practical application have become a research hotspot. The research on friction and wear properties will serve as a reference for understanding the failure of composite materials under periodic applied loads. This research is beneficial for monitoring material wear in practical engineering applications and predicting the service life of materials in advance.

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