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Review

Progress in Aluminum-Based Composites Prepared by Stir Casting: Mechanical and Tribological Properties for Automotive, Aerospace, and Military Applications

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Abstract: Manufacturing sectors, including automotive, aerospace, military, and aviation, are paying close attention to the increasing need for composite materials with better characteristics. Composite materials are significantly used in industry owing to their high-quality, low-cost materials with outstanding characteristics and low weight. Hence, aluminum-based materials are preferred over other traditional materials owing to their low cost, great wear resistance, and excellent strength-to-weight ratio. However, the mechanical characteristics and wear behavior of the Al-based materials can be further improved by using suitable reinforcing agents. The various reinforcing agents, including whiskers, particulates, continuous fibers, and discontinuous fibers, are widely used owing to enhanced tribological and mechanical behavior comparable to bare Al alloy. Further, the advancement in the overall characteristics of the composite material can be obtained by optimizing the process parameters of the processing approach and the amount and types of reinforcement. Amongst the various available techniques, stir casting is the most suitable technique for the manufacturing of composite material. The amount of reinforcement controls the porosity (%) of the composite, while the types of reinforcement identify the compatibility with Al alloy through improvement in the overall characteristics of the composites. Fly ash, SiC, TiC, Al_2O_3, TiO_2, B_4C, etc. are the most commonly used reinforcing agents in AMMCs (aluminum metal matrix composites). The current research emphasizes how different forms of reinforcement affect AMMCs and evaluates reinforcement influence on the mechanical and tribo characteristics of composite material.

Keywords: aluminum-based material composites; reinforcing agent; mechanical properties; tribological properties

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1. Introduction

Over the past few decades, researchers have concentrated on creating materials that are both light and strong. As a result, the scientists' attention switched from researching monolithic materials to investigating composite materials. Composite is a material system made up of a continuous phase (matrix) and a discrete component (reinforcement). Composite materials, such as polymer matrix, metal matrix, and ceramic composites, are often classified based on the physical or chemical properties of the matrix phase [1]. However, metal matrix composites, or MMCs, are metals reinforced with additional metal, ceramic, or biological components that are dispersed throughout the metal matrix [2]. Reinforcements are often used to improve the properties of the base metal, including its conductivity, strength, stiffness, resistance to corrosion, and wear [3]. Metal matrices for composite materials are commonly made of metals, including silicon, aluminum, copper, titanium, magnesium, and nickel. The most attention has been paid to aluminum and its alloys as base metals for metal matrix composites (MMCs) owing to their outstanding corrosion resistance, low weight, high strength, appropriate electrical and thermal conductivity, exceptional malleability, and simplicity of machining [4]. Aluminum alloys from 2000, 5000, 6000, and 7000 alloy families are most commonly used as a matrix phase. Fibers, whiskers, monofilaments, and particulate types are commonly used as reinforcement phases. Particle reinforcements homogenize in the matrix material more effectively due to their higher isentropic properties compared to others. Aluminum-based composites are predominantly utilized as particle reinforcements in car applications due to their exceptional tribological performance [5]. Automotive, aerospace, and structural sectors have placed greater emphasis on Al-based composite materials due to their enhanced mechanical properties and robust temperature stability [6]. Composite utilizes the combining effects of matrix and reinforcement, imparting outstanding ductility and density (low) of the alloys while producing materials with significantly higher strength compared to the base material. Adding reinforcements in the form of high-strength particles is an additional method to overcome any disadvantages with matrix materials [7]. Incorporating reinforcement into an aluminum matrix enhances the composite's hardness, impact resistance, compressive strength, and tensile strength [5–7].

AMMCs often outperform aluminum alloys or unreinforced aluminum in terms of wear resistance through the usage of a wide range of materials that are employed as reinforcements. By incorporating micro- or nano-sized reinforcing particles made from synthetic substances, ceramics, waste from industries, and agricultural waste into aluminum-based material, it is possible to efficiently create aluminum-based composites [8]. Modern materials have evolved where aluminum metal matrix composites are concerned. The creation of lightweight alloys raises the standard of the material that is favored for design purposes. Aluminum metal matrix composites (AMMCs) gained significant attention owing to their lightweight, having a low thermal expansion coefficient, high specific modulus, excellent wear resistance, high strength-to-weight ratio, outstanding corrosion resistance, and high specific modulus [9,10]. However, the fundamental requirement of the automobile industry is to discover new materials that can decrease fuel consumption and vehicle emissions. Aluminum, magnesium, and titanium are frequently used as the matrix in structural applications to provide robust support for the reinforcement. Cobalt and cobalt-nickel alloy matrices are commonly used in applications that require extremely high temperatures [11]. In composites, the matrix is infused with the strengthening agent. Reinforcement also alters COF, wear resistance, and thermal conductivity. Discontinuous metal matrix composites (DMMCs) can exhibit isotropic properties and can be effectively processed using conventional techniques, i.e., rolling, forging, or extrusion [12]. Reinforcement, such as silicon carbide/carbon fiber, is employed for the purpose of providing continuous reinforcement. An anisotropic structure is produced, where the orientation of the material influences its strength as a result of the fibers being inserted into the matrix in a certain direction. Boron filament was mainly employed as reinforcement. Particles, small strands, or whiskers are used in discontinuous reinforcement [13]. Within this group, silicon carbide and alumina are the most often used reinforcing elements.

Although composites are viable substitutes for traditional materials, there are still several drawbacks that need to be explored. Achieving enhanced material characteristics is the main goal of composite manufacture, and it depends on a number of variables, including the fabrication method, process parameters, component materials, and composition [14]. For MMCs, a wide variety of production processes have been investigated, including liquid-state and solid-state processes. The stir-casting process is the most widely used manufacturing route in the commercial world because of its unique characteristics [15]. Large-scale manufacturing may be economically facilitated by this cost-effective technology due to its simplicity and versatility. Stir casting is used to create complex profiled MMCs without destroying the reinforcing particles. When creating composites using the stir casting process, a homogeneous distribution of reinforcing components occurred [16]. Aluminum metal matrix composites consist of two distinct phases: the matrix phase and the reinforcement phase. The reinforcement phase comprises robust reinforcements such as SiC, B_4C, TiC, and Al_2O_3. Applying a coating to the reinforcing zone can prevent chemical reactions with the matrix [17]. Carbon fibers are commonly utilized in an aluminum matrix to produce composites that exhibit a low density and high strength. However, the combination of carbon with aluminum leads to the formation of the water-soluble and fragile complex aluminum carbide over the fiber surface. To counteract this, carbon fiber is coated with titanium boride/nickel. Singla has been working on developing Al-based material reinforced with SiC particulate with the aim of attaining uniform dispersion of ceramic material and creating a traditional, cost-effective method of generating MMCs [18]. The stir casting technique's two-step mixing process has been used, showing hardness and impact strength enhanced with the amount of SiC.

Further, Sharma et al. studied the surface structure and mechanical characteristics of Al/SiC-reinforced composites prepared by stir casting and revealed hardness and tensile strength have been strengthened with the addition of silicon carbide reinforcements [19]. Al Matrix's microstructural examination showed that the SiC particles were non-homogeneously distributed and clustered. James examined the impact of incorporating silicon carbide (SiC) and titanium diboride (TiB_2) into the metal matrix of hybrid aluminum composites on their mechanical properties and ability to be machined [20]. Aside from analyzing machining characteristics (feed rate, cutting speed, surface roughness, and depth of cut), the mechanical characteristics (hardness, density, and UTS) also improved. Flanagan et al. analyzed the mechanical behavior of the Al/SiC composite and showed that as temperature increases, the material's hardness decreases progressively [21]. Prabha discussed the optimization of the Taguchi methodology and the performance of dry sliding in hybrid metal matrix composites made from Al7075, TiC, and MoS_2, which were produced using stir-casting, revealing that the wear characteristics improved [22]. However, reinforcement has a detrimental effect on losing weight. When reinforcement is increased, weight loss diminishes. The second generation of AMC (alloy matrix composite), known as HAMC, has better mechanical and physical characteristics than single-reinforcement AMC. HAMC (hybrid alloy matrix composite) uses a large amount of aluminum and two or more reinforcements [23]. The advantageous nature of HAMC depends on the size and amount of reinforcement added to the aluminum matrix. Secondary reinforcement successfully combines desired composite characteristics, while additional primary reinforcement improves the fundamental [24]. Thus, in several industrial applications, HAMC replaces traditional aluminum. HAMC is separated into three categories: synthetic reinforced ceramics mixed with agricultural residue, synthetic ceramics reinforcement, and waste from industry [23–25].

Further, nanocomposites created through stir casting demonstrated improved mechanical properties. Nevertheless, there is a scarcity of research on the stir casting of Al MMNCs. A significant issue noted in this process is the formation of porosity. The nano-sized reinforcement particles possess a greater surface-to-volume ratio but low wettability, leading to an uneven distribution of nanoparticles within the matrix [26]. This heterogeneous distribution of reinforcement particles also impacts the composite's properties. An increase in the reinforcement weight fraction beyond a certain threshold result in a deterioration of characteristics. Typically, at elevated reinforcement levels, nanoparticles tend to cluster and agglomerate, negatively influencing the properties [27]. Additionally, as the quantity of nanoparticulate rises, the volume of porosity will also increase [28]. Therefore, it is essential to carefully regulate the addition of reinforcement. The existing research indicates that employing ultrasonic-assisted stir casting tailed by squeeze casting can significantly minimize porosity while enhancing the uniform dispersion of nanoparticles [29]. The use of ultrasonic vibrations proves highly effective for achieving an even dispersion of nanoparticles within the matrix [30]. The intense vibrations produced by the ultrasonic vibrator can prevent the development of clusters and agglomeration within the composites. High-power ultrasonic vibrations from the ultrasonic probe can result in strong cavitation effects and acoustic streaming [31]. The transient cavitation phenomenon initiates the disintegration of gas microbubbles located near the clusters of reinforcement particles, effectively breaking apart these clusters and ensuring a uniform dispersion within the molten pool [32]. Furthermore, the movement of liquid induced by the acoustic pressure gradient, known as acoustic flow, contributes to the efficiency of the stirring process. It is highly advisable to utilize squeeze casting for the composite, as it significantly minimizes material defects and enhances mechanical properties. The application of pressure during solidification leads to a microstructure characterized by fine grains and uniform dispersion [33]. Future research may explore the production of MMNCs through a combination of stir casting and squeeze casting, given that this approach has demonstrated both cost-effectiveness and efficiency in MMNC fabrication. The current research emphasizes how different forms of reinforcement affect AMMCs and evaluates reinforcement influence on the mechanical and tribo characteristics of composite material.

2. Processing Approach: Stir Casting

A wide variety of techniques have been developed in the last 10 years to produce MMCs. The preparation strategy is crucial in assessing the mechanical behavior of composites and also determines the cost of production. Depending upon the state of the metal, the manufacturing procedures can be categorized as solid-state and liquid-state processing. In addition, there are other techniques available that involve a partially solid matrix, including rheo-casting, compo-casting, spray deposition, and in situ fabrication. However, utilization is not as prevalent as solid/liquid state approaches [34]. In solid-state manufacturing, the bonding of matrix and reinforcing agents occurs due to the mutual diffusion that occurs between them at elevated pressure and temperature levels in the solid state [35]. Reinforcements are dissolved into the molten matrix during liquid state production, and then the matrix solidifies using casting or infiltration techniques. Compared to solid-state manufacturing approaches, liquid-state techniques are more affordable. Amongst liquid state techniques, stir casting is a widely used and cost-effective, commercially available technique that offers improved wettability, decreased porosity, and rather uniform distribution of reinforcements throughout the matrix [36]. The main process of stir-casting included the mixing of reinforcing agents with Al-based material through stirring. The stir-casting furnace is frequently powered by electrical energy, and the most popular way to produce heat is by electrical resistance heating [37]. The procedure entails raising the temperature of the matrix within the crucible until it melts. The crucible is constructed to be chemically inert to the reinforcements and matrix. However, it is essential to preheat the reinforcements in order to enhance the mixing of the components. Melting occurs during the mixing stage. To lower the possibility of casting defects, an inert state is maintained throughout stirring. Generally, an injection cannon is used to feed particulate reinforcements in order to minimize the risk of gas entrapment [38]. Rotational motion is provided by the stirrer's propeller blades, which are fixed to a shaft that is linked to the electrical motor's output. A lead screw arrangement driven by a different electrical motor may efficiently regulate the stirrer's vertical motion. Stepper motors are frequently utilized for alteration in spinning speed through a stirrer [39]. However, the matrix and reinforcement need to be wettable for a homogeneous mixture. The schematic experimental setup of the stir-casting approach is depicted in Figure 1. The properties of AMCs are largely dependent on a number of stir-casting process variables, including the size of the reinforcement, the stirrer's speed, the duration of the stirring, the design of the stirrer blade, and the melt temperature [40]. The stir-casting process parameters are mentioned below.

2.1. Reinforcement Size

The size of the reinforcement has a significant impact on the material's strength, as it is fabricated via stir casting [41]. A micro-ceramic particle is included as reinforcement into the liquid metal matrix, which increases the material's strength while decreasing its elongation [42]. Introduction of nano-ceramic particles in the composite revolutionaries the research scenario of composite material. The size of ceramic reinforcements significantly influences composite material. It improves the base material properties while preserving high resistance to temperature creep and beneficial elongation. However, the nano-sized reinforcing particles promote lower wettability, signifying the non-homogeneity of reinforcing agents in the matrix [43]. The characteristics of composites are also influenced by the heterogeneous dispersion of reinforcing particles inside the matrix. Composites with lower reinforcing sizes frequently have better mechanical behavior. Composites of Al-10Sb cast aluminum alloy and SiC were created by Youssef et al. with SiC particles with diameters of 115 μm, 225 μm, and 350 μm and weight fractions of 3%, 5%, and 9% chosen to reinforce the matrix [44]. The composite with the finest reinforcement particles (115 μm) and 9 wt.% SiC showed the greatest increase in mechanical characteristics when subjected to material characterization. The use of finer reinforcement particles maximizes the strengthening effect. AZ91D alloy-SiC AMC was created by Poddar et al. using the stir-casting technique for 15 vol.% of SiC (15 μm and 150 μm) [45]. The addition of reinforcements resulted in a decrease in average grain size. Comparing composites reinforced with 150 μm particles, the grain size of the former was much larger than the latter. Finer particles increased the refining of grains. In comparison to AZ91D alloy-150 μm SiC, composites made with AZ91D alloy-15 μm SiC likewise possessed better mechanical properties.

2.2. Stirring Speed and Stirring Time

The characteristics of reinforcement distribution in AMC are largely determined by the viscosity of the molten matrix. Increased viscosity hinders the reinforcement particles' smooth motion during stirring, which is undesirable [46]. Conversely, reduced viscosity is ineffective for suspending and retaining particles. The inter-particle distance can be increased by increasing the stirring speed. The stirrer blade profile affects the stirrer speed [47]. The homogeneous dispersion of reinforcements will result in the maximum properties of the composites. At longer stirring times, increased interparticle distances and distribution uniformity can be attained. Stirring time is differentiable based on the blade profile [48]. Moses et al. found that the mechanical characteristics of AMC were significantly impacted by a variety of stir-casting parameters, including stirring temperature, blade angle, speed, and duration [49]. Poor ultimate tensile strength is accountable for porosity, clumping, and segregation at the grain boundaries, attained with low or high values of parameters. The optimized range of process variables produced the least porous and most effective casting products with evenly distributed reinforcements. As a result, it is chosen over extremely high parameter values.

2.3. Melt Temperature

A high melt temperature can improve the wettability of the melt. High temperatures, however, are not usually preferred, causing the melt's viscosity to decrease [50,51]. Particle agglomeration in a melt is encouraged by a low melting temperature. Therefore, the middle-range temperature value is preferred, providing improvement in mechanical characteristics.

2.4. Stirrer Blade Design

Since zirconia may stop reactions among stainless steel and Al-based materials at high temperatures, it is frequently employed as a coating material for stirrer blades [52]. As a result, while stir-casting AA 6061 MMCs, a zirconia covering is strongly advised. In order to achieve ideal melting mixing, an impeller design helps to create a vortex.

Further, Unlu conducted a study comparing the PM (powder metallurgy) and casting methods and determined that the casting process exhibited higher mechanical behavior compared to the powder metallurgy approach [53]. Problems with the PM approach include porosity, insufficient bonding between the reinforcement and matrix, challenges in achieving an even distribution of particles, inadequate wetting of the reinforcement and matrix, chemical reactions between the reinforcement material and the matrix alloy, and clumping caused by differences in density between the matrix and reinforcement [54]. Several manufacturing casting process variables, such as the size of the sink, stirring time, capacity and size of the impeller, the temperature of the molten metal, length of melting, stirring speed, type and size of reinforcement, melting rate, and mold temperature, etc., are accountable for assessing and improving the mechanical behavior of composite [54]. During the stir-casting process, it is crucial to observe and assess the dispersion of reinforcing particles inside the matrix. Ensuring homogeneity in dispersion throughout is typically challenging because of density differences [53,54]. Aluminum alloy composites prepared with ceramic particles are extensively utilized in the automotive and aerospace industries.

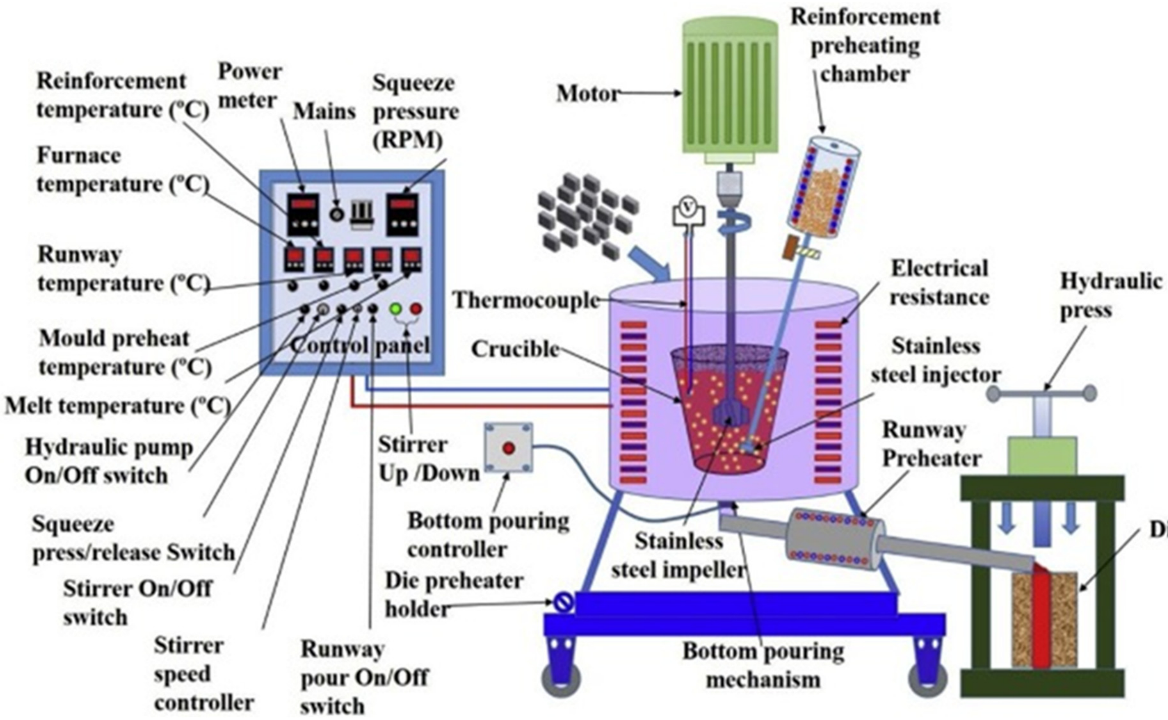

Figure 1. Schematic experimental setup of stir casting approach [54].

The dispersion and distribution of ceramic nanoparticles in liquid metal are the only factors that affect the characteristics of metal matrix nanocomposites [55]. The effects of stirring temperature and duration on ABOw (aluminum borate whisker) and SiCp-reinforced Al6061 composite were examined by Guan et al. [56]. The microstructure showed accumulation of composites with ABO_w and SiC_p, as when the stirring temperature and duration are increased, the uniformity of the reinforcement distribution first rises and subsequently declines (Figure 2a–d) [56]. To further conclude, the evidence of ABO_w and SiC_p was depicted in the XRD and TEM. The XRD results of the composite produced at 640 °C for 30 min are illustrated in Figure 2e. It is evident that neither Al_4C_3 nor $MgAl_2O_4$ is present in the composites, indicating that the pretreatment of ABOw and SiCp successfully inhibits interfacial reactions with the matrix alloy. However, the diffraction peak corresponding to ABOw is not visible in Figure 2e, attributed to its low concentration within the composite [56]. Figure 2f present the TEM micrograph of the hybrid composite, revealing the presence of ABOw and the formation of an Al_2O_3 interlayer between the matrix and the ABOw reinforcement. This suggests that during stirring and squeeze casting, ZnO can react with molten aluminum, enhancing the wettability between ABOw and the matrix alloy while effectively preventing damage to ABOw [56]. Shear and friction between the semisolid slurry and reinforcement, which is proportionate to the viscosity, is the concern behind [57]. The semi-solid slurry's viscosity and solid fraction both rise at a lower churning temperature. When the temperature drops to 630 °C, the matrix alloy is no longer liquid during stirring. It becomes extremely difficult to stir completely because of the significantly increased viscosity or friction resistance, which makes it impossible to distribute reinforcement uniformly throughout the composites [56]. The optimized value of stir parameters is taken as 640 °C and 30 min.

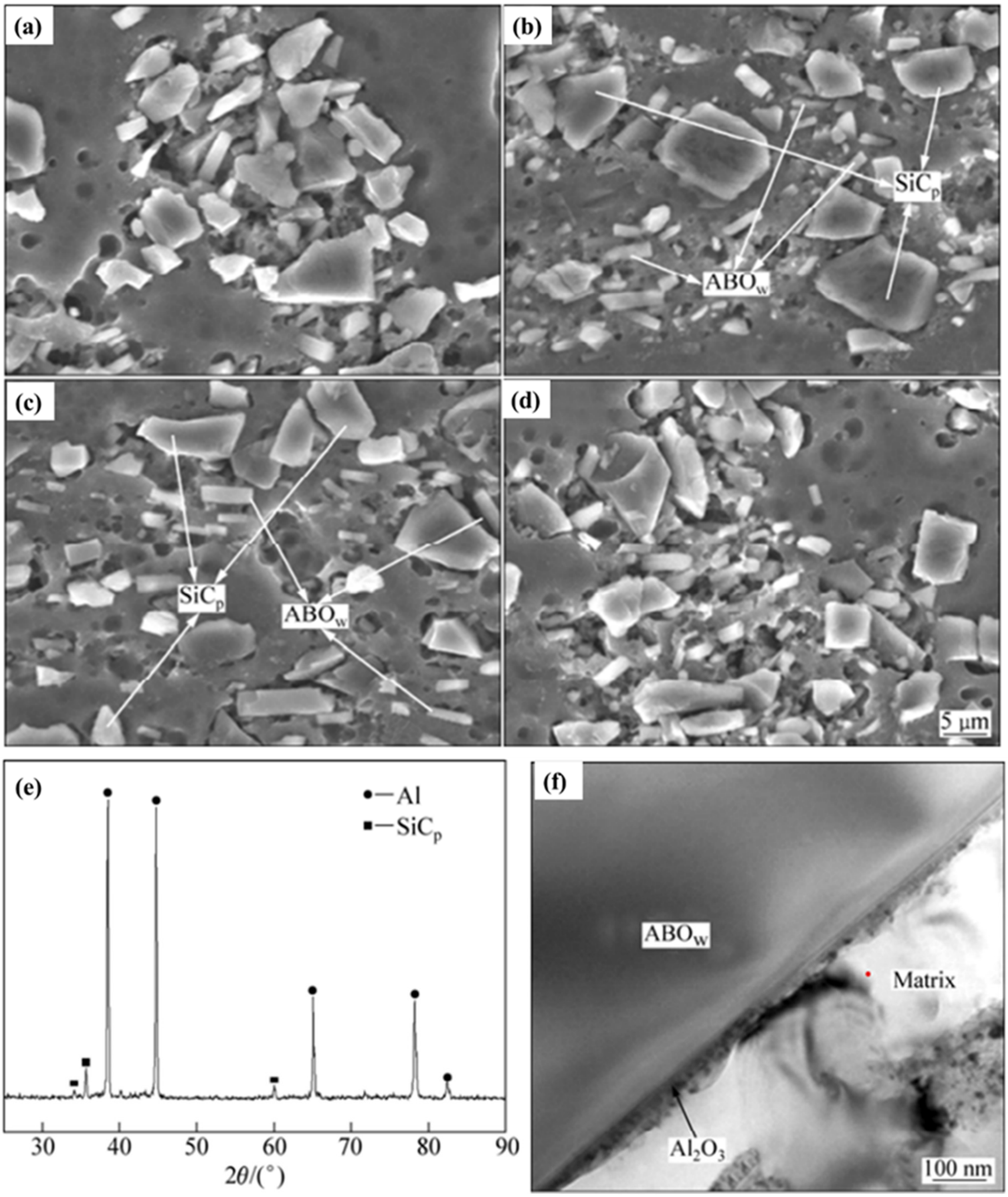

Figure 2. SEM image of composites made of (5%ABO_w + 15%SiC_p)/6061Al and subjected to varying stir temperatures for 30 min: (**a**) 680 °C, (**b**) 650 °C, (**c**) 640 °C, and (**d**) 630 °C. Further, (**e**) shows the XRD pattern of the composite, and (**f**) reveals the TEM micrographs of composites [56].

3. Reinforcement Materials in AMMCs: Properties, Processing, and Performance Trends

Particulate reinforcements such as SiC, Al_2O_3, B_4C, and TiC are most commonly used for the enhancement of composite properties [58]. Al-based composite also includes various additional reinforcing agents, including bamboo charcoal, glass, rutile, hematite, and iron ore [59]. The uniform dispersion of reinforcements inside the matrix indicates that stir casting is the most effective technique for composite preparation. Hardness, compressive, and tensile strength are directly dependent upon the weight fraction of reinforcement [60]. Additionally, the reinforcing particles in composites significantly improve wear properties. The addition of reinforcement resulted in a reduction in grain size. Agglomeration, increased porosity, and non-uniform particle dispersion remain a critical issue while assessing the amount and types of reinforcement [61]. Hybrid composites utilize different (two or more) types of reinforced materials, which directly or indirectly affect the mechanical characteristics of the composite. Research scenarios pertain that an increase in the weight percentage of MoS_2 particles resulted in a decrease in the composite's tensile strength and hardness [62]. Nonetheless, the composite's resistance to wear and friction was enhanced by the addition of MoS_2. Further, the stir-casting process was selected as an optimal method for hybrid composite preparation, signifying casting free from porosity. The usage of agricultural and industrial waste materials in the dispersed phase widens the application usage of hybrid composites [63]. Fly ash, rice husk, and bamboo charcoal have also been utilized.

Reinforcement pre-treatment improves compatibility with the matrix, preventing weakening bonding reactions [64]. Controlling process variables like stirring speed and duration helps maintain consistent dispersion of reinforcement, reducing clustering and segregation [65]. Maintaining optimal melt temperature enhances wettability, facilitating robust bonding and preventing agglomeration and degradation [66]. Coatings like nickel or titanium boride can inhibit harmful chemical reactions and enhance interface strength [67]. Optimal reinforcement size and content improve bonding by increasing surface area and maintaining the reinforcement's weight percentage within an ideal range [68,69]. Ultrasonic-assisted stir casting promotes uniform particle dispersion, minimizes porosity, and enhances interfacial bonding [70]. Post-fabrication heat treatment refines the microstructure and strengthens the bond between the matrix and reinforcement, enhancing mechanical characteristics, durability against wear, and overall strength of the composite material [71]. These actions enhance the composite material's mechanical characteristics, durability against wear, and overall strength. The properties of the composite deteriorate beyond the optimal limit of reinforcement. Higher reinforcement content often causes the nanoparticles to aggregate and cluster, which alters the characteristics [72]. The amount of nano-particulates is directly related to porosity. Therefore, it is important to quantify the optimal limit of nano-particulates.

Porosity may be successfully reduced, and the homogeneous distribution of nanoparticles can be increased through ultrasonic-embedded stir casting [73]. Homogeneous dispersion of nanoparticles inside the matrix is achieved by the utilization of ultrasonic vibration. Strong vibration produced by the ultrasonic vibrator prevents composites from clumping and agglomerating. Strong cavitation effects and acoustic streaming result from the ultrasonic probe's high-power ultrasonic vibrations. The collapse of gas microbubbles close to the clusters of reinforcement particles is triggered by transient cavitation, which breaks up the clusters and distributes them evenly throughout the molten pool [74–76]. Furthermore, the acoustic flow, i.e., the liquid's flow as a result of the acoustic pressure gradient, makes stirring incredibly efficient. Predominantly, squeeze casting is highly preferred for defect- and porosity-free casting. The uniform dispersion and tiny grains would arise from solidification under pressure [77]. Future research might concentrate on the affordable and efficient way of manufacturing metal matrix nanocomposites that involve stirring casting in conjunction with squeeze casting. In general, mechanical behavior such as impact strength, tensile strength, and hardness improve with reinforcement in the composite.

Further, the addition of ceramic reinforcements such as alumina, silicon carbide (SiC), and titanium diboride (TiB_2) generally improves the mechanical strength of aluminum MMCs but may have a negative impact on ductility. This is primarily due to the hard-brittle nature of ceramic materials, which can lead to crack formation and propagation when deformed [78,79]. Studies have shown that increasing the weight percentage of alumina in an aluminum matrix initially increases hardness and yield strength, but too high a content can lead to a decrease in ductility. For example, increasing the alumina content from 0% to 20% results in an improvement in compressive strength but a reduction in elongation at break [79]. Adding SiC to aluminum can improve wear resistance but can also have a negative impact on ductility. Improvements in tensile strength have been observed in hybrid composites containing fly ash and SiC, but elongation tends to decrease with increasing reinforcement content [80,81]. The introduction of nano-ceramic reinforcements shows the potential to simultaneously improve the strength and ductility of aluminum composites. For example, when processed using special techniques, nano-TiB_2 reinforcements exhibit improved mechanical properties without significantly affecting ductility [78]. The volume fraction of ceramic reinforcement plays a crucial role in determining the mechanical properties of aluminum MMCs. A balanced approach is required; while low ratios may not significantly improve strength, high ratios may result in brittleness and reduced ductility [80,81]. Improving wettability by chemical modification or the addition of alloying elements can improve the bonding of the matrix–reinforcement interface, which helps to maintain a certain degree of ductility in the presence of hard ceramic particles [79,82]. The microstructure produced by different processing conditions can affect the performance of MMC under stress. Fine microstructures with uniformly distributed reinforcements tend to show better ductility than fine microstructures with coarsely distributed or poorly distributed reinforcements [78–82].

The bonding between the matrix and reinforcement is significantly enhanced through improved quality and surface treatments of reinforcements [83]. Coatings or surface modifications inhibit chemical reactions and improve wettability, resulting in superior mechanical properties [11]. The characteristics of a reinforcement's surface play a crucial role in its uniform distribution within the matrix. When surface quality is inadequate, clustering or agglomeration can occur, which negatively affects mechanical properties such as tensile strength and hardness [84]. However, the surface treatments promote better bonding and also lead to enhancements in properties like hardness, impact resistance, and tensile strength [85]. For instance, ceramic reinforcements with optimized surface conditions bolster the composite's ability to bear loads. Additionally, the better surface quality of reinforcement surfaces lowers porosity and facilitates better integration with the matrix, thereby improving the tribological performance of metal matrix composites (MMCs). However, the issues arising from insufficient surface quality, such as porosity, weak bonding, and uneven distribution of reinforcements, can result from inadequate preparation of surfaces [85]. Highlighting the significance of reinforcement surface quality emphasizes the necessity for pre-treatment methods, including coating or preheating, to guarantee optimal integration and enhancement of the properties of composites.

The mechanical, thermal, and tribological performance of MMCs is significantly influenced by factors such as density, porosity, CTE, dislocation density, and thermal mismatch [86]. Specifically, density affects the specific strength (strength-to-weight ratio), which is essential for sectors like aerospace, automotive, and structural engineering [87]. While a higher density stemming from a dense matrix or heavy reinforcements can enhance stiffness and impact resistance, it may also pose challenges for lightweight design needs [88]. Conversely, employing low-density reinforcements (such as fly ash or carbon fibers) can decrease the overall weight of the composite, thereby improving fuel efficiency and increasing load capacity in transportation applications [87]. Reinforcements like SiC and B_4C contribute to enhanced mechanical properties with only a slight increase in weight due to their moderate density in comparison to conventional metals [89]. Porosity can significantly weaken the mechanical properties of composites, such as tensile strength, fatigue strength, and toughness, because it creates stress concentration points and disrupts load transfer between the matrix and reinforcement [90]. High porosity creates opportunities for environmental factors to degrade the material, which can negatively affect wear and corrosion resistance. Improved manufacturing techniques, such as optimized stir casting, ultrasonic-assisted casting, or squeeze casting, can help reduce porosity and improve bonding at the matrix–reinforcement interface [70]. A CTE (coefficient of thermal expansion) mismatch between matrix and reinforcement materials can generate thermal stresses during temperature fluctuations, which can cause microcracks or delamination in the composite [91]. Low CTE reinforcements (e.g., SiC, Al_2O_3) can reduce the overall CTE of the composite, improve thermal stability, and minimize deformation under high-temperature conditions [92]. Thermal stability due to controlled CTE is essential for electronic packaging, aerospace parts, and engine components where dimensional accuracy is critical [93]. Reinforcements induce dislocation density in the matrix due to thermal mismatch and mechanical load transfer. This increases strength and hardness through solidification effects [94]. High dislocation density improves wear resistance by making the surface harder and more wear-resistant but reduces ductility and toughness. Dislocations improve mechanical interlocking and load transfer but can cause localized stresses that affect long-term reliability [94]. A thermal mismatch between matrix and reinforcement affects mechanical and tribological properties. Residual thermal stresses increase hardness and strength, but excessive stresses can lead to microstructural instability, especially under cyclic thermal conditions [95]. Reinforcements with higher thermal stability, i.e., SiC and TiC, enhance wear resistance at high temperatures. In high-temperature applications such as engines, materials with better thermal mismatch can provide longer service life and lower wear rates [95].

Gravity segregation during stir casting often arises from density differences in reinforcing agents and matrix material. Additionally, clustering and agglomeration can occur due to insufficient wetting of reinforcement particles and improper stirring conditions, such as speed, temperature, and duration. Thus, optimizing these process parameters is essential for achieving a consistent distribution of reinforcements and preventing clustering [96]. Employing finer reinforcement particles along with optimized stirring configurations, like blade design, can enhance particle distribution. In addition, preheating the reinforcement improves wettability and reduces segregation during the mixing stage. Ultrasonic-assisted stir casting breaks up agglomerates through cavitation, which helps in the uniform distribution of particles in the matrix material [70]. In addition, curing under pressure minimizes porosity and promotes uniform particle distribution.

Further, the temperature during processing and subsequent heat treatment plays a crucial role in affecting the hardness of aluminum-based composites. Research indicates that the hardness of AMMCs is improved by heat treatment at higher temperatures, which promotes the precipitation of strengthening phases within the matrix [97–99]. The T6 heat treatment method, entailing solutionizing followed by aging, has been shown to significantly elevate hardness levels. For instance, composites have demonstrated an increase in hardness from 72 HB to 105 HB after suitable heat treatment [100]. Additionally, elevated temperatures during processing can induce microstructural alterations that influence hardness. While higher temperatures may encourage grain growth, they also aid in dissolving reinforcing particles and lead to a more refined microstructure upon cooling [101]. If processed appropriately, this dual effect can further enhance hardness. Studies show that there is an ideal temperature range for processing aluminum composites, where hardness reaches its maximum before decreasing due to excessive grain growth at higher temperatures. Temperatures between 500 and 550 °C during stir casting have been found to produce composites with greater hardness than those processed at either lower or excessively high temperatures [102].

The wear resistance of aluminum-based composites is primarily influenced by their microstructure and the type of reinforcement utilized. Common wear mechanisms include abrasive wear, adhesive wear, and fatigue wear [103]. The incorporation of hard reinforcement particles like SiC or Al_2O_3 greatly enhances wear resistance by redirecting crack propagation and bridging fractures [104]. Temperature also plays a vital role in wear resistance; higher processing temperatures improve the interfacial bonding between the matrix and reinforcement, which enhances load transfer during wear evaluations [105]. Composites processed at higher temperatures exhibit better wear resistance due to improved mechanical interlocking between the matrix and reinforcement particles. However, the research studies depicted that increases in temperature during wear testing have been associated with changes in wear rate [106]. For instance, increasing the test temperature from room temperature to 200 °C reduced the wear rate of certain aluminum composites due to improved lubrication at elevated temperatures [107].

Concerning the optimal limit of the reinforcement in order to counter agglomeration, porosity, and cluster formation, the effects of various reinforcements in affecting the overall characteristics of the composite were critically assessed and shown below:

3.1. AMMCs Reinforcement with Silicon Carbide (SiC)

Research has shown that incorporating SiC into AMMCs as a reinforcing particle result in enhanced machinability and mechanical characteristics. Ozden et al. examined the effects of SiC reinforcement on the resulting behavior of an aluminum alloy [108]. Further, the impact behavior of composites at variable temperatures is also assessed. The impact behavior is affected by bond strength among the matrices and reinforcement, the aggregation of particles, and the agglomeration of particles [109]. However, the test temperature has a minimal influence on the material's impact behavior. With an increase in temperature, the composite experiences a drop in its modulus, ductility, and strength. Thunemann et al. [110] assessed AMMCs mixed with polymethyl siloxane (PMS at 1.25 wt.%) as a binder, which is reinforced with SiC and retains superior mechanical characteristics. Peng et al. [111] assessed the occurrence of particle clusters and their influence on the flow properties of composites reinforced by SiC particles. Particle clustering plays a major role in the deformation (plastic) and the matrix's mechanical reaction during tensile deformation. The impact on plastic deformation is greater than that on mechanical behavior. Prabhu et al. [112] examined how the speed and duration of agitation affect the dispersion of the particles in SiC-reinforced AMMCs. The outcomes revealed that when the stirring time and speed are shorter, particles tend to clump together in some locations. Conversely, when the stirring time and speed are higher, the particles disperse more evenly. Agitating for one minute at a pace of 600 rotations per minute yielded a consistent level of hardness. Barekar et al. found that the process of regular stir casting causes particles to clump together, which in turn reduces the flexibility of composites [113]. To reduce the roughness of the surface, Kılıçkap et al. [114] made adjustments to the feed rate, volume percent of SiC, and the speed of cutting. A carbide cutting tool that is coated with composite material for better surface qualities. Natrajan et al. [115] conducted a comparison of the wear behavior of A356/25 wt.%SiC with A356, revealing that the composite exhibited a very high wear resistance, indicating its suitability as a material for drum brake linings. Zehua conducted a study on the wear behavior of tools used in SiC-reinforce composite machining, revealing that abrasive wear is responsible for damage to the tool flank edge [116]. However, brittle failure imparts high tool hardness. Sam et al. [117] quantify the role of carbide ceramics as reinforcement on the mechanical strength of Al composites. The hardness increases as the plastic deformation tendency increases with reinforcement. Kumar et al. [118] assessed resistance to wear caused by dry sliding of Al6061-SiC composites, revealing a reduction in wear rate with reinforcement. The reinforcement played a vital role in reducing the wear rate of the Al-based material, imparting proper bonding between the matrix and reinforcing agent. Using stir-casting techniques, Coyal et al. [119] produced inexpensive AMMCs containing SiC and jute ash particles that had improved characteristics. A pin-on-disc tribometer assessed wear behavior and revealed that wear resistance is increased by the addition of reinforcement particles. The composite has a wear resistance around four times greater than that of the basic material. The presence of the reinforcement causes a significant reduction in COF due to the creation of a mechanically mixed layer.

3.2. AMMCs Reinforcement with Alumina Oxide (Al_2O_3)

Alumina oxide (Al_2O_3) is the most commonly utilized reinforcing material for AMCs, second only to silicon carbide, due to its remarkable interfacial compatibility. Al_2O_3 is a hard ceramic material with a moderate density (3.97 g/cc) and a large thermal expansion coefficient. Park et al. [120] investigated the impact of incorporating Al_2O_3 (5 wt.% to 30 wt.%) into aluminum and revealed that the presence of gaps between particles within nucleated micro-voids leads to a decrease in fracture toughness. Park et al. [121] assessed the fatigue characteristics of Al_2O_3 (5 vol.% to 30 vol.%) reinforced Al6061-Mg-Si alloy and showed that composites had a higher fatigue strength with PM than liquid metallurgy. Koket et al. [122] created an Al alloy composite reinforced with Al_2O_3 particles using the vortex process and then examined the mechanical characteristics of the material. Preheat mold at 550 °C, stirring at 900 rpm (20 min), particles at a rate of 5 g/min, pouring temperature (700 °C), and pressure of 6 MPa are ideal conditions. Applying pressure decreases porosity but enhances the strength of the composite. Kumar et al. [123] investigated the properties of A359/Al_2O_3 composites and revealed that the use of electromagnetic-assisted stirring resulted in a reduction in grain size. Further, the bonding between the particles and the matrix leads to an increase in the tensile strength of the composite. The inclusion of Al_4C_3 and Al_2O_3 in Al-based material not only withstands high temperatures but also enhances the hardness as well as compressive strength [124]. Mondal et al. [125] assessed how the load and size of abrasive particles affect the wear of the Al/Al_2O_3 composite. The abrasive particle size, as well as load, have a greater impact on the wear of composites compared to Al alloys.

3.3. AMMCs Reinforcement with B_4C

Boron carbide (B_4C) exhibits metallic luster and is recognized as the hardest reinforcing agent amongst the ceramic's reinforcement. Its remarkable thermal and chemical stability makes it a highly desirable reinforcement material. Additionally, B_4C possesses a low density (2.52 g/cc) comparable to Al_2O_3 and SiC. This material is utilized in the production of military tanks and bulletproof vests [124]. Consequently, B_4C-reinforced aluminum matrix composites (AMCs) produced via the cost-effective stir casting technique have gained significant appeal. Vogt et al. [126] investigated B_4C and cryo-milled aluminum nanocomposite material plates that were created in two distinct ways: hot isostatic pressing (HIP) combined with two steps of quasi-isostatic forging (QIF) and HIP combined with high-strain-rate forging (HSRF). The results indicate that QIF plates have lower strength compared to HIP/HSRF plates; however, they exhibit higher ductility. HSRF suppresses the process of dynamic recrystallization, resulting in HIP/HSRF plates that exhibit enhanced strength and reduced ductility. Babu et al. [127] evaluated the surface quality of mixed composites (Al-SiC-B_4C) by employing the Taguchi technique in order to assess the surface roughness of the processed hybrid composite. The results concluded that the feed rate, in conjunction with the cutting speed, is the most crucial factor. The feed rate has very little effect on the characteristics of the surface. Previtali et al. [128] employed the conventional investment casting approach to manufacture Al-composites with SiC-reinforced exhibit superior wear resistance compared to B_4C-reinforced AMMCs. The research studies concluded that B_4C concentration in Al-based materials causes the peak of B_4C to increase while the peak of Al decreases. The Al peak exhibits a diminished divergence comparable to alloy. The XRD confirms the absence of any interaction between the B_4C particles and the aluminum matrix [129]. The development of a Ti layer around the B_4C is thought to be the cause of the reaction barrier, which stops an interfacial reaction between the B_4C and aluminum. Kalaiselvan et al. [130] examined the mechanical properties of Al6061/B_4C composites and revealed that micro- and macro-hardness and grain size decreased with an increase in reinforcement.

3.4. AMMCs Reinforcement with Fiber

Fiber-reinforced aluminum composites, especially carbon fibers, offer significant improvements in mechanical properties and performance. These composites have higher tensile strength, yield strength, and elastic modulus, making them suitable for harsh environments where durability is critical. Stir casting is a common technique for producing fiber-reinforced aluminum matrix composites, where aluminum is melted at temperatures around 680 °C and infiltrated with fibers during a stirring process [131]. The presence of fibers not only strengthens the matrix but also helps refine the grains, improving hardness and overall structural integrity. These composites can be used in various industries, including aerospace, automotive, and military. The stir-casting process ensures optimal integration of the fiber reinforcements into the aluminum matrix. Sayman et al. [132] investigated the stress behavior of AMMC-laminated plates in the plane, considering both elasticity and plasticity. Laminated plates induce a strong bond among the matrix, and the fibers supported more weight at 30 MPa and 600 °C. Using elastic–plastic stress analysis, Atas studied how the plastic area expanded in aluminum metal matrix laminated plates, yielding in steel-fiber-reinforced laminated plates initiates along the edges. In contrast, the corners of the plates remain unaffected by yielding [133]. Using a low-cycle fatigue model, Ding et al. [134] assessed Al_2O_3 addition to Al-based material to refine its microstructure and decrease its fatigue ductility. The characteristics of a carbon-fiber-reinforced Al7075 AMMC were found by Lee et al. in relation to temperature and strain rate [135]. The work-hardening rate decreases as a result of temperature and strain increases. Rams et al. [136] examined an Al-based material composite reinforced with Ni-coated SCF (short carbon fibers). Research indicates that the addition of electroless nickel-coated fibers enhances the wettability of the composite. The formation of a transitory intermetallic layer of Ni–Al–P occurs due to the application of heat, which explains this phenomenon. Fu et al. [137] assessed the wear characteristics of hybrid composites and revealed that the wear resistance of the saffil/Al/SiC composite outperforms the saffil/Al_2O_3/Al composite at room temperature and higher temperatures.

3.5. AMMCs Reinforcement with Zirconia

With exceptional mechanical and wear behavior, zirconia (ZrO_2) is one of the most affordable and accessible materials. Aluminum alloys that contain ZrO_2 particles demonstrate notable enhancements in their mechanical and wear characteristics. Rino et al. [138] investigated the properties of the Al6063 matrix reinforced with alumina (Al_2O_3) and zircon sand. The 4 vol.% Al_2O_3 + 4 vol.% zircon sand exhibits a higher hardness value and tensile strengths along with homogeneous particle dispersion with fewer pore sites. Das et al. [139] studied the effects of employing zircon sand and alumina as reinforcing materials and claimed that adding zircon sand and alumina improves the Al-Cu alloy's resistance to wear. In comparison to the alumina-reinforced composite, the zircon-reinforced composite shows improved wear resistance because of particle-matrix bonding. Kumar et al. [140] assessed the microstructural behavior of the Al/Zr composite, which revealed a homogeneous distribution of reinforcement particles that exhibit both porosity and particle cluster. However, Abdizadeh et al. [141] conducted an analysis on a $ZrSiO_4$-reinforced Al-based material, revealing uniform dispersion of grain particles as well as the transformation from needle-like to compact spherical silicon near the zircon sand. Das et al. [142] investigated the abrasive wear properties of aluminum alloy reinforced with zircon and compared the wear behavior with alumina-reinforced aluminum alloy. When the reinforcement's particle size decreases, the wear resistances of both composites rise. However, the zircon-reinforced composite had superior wear properties than the alumina particle-reinforced composite, revealing that bonding between zircon and Al is stronger than Al and alumina particles.

3.6. AMMCs Reinforcement with Fly Ash (FA)

Fly ash-reinforced aluminum composites have attracted attention due to their improved mechanical properties and potential applications in various industries. Fly ash is a byproduct of coal combustion and acts as an effective reinforcement material due to its fine particle size and high silica content [143]. FA particles, which are composed of SiO_2, Al_2O_3, and Fe_2O_3, are low-density, low-cost wastes from thermal power plants that may be utilized as reinforcements [144]. Table 1 depicts the actual chemical composition of fly ash. The incorporation of fly ash into the aluminum matrix significantly improves tensile and fatigue strength, wear resistance, and hardness. The addition of fly ash reduces the wear rate, making these materials suitable for applications in abrasive environments. The fatigue strength of these composites also benefits from the presence of fly ash, with significant improvements observed due to the uniform distribution of fly ash particles in the aluminum matrix, enabling efficient load transfer and reduced crack propagation [145]. Al7Si0.35 Mg/FA produced using stir casting by Rajan et al. revealed that even while the tensile strength of the composite decreases, the enhanced composite strength was obtained in comparison to the matrix alloy [146]. An aluminum alloy-FA composite to block electromagnetic radiation was investigated by Dou et al. and revealed that imparting electromagnetic shielding properties to the composite material leads to a decrease in its tensile strength [147]. Ramachandra assessed the wear and corrosive properties of aluminum matrix composites made with a fiber reinforcement alloy (FA) and revealed that adding FA causes an increase in corrosion and wear resistance [148].

Table 1. Shows the chemical composition of fly ash [144].

Condition	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	L.O.I. (Left on Ignition) (%)	Moisture (%)	Additional
Fly ash (untreated)	58.5	25.4	5.0	4.0	0.3	Balance
Fly ash (treated)	68.1	27.0	3.0	0.19	0.2	Balance

3.7. AMMCs with Other Reinforcement

The specific strength of Al6061/TiC composites assessed by Gopalakrishnan et al. revealed the increase in tensile strength of the composite with the amount of TiC. Further, TiC addition lowers the percentage of elongation [60]. Girisha et al. [149] conducted a study on the mechanical characteristics of a stir-cast composite material consisting of multiwall carbon nanotubes (MWCNTs) as a reinforcing agent. The yield strength is enhanced proportionally with the rise in the weight percentage of MWCNTs. The tribological characterization of composites based on Al–TiC composites was studied by Tyagi et al., indicating that wear rate fluctuates under a typical load, which is consistent with Archard law [150]. In Figure 3a, the uniform distribution of the macro-void indicates ductile fracture. Figure 3b showcases a considerable amount of permanent deformation revealed by micro-pits. Figure 3c shows micro-pits clustered at several locations, revealing the formation of different sizes of micro-pits over the surface. As a result, the crack formation occurred over the surface due to high surface stresses present near TiC. Figure 3d shows the mixed behavior of fracture, i.e., brittle and ductile, due to the increase in concentration of macro- and micro-voids. However, the higher concentration of TiC only shows macro-voids, highlighting brittle failure. Furthermore, Figure 3f shows TiC particles present in the interdendritic region. The volumetric loss of the matrix and its composites is directly proportional to the increase in load (Figure 3g). With an increase in the concentration of TiC, the microhardness of the composite increased (Figure 3h).

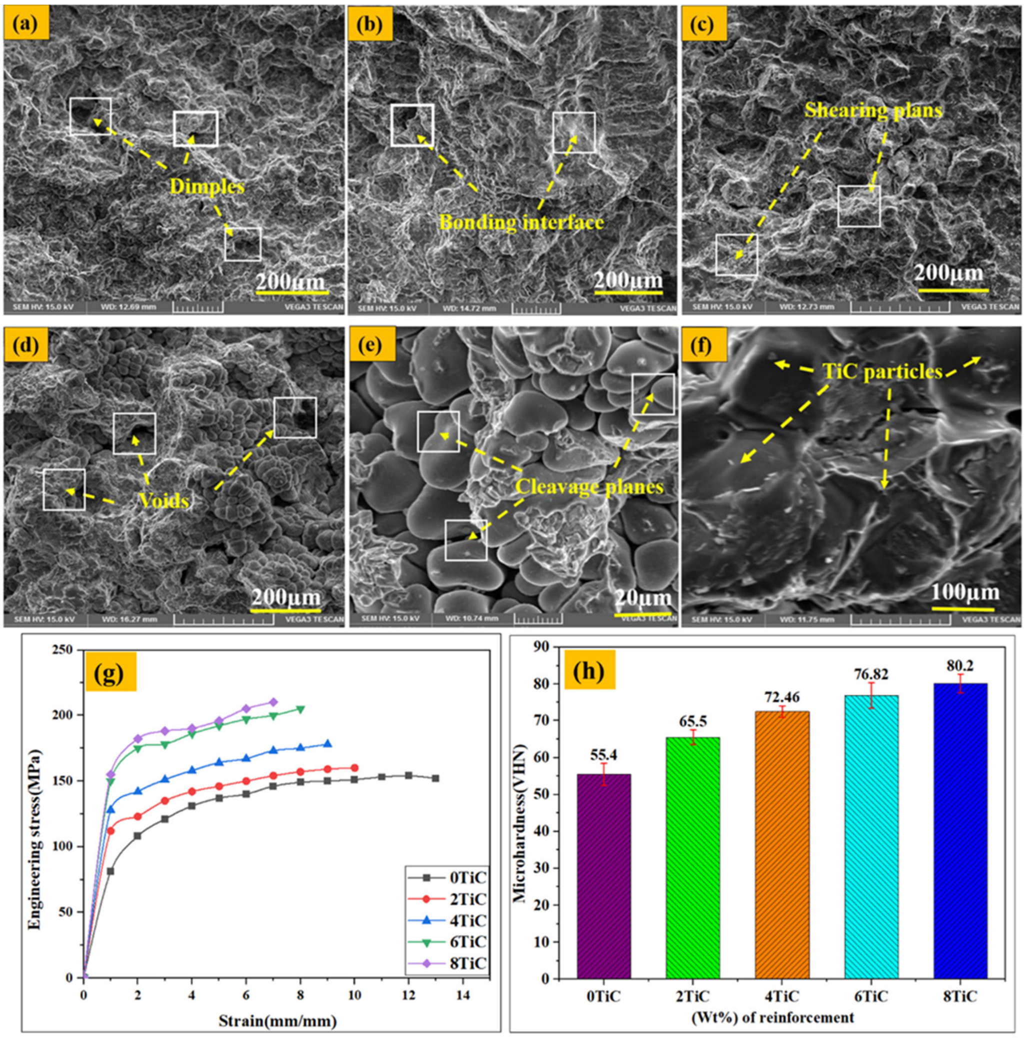

Figure 3. (**a**–**f**) Wear resistance caused by dry sliding of Al6061-TiC composites. (**g**) Stress vs. strain curve, and (**h**) microhardness for Al6061/TiC [150].

3.8. AMMCs with Hybrid Reinforcement

Al-based materials exhibit better mechanical characteristics (high stiffness and strength, low density) and tribological aspects than unreinforced materials subjected to changes in microstructure [18–20]. The microstructure of Al-based material, including thermomechanical, tribological, and mechanical properties, is greatly influenced by the presence of hybrid reinforcements such as zirconium, CNTs, FA, Al_2O_3, and SiC [34]. The primary factors contributing to the enhancement of mechanical properties include enhanced bonding between the matrix and reinforcement, uniform distribution of reinforced particles within the matrix, and more refined grain size [24–28]. A more intricate structural morphology exhibits improved mechanical qualities in comparison to a less intricate morphology [65]. The hybrid zircon sand and graphite particles in the Al6061 composite were characterized by Gopi et al. and revealed Al dendrite boundaries with coarse intermetallic particles [151]. However, the heat treatment of composite produces a structure with a finer texture. Sharma et al. [152] examined zircon/SiC reinforced with an Al-based material composite and revealed a precise dispersion of spherical eutectic silicon carbide occurs in proximity to the reinforced particles. Al6061 composites, in particular, Al6061–SiC/CSA composites, were assessed by Satheesh, revealing that the inclusion of CSA and SiC increased the tensile strength and hardness of the composite (Figure 4a–d) [153]. The agglomerations of reinforcing agents were a concern while dealing with hybrid composites. Coconut shell ash (CSA) and SiC were combined in a composite material strengthened using the process of stir casting, revealing that reinforcement particles are uniformly dispersed and do not exhibit agglomeration. Al6061/SiC/10%CSA composite showed reinforcing material was present in clumps and empty spaces.

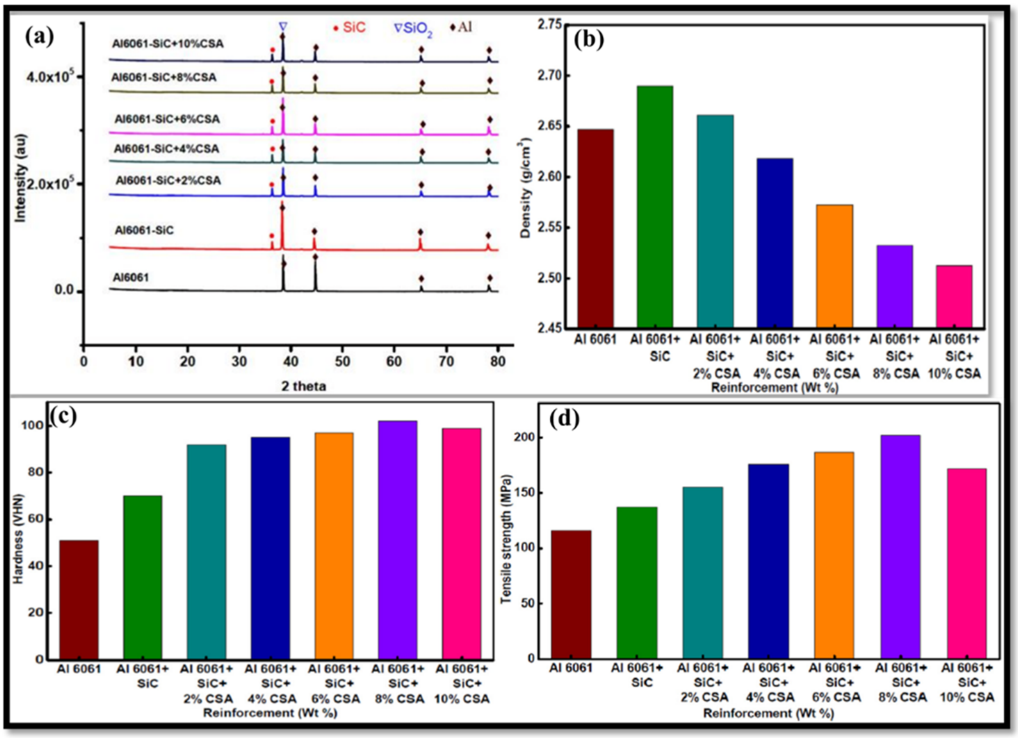

Figure 4. (**a**) XRD pattern, (**b**) density (g/cc), (**c**) hardness (VHN), and (**d**) tensile strength of Al6061 alloy along with the various reinforcements [153].

The addition of lightweight reinforcement particles, such as fly ash or SiC, is responsible for the reduction in density. When integrated into the aluminum matrix, fly ash, a low-density material, lowers the overall density of the composite. Furthermore, the incorporation of hard ceramic particles like SiC or alumina leads to an increase in hardness. These reinforcements hinder the movement of dislocations within the aluminum matrix, resulting in improved hardness. The enhancement is also aided by the uniform distribution of these particles, achieved through techniques such as stir casting. Additionally, improvements in tensile strength arise from the load transfer mechanism, where reinforcement particles absorb a substantial portion of the applied stress [153]. A crucial factor in this enhancement is the strong interfacial bonding between the matrix and the reinforcement. The addition of reinforcements not only improves the mechanical properties but also affects the microstructure, i.e., grain refinement and uniform particle distribution [60]. Grain refinement leads to an increase in yield strength and tensile strength, as described in the Hall–Petch relationship [154]. The reduction in density is particularly beneficial for aerospace and automotive applications and meets the industry's demand for lightweight yet strong materials.

The mechanical behavior of Ni-P-coated SiN-reinforce Al-based material was also investigated by Ramesh et al. in addition to the stir cast technique [155]. Microhardness is greatly increased in the matrix alloy by adding Ni-P-coated silicon nitride particles. The inclusion of the rigid ceramic phase enhances the hardness of composite materials by diminishing the proportion of malleable metal. The hybrid reinforcement showcases better mechanical properties as compared to Al6061/CSA reinforcement, which was investigated by Lakshmikanthan [156]. Kumar et al. [157] assessed hybrid Al6061/WC/Gr composites and revealed a decrease in ductility. Santosh et al. [158] assessed SiC/graphite to Al6063 alloy improved the mechanical characteristics of composites, utilizing a stir casting approach with the incorporation of SiC (2 wt.%) and graphite (1 wt.%, 2 wt.%, and 3 wt.%) as reinforcing agents. The enhancement in tensile strength (57%) with only SiC and no graphite, but reduction was obtained when 3 wt.% of graphite was added. Using a semi-solid stirring method, Guan et al. effectively created hybrid composites composed of Al6061/5 vol.%ABO_w/15 vol.%SiC particles [159]. The tensile strengths were increased at stirring temperatures (630 °C to 680 °C) and stirring time (20 min to 30 min). Mechanical behavior of hybrid B_4C (4 wt.%, 8 wt.%, and 12 wt.%) and MOS_2 (lubricant) reinforced Al composites was conducted by Liu et al. using stir casting processes [160]. The reinforcement particles, which resemble tiny dendrites, are evenly distributed throughout the matrix, enhancing the hardness, compressive, and tensile strength of reinforced composites compared to monolithic alloys. The process of load transmission between the matrix and the reinforcing particles strengthens the overall characteristics of composites by increasing the interfacial bonding, grain size, and strain gradient. Multiple researchers have discovered that improving the mechanical characteristics of composites necessitates the use of nanoscale reinforcement. Logesh et al. [161] utilized the stir casting technique to produce AlN/MWCNT/graphite/Al composites, revealing enhanced mechanical properties. Particle strengthening is accomplished by utilizing integrated-shape reinforcements, while grain refinement is performed by incorporating AlN (aluminum nitride, a ceramic material known for its high thermal conductivity and electrical insulation properties). AMMCs reinforced with SiC were synthesized by Sujan et al. and assessed the comparative tribo-behavior of Al-based composites reinforced with SiC and Al_2O_3, revealing the reduction in wear rate with an increase in the amount of reinforcement [162]. However, the low wear rate was obtained for Al/SiC composites rather than Al/Al_2O_3 composites. Radhika et al. [163] conducted an investigation on tribo properties of Al-based material that was reinforced graphite and alumina using Taguchi's approach with an L27 array to ascertain the impact of parameters on the coefficient of friction and wear rate. The elements that most affect wear rate include sliding distance (46.8%), sliding speed (14.1%), and the applied load (31.5%). The sliding distance (50%), the applied load (35.7%), and the sliding speed (7.3%) affect the COF. Numerous natural fiber materials can be employed in cutting-edge technical applications. Mahesh et al. [164] reinforced aluminum alloy by combining jute and rubber in stacking configurations and assessed process variables on the wear characteristics of the composite. The wear rate was most affected by the abrading distance as opposed to the load and composite structure.

Tribology governs the interaction of two opposing surfaces that are in motion with each other, which includes wear, friction, and lubrication. Numerous factors, including the applied stress, sliding distance, surface quality of the surrounding environment, the shape of the reinforced particles, and the proportion of reinforcement weight, affect the tribological characteristics of AMMCs [165]. The sliding wear resistance is affected by the microstructure, including the size and volume percentage of the particles, as well as the material of the counter-face, as depicted by Alpas et al. [166]. Applied loads resulted in the identification of three wear regimes discussed in Table 2. Reinforcing particles in AMMCs bear the applied load with less force, leading to enhanced wear resistance compared to aluminum alloys. Ceschini et al. [167] conducted a study on the wear and friction characteristics of composites in dry sliding conditions. Several studies have asserted that enhancing the ceramic phase can increase wear resistance by up to 70%. Uyyuru et al. [168] conducted a study to examine the impact of size distribution and reinforcing volume percentage on the tribological behavior of a tribo-couple consisting of an Al-composite and a brake pad. The wear resistance during dry sliding increases as the percentage of particles in the volume increases. Wear studies demonstrate that adhesive and abrasive wear occurs when there are particles of wear debris, resulting in the plastic shearing of asperities [118]. The SiC and Al_2O_3 reinforcements serve as additional abrasives on the counter-face, hence intensifying the wear on the counter-face. Moreover, the reinforcement that has become detached as wear debris acts as a tertiary abrasive on both the matrix and the reinforcement. Composites that have less SiC in the matrix alloy by volume are more likely to experience wear surface groove development under high-stress situations

(Figure 5a,b). Consequently, this leads to increased damage caused by the deformation of plastic materials. The tendency for grooving in the composite's worn surface decreases as SiC concentration rises, indicating a slower rate of material loss than in the unreinforced material matrix (Figure 5c–f) [162]. The research studies have demonstrated that the presence of soft particles in CSA (composite solid lubricant additive) leads to a decrease in wear loss in hybrid composites due to reduced friction between the mating surfaces. The wear loss is directly proportional to the applied tension due to the increased friction between the pin surface and the disc. The inclusion of SiC and CSA particles appears to improve the material's resistance to wear, based on the decrease in plastic deformation of the material in the same direction as the sliding motion (Figure 5g) [169]. Table 3 compares the study of different Al-based composite materials processed by the stir-casting approach.

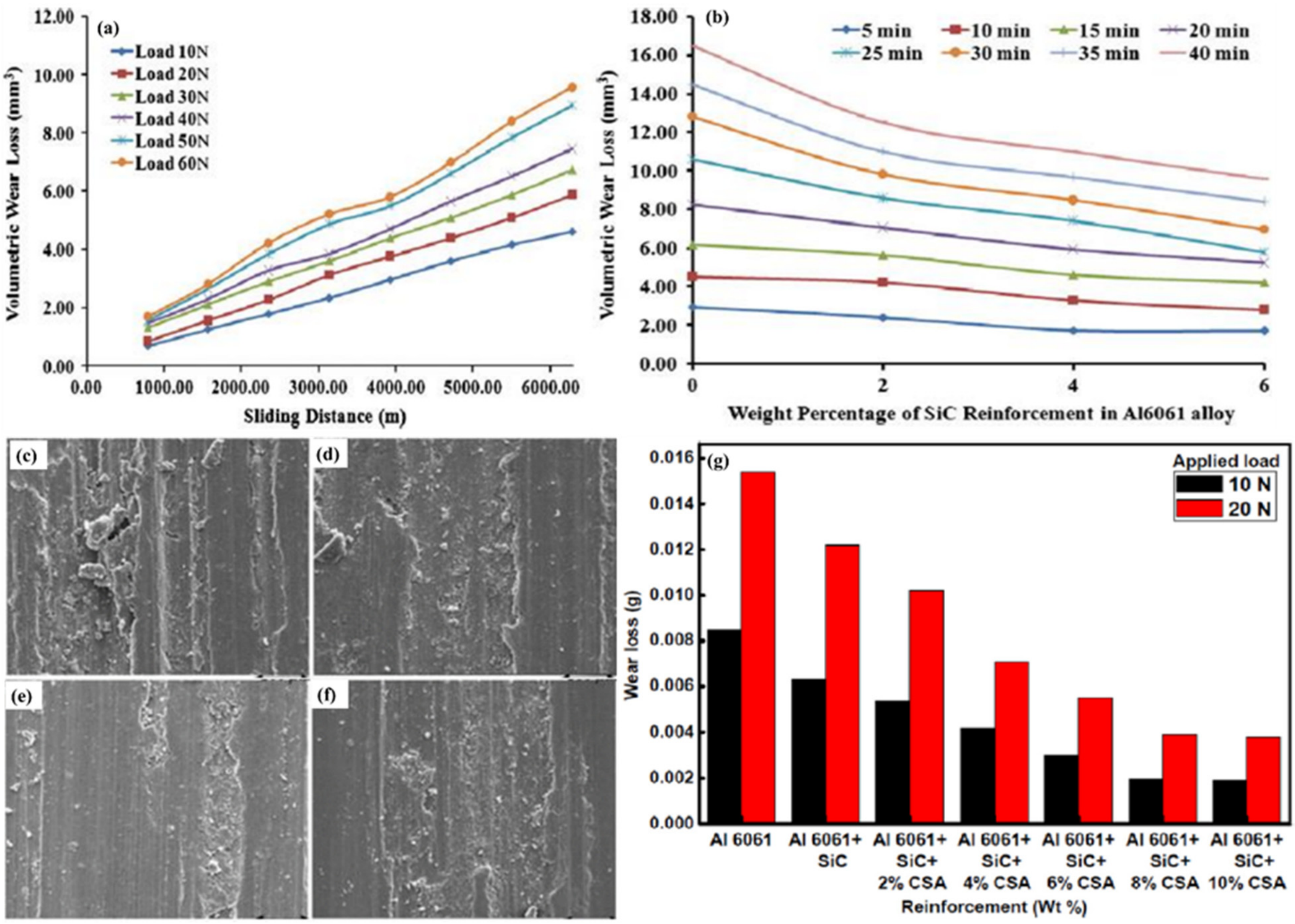

Figure 5. Volumetric wear loss as a function (**a**) load, and (**b**) time for Al6061 alloy. (**c**–**f**) Tendency for grooving in the composite's worn surface decreases as SiC concentration rises, indicating a slower rate of material loss. (**g**) The inclusion of SiC and CSA particles appears to improve the material's resistance to wear, based on the decrease in plastic deformation of the material [118].

Table 2. Shows the three-wear regime that arises due to the applied load.

S. No	Wear Regime	Overview of Wear Regime	Effects of Parameter on Wear
1	Mild Wear Regime	The surface remains largely intact, with minimal material loss. The primary reasons for wear are attributed to adhesion or oxidation.	1. **Load**: A reduction in loads leads to the prevalence of minor wear. 2. **Reinforcement Type**: Hard ceramic materials such as SiC or Al_2O_3 offer resistance to abrasion, enabling the maintenance of a mild wear regime even under slightly increased loads. 3. **Sliding distance and sliding velocity**: Mild wear is generally associated with moderate speeds and low sliding distances.
2	Moderate wear regime	Moderate increases in wear occur as surface degradation initiates, resulting from a combination of abrasion, adhesion, and some deformation.	1. **Load**: As loads rise, the material shifts from mild wear into this regime, with the reinforcement's capacity to support the applied load playing a crucial role in this transition. 2. **Particle Size and Distribution**: The onset of the transition wear regime is postponed by uniformly distributed fine particles 3. **Material Composition**: An increased weight fraction of reinforcements such as TiC or B_4C enhances load-bearing capacity, further delaying the transition.
3	Severe Wear Regime	Significant material loss occurs as a result of plastic deformation, extreme abrasion, or even delamination.	1. **Load**: When loads increase, they cause substantial wear as the reinforcement's ability to endure stress is exceeded. 2. **Velocity of Sliding and Distance**: Increased speeds combined with longer sliding distances lead to heat generated by friction, which softens the matrix and speeds up wear. 3. **Type and Volume of Reinforcement**: While hard reinforcements mitigate significant wear, they can fail in extreme situations if their bonding is inadequate or their volume is insufficient. 4. **Wear Debris**: The separation of matrix material or reinforcement particles can serve as secondary abrasives, leading to an increase in wear rates.

Table 3. Comparative study of different Al-based composite materials processed by stir casting approach.

References	Material Utilizes	Composition	Major Outcomes
[170]	Al7075/Al_2O_3/Mg	Al_2O_3: 1, 2, 3, 4 wt.%, Mg: 1 wt.%	Tensile, hardness, and toughness gradually increase, increasing the amount of Al_2O_3. Surface structure showed Al_2O_3 were homogeneously dispersed in Al.
[171]	Al7075/TiC	TiC: 2, 4, 6, 8, 10 wt.%	Up to 8 wt.% of TiC in the Al7075 alloy demonstrated good wear resistance. Wear rate and COF both decrease as the weight fraction of TiC-reinforced particles rises.
[172]	Al7075/TiC	TiC: 2, 4, 6, 8, 10 wt.% (Taguchi Optimization)	TiC inclusion results in an improvement in resistance to wear of Al7075 alloy. When sliding distance and sliding velocity increased, the degradation rate reduced and rose with the weight percentage of reinforcement.
[173]	Al7075/TiC/MoS_2	TiC: 10 wt.%, MoS_2: 10 wt.%	The amount of molybdenum disulfide, applied stress, and sliding velocity all have a big impact on how quickly aluminum composites wear down. The wear rate and sliding velocity have a direct proportional connection, followed by the parameter interactions.
[174]	Al7075/SiC/MoS_2	SiC: 5, 10, 15 wt.%, MoS_2: 3 wt.%	The tensile strength was increased only up to 5 wt.% of SiC, beyond which there is a minor reduction in the tensile strength of the composites.
[175]	Al7075/TiC/MoS_2	TiC: 0, 5, 10 wt.% MoS_2: 3 wt.%	The proportion of reinforcement and the applied load have an impact on wear loss and COF, respectively.

Table 3. *Cont.*

References	Material Utilizes	Composition	Major Outcomes
[176]	Al7075/TiC	TiC—0, 2, 4, 6, 8 wt.%	The density, wear resistance, and hardness were enhanced by the addition of TiC particles. When sliding velocity rose, the wear rate of the composite declined and rose with the weight percentage of reinforcement.
[177]	Al7075/SiC/MoS_2/ Gr/Hexagonal boron nitride hBN	SiC: 5 wt.%, Gr: 5 wt.%, hBN: 5 wt.%, MoS_2: 5 wt.%	The mechanical characteristics of the Al7075 alloy are significantly affected by the presence of graphite reinforcement. SiC particles improve the material's ductility, whereas graphite strengthens the composite. The mechanical qualities are increased by the uniform distribution of reinforcements produced by the stir-casting procedure. Nonetheless, hBN reinforcement has better wear characteristics than SiC, Gr, and MoS_2.
[178]	Al7075/TiC	TiC: 2, 4, 6, 8, 10 wt.%	AA7075 alloy with 8 wt.% of TiC particles had the highest micro-hardness. The wear factor, wear rate, and coefficient of friction change with sliding distance and reinforcing percentages. When the weight proportion of TiC in composites increased relative to the base alloy, the composites' rate of wear reduced.
[179]	Al7075/Chromium Nanoparticle/Zinc Nanoparticle	Cr—2, 3, 4, 5, 6 wt.% Zn: 1 wt.%	When zinc nanoparticles were added, the tensile characteristics of the composites were significantly enhanced, comparable to Al alloys. Also, the manufactured composite's hardness value increased. In contrast to other specimens, the composite containing (Al-97%Cr-4%Zn-1%) finally showed high tensile strength and hardness.
[180]	Al7075/Al_2O_3/B_4C	Al_2O_3: 3, 6, 9, 12, 15 wt.% B_4C—3 wt.%	As the weight proportion of Al_2O_3 in composites improves, the wear resistance is also enhanced.
[181]	Al7075/Al_2O_3/SiC/ Mg	(Al_2O_3 + xSiC): 1, 2, 3, 4 wt.%	The weight proportion of reinforcement increases with a rise in tensile and compressive strength, along with hardness. Al_2O_3 and SiC are clearly visible according to XRD examination.
[182]	Al6061/SiC Al7075/Al_2O_3	SiC—0, 2, 4, 6 wt.% Al_2O_3—0, 2, 4, 6 wt.%	The composites have greater wear resistance with the addition of SiC.
[18]	Al7075/SiC	SiC—10 vol.%	Composites attain uniform dispersion of ceramic material.
[183]	Al/SiC (320 grit)	SiC: 5, 10, 15, 20, 25, 30 wt.%	An increase in impact strength and hardness is noticed with the addition of SiC. There is an increasing trend in the uniform dispersion of SiC in Al samples prepared without a stirring procedure, with manual stirring, and utilizing the two-step stir casting approach.
[184]	Al6061/SiC/TiB_2/ Mg	SiC–10 wt.% TiB_2—0, 2.5, 5 wt.% Mg—2 g	The presence of 10% SiC and 5% TiB_2 in the composite results in the creation of clusters. The introduction of reinforcements has an impact on the hardness value. However, the inclusion of TiB_2 up to a maximum of 5% results in the formation of pores, which in turn influences the hardness value. The addition of SiC to the base metal resulted in a 20% increase in strength for the composite. However, the inclusion of TiB_2 led to a significant decrease in strength, with a measured fall of 50–60%.

Table 3. *Cont.*

References	Material Utilizes	Composition	Major Outcomes
[185]	Al12Si/(LM6)/SiC/Sr	0.01% Sr/0.02% Sr/0.5% Sr/0.02% Sr + 10% SiC/0.5% Sr + 10% SiC	By adding Al-10Sr, the morphology of the Al has undergone a significant alteration. The vortex approach yields the greatest results when 0.5 weight percent Al-10Sr and 10 weight percent SiC are added to aluminum. SiC and Sr were added, increasing the UTS for aluminum.
[186]	Al/SiC	SiC—0, 2.5, 5, 7.5, 10 wt.%	Al-SiC has a far higher hardness than aluminum metal. Hardness and material toughness improve with increasing silicon carbide concentration; the greatest value is achieved at 10% SiC content.
[187]	Al6061/SiC/ MWCNT	SiC–15 wt.% MWCNT—0, 0.5, 1 wt.%	SiC and MWCNT-reinforced aluminum show superior resistance to dry abrasive wear.
[188]	Al6061/B_4C/ Graphite	B_4C—15 wt.% Graphite—5 wt.%	Strong bonding between the matrix and the reinforcements evidenced an even distribution of reinforcement in the matrix material and decreased porosity.
[189]	Al2219/B_4C/MoS_2	B_4C—3 wt.% MoS_2—3, 4, 5 wt.%	By increasing the proportion of B_4C and MoS_2 reinforcing material, density rises. The hardness of composites rises as the percentage of reinforcement increases.
[190]	AA1060/SiC/0.3MNaCl/ 0.5M H_2SO_4 Solution	SiC—7.5 wt.% at particle size (0, 3, 9, 29, 45 µm)	Composite exhibits greater resistance to corrosion when using the smallest and largest SiC particle sizes (3 µm and 45 µm).
[191]	Al6063 (x)/ Mortar ash (MA)/Met coke ash (MCA)/Nano fibrillated composite (NFC)/Straw ash (SA)	x, x + 5 wt.% MA, x + 5 wt.% MCA, x + 5 wt.% NFC, x + 5 wt.% SA, x + 5 wt.% of MCA, NFC, SA, and MA	Because of the strong atomic bonds between the atoms, the MMCs have a higher hardness than the Al 6063 alloy. The MA composite increases the hardness of MMCs. The impact strength rose with the addition of MA and SA reinforcements. Additionally, the addition of NFC and MCA reduces surface roughness during turning.
[192]	Al/Groundnut shell ash (GSA)/ SiC	GSA and SiC (10:0, 7.5:2.5, 5.0:5.0, 2.5:7.5, 0:10)	Tensile strength and hardness rose as the weight percentage of the reinforcing phase grew, but they somewhat decreased as the GSA content increased. The percentage elongation slightly increased as the GSA content rose. There was no continuous pattern of improvement with increasing SiC–GSA amount. GSA content increased along with improvements in fracture toughness. GSA complimentary reinforcement can be used to produce high-performance, low-cost aluminum matrix composites.
[193]	Al/SiC (360 grit)–	SiC: 5, 10, 15, 20, 25, and 30 wt.%	As reinforcement is added, density (g/cc) and hardness (BHN) both rise. Impact Strength rises with an increase in SiC particle weight fraction and falls with an increase in reinforced. SiCp was distributed uniformly.
[194]	Al6061/Red-mud	Red-mud: 4, 4, 12, 16, 20 wt.%	The surface characteristics of the castings that have undergone heat treatment have improved. Red muck is distributed throughout the alloy very uniformly.
[195]	Al6061/Al_2O_3/Bagasse ash	Al_2O_3–5 wt.% Bagasse ash–8 wt.% (37 µm, 53 µm, 75 µm)	Because the reinforcements in hybrid composites are smaller than those in base metal, they have greater mechanical characteristics. The microstructural pictures showed that the aluminum reinforcements were distributed uniformly.

Table 3. *Cont.*

References	Material Utilizes	Composition	Major Outcomes
[196]	Al7075/TiC/MoS_2	TiC—0, 2, 4 wt.% MoS_2—0, 2 wt.%	TiC is a hard ceramic substance; thus, as the amount of TiC grew, the hardness increased as well. The soft phase MoS_2 is what caused the hardness values to decrease when MoS_2 was added to the aforementioned AMCs. The microstructures of the synthesized AMCs, created using the stir casting procedure, demonstrate that the TiC and MoS_2 microparticles are dispersed randomly throughout the AA7075 matrix.
[197]	Al365/SiC/ Graphite (Gr)	SiC: 3, 6, and 9 wt.% Gr: 3 wt.%	Reduced normal load and increased sliding speed result in a reduction in wear rate. Car disc brakes benefit from the improved tribological qualities of composite materials due to the increase of SiC in the material and the solid lubrication provided by graphite particles.
[198]	Al2219/n-B_4C/MoS_2	Al2219 Al2219 + 2% n-B_4C Al2219 + 2% n-B_4C + 2% MoS_2	In comparison to the Al2219 matrix, the specific wear rate of Al2219 is greater and that of nanocomposites is lower. The wear rates of Al2219 + 2% n-B_4C and Al2219 + 2% n-B_4C + 2% MoS_2 nanocomposites steadily decrease when temperature is raised (500 to 1000 °C). Al2219 + 2% n-B_4C + 2% MoS_2 has a greater wear resistance than Al2219 + 2% n-B_4C and Al2219 matrix.
[199]	Al7075/B_4C/MoS_2	B_4C–4, 8, and 12 wt.% MoS_2–3 wt.%	Hybrid composites' hardness, ultimate strength, and yield tensile strength rise with an increased proportion of multi-reinforcement. Friction coefficient rises in B_4C.
[200]	Al7075/SiC/MoS_2	SiC—3, 6, and 9 wt.% MoS_2: 1 wt.%	Out of all the specimens, the one with the highest strength in the tensile test is Al7075 + 9% SiC + 1% MoS_2. As the weight percentage of silicon carbide (SiC) grows, the hardness value also increases.
[201]	Al7075/Graphene/Beryl	Graphene—0, 0.5, 1 wt.%, Beryl: 6 wt.%	The wear of the composite decreases with increasing reinforcing weight proportion.

4. Strengthening Mechanism

The effect of particle quantity and size on the strength of composites is widely acknowledged. Research indicates that larger particles can create voids around them, which diminishes the overall strength of the mixture due to their dispersion. When the size of the reinforcing particles is reduced, the spacing between them in metal matrix composites (MMCs) decreases. This reduction enhances the resistance to dislocation movement, thereby increasing the strength of the MMCs [202]. Additionally, the nano-reinforcing agent improves particle hardening mechanisms, thereby enhancing the overall characteristics of composites and alleviating stress concentrations at their edges [203,204]. Research has demonstrated that incorporating ceramic nano-particulates smaller than 100 nm can greatly improve the strength of composites while preserving their ductility [205].

The smaller grain structure and limited dislocation movement contribute to the enhanced durability of the composites [206]. However, when analyzing reinforced nanoparticles that fall below a critical size, the Orowan reinforcement effect shows a notable increase [207]. In contrast, this effect diminishes when the nanoparticle size surpasses the threshold value (<100 nm). A notable improvement in durability is observed with reinforcement size <20 nm, as interfacial surface contact is improved [208]. Nonetheless, reduction simultaneously diminishes the load-bearing capacity of composites [209]. Jayalakshmi et al. observed a significant increase in durability with a decrease in ductility with the addition of nano-size reinforcement in Al-based material [210]. However, strengthening is accompanied by the load transfer ability of material offering strong interfacial bonding [211]. At the same time, the integration of hard particles has a substantial effect on the fundamental mechanism responsible for enhancing the composite's strength. Ceramic particle-reinforced aluminum metal matrix composites (AMMCs) are widely known for their enhanced mechanical properties, making them suitable for a variety of aerospace, automotive, and military applications. The incorporation of ceramic reinforcements into an aluminum matrix results in a variety of reinforcement mechanisms that significantly improve the material's properties [212]. The detailed discussion regarding strengthening mechanisms focusing on how they contribute to the overall properties of AMMCs was depicted below:

4.1. Mechanism of Load Transfer

The mechanism of load transfer plays a crucial role in the enhancement of strength in AMMCs. When external forces are applied to a composite material, the harder ceramic particles distribute the load alongside the more malleable aluminum matrix. This mechanism proves to be especially effective at an increased volume fraction of ceramic particles, which can result in more efficient load distribution [213]. Further, the effective load transfer is guaranteed by strong bonding at the interface between the aluminum matrix and ceramic particles [214]. Inadequate bonding may cause debonding, diminishing the effectiveness of this process. The size, shape, and arrangement of ceramic particles within the matrix significantly influence the effectiveness of load transfer [215]. For instance, smaller particles generally enhance load transfer by facilitating a more consistent distribution of stress. The yield strength (σ_{yc}) using the load transfer mechanism for composite is calculated using Equation (1) [216],

$$\sigma_{yc} = \sigma_{ym}[V_r(0.5S + 1) + V_m] \quad (1)$$

where σ_{ym} is matrix yield strength, V_r is reinforcement volume fraction, V_m is matrix volume fraction, and S is reinforcement particulate aspect ratio, with $S = 1$ for particulates with a spherical or equiaxed shape.

4.2. Orowan Strengthening Mechanism

In the MMCs, fractures within the particle agglomerates are initiated by the applied load. Due to the continuous application of load, the composites undergo a gradual spread of defects, which ultimately results in early failure [217]. Achieving a uniform dispersion of reinforcing particles through acoustic ultrasonic cavitation and streaming significantly reduces the initiation of fractures in areas where particulate agglomeration takes place. The increase in yield strength (YS) is attributed to the interplay between dislocations in the grains of the matrix and the robust reinforcing particulates [218]. This interaction inhibits the development of fractures under applied stress. Additionally, the notable difference in the modulus of elasticity between the reinforcement particulates and the alloy matrix creates a distinct interaction between the reinforcement particulates and dislocations. A crucial mechanism known as Orowan strengthening takes place when dislocations navigate around hard ceramic particles. When these dislocations meet such particles, their hardness makes it difficult for them to pass directly through. Instead, the dislocations curve around the particles, forming loops that enhance the overall strength. Hard ceramic reinforcements result in dislocations bowing outward in the spaces between them, which effectively raises the stress needed for the movement of dislocations [219]. Localized stress concentrations arise from the interaction of dislocations with ceramic particles, thereby improving overall strength [220]. This mechanism is especially important when working with tough ceramics like silicon carbide (SiC) or alumina (Al_2O_3), both of which exhibit high hardness levels. Dislocation loops associated with Orowan reinforcements act as barriers to dislocation motion, thereby increasing the overall strength of the composite [221]. As the reinforcement content in the alloy matrix increases, the resistance to dislocation motion and fracture propagation also increases, resulting in increased strength of MMCs at higher strengthening levels.

4.3. Dislocation Strengthening Mechanism

The improvement in mechanical properties of MMNCs is attributed to the larger interface area between reinforcement and matrix due to the incorporation of nano-size reinforcement [222]. In addition, the thermal mismatch between the nano-size reinforcement and Al alloy matrix induces thermal stresses (cooling), inducing plastic deformation at the interface as thermal equilibrium is only established at the contact temperature during processing. Therefore, the appearance of tiny defects, such as dislocations in the vicinity of nanoscale particles, occurred [223]. The research studies confirm the presence of dislocation density near the matrix–reinforcement interface [224–227]. High cohesion at the atomic level between the matrix and reinforcement enhanced the direct bonding between the nanoparticles and the matrix [228]. Further, the yield strength is directly associated with dislocation motion, which is hindered by several obstacles. The presence of volume stress leads to the generation of geometrically necessary dislocation loops (GNDs) near the reinforcing particles, which is accompanied by variation in CTE between reinforcements and the alloy matrix, consistent with the Taylor strengthening process [229]. These GNDs can compensate for the dislocations generated due to the significant change in CTE. This increases the yield strength of the composite [230]. The strength of the MMC increases with nanoparticles, depicting a high incidence of the GND loop.

4.4. Grain-Refined Strengthening

Grain refinement takes place when ceramic particles serve as nucleation sites throughout the solidification process. This phenomenon results in a more refined microstructure within the aluminum matrix, which plays a crucial role in enhancing strength via the Hall–Petch effect [231]. According to the Hall–Petch relationship, smaller grains obstruct dislocation movement more efficiently than their larger counterparts, leading to an increase in yield strength. However, ceramic particles facilitate heterogeneous nucleation during the solidification process, resulting in reduced grain sizes. The presence of smaller grains elevates dislocation density, which additionally aids in strengthening via interactions among dislocations [232]. Studies indicate that AMMCs featuring fine-grained microstructures possess enhanced mechanical properties in contrast to their coarser-grained counterparts, owing to these influences [233–235]. The increase in strength can be attributed to the increase in matrix grain fineness. The hindrance of dislocation movement is caused by the increase in lattice disorder caused by this refinement. The improperly arranged lattice structure requires excess energy to reallocate dislocation movement and transfer to adjacent grains [236]. Due to grain refinement, the grain boundary area increases, restricting dislocation movement and contributing to the increase in yield strength. However, nanoparticles are included at the matrix grain boundaries during solidification, hindering grain development and leading to a finer microstructure.

5. Challenges in Fabricating AMMCs

The problem in producing HAMC is devising a production procedure that is simultaneously efficient and effective. Stir casting is the most effective technique for mass manufacturing. However, the matrix's inadequate dispersion of nanoparticles and its high porosity counterbalance this advantage. The process of fabricating Al-matrix composites with alumina particles by casting is often challenging because of the poor wetting capacity of alumina particles and the tendency for them to clump together. These issues lead to an uneven distribution of particles. Manufacturing of composites is expensive and challenging due to the poor wetting behavior. PM is the effective approach for optimal homogeneity. However, its application to mass production is challenging because it incurs very significant costs. Diffusion bonding produces a joint material that is uniform in nature and exhibits consistent properties. This process is highly efficient and adaptable while also being relatively straightforward. There has been a substantial increase in usage of composites utilizing diffusion-bonding approaches. Nevertheless, the utilization of the diffusion-bonding technique in numerous industrial applications has been restricted owing to the high cost associated with removing the oxide layer. Concerning environmental issues, additional research will need to be conducted on the utilization of scrap, biowaste, and mineral waste as possible reinforcing materials for HAMC and its sustainability. The joint material produced by diffusion bonding has homogeneous characteristics and is a highly prolific, versatile method that is reasonably easy.

6. Conclusions

The characteristics of the aluminum-based composite material are significantly impacted by various aspects related to the stir-casting process, including the speed of the stirrer, the duration of stirring, the design of the stirrer blade, the size of the reinforcement, and the temperature of the melt. Factors such as density, porosity, CTE, dislocation density, and thermal mismatch significantly influence the performance of MMCs. Optimizing process parameters, such as finer reinforcement particles, optimized stirring configurations, preheating the reinforcement, and curing under pressure, is essential for achieving consistent distribution of reinforcements and preventing clustering. The addition of ceramic reinforcements like alumina, silicon carbide, and titanium diboride generally improves the mechanical strength of aluminum MMCs but may have a negative impact on ductility. Nano-ceramic reinforcements show the potential to simultaneously improve the strength and ductility of aluminum composites.

Bonding between the matrix and reinforcement is significantly enhanced through improved quality and surface treatments of reinforcements. Pre-treatment methods, including coating or preheating, are necessary to guarantee optimal integration and enhancement of properties in MMCs. The hardness of aluminum-based composites (AMMCs) is significantly influenced by the temperature during processing and subsequent heat treatment. High temperatures can promote the precipitation of strengthening phases within the matrix, leading to an increase in hardness levels. Additionally, higher temperatures can induce microstructural alterations that influence hardness, such as grain growth and dissolving reinforcing particles. The incorporation of hard reinforcement particles like SiC or Al_2O_3 greatly enhances wear resistance by redirecting crack propagation and bridging fractures.

Temperature also plays a vital role in wear resistance, as higher processing temperatures improve interfacial bonding between the matrix and reinforcement, enhancing load transfer during wear evaluations. Particle size also plays a significant role in the strength of composites. Reducing the size of reinforcing particles decreases spacing between them, increasing resistance to dislocation movement and increasing the strength of MMCs. Nano-reinforcements improve particle hardening mechanisms, enhancing the mechanical properties of the matrix. Furthermore, the strengthening mechanism, i.e., mechanism of load transfer, Orowan strengthening mechanism, dislocation strengthening mechanism, and grain-refined strengthening, were critically discussed, which focused on improving the overall characteristics of AMMCs.

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