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Recent Progress in Stir Cast Aluminum Matrix Hybrid Composites: Overview on Processing, Mechanical and Tribological Characteristics, and Strengthening Mechanisms

Jalli Kantha Rao[1] · Reddypogula Madhusudhan[2] · Thella Babu Rao[3]

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Abstract

Aluminum matrix hybrid composites (AMHCs) in the current generation materials category are becoming a potential for many advanced engineering applications requiring customized properties. The selection of an acceptable reinforcement agent for the chosen aluminum alloy matrix, as well as a suitable processing approach and conditions, allows for customization of the attributes of these materials. As a result, hybrid composites have gained increasing attention more than traditional aluminum matrix composites with single reinforcement due to their ability to achieve superior custom properties. In addition, hybrid composites can be processed utilizing traditional metal matrix composite processing procedures and equipment, which has the advantage of lowering production costs while achieving superior qualities. The investigations have given the derived properties for the use of several reinforcement agents accessible on the commercial market, to achieve the goal of developing AMHCs. The purpose of this study is to show that it is possible to make AMHCs with improved mechanical and tribological properties and to stimulate their use on the characteristics of AMHCs manufactured using the stir casting method, as well as the processing obstacles are critically examined and presented.

Keywords Aluminum matrix hybrid composites · Liquid processing · Dispersion of reinforcement · Mechanical properties · Tribological properties · Strengthening mechanisms

1 Introduction

Aluminum matrix composite (AMC) materials have grown in popularity in recent decades as a means of producing a wide range of structural components that require high wear resistance, lightweight, and high strength [1, 2]. With the suitable selection of one or more reinforcement agents for the specific aluminum matrix alloy, such a combination of physical, microstructural, mechanical, and tribological properties can be achieved with AMCs [3]. Al_2O_3 [4–7], SiC [8–12], WC [13, 14], TiC [15, 16], TiB_2 [17–20], Si_3N_4 [21, 22], B_4C [23, 24], graphite [25, 26], fly ash [27, 28], boron nitride [29], ZrO_2 [30, 31], carbon nanotube [32, 33], carbon fiber [34], WS_2 [35], and MoS_2 [36] are the most commonly used reinforcement agents in the development of aluminum-based composite materials in the literature. Aluminum matrix hybrid composites (AMHCs) are comprised of two different reinforcements with a single matrix alloy designed to achieve the combination of properties for multifunctional applications that AMCs cannot accomplish [37]. The standard equipment required for processing AMCs includes a casting furnace, stirring mechanism, casting die, and die preheating systems. AMHCs have two or more reinforcement phases, which offer a variety of qualities to the composite, whereas AMCs with simplex reinforcement can only offer a restricted set of properties when compared to AMHCs. The processing technology and equipment needed to make

✉ Jalli Kantha Rao
jallikantharao@gmail.com

Reddypogula Madhusudhan
prof.rmadhusudhan@andhrauniversity.edu.in

Thella Babu Rao
thellababurao@nitandhra.ac.in

1 Department of Mechanical Engineering, Sasi Institute of Technology & Engineering, West Godavari Dist., Tadepalligudem, Andhra Pradesh 534101, India

2 Department of Mechanical Engineering, Andhra University College of Engineering (A), Visakhapatnam, Andhra Pradesh 530003, India

3 Department of Mechanical Engineering, National Institute of Technology Andhra Pradesh, West Godavari Dist., Tadepalligudem, Andhra Pradesh 534101, India

AMHCs are the same as those needed to make AMCs. As a result, AMHCs have a clear advantage over AMCs in terms of producing components with greater attributes while using the same equipment and manufacturing methods [37–40]. The most often utilized processes for processing AMHCs are powder metallurgy as a solid-state processing approach [41], stir casting as a liquid-state processing technique [42, 43], and squeeze casting as a semi-liquid-state processing technique [44].

Stir casting is a well-established technology for producing bulk composites in large quantities because it is easy, cost-effective, and adaptable. The current state-of-the-art in advanced materials research is to design materials to meet the ever-changing functional characteristics requirements for components in high-performance applications. As a result, recent research into the production of innovative materials has focused on the processing of AMHCs. The research and studies were carried out on the derivable properties of the chosen aluminum matrix alloys with the addition of various combinations of reinforcing agents available on the commercial market [45–51]. This study aims to emphasize the viability of creating AMHCs with improved mechanical and tribological properties to encourage their growing use in widespread industrial applications, based on reported studies in such investigations. Recent experimental discoveries on the characteristics of AMHCs manufactured using the stir casting method, as well as the problems encountered during the process, are critically examined and presented. The compressive review in this study looked at several reinforcing agent combinations utilized in the processing of AMHCs to improve their mechanical and tribological properties, as well as the effect of such reinforcement combinations on improved qualities.

During the previous decade, a significant increase in the number of publications on the creation of aluminum matrix hybrid composites has been documented, as shown in Fig. 1. This demonstrates the critical necessity of research into the creation of such composites for industrial uses. Figure 2 shows that 46.07 percent of papers were published as original research articles, 57.76 percent of papers were published as conference proceedings, and 2.17 percent of papers were published as review articles. Also, as shown in Fig. 1, there is still a need for more information on processing and characterization in the field of aluminum matrix hybrid composites research.

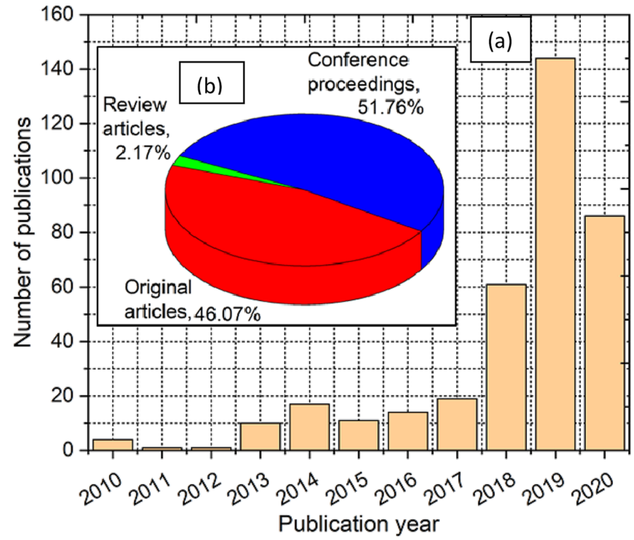

Fig. 1 Research articles on aluminum matrix hybrid composites processed through stir casting approach: **a** total number of publications in year wise during the past decade, **b** percentage breakdown of publications

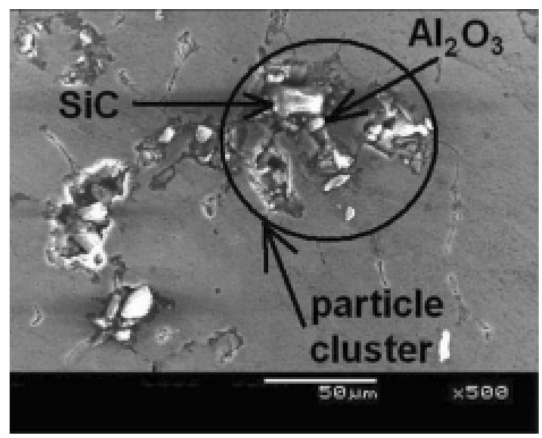

Fig. 2 Al 6351 composites show the formation of particle agglomerations for the addition reinforcement from mono to hybrid [98]

2 Reinforcement Particle Dispersion and Particle–Matrix Interfacial Bonding

With the processing of metal matrix composites in liquid state fabrication, reinforcing particle agglomerations and cluster formations are unavoidable problems. One of the primary aspects that has a considerable influence on the uniformity of particle dispersion is compatibility in physical and chemical properties, i.e., matrix-reinforcement wettability [52–54]. The uniform distribution of reinforcement in the matrix, on the other hand, has a direct impact on the composites' ability to achieve the desired properties improvement. Particle agglomerations and clusters have been regarded as particularly difficult to eliminate, even though they are necessary for defect-free composite material manufacturing. Pradeep et al. [55] demonstrated reasonably distributed reinforcement particles with strong interfacial bonding using a ball-milled blend of silicon nitride (Si_3N_4) and graphite (Gr) particles for better dispersion of reinforcement in the aluminum matrix alloy. Cast composites, on the other hand, produced much smaller clusters due to the density differential between the reinforcing particle mixture and the matrix aluminum alloy. Up to 5% weight of ($Al_2O_3 + TiO_2$) ceramic reinforcement in Al2218 aluminum matrix alloy resulted in acceptable particle dispersion, but above that weight, it tended to form agglomerations due to segregations and rejection of the particles, resulting in agglomerations [56]. To allow a larger weight percentage of ceramic reinforcement, they proposed increasing the stirring duration to a faster stirring speed. Manikandan et al. [57] In the hybrid Al7075/(B4C + CDA) composite, the temperature mismatch between matrix and ceramic particles is the most important factor in the development of reinforcement particle clusters. The thermal mismatch causes the reinforcement-matrix alloy slurry to solidify at a slower rate, resulting in particle clusters in the matrix. For Al7075/Al_2O_3/SiC hybrid composites, adding magnesium during the stirring process was recommended to improve interfacial bonding between the reinforcements and matrix, reduce cluster formation, and improve wettability [58]. The wettability of the matrix and reinforcement is improved by the reaction between reinforcement and magnesium. As a result, adding a little amount of magnesium to the composite while stirring improves the wettability of the reinforcement particles with the matrix alloy. Satish et al. [59] and Kumar et al. [60] both found similar results in their investigations. The high moisture content of the Fe_2O_3 and B4C reinforcements in liquid metal allows for effective interfacial bonding with the Al6061 matrix alloy [61]. Up to 5% of each reinforcement's addition, Bhasha et al. [62] reported uniform distribution of TiC and RHA particles, but beyond that, Rice husk ash (RHA) promotes agglomeration in the composite, resulting in low strength and porosity. The agglomeration is caused by a substantial amount of RHA, a pore-filling element that fills the gap between bonding elements such as grain boundaries [63]. The inclusion of magnesium in the Al6061 aluminum alloy influenced the graphite distribution homogeneity in the Al6061/TiC/Gr hybrid composite [64]. In a hybrid metal matrix composite, the creation of a solid solution of TiO_2 and MoS_2 improves the bonding between the reinforcement and the matrix alloy LM13 [65]. The inclusion of ceramic reinforcement leads to the formation of particle clusters from mono reinforcement to hybrid reinforcement, as seen in Fig. 2. As seen in Fig. 3, the reinforced particles are consistently dispersed throughout the matrix after being stir cast.[66].

Using ideal parameters such as temperature, time, stirring speed, and reinforcement particle preheating temperature, the reinforced particles are equally dispersed throughout the matrix. Magnesium in composites lowers agglomeration and porosity while also providing great bonding between the matrix and reinforced particles.

3 Mechanical Properties

AMCs' mechanical qualities are essentially determined by the mechanical properties of its integral materials, such as the aluminum matrix and reinforcement agents. The hardness of a composite with tougher reinforcement, for example, is superior to that of a composite with soft reinforcement. The inclusion of a large number of ceramic particles in a matrix provides additional resistance to deformation due to applied loads, causing the composite's tensile strength and hardness to be increased to the maximum extent possible, but at the expense of its elongation [67–70]. However, the inclusion of SiC/B4C reinforcement

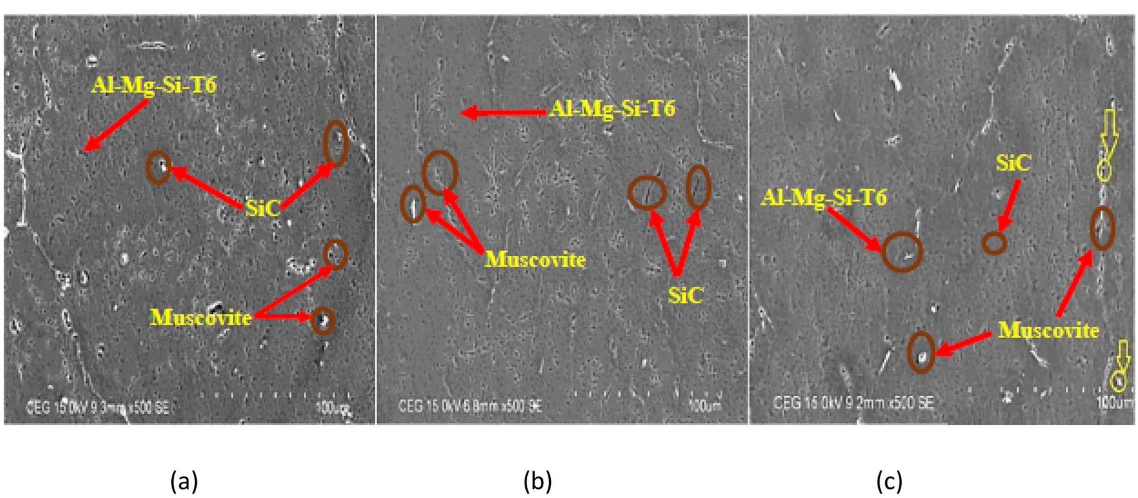

Fig. 3 **a** SEM micrograph of Al þ SiC (5%) þ muscovite or hydrated aluminum potassium silicate (2%) composition, **b** (3%) composition, and **c** (4%) composition [66]

increased the strength and hardness by up to 20%, and further reinforcement resulted in a drop in tensile strength due to the production of a high level of particle agglomerations and porosity [71]. Shirvani Moghaddam et al. [72] indicate the best amount of reinforcement for achieving maximum strength, and they found that raising the reinforcement percentage over the optimal values resulted in lower strength. When the composite material consisted of particle agglomerations and porosity, the ductility of the composite was also negatively impacted by the resistance to flowability [73]. Keneth et al. [74] found that adding rice husk ash (RHA) as reinforcement into the Al–Mg–Si alloy matrix improved tensile strength and ductility, but that increasing RHA % and reducing Al_2O_3 lowered tensile strength and hardness in hybrid composites. The presence of Al_2O_3 particles as barriers to dislocation movement in the Al6061/Al_2O_3/graphite hybrid composite helped to boost the composite's hardness [75].

According to Mohammed et al. [76], adding Bagasse-ash as reinforcement to the Al7075 matrix alloy increased mechanical strength while causing a large slag formation during casting since Bagasse-ash contains carbon and oxygen. As a result, the authors reinforced graphite as a secondary reinforcement to reduce the production of slag with the addition of Bagasse-ash and observed a favorable effect of increased wear resistance. Improved mechanical properties with the addition of SiC and fly ash to the Al–Zn alloy. They also detected the creation of fly ash particle clusters, which resulted in increased porosity in the composite, lowering its mechanical characteristics [77]. Ambigai et al. [78] investigated Al–Gr/Si3N4 composites and found that hybrid composites had better characteristics than single-reinforced composites. Because of the soft nature of the reinforcements compared to the ceramic reinforcement agents, the hardness of the composite is lowered when Kumar et al. [79] and Prasad Reddy et al. [80] add red mud particles to Al6061 alloy. In the examination of Baradeswaran et al. [81] for the development of Al7075/Al_2O_3/5 wt% Gr. hybrid composites with beneficial results, Al_2O_3 particles as hard ceramic agents were included together with the soft reinforcements to counteract the drop in hardness.

Pardeep et al. [82] found that using composites reinforced with ball-milled ceramic particles improved hardness and tensile characteristics significantly, as illustrated in Figs. 4 and 5.

The enhanced hardness and tensile properties of the composite are due to the evenly dispersed ceramic hard particles, which contributed to the composites' strength improvement via several strengthening mechanisms. However, because of the additional reinforcement, the ductility of the composites was reduced, resulting in a lower elongation percentage, as seen in Fig. 6. In the experiment of Mummoorthi et al. [61], a similar trend in tensile characteristics improvement was obtained with the Al/Fe_2O_3/B4C composite, as shown in Fig. 7.

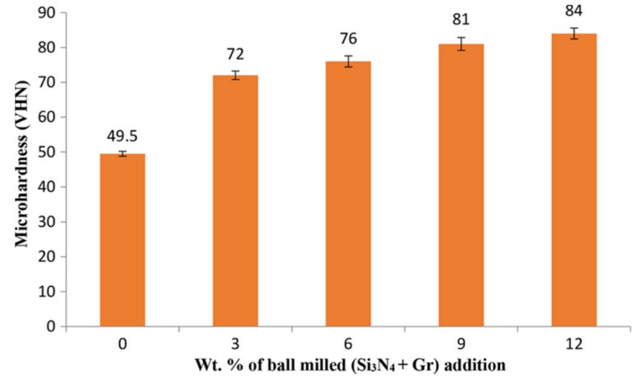

Fig. 4 The effect of (Si_3N_4 + Gr) reinforcement on Microhardness of AA6082 stir cast hybrid composites [82]

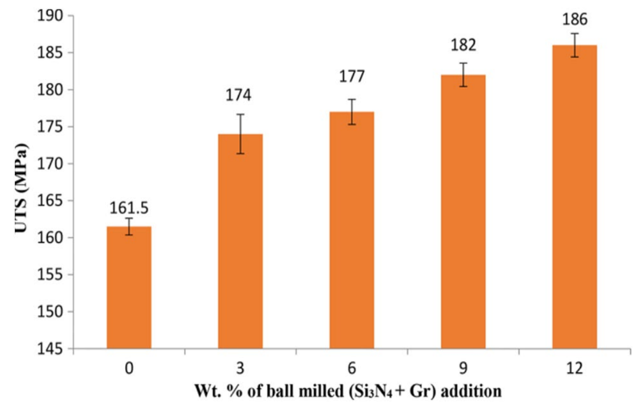

Fig. 5 The effect of (Si_3N_4 + Gr) reinforcement on ultimate tensile strength of AA6082 stir cast hybrid composites [82]

The ductility of the composites was lowered because of the increased reinforcement, resulting in a lower elongation %, as seen in Fig. 6. The Al/Fe_2O_3/B4C composite showed a similar trend in tensile properties improvement in Mummoorthi et al. [61] experiment, as illustrated in Fig. 7.

4 Tribological Properties

To improve wear resistance, the presence of highly wear-resistant hard ceramic particles with the soft matrix alloy is studied [83]. The chemical and mechanical properties of both the reinforcement and matrix materials, as well as the application of the load, speed, sliding distance, and surrounding atmospheric and sliding conditions, all influence the improved wear properties of AMCs with ceramic particle reinforcement. The wear experiments were utilized to investigate the tribological properties of hybrid AMCs

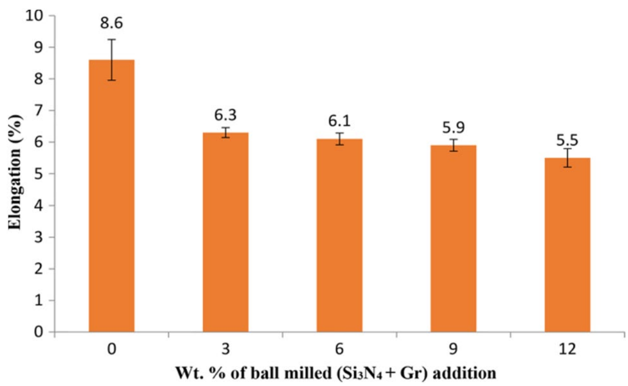

Fig. 6 The effect of (Si_3N_4 + Gr) reinforcement on elongation percentage of AA6082 stir cast hybrid composites [82]

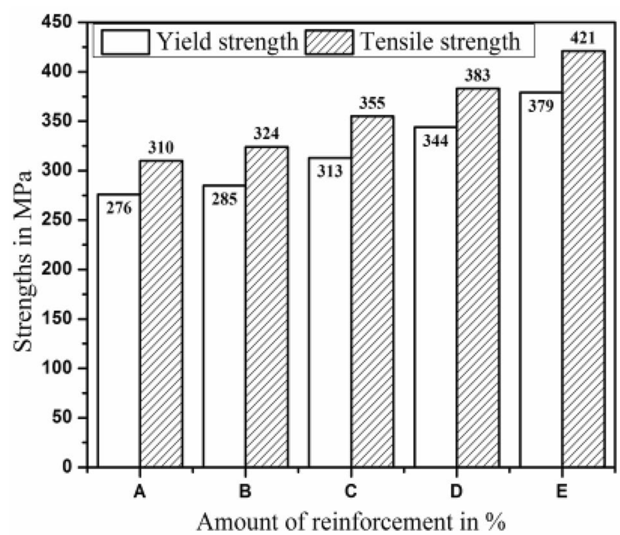

Fig. 7 The variation of tensile properties of aluminum matrix composite for increased percentage of (Fe_2O_3/B_4C) reinforcement [61]

under a variety of wear conditions, including applied load, sliding velocity, sliding distance, sliding time, and sliding speed [84–86]. Kaushik et al. [87] utilized SiC and Gr as wear-resistant reinforcing agents to improve the wear resistance of Al6082 alloy. When compared to the base alloy, the wear resistance of the hybrid composite improved by 16.4% and 27 percent in the as-cast and heat treatment conditions, respectively. This indicates the increased wear resistance that comes with age [88]. Siddesh et al. The inclusion of nanosized B4C + MoS2 into AA2219 alloy increased wear resistance by forming a lubricant-rich tribo-layer between pin and disk. The combined effect of Al_2O_3 + Gr in AlSi 10 Mg matrix composite results in improved wear resistance due to the strong Al_2O_3 ceramic resistance to wear and graphite particles delaying the transition from mild to harsh wear under working conditions, according to Radhika et al. [89]. The improved wear resistance can be attributable to the reinforcements' improved hardness, strength, and uniform distribution [90], as illustrated in Fig. 8.

Krishna et al. [91] investigated the wear loss of an Al7075/WC/Cobalt hybrid composite under different loads, speeds, and sliding distances, as well as variable reinforcement weight percentages. In comparison to composites, the soft nature of matrix alloy causes higher wear loss and adhesive wear, according to the researchers. Abrasive wear is caused by the hardness of reinforced particles, which minimizes wear loss. The influence of load, sliding velocity, and sliding distance on wear loss is shown in Figs. 9, 10, and 11. The formation of a mechanically mixed layer acts as an intermediate lubricant layer between the rubbing surfaces, reducing wear loss as the sliding speed increases, while the longer contact time during rubbing raises the temperature between the sliding surfaces, increasing the sliding distance and thus increasing wear loss.

As demonstrated in Fig. 12, 5 weight percent of reinforcement in Al2218/Al2O3/TiO2 hybrid composite has greater wear resistance than matrix, 2 weight percent, and 7 weight percent of reinforcement. The composite had a better particle dispersion, less porosity, and enhanced particle retention at 5 wt% reinforcement [56]. Due to the increasing contact pressure between the mating surfaces, the wear loss of the Al–Mg–Si-T6/SiC/muscovite-hybrid metal matrix composites has shown a declining trend as illustrated in Fig. 13 [66] for varied load situations.

During wear testing, the inclusion of SiC reinforcement particles creates a mechanically mixed hard layer and graphite acting as a solid lubricant. In comparison to a composite consisting of a single reinforcement and an unreinforced alloy, the combined action of SiC and graphite reinforcement with the matrix alloy improves overall wear performance

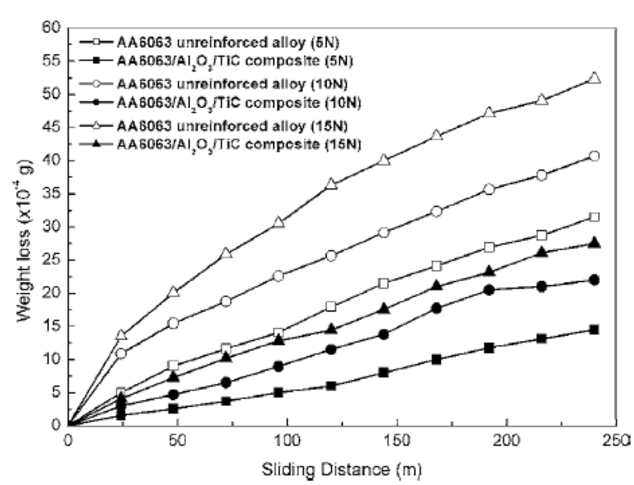

Fig. 8 The effect of applied load and sliding distance on weight loss during dry sliding of AA6063/Al2O3/TiC hybrid composite [90]

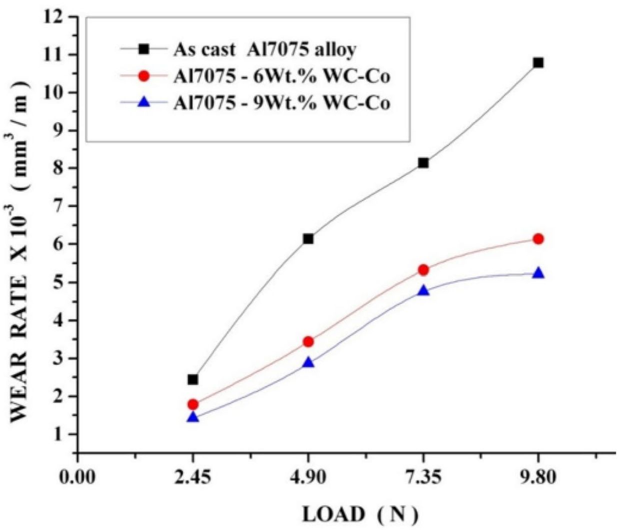

Fig. 9 Graph showing the wear rate of Al7075 alloy and Al7075—6 and 9wt% of WC–co composite under different loading conditions [91]

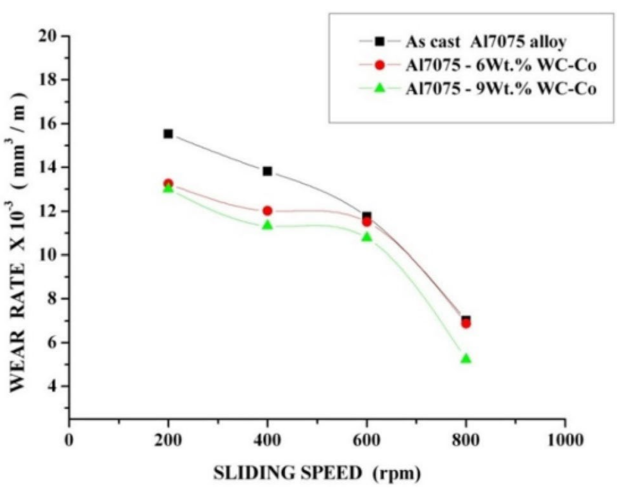

Fig. 10 Graph showing the wear rate of Al7075 alloy and Al7075—6 and 9 wt% of WC–co composite under variable speeds [91]

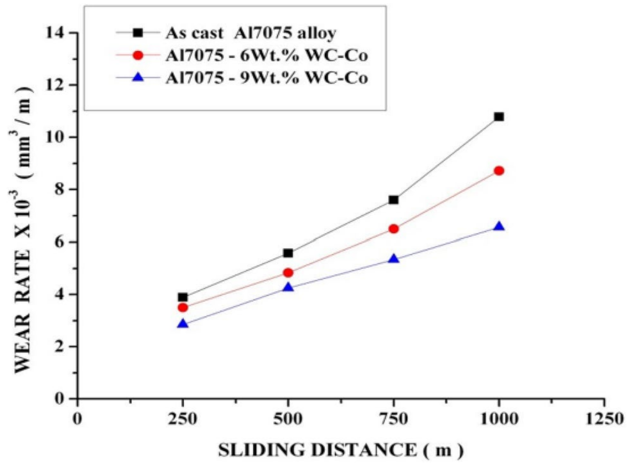

Fig. 11 Graph showing the wear rate of Al7075 alloy and Al7075—6 and 9 wt% of WC–co composite under different sliding distance [91]

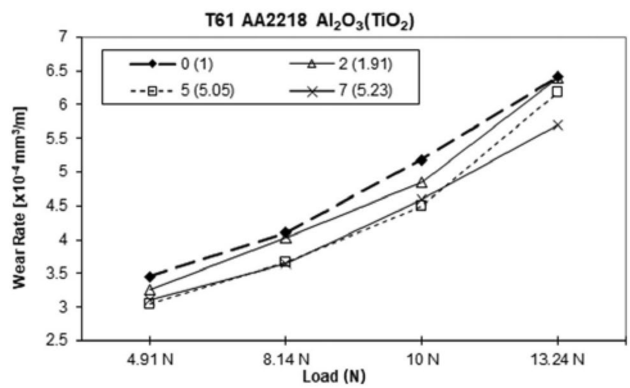

Fig. 12 Wear rate versus normal loads for all particle additions [56]

[92, 93]. According to Prasat et al. [94], increasing the weight percentage of fly ash while keeping the graphite constant reduces wear loss in AlSi10Mg/Fly Ash/Graphite hybrid composites by wearing out the reinforcements and forming a mechanically mixed layer between the pin and disk surfaces that acts as a solid lubricant.

Singh et al. [95] reported that: (i) increased normal load causes increased wear loss, (ii) increased sliding speed causes increased wear loss because heat development is greater at higher speeds, and (iii) at lower track diameter, the formation of a non-uniform tribo-layer throughout the specimen caused an increase in wear loss. The combination of SiC and MWCNT reinforcements to LM13 alloy reduces wear rate due to an increase in micro-hardness, resulting in increased hybrid composite strength [96]. In conjunction with Al_2O_3 and RHA, graphite played a significant effect in increasing wear resistance [97]. The presence of graphite resulted in the formation of a solid lubricant layer at the rubbing surfaces' interface. However, increasing the proportion of graphite reduces wear resistance because of graphite's brittle nature, which reduces hardness [83]. Due to the formation of clusters, the wear resistance of the hybrid composite Al 6351/Al_2O_3/SiC is higher than that of Al 6351/Al_2O_3 [98]. Due to an increase in hardness, the wear resistance of the Al6061 hybrid composite is increased up to 1.2 wt% SiC and 0.5 wt% graphite reinforcement for all applied loads. The wear rate increased as the weight percent of SiC rose from 1.2 to 1.6 due to the agglomeration of hard ceramic SiC particles [99]. This is owing to the soft SiC obstructing dislocation movement, and sheared graphite particles acting like a protective layer between the contacting surfaces. With the inclusion of carbon-based materials, the wear resistance

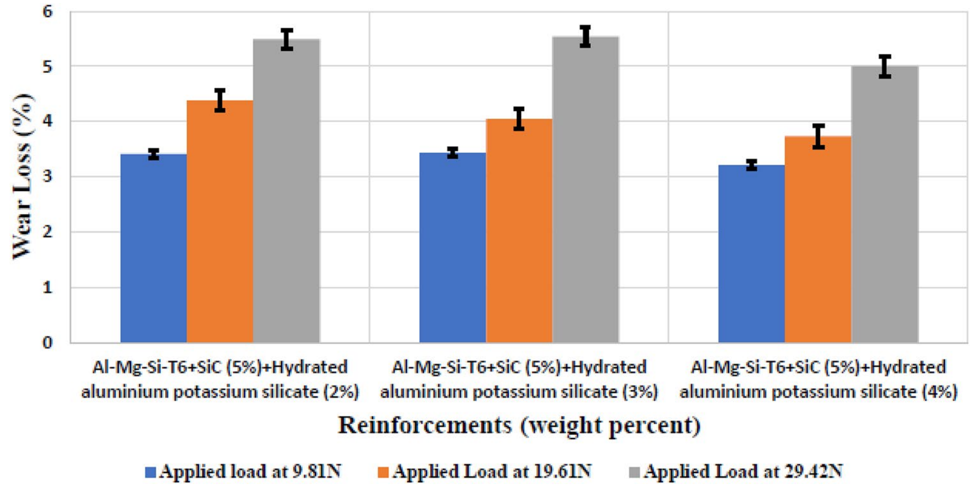

Fig. 13 Wear loss of various compositions at different loading conditions [66]

was enhanced, and a protective layer will form between the mating surfaces that will act as a lubricant [100]. For the Al/Al_2O_3/TiO_2 hybrid composite, the worn surface morphology resulted in deeper grooves, wear debris, rough surface, and greater delamination at the minimum % of reinforcement due to adhesive wear, as illustrated in Fig. 14 [101]. Palanikumar et al.[102] reported similar results in Al6061/B4C/Mica Hybrid Composites.

For higher stress due to increased plastic flow at the interface of the sliding surfaces, Elango et al. [103] observed increasing breadth and depth of the grooves. Due to the creation of a mechanically mixed hard layer and a solid lubricant between the pin and counter disk, the wear characteristics of composites improve as the weight % increases.

5 Strengthening Mechanisms

There have been few studies that have looked at the various strengthening methods of AMCs for the addition of hard ceramic reinforcement agents. The commonly mentioned strengthening mechanisms are highlighted in this article. The strength of the composite is evaluated using the resultant grain size in the Hall patch strengthening method [104, 105]. The strength of the composite is determined using the interaction between the reinforced particles within the composite structure and the grain dislocations in the Orowan strengthening process. According to this process, the rate of blockage to grain dislocations is determined by the degree of dispersion of the reinforcing particles. However, it has been observed that when the particle size is greater than 1 m, the Orowan mechanism cannot be used to estimate the strength of the composite because the inter-particle distance is greater [106, 107]. The difference in thermal expansion coefficients between the reinforcement and matrix alloys causes residual stresses in the composite, which induce dislocation near the reinforced particles and increase the composite's strength [108]. The thermal mismatch strengthening mechanism is the name of the mechanism. The homogeneous distribution of reinforced particles in matrix alloy induced strength enhancement due to load transmission from matrix alloy to reinforcement, according to the load-bearing strengthening mechanism [109–112].

Gautam et al. [113] investigated Al5052/Al3Zrmp/ZrB2np hybrid composites and found that, as shown in Fig. 15, the matrix grain size was continually lowered to increase the volume percentage of second-phase reinforcement particles. Secondary reinforcing in the hybrid composite limited grain formation during solidification while enhancing ultimate tensile strength and hardness qualities. However, for a lesser proportion of secondary reinforcement, the percentage of elongation increased, and its further increase had a detrimental effect. The theoretical strength of the dislocation, Orowan, grain refinement, and solid solution strengthening mechanisms has been found to be 5–8% higher than the experimental values.

Mechanical properties of Al7075/CNT/GNP composites were investigated by Siavash et al. [114] at various weight percentages. Higher reinforcements increase the hardness and yield strength of the composites due to increased dislocation density. In terms of increasing yield strength, the load transfer strengthening mechanism contributes more than the Orowan and CTE mismatch mechanisms. The Hall–Petch mechanism has no effect on the increase in yield strength owing to grain refinement during 400 °C accumulative roll bonding.

Because of the reduced free zones in the matrix alloy [115], the grain size of the Al6061/B4C composite dropped from 5 to 20 wt% with the addition of B4C reinforcement particles, resulting in improved mechanical properties. Increased reinforcing reduced grain size and the yield strength of the composite calculated using the hall patch

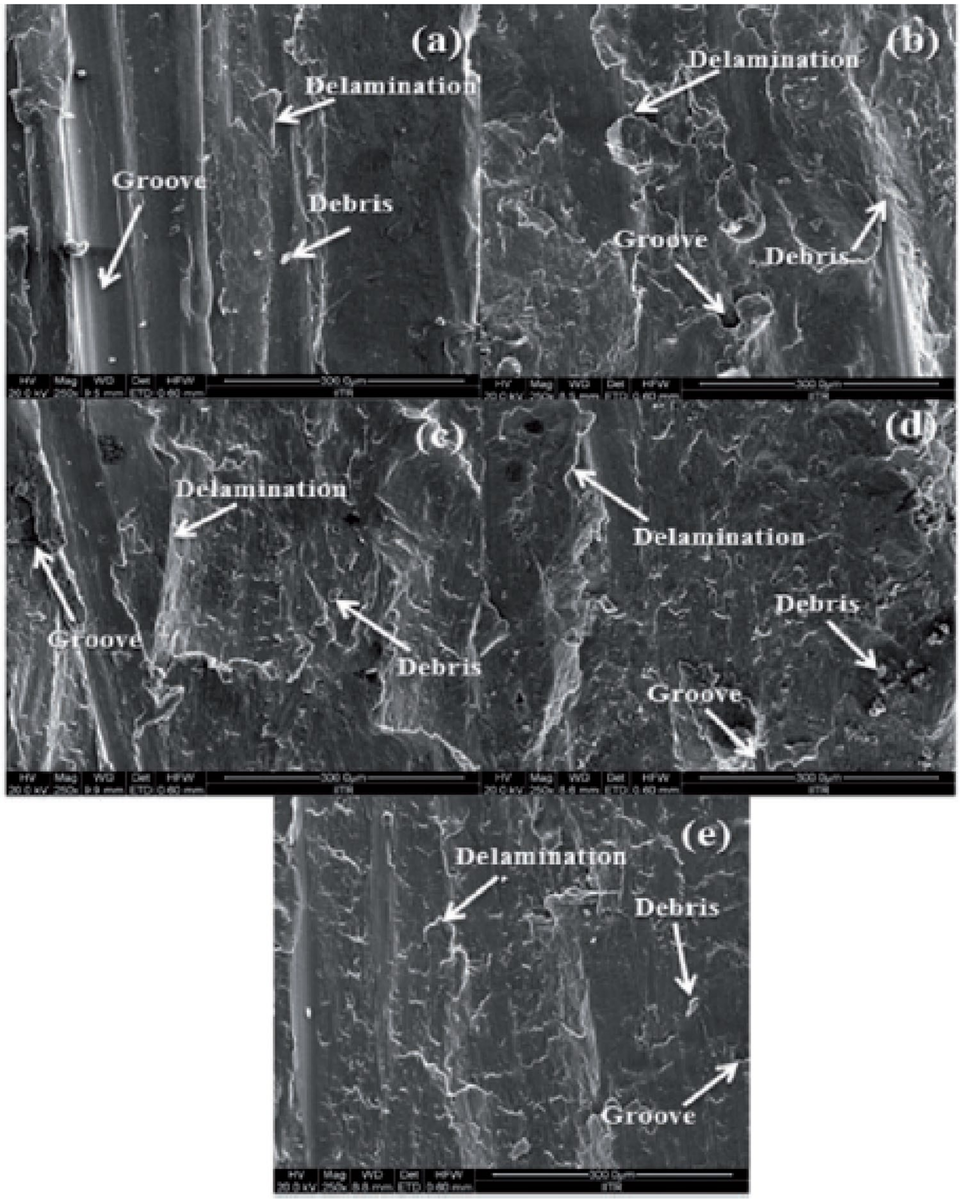

Fig. 14 SEM micrograph of the worn surface of specimen **a** Pure Al **b** Al with 5% reinforcement **c** Al with 10% reinforcement **d** Al with 15% reinforcement **e** Al with 20% reinforcement at 20 N load and 250 × magnification [101]

mechanism matched the experimental values. The inclusion of B4C reinforcement particles increased the strength of the material due to grain refinement, higher density, and obstruction of grain dislocation reinforcement at grain borders. Because the thermal expansion coefficient between the matrix and reinforced particle increases with an increase in temperature, which increases dislocation density, the dislocation strengthening mechanism is more dominant in increasing volume fraction and decreasing particle size as shown in Fig. 16 than the other mechanisms.

The addition of TiB_2 in Al alloy reduced grain size, according to Chen et al. [116], because the hard ceramic particles surrounding the grain prevented its expansion during solidification. The enhanced yield strength for the increasing percentage of reinforcement due to the smaller grain size and obstruction of the grain dislocation for uniform distribution of reinforcement particles was also demonstrated by the strength evaluated using the Hall patch and Orowan processes. In research on the Al7075/TiB_2 composite, Prasanna et al. [117] found comparable results. According to N Kumar et al. [118], the higher number of nucleations generated by the increased proportion of ZrB2 particles added to the AA5052 aluminum alloy resulted in improved grain growth resistance. Due to increased grain refinement and the presence of hard reinforced particles, the mechanical characteristics of the composite improved when the reinforcement percentage was raised. The strengthening processes also showed that reduced grain size, increased dislocation, and interaction between the dislocation and reinforcement boosted composite strength. In the research of Bembalge

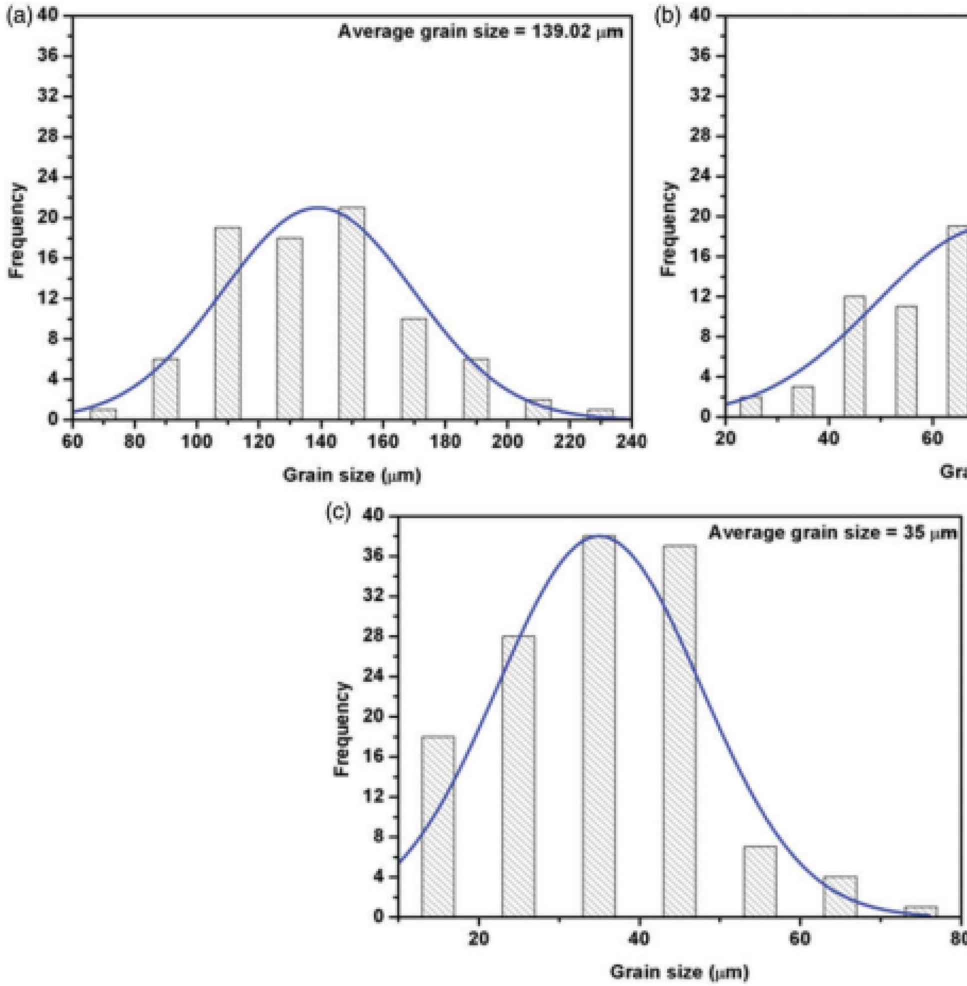

Fig. 15 Grain size distribution curves of matrix in **a** AA5052 base alloy, **b** hybrid composite with 10% Al_3Z and 1% ZrB_2, and **c** hybrid composite with 10% Al_3Z and 3% ZrB_2 [113]

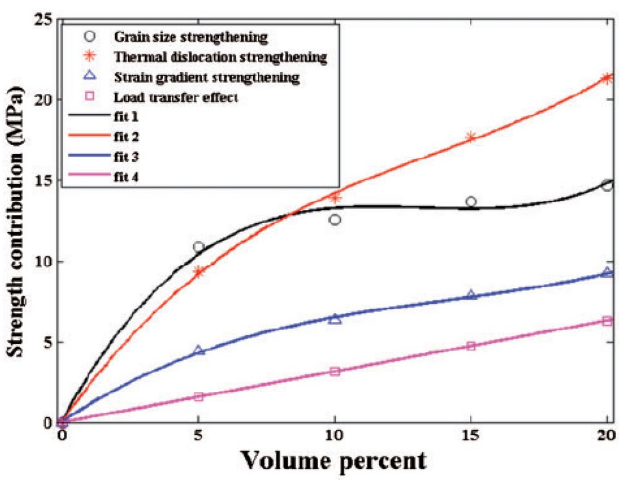

Fig. 16 Comparison of strength contribution from different mechanisms as a function of volume fraction for the average [115]

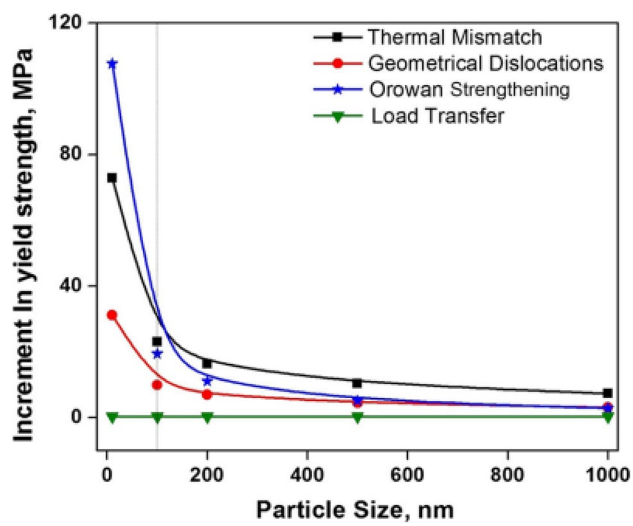

Fig. 17 Influence of reinforcement particle size on strength enhancement due to various strengthening mechanisms [120]

Table 1 The findings reported on Stir cast Al6XXX matrix hybrid composites

S. No.	Hybrid AMCs	Observations on the enhancement of properties	Reference
1	Al6061/Fe_2O_3/B_4C	The density of composites like Hardness, compression, and tensile strength has increased for an increasing percentage of reinforcements. There is also an increase in the percentage of Wear resistance	[61]
2	Al6061/TiC/Gr	Tensile strength of composite increased up to 4% addition of TiC with 5% of graphite. Beyond 4% of TiC, the strength of the composite was decreased. Increase in composite wears resistance to increase reinforcement percentage	[64]
3	Al6061-T6/SiC/Al_2O_3	The mechanical properties of the composite are increased by increasing the percentage of reinforcement. The ductility in the composite has been reduced	[73]
4	Al6061/Gr/B_4C	The existence of hard ceramic particles provided better resistance to dislocations and thus increased the tensile strength of the composite	[70]
5	Al6061/SiC/Gr	(1) The addition of hard ceramic particles enhanced the hardness of the hybrid composite and withstood the dislocation movement of the composite's grain (2) The addition of soft graphite particles created a protective layer between the mating surfaces, which increased wear resistance	[105]
6	Al6061/SiC/Gr	The tensile strength, wear resistance, and hardness of the composites have been improved by increasing the reinforcement percentage because of a good transformation of the reinforcement load to the matrix	[123]
7	Al6061/SiC/B_4C	The microstructure conforms to this uniformly distributed reinforcement throughout the matrix alloy. The composite's hardness and tensile strength increase with increasing weight% B4C and decreasing weight% SiC due to the extraordinary hardness and tensile strength of both B4C and SiC	[124]
8	Al6063/Al_2O_3/RHA/Gr	The wear resistance was increased by the addition of combined reinforcements. Formation of a Solid lubricant because of the presence of graphite and the hardness of the co-particles. The hardness of the composite has been reduced through the fragility of the graphite	[97]
9	Al6063/Al_2O_3/TiC	Hard ceramic particles resist strain from hybrid composites and improve the wear resistance	[90]
10	Al6082/SiC/Gr	(1) The composite has a higher SiC reinforcement than with SiC + Gr. Because Gr does not influence the improvement of hardness due to its softness (2) The wear resistance of the hybrid composite is greater after aging than the untreated composite because of the formation of intermetallic precipitates formation with aging	[87]
12	Al6082/Al_2O_3/B_4C/Gr	(1) The uniform distribution of reinforced particles in the microstructure was observed in the composite. Agglomeration formation has been increased to increase particle weight (2) Hardness and wear resistance have been increased with an increasing percentage of the reinforcement up to 10% of Al_2O_3, 3% of Gr, and 1% B_4C. Properties were reduced for an additional percent reinforcement due to the formation of agglomerations	[95]
13	AA6082-T6/SiC/B_4C	The hardness and tensile strength of the composite have been increased by increasing the reinforcement percentage up to 15% and beyond, and the properties have been diminished	[71]
14	Al 6351/Al_2O_3/SiC	(1) The extra reinforcement improved the hardness (2) To increase the weight% of reinforcements, increased the number of clusters in composites and resisted wear loss	[98]

et al. [119], however, the size reduction of the ceramic reinforcement particle (SiC) improved the mechanical properties of the Al6063 matrix composite. The smaller particle size allows for more space at the dendrite's grain boundary, limiting grain dislocation under loading conditions. This boosted the composite's strength but had a negative impact on its elongation. Higher strength due to grain refining, load transmission, and increased density of dislocation led to a rise in the composite's strength, according to the strengthening process. The contribution of various strengthening processes is proportional to the size of the reinforcement particles, as shown in Fig. 17 [120]. The role of Orowan loops was not examined due to the coarseness of the reinforcement particles in Gupta et al. [121]. analysis, which found that thermal mismatch was the primary cause of strengthening.

While Baburao [122] found that Orowan loops strengthen composites, and that solid solution has a major role in increasing composite strength. With increasing percentages of reinforcement content in the composite, the strengthening contributions of dislocations interactions between matrix-reinforcement particles, grain refinement, and load transfer mechanism grew monotonically.

By considering several characteristics such as grain size, grain dislocation, coefficient of thermal expansion, and

Table 2 The findings reported on Stir cast Al7075 matrix hybrid composites

S. No.	Hybrid AMCs	Observations on the enhancement of properties	Reference
1	$Al7075/B_4C/CDA$	The composite's Hardness, tensile strength, and wear resistance were reduced by increasing the percentage of CDA. As a result of an increase in the percentage of B_4C and a decrease in the percentage of CDA, the mechanical properties were increased	[57]
2	$Al7075/Al_2O_3/SiC$	The tensile strength, compression strength, hardness, and wear resistance of composites are improved to increase the reinforcement percentage	[58]
3	Al7075/ Al_2O_3/Gr	1. The tensile strength and hardness have been improved for an increasing percentage of Al_2O_3 reinforcement due to its hard nature and act as impediments to the sliding of grain dislocation 2. The wear rate of the composite increased due to the presence of hard Al_2O_3 and the formation of a thin solid lubricant by the graphite	[81]
4	Al7075/ Bagasse-ash/Gr	The tensile strength, yielding strength, and hardness of composites were increased to keep the percentage of graphite constant and varying bagasse ash. The presence of graphite reduced slag formation during casting and improved properties	[76]
5	Al7075/Fly ash/SiC	The increasing percentages of reinforcement have increased the mechanical properties of the composites	[77]
6	Al7075/ B_4C/Fly ash	The addition of reinforcement enhanced the mechanics of the composite. The wear rate of the composite has been reduced to increase the percentage of particles up to 3% by weight B_4C and 7% fly ash and to further increase the percentage, the wear rate was raised	[125]

Table 3 The findings reported on Stir cast Al2XXX matrix hybrid composites

S. No.	Hybrid AMCs	Observations on the enhancement of properties	Reference
1	$Al2218\text{-}T61/Al_2O_3/TiO_2$	The hardness and wear resistance are increased up to 5% of reinforcement. For the addition of more than 5 percentage of reinforcement, the properties are reduced	[56]
2	Al2219/SiC/Gr	The wear resistance increased for the addition of reinforcement due to the generation of the mechanically mixed layer and tribo-layer at the mating surfaces	[126]
3	Al 2219/15SiC/3Gr	Higher the wear resistance of the hybrid composite compared with its matrix alloy and the composite with single reinforcement. The formation mechanically mixed layer of matrix reinforcement at the mating surface is the reason for the enhancement due to the presence of because of graphite	[93]
4	$Al2219/B_4C/MoS_2$	(1) The density of the composite is lower when it is with B_4C as a mono reinforcement compared with the composite with MoS_2along. This is due to the higher density of MoS_2 compared with B_4C density (2) Higher the hardness of the composite with B_4C compared with the hybrid composite due to the hard nature of B_4C and soft nature of MoS_2 (3) Higher the wear resistance of the hybrid composite due to the formation of a lubricant tribo-layer between pin and disk by nanosized MoS_2 particles	[88]

thermal mismatch, the above-mentioned mechanisms play a vital role in the enhancement of mechanical properties. Tables 1, 2, 3, and 4 summarize the improvement in various features of various grades of aluminum alloys as a matrix with the refinement of various combinations of particulate agents treated using the stir casting technique.

6 Conclusions

A thorough overview of the microstructural, mechanical, and wear aspects of aluminum metal matrix hybrid composites treated using liquid state processing is presented in this article, along with a complete collection of recently published research findings. The presentation of numerous debates on various strengthening mechanisms recognized as the primary causes for the development of such qualities with metal matrix composites has received specific attention.

The findings of the review demonstrate that,

(1) The most important elements in stir casting for the effective fabrication of sound aluminum matrix hybrid composites are stirring speed, time, and temperature, reinforcement particle preheating temperature, and matrix-reinforcement slurry transferring temperature.
(2) The consistently dispersed reinforcement particles increased grain refinement, indicating effective reinforcement-to-matrix alloy bonding. While particle agglomeration and cluster formation can be reduced

Table 4 The findings reported on Stir cast Al-Si–Mg and other grade aluminum matrix hybrid composites

S. No.	Hybrid AMCs	Observations on the enhancement of properties	Reference
1	Al-Si–Mg/$ZrSiO_4$/Al_2O_3	Higher the compressive strength and hardness of the composite at 11.15% of alumina and 3.75% of zircon due to a high amount of hard alumina. At 15% of alumina and zero percentage of zircon, these properties were decreased	[59]
2	Al–Mg-Si/RHA + Al_2O_3	The tensile strength and hardness of the composite were decreased by increasing RHA and decreasing the percentage of Al_2O_3, respectively. But the tensile strength and ductility were reasonably good at 2% of RHA as RHA containsSiO_2 which is having a lower hardness than Al_2O_3	[74]
3	Al–Mg-Si/SiC/GSA	The tensile strength, hardness, yield strength, and specific strength of hybrid composite reduced for an increasing percentage of GSA with a reduced percentage of SiC particles	[127]
4	AlSi10Mg/Al_2O_3/Gr	(1) The wear resistance and hardness were increased for increasing reinforcement Al_2O_3 particles percentage (2) The presence of Gr particles caused to delay of mild wear transition to severe wear by the formation of a tribe-layer between the rubbing sides of pin and disk	[89]
5	AlSi10Mg/Fly Ash/Gr	(1) The hardness and density of hybrid composite were increased for the increased percentage of fly ash due to its higher hardness (2) The formation mechanically mixed layer of matrix reinforcement at the mating surface is the reason for the enhancement due to the presence of because of graphite	[94]
6	LM6/Gr/Si_3N_4	Mechanical and wear characteristics were improved with the hybrid composite	[78]

by carefully managing process parameters during composite manufacture.

(3) When compared to simplex reinforcement, the mechanical properties of hybrid composites such as tensile, yield, compressive, flexural strength, and hardness are considerably improved due to the involvement of numerous reinforcing phases. The use of numerous reinforcements, on the other hand, significantly reduced ductility due to the increased limitation imposed by the larger volume of hard ceramic particles.

(4) For the addition of reinforcements, the increase in wear characteristics is proportionate to the increase in hardness. Due to their inclination to generate a protective layer at the mating surfaces that acts as a lubricant, the wear resistance was substantially enhanced with the inclusion of carbon-based materials.

(5) The wear characteristics of composites were improved with the inclusion of hard ceramic particles by forming a matrix-reinforcement mechanically mixed layer and a tribe layer between the contacting surfaces. The addition of hard ceramic particles, on the other hand, increased the coefficient of friction of composites.

(6) The addition of hard ceramic reinforcement particles improved the strength by reducing grain size, grain refinement caused by the thermal mismatch between the matrix alloy and reinforcement, and load transfer from matrix alloy to reinforcement, according to the studies on strengthening mechanisms.

7 Future Scope

The described investigations did not reveal the best processing conditions for fabricating hybrid composites with good mechanical and tribological properties. In addition, only a few studies have been published on the fundamental knowledge of the role of various reinforcements in the hybrid composite idea. For the development of hybrid aluminum matrix composites, promising research in this sector remains unexplored. Extensive industrial-oriented research, as well as hybrid manifestations, should be conducted on these factors.

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Data Availability There are no data associated with this investigation.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Approval As an expert scientist, I submitted the work with full responsibility, following the proper ethical protocol, and there is no duplication, fraud, plagiarism, or worries regarding animal or human experiments.

Consent to Participate We all agreed to take part in this research project of our own choice.

Consent for Publication We have all agreed willingly to have this research study published in the Journal of Bio- and Tribo-Corrosion.

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