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Review Article

An Insight into Mechanical and Metallurgical Behavior of Hybrid Reinforced Aluminum Metal Matrix Composite

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Hybrid reinforced particulate aluminum matrix composite materials (HAMCs) are a breakthrough kind of material made by combining two or more distinct reinforcing components in the aluminum (Al) matrix. Composites with many reinforcing phases offer a superior overall mix of characteristics than composites with only one. This article's wide literature review of metal matrix composite (MMC) especially for aluminum matrix composites (AMC) was carried out. Discussions of various widely adopted synthesis methods such as stir casting and powder metallurgy have been presented. The effect of various reinforcement ceramic particles such as silicon carbide (SiC), aluminum oxide (Al_2O_3), graphite (Gr) on the mechanical and metallurgical properties of MMC has been reviewed. The summary of various characterizations such as X-ray diffraction (X-RD), and optical microscopy (OM) including testing such as hardness, tensile, compressive, and tribological behavior has been discussed in detail to demonstrate a full grasp of the many features of HAMCs, such as manufacturing, physicomechanical properties, wear, and corrosion characteristics. Future developments and potentially useful materials as alternative reinforcements are discussed at the end of the review.

1. Composites

Composites are made up of two or more physically distinct aspects that, when mixed, result in qualities that are superior to those of their constituent parts [1, 2]. Composite materials are the most fascinating engineering materials because their structures are more complex than those of the other three categories (metals, ceramics, and polymers) [3, 4]. The fact that the qualities of composites are not only different from their parts, but are often much better, has led to technological and industrial investments in them [5]. The matrix phase, also known as the continuous phase, makes up the majority of the composites, while the discontinuous phase, also known as the reinforcement or reinforcing material, makes up the minority. Discontinuous phases are more powerful than continuous phases. When compared to conventional materials such as metals and their alloys, composites are more robust and lightweight [6]. To minimize the pressure on each component, many components in sectors including autos, aircraft, and military are being switched to composites from traditional basic metals and alloys [7].

Composite materials, whether natural or artificial, are made up of two or more different materials that provide superior physical, mechanical, chemical, and tribological characteristics [7]. At the microscopic and macroscopic scales, each constituent material's chemical properties remain independent inside the final structure of composites [8]. When compared to monolithic alloys, it is one of the most effective dominant profits of composite materials. These constituents collaborate to advance the composites' assets. These composite materials outperform monolithic/base materials in terms of strength.

Within the matrix phase, the reinforcing phases can take the shape of fibers, whiskers, sheets, or particles [9]. Reinforcing materials include ceramic carbides, nitrides, borides, oxides, and solid wastes from agricultural, industrial, or postconsumer polymer wastes, which are robust and also have lower densities [10]. In comparison to the reinforcement, the matrix is generally a weaker and more pliable material [3]. The strength of the matrix and reinforcement combination is also determined by strengthening methods such as Hall-Petch strengthening, thermal mismatch strengthening, and work hardening [11]. If the composite is designed and manufactured appropriately, it combines the reinforcing material's strength with the matrix's toughness to create a unique mix of desired attributes not found in any other conventional material [12]. Composites have the advantage of being tailorable, which means that qualities such as strength, hardness, and stiffness may be achieved by altering the amount or orientation of reinforcing material [12, 13].

Hybrid composite materials are a newer type of advanced composite material that is created by combining two or more different reinforcing components in a matrix [14]. Hybrids provide a superior overall mix of characteristics than composites with only a single reinforcing phase [1]. The synthesis of HAMCs has lately gotten a lot of interest due to its applications in industry and scientific research in the creation of value-added materials with dramatically increased physical, mechanical and tribological characteristics [15, 16]. The produced HAMCs outperformed typical single and binary reinforced MMCs in terms of physicomechanical, thermomechanical, and wear and corrosion characteristics [17, 18]. According to Singh et al. [12], HAMCs are the composites of the future, intending to replace single-reinforced AMCs in specific application areas due to enhanced and superior characteristics. Based on the reinforcement's combination and form, they determined that hybrid MMCs provide greater flexibility and reliability in the required potential portions.

Sharma et al. [5] investigated the different production processes for AMCs and discovered that independent of the manufacturing process, single-reinforced composites outperform Al and its alloys in terms of thermomechanical and wear properties. Furthermore, HAMCs outperform single-reinforced AMCs in physical, thermomechanical, and wear properties. HAMCs outperformed pure aluminum composites in mechanical and tribological qualities. When additional reinforcements are combined with single-reinforced AMCs, the wear and friction resistance of the majority of HAMCs improves [17].

2. Classification of Composite Materials

Composites can be broadly categorized based on their type of matrix, reinforcement, size, form, composition, temper state, etc. [19].

2.1. Composite Material Classification Based on Matrix Type.

Organic matrix composites (OMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs) are the three primary composite material types based on matrices (see Figure 1) [20, 21]. Polymer matrix composites (PMCs) and carbon matrix composites, often known as carbon-carbon composites, are thought to make up organic matrix composites.

2.1.1. Polymer Matrix Composites. Polymer matrix composites (PMCs) are composites made entirely of short or continuous fibers that are linked together by an organic molecule matrix [22]. PMCs are designed to transmit loads from fibers to the matrix. From electrical components to a vast range of automotive parts, they may be found in practically every area of modern life. PMCs are composed of a thermoplastic or thermosetting polymer matrix with one or even more reinforcements including metal, glass, carbon, and natural/synthetic fibers [23]. Polymers are well-known for their lightweight properties. PMCs have a wide range of characteristics. High strength, excellent impact, compression and fatigue characteristics, cost-effective manufacturing and tooling methods, excellent chemical and corrosion resistance, chemical inertness at a low cost, and excellent mechanical characteristics are among them [24]. PMCs are commonly used in rockets, aircraft, and sports equipment [25, 26].

2.1.2. Carbon-Carbon Composites (CCCs). Carbon fibers incorporated into a carbon matrix make up CCCs [21]. CCCs are a type of carbon-fiber-reinforced material with superior thermomechanical features under high temperatures. CCCs have been employed as heat protection, missile and rocket nozzles, airplane brakes, and cutting-edge materials in vehicles that go at hypersonic speeds since their mechanical properties must be kept at temperatures above 2000°C [27]. They are lightweight materials with exceptional thermal shock, hardness, ablation, and high-speed friction properties [28].

2.1.3. Ceramic Matrix Composite (CMC). A CMC is an amalgamated material that's composed of a ceramic matrix such as SiC, Si_3N_4, Al_2O_3, or other ceramic materials and reinforcements [29]. Ceramic-grounded matrix materials are suitable for applications demanding a high strength-to-weight ratio that does not give way at temperatures beyond 1500°C [30] due to their high melting points, exceptional wear and corrosion resistance, chemical inertness at extreme temps, and excellent mechanical properties. Ceramic matrices are, of course, the best choice for high-temperature activities [31]. Because of their ceramic matrix, they are particularly well suited for usage in ultralight, high-temperature devices, such as those for aircraft jet engines [31, 32].

2.1.4. Metal Matrix Composite (MMC). The matrix is a completely continuous monolithic or fundamental substance that might be a pure metal or an alloy [33]. The matrix material is frequently a lighter metallic material, such as Al, Mg, Cu, or Ti, in structural applications and acts as a guide for reinforcements [34]. A reinforcing substance is dispersed into a metal matrix to create MMCs [12]. MMCs are frequently constructed of light, low-density metals such as Al or

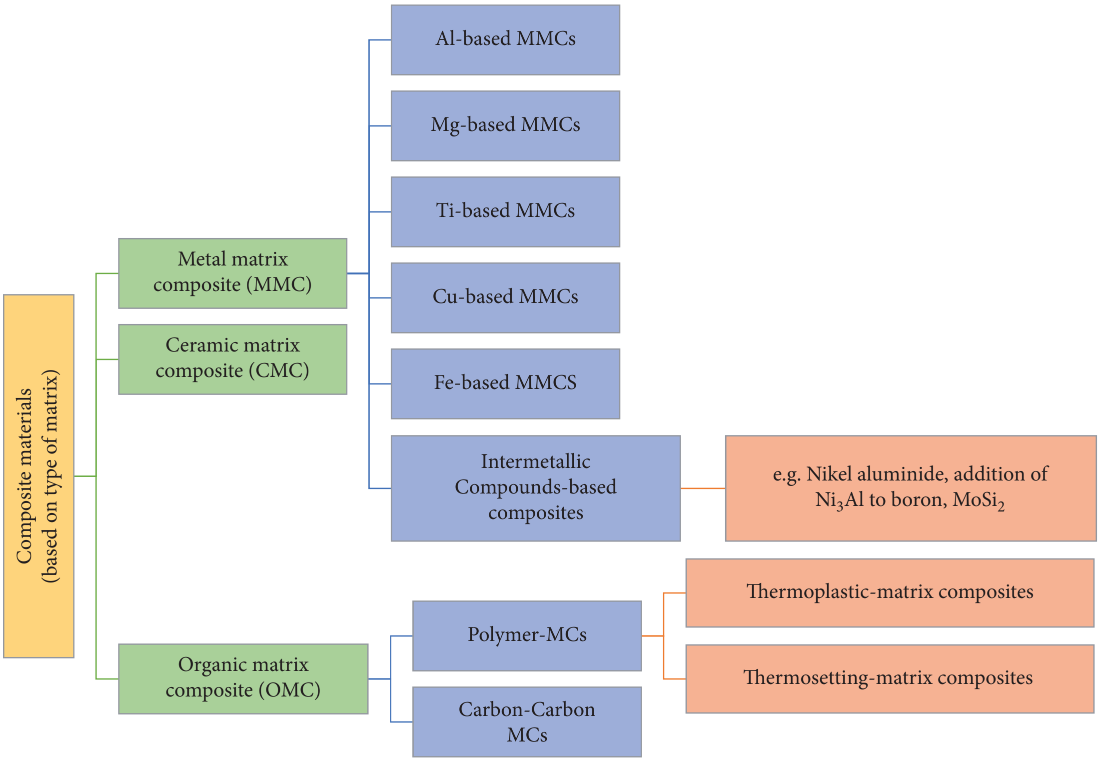


Figure 1: Composite material classification based on matrix type, reproduced with permission from Ref. [20], copyright 2021, Elsevier.

Mg that are strengthened with hard ceramic particulates or fibers such as SiC or Gr [15, 35]. MMCs outperform unreinforced metals in terms of specific stiffness and strength-to-weight ratio, working temperature, and wear and corrosion resistance, as well as the ability to tailor these properties to a given application [36, 37]. With a lower weight per unit volume, aluminum is the second least dense material after magnesium (Table 1).

2.2. Classification of MMCs. Composites can be broadly categorized based on their type of matrix andreinforcement.

2.2.1. Classification of MMC Based on Matrix Materials. Matrix types can also be used to classify MMCs. With green technologies attracting a great deal of attention worldwide, manufacturing companies have used MMCs to manufacture lighter and more efficient composite materials for fuel-efficient cars and airplanes [38, 39]. AMCs are increasingly being utilized in hybrid and electric vehicles, as well as power transmission cables because of their reduced weight and great strength [40]. Table 2 depicts the types of MMCs with prospective applications, appropriate reinforcing materials, potential benefits, and MMC manufacturing processes.

2.2.2. Classification of MMCs Depending on Reinforcing Type. Figure 2 illustrates how MMCs are divided into four groups according to the type of reinforcement they use nanocomposites, structural composites, fiber-reinforced composites, and particulate-reinforced composites [42, 43].

Table 1: Metallic matrix and their drawbacks [20, 37].

Matrix materials	Density (g/cm^3)	Major drawbacks to Be filled by reinforcements
Al	2.70	1. Temperature range is restricting its potential application in high temperatures 2. Low hardness and strength
Mg	1.74	3. Low wear and corrosion resistance, rapid creep rate, and chemical reactivity
Cu	8.92	4. Low tensile and compressive strength, as well as low creep resistance. 5. Low hardness
Ti	4.50	6. Problems with powder formation and diffusion bonding due to chemical reactivity and oxide development
Fe	7.87	7. Low tensile yield strength, low hardness, and poor wear and corrosion resistance

According to the type of reinforcement, MMCs can be further divided into four groups: particle reinforced MMCs; short fiber or whisker-reinforced MMCs; continuous fiber-reinforced MMCs; and continuous sheet reinforced MMCs (Figure 3) [42].

2.3. Particulate Reinforcements on AMCs and HAMCs. MMCs outperform matrix alloys in terms of temperature resistance, stiffness, and strength, as well as a lower CTE [44]. Furthermore, standard methods can be used to produce various particulates and whisker-reinforced MMCs [15]. Incorporating ceramic components, on the other hand, may reduce ductility, fracture toughness, and heat conductivity [45]. Fiber-dispersed metal matrix

Table 2: Some of MMCs and their potential applications in automotive and aerospace [41].

Type of MMCs	Possible reinforcements	Potential application	Possible advantages	Fabrication techniques
Al-MMCs	(i) SiC particles and fibers (ii) Al_2O_3 particulates and fibers	(i) Pistons and connecting rods (ii) Thermal management (iii) Aero engines (iv) Space applications (v) Engine parts	(i) Customizable CTE (ii) Low density (iii) Relatively cheap (iv) High specific rigidity (v) Good fatigue and ⇨ wear resistance	(i) Powder metallurgy (ii) Casting/hot isostatic pressing (iii) Additive manufacturing
	(i) Br, TiC-particulates ⇨ agro-industrial waste -particulates	(i) Orbiter of the space shuttle such as landing gear connection and tubular strut frame	(i) Lightweight (ii) Better stiffness, (iii) Reduced CTE, (iv) Respectable electrical conductivity	(i) Powder metallurgy (ii) Additive manufacturing
Mg-MMCs	(i) Gr, Al_2O_3 particulates	(i) Tubes used in truss construction applications	(i) Good thermal conductivity (ii) Better dimensional stability (iii) Reduced CTE	(i) Vacuum assist casting (ii) Powder metallurgy
Cu-MMCs	(i) Al_2O_3 fibers (ii) Gr- particulates	(i) Compressed air turbo pump, rocket propulsion housing (ii) Thermal regulation	(i) Dimensional stability (ii) High thermal conductivity (iii) High-temperature capability,	(i) Pressure infiltration (ii) PVD (iii) Additive manufacturing (iv) Friction stir consolidation
Ti-MMCs	(i) Monofilament and fibers made of SiC	(i) Exhaust valves aero engine components such as blades and vanes, compressor bling, casings, shafts, struts, and links	(i) Increased rigidity, (ii) Max hardness, (iii) Reduced weight and resilience to high temperatures	(i) Hot isostatic pressing (ii) Plasma spray technique (iii) Extrusion and forging
Fe-MMCs	(i) Titanium diboride	(i) Piston, cylinder, and engine parts of automobile	(i) Reduction in weight, high elastic modulus, high mechanical and fatigue features	(i) Powder extrusion and machining

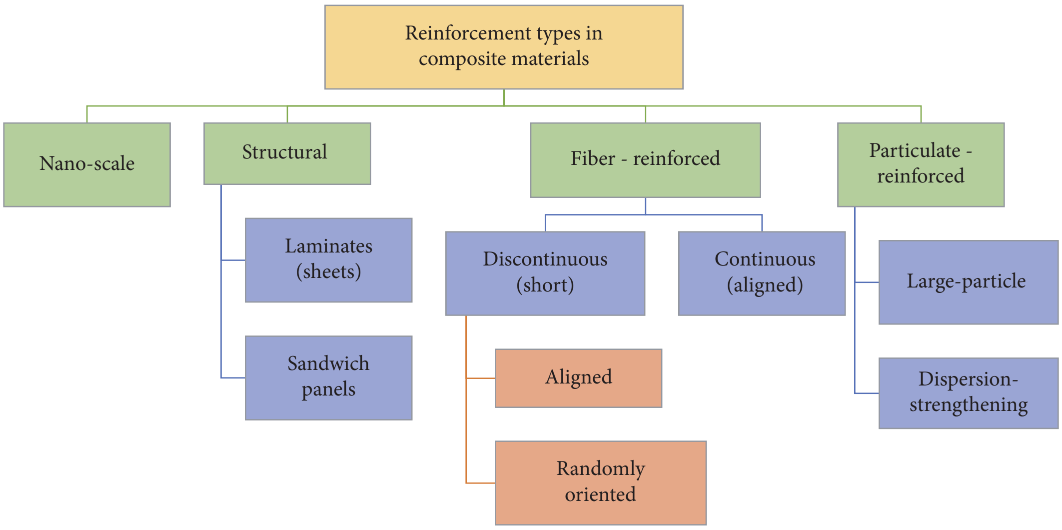


Figure 2: MMC classification is based on reinforcement type, reproduced with permission from ref. [42], copyright 2018, Wiley Online Library.

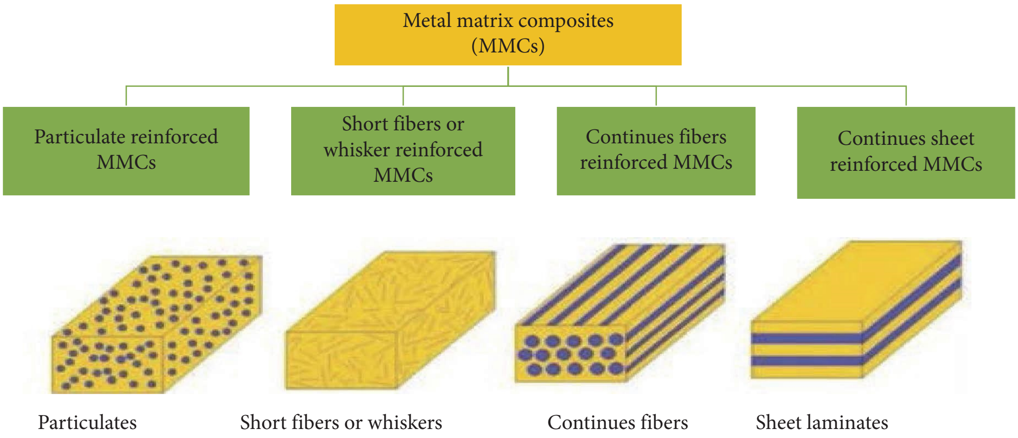


Figure 3: Metal matrix composite reinforcement-based schematic description [43].

composites have a greater cost, more difficult fabrication procedures, and recyclability issues when compared to particulate-reinforced metal matrix composites [46]. Furthermore, particulate reinforcement has a significant advantage over other forms of reinforcement such as fiber and whisker reinforcement in that it is relatively compatible with most traditional processing routes such as casting and spray deposition and is especially compatible with the powder metallurgy processing route [47]. Despite the fact that particle reinforcement is less than continuous fiber, short fiber, or whisker reinforcement, integrating this particulate type reinforcement into a matrix can result in significant improvements in material qualities when compared to the unreinforced matrix material. The isotropy of their material property distinguishes particle-reinforced metal matrix composites (PRMMCs) from other types of MMCs. Compared to unreinforced materials, PRAMCs offer the following advantages [13, 46, 48]:

(i) Extremely strong
(ii) Improved stiffness
(iii) Density (weight) reduction
(iv) High-temperature characteristics have been enhanced.
(v) Controlled thermal expansion coefficient
(vi) Thermal/heat control
(vii) Electrical performance that is improved and adapted
(viii) The resistance to friction and wear has been enhanced.
(ix) Compared to whiskers, particle reinforcement can be handled quickly and safely without the use of specialist equipment.

Because of the improvements in qualities that may be gained, the low cost and availability of particulate materials, and the adaptation of particle-reinforced materials to conventional technology, PRMMCs is now the most widely explored and utilized form of MMC [49]. SiC, Al_2O_3, Si_3N_4, TiC, and B_4C are the most popular particle reinforcing materials [50]. Figure 4 shows reinforcements contribution in wt% in AMCs [51]. Among individually reinforced particles in AMCs, silicon carbide (SiC) exhibits unique combination properties (Figure 5) [52]. In the past few years, HAMCs have received increasing attention for their superior performance. They are regarded as the next generation of composite materials, capable of replacing single-reinforced AMCs [54]. Table 3 compares hybrid reinforced metal matrix composites, single-reinforced metal matrix composites, and monolithic materials.

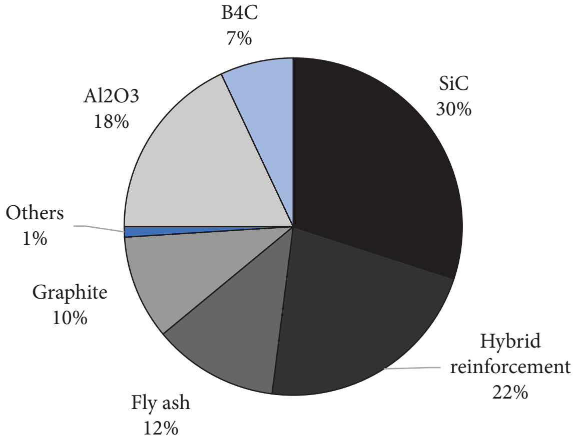


Figure 4: Research on reinforcement's contribution in wt% [51].

2.3.1. SiC and Al_2O_3 Particulate Reinforced AMCs and HAMCs. According to Mussatto et al. [15], the most often utilized dispersed materials are SiC, Al_2O_3, $TiBr_2$, TiC, and Gr. Al_2O_3 is less dense and has poorer wettability capabilities than SiC. It is, however, more resistant to oxidation and environmentally benign than SiC and its oxidative performance can also be regulated to a wide range of values. Generally, SiC offers increased physicomechanical and tribological characteristics. Carbon nanoparticles, carbon nanotube, graphene nanosheets, MWCNT, SWCNT, graphene oxide, and other carbon-based nanomaterials come in a variety of morphologies and topologies. In MMCs, the distributed material is quite important. The matrix material,

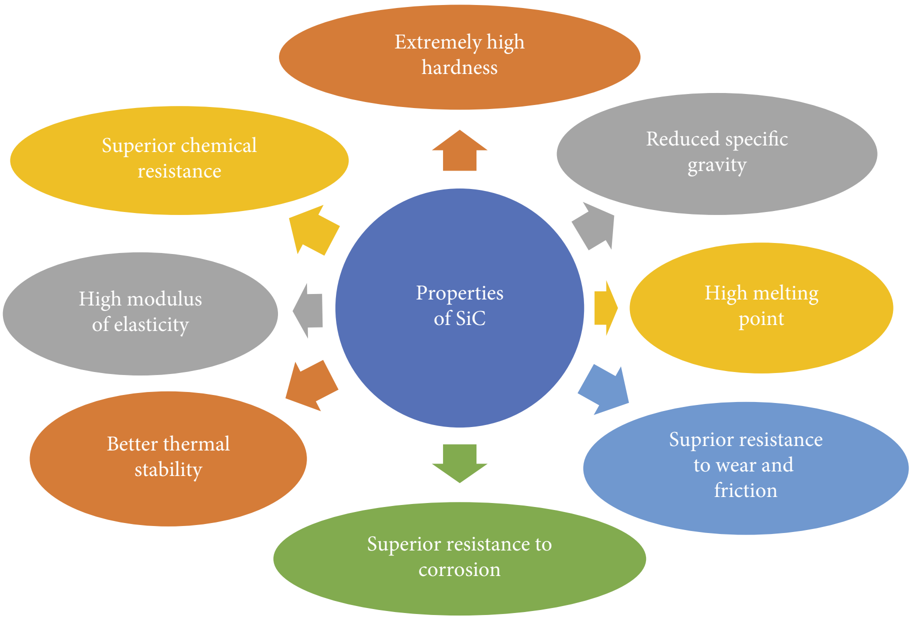


Figure 5: Property of SiC [52, 53].

Table 3: Comparison of monolithic and single and hybrid reinforced aluminum matrix composites [1, 5, 35, 55–60].

Properties for comparison	Materials type		
	Monolithic (pure Al or its alloys)	Single reinforced aluminum composite	Hybrid reinforced aluminum composites
Physical	Insufficient	Good	Best
Mechanical	Low-to-medium	Medium-to-high	Very high or superior to the others
Wear	Wearable	Depends on the percentage of reinforcement, still insufficient	Excellent wear resistance
Corrosion	Moderate	Depends on the type of reinforcement, still not enough	Excellent corrosion resistance
CTE	High	Low	Very low CTE
Chemical stability	Low-to-medium	Depends on the percentage of reinforcement, still insufficient	Very high or superior to the others
Application areas	Limited	More customizable	The most comprehensive, superior, and adjustable characteristics allow for tailorable application in various areas.

production process, uniformity of secondary phase dispersion, and appropriate interfacial bonding all influence the ultimate attributes of composite materials [9, 60]. The percentage of reinforcement, type, size, numerous reinforcements, and Al matrix kinds are the critical criteria for enhancing physicomechanical, thermal, and wear and corrosion characteristics [61].

Two or more types of dispersed phases are used in hybrid composites (for instance: $SiC + Al_2O_3$, $Al_2O_3 + Gr$, $SiC + Gr$, and $SiC + Al_2O_3 + Gr$) inside the same matrix, as compared to single-reinforced composites [35, 62]. Hybridization promotes synergy between the interparticle materials used. As a result, hybrid reinforcing can display novel structural features. At the same loading, HMMCs can outperform composites made out of separate reinforcements [12]. This is because the use of hybrid reinforcements has a substantial synergistic influence on the composite characteristics. As a consequence, hybrid composite materials are being researched towards components that require wear resistance, ultralight, chemical resistance, and the integration of dispersed phase benefits depending on the application requirements [63]. This hybrid composite material has a wide range of uses, including aviation, defense, aerospace, and vehicles. Strategies will need to reduce their losses while boosting their advantages, just as they did with single reinforcement [15, 60].

Natrayan et al. [64] used powder metallurgy to produce $Al/SiC/Al_2O_3$ HAMCs with 7.5, 15 wt% SiC and 7.5, 15 wt% Al_2O_3 to compare mechanically and wear characteristics. According to the findings, adding SiC and Al_2O_3 to the matrix material increases its physicomechanical, wear, and friction behavior by up to 25% and 40%, respectively. In comparison to Al_2O_3, the addition of SiC resulted in higher wear resistance. Kumar M. et al. [65] examined the physicomechanical and morphological characteristics of HAMCs strengthened with 5 wt% Al_2O_3 and 0–8 wt% SiC developed by using the powder metallurgical processing technique. The outcomes revealed that increasing the percentage of SiC (0–8 wt%) reinforcement enhanced density, hardness, and compressive strength. According to the SEM analysis, the homogenous distribution of reinforcing particles results in superior physicomechanical characteristics. Table 4 discusses the most often utilized ceramic particles and their physicomechanical characteristics suited for AMCs and HAMCs.

Table 4: Physicomechanical properties of hard particulate reinforcements used for AMC and HAMCs development [66, 67].

Properties	SiC	B_4C	Al_2O_3	TiC	ZrB_2	TiB_2	AlN
Density (g/cm^3)	3.2	3.52	3.96	4.93	6.09	4.52	3.26
Melting pt. (°C)	2730	2350	2054	3076	3010	3225	2200
HV (GPa)	35–45		11–20	24–32	22–26	25–35	11.8
E (GPa)	450	308	390	395	350	550	330
CTE, α (10^{-6}/K)	4.3	5.0	8.1	8.05	5.3	7.4–8.6	5.27
TC σ (W/mK)	12–22	17–40	28–32	17–30	23	60–120	280
Crystal structure	H	R	H	C	H	H	W

E is elastic modulus, HV is Vickers hardness, H is hexagonal, C is cubic, *R* is Rhombohedral and W is wurtzite.

2.3.2. SiC and Gr Particulate Reinforced AMCs and HAMCs.

In terms of reinforcement content and load level, Velikovi et al. [57], investigated the tribological properties of Al/SiC/Gr HAMCs. The difficulties in the fabrication process and machining of those hybrid composites were caused by the use of a larger volume share of SiC particles in composites fabrication in previous years. The reason for this was due to the increased hardness of those composites, which was primarily determined by SiC particles. The content of SiC particles then gradually decreased to a range of 3–10 wt%. This helped to enhance the manufacture and machining of hybrid composites using an Al matrix. The form and arrangement of SiC or Gr particles reinforced in the matrix also significantly affect the friction and wear parameters of hybrid composites [1, 68]. HAMCs' strength and wear resistance are improved by SiC particles, but their overall ductility is reduced. Gr particles, on the other hand, are fascinated by the moving and rearranging of reinforcing particles within the matrix, allowing for a minimal porosity level to be achieved [59].

To comprehend and improve the performance of Al/2SiC/Gr hybrid nano-composites, Mosleh-Shirazi, et al. [69] examined the microstructure, corrosion, corrosive wear, and abrasive wear of the materials. The hybrid nanocomposites were synthesized via powder metallurgy and contained 0, 2, 5, and 7 vol% of Gr microparticles along with 2 vol% of SiC nanoparticles. It has been proven that increasing Gr causes the nano-composites hardness to decrease. In comparison to Al/2SiC, the hybrid Al/2SiC/2Gr nanocomposite has superior wear resistance and a lower friction coefficient. However, as the percentage of graphite increased beyond 2%, the volume wear loss and friction coefficient of nanocomposites increased due to decreased toughness and reduced hardness generated by brittle graphite particles. SEM micrographs of worn surfaces (dry wear) showed that whereas adhesive wear predominated in Al/2SiC nanocomposites, abrasive wear was present in Al/2SiC/Gr hybrid nano-composites (Figure 6). As shown in Figure 7, the friction coefficient of the Al/2SiC/2 Gr hybrid composite is lower than that of Al/2SiC composite materials by 20%. These findings are consistent with those published by Vencl et al. [73], who discovered that the friction coefficient of the Al/10SiC/1Gr hybrid composite was lower than that of the base material (A356). However, the friction coefficient rose as the amount of Gr went over a crucial level of 2%. The examination also proves the greater friction coefficients of the Al/2SiC/Gr hybrid composites with more than 2% Gr addition. The increasing thickness of the Gr layer on the wearing surface may lead to extensive penetrating of the crystallites on the counter-face, resulting in higher resistance to movements [69]. Figure 6(a) depicts fine grooves with minor plastic deformation at the groove borders, indicating that delamination wear was the dominating process [69]. The existence of continuous grooves in the hybrid nanocomposites in Figures 6(b)–6(d) implies that abrasion is the primary wear mechanism. A black lubricating layer covers the surface morphology of hybrid nanocomposites. More graphite is discharged to the worn surface during sliding wear as the graphite concentration increases [69].

Using a stir casting procedure, Viswanatha et al. [74] examined the morphological and physicomechanical behaviors of HAMCs using A356 alloy as the matrix with particulates containing 0, 3, 6, and 9 wt% SiC and 3 wt% Gr. The microstructure of the produced HAMCs was examined using SEM in order to better understand the particle dispersion in the matrix phase. The findings confirmed that increasing the wt% of SiC particles results in a significant improvement in mechanical and physical properties as well as a reduction in the percentage of elongation, with maximum hardness and tensile strength obtained at 9 wt% of SiC particles [59].

The characteristics of Al/SiC/Gr HAMCs which might be used in a variety of tribological applications were described by Singh [59]. The processing approach, according to the research, is critical in achieving a uniform microstructure for these HAMCs. In powder metallurgy, matrix and reinforcement size are crucial, but in liquid metallurgy, the wettability of the reinforcing particles and the molten alloy is a key difficulty [13]. The addition of SiC particulates in AMCs improves their physicomechanical and resistance to wear and friction. The ejection of these particulates, however, can decrease the wear and friction resistance of AMCs under harsh circumstances. Gr particulates aid in the formation of a dense and extensive trilayer on the wear surface. This layer minimizes direct interaction among rubbing surfaces under certain situations, minimizing the wear rate and friction coefficient. The HAMCs display, as proven by morphological investigation of worn surfaces. As reviewed by Bodunrin et al. [1], the performance of aluminum hybrid

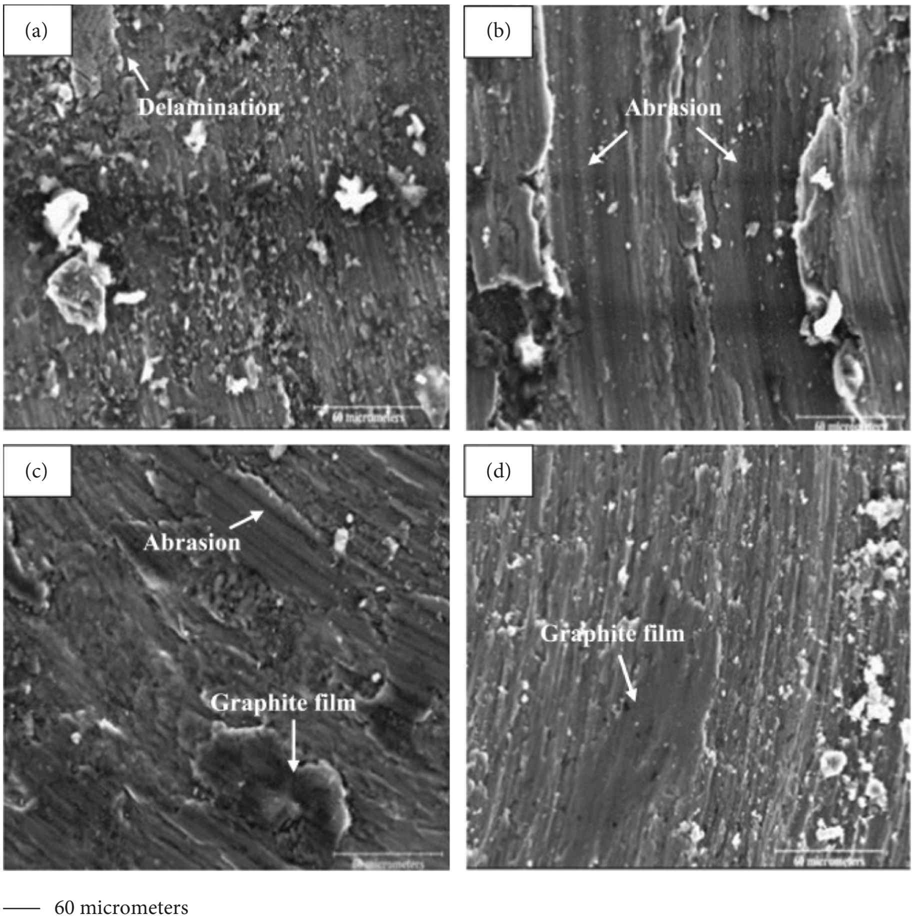


Figure 6: Typical SEM micrographs of the worn surfaces of (a) Al/2SiC, (b) Al/2SiC/2Gr, (c) Al/2SiC/5Gr, and (d) Al/2SiC/7Gr hybrid nanocomposites [69–72].

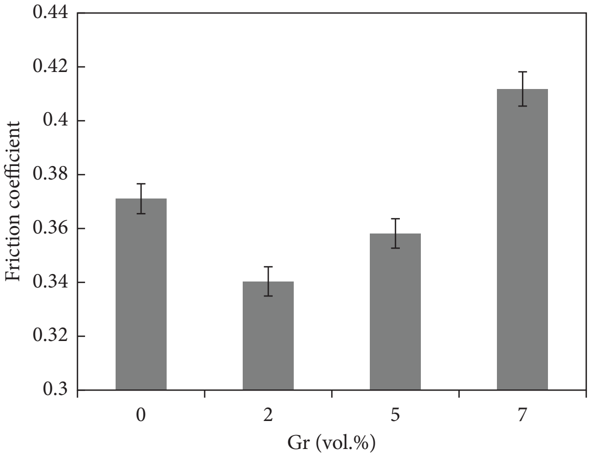


Figure 7: The dry sliding friction coefficient of Al/2SiC/Gr hybrid nanocomposites with different amounts of Gr [69].

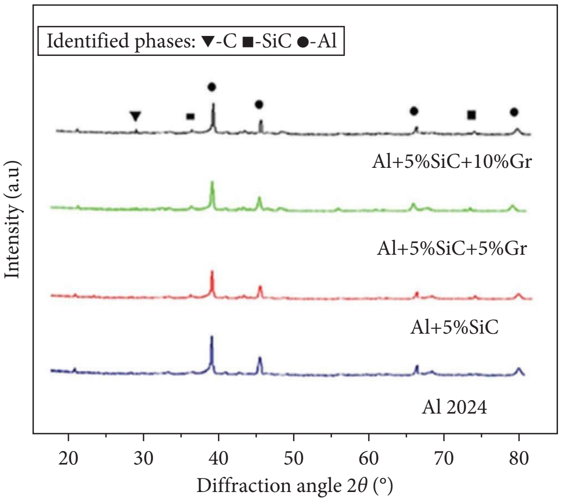


Figure 8: XRD analysis of Al/SiC/Gr and HAMCs products with various compositions, reproduced with permission from Ref. [72, 75], copyright 2013, Elsevier.

composites was indeed primarily determined by the selection of the appropriate reinforcement combination, as some processing parameters are directly related to the reinforcing particulates [1]. Ravindran et al. [72] experimented with different peaked patterns in powder metallurgy-produced HAMCs (Figure 8). The major peaks included aluminum, whereas the lesser peaks contained SiC and Gr particulates in the HAMCs.

The largest peaks in these results point to the presence of aluminum, while smaller peaks point to the presence of silicon carbide particles and carbon. In the hybrid composites, a carbon peak that is easily seen can be seen. It is clear that as the composite's graphite content rises, the carbon peaks' intensity rises as well. A steady marginal shift of the Al peaks to higher angles with an increase in the weight% of the graphite component is also noticeable. The samples in the sintering process do not undergo any oxygen reactions, as shown in Figure 8. For each hybrid nanocomposites, the XRD investigation revealed comparable phases. These patterns demonstrate that the aluminum matrix's reinforcing particles are evenly dispersed. The hybrid nano-XRD composite's pattern verified the existence of aluminum, Gr (C), and SiC particles. The XRD pattern of Al 6063-T6 exhibits three aluminum peaks at 2 angles of 44, 65, and 78, which correspond to the diffraction planes of (200), (220), and (311), respectively, according to different research by Ramadoss, N., et al. [76]. Figure 9 displays the XRD patterns of Al 6063-T6, Al 6063 + 3%SiC, and Al 6063 + 3%SiC + 3%MoS2. The Al 6063 + 3% SiC XRD pattern exhibits three peaks of aluminum along with two minor peaks of SiC at about 55 and 72°. The reported peak analysis of Al (311) in Al 6063 + 3% SiC may have resulted from residual matrix tensile shearing and/or probable Al-Si reaching evaluation to Silalumin Composite production. The diffraction pattern of the Al6063 + 3%SiC + 3%MoS2 sample, on the other hand, displays only one peak of aluminum with the desired orientation of Al (200). The appearance of an undetectable SiC and MoS2 peak in Al6063 + 3%SiC+3% MoS2 might be attributed to thick refractories and uneven matrix embedding [76]. The SiC peak was also reduced by the level of noise, which is significantly greater given the lack of identifiable typical MoS2 peaks. It suggests that the MoS2 in the composite is most likely in an amorphous or nearly amorphous condition.

Ravindran et al. [77] investigated the fundamental tribological properties of Al 2024/5 wt% SiC/(0, 5, and 10) wt% Gr HAMCs using powder metallurgy and pin-on-disc equipment. The friction and wear properties of HAMCs were evaluated in terms of applied load, sliding speed, and sliding distance. Three types of combinations of composites were developed in this study: Al reinforced with 5 wt% SiC AMC, Al reinforced with 5 wt% SiC and 5 wt% Gr HAMCs and Al reinforced with 5 wt% SiC and 10 wt% Gr HAMCs. The findings revealed that as the sliding velocity and applied load grew, so did the wear loss and friction coefficient; however, increasing the graphite wt% reduced the wear loss. Due to graphite's self-lubricating action, the composite with 5 wt% graphite had the lowest wear loss and friction coefficient. Wear loss and friction coefficient in composites containing 10 wt% Gr increased significantly due to the softening characteristic of graphite. The hardness and density of the HMCs decreased as the Gr content rose. Wear resistance and friction coefficients were both good in the HAMCs having 5 wt% Gr. The addition of solid lubricant particulates to the aluminum matrix as a secondary reinforcing phase improves wear and friction characteristics significantly [18]. The Al–5 wt% SiC composites' wear process was oxidative wearing with substantial plastic deformation, as per SEM evaluations of worn surfaces and wear debris. The Al–5 wt% SiC–10 wt% HAMCs showed oxidative wearing with delamination wearing as the wear mechanism. In the Al/5 wt% SiC/5 wt% Gr HAMCs, delamination wearing was the most popular method of wearing. Wear loss and friction coefficient was reduced by applying a homogenous Gr coating on top of the worn surface. As a result, the Al/5 wt% SiC/5 wt% Gr HAMCs did not suffer from excessive wear.

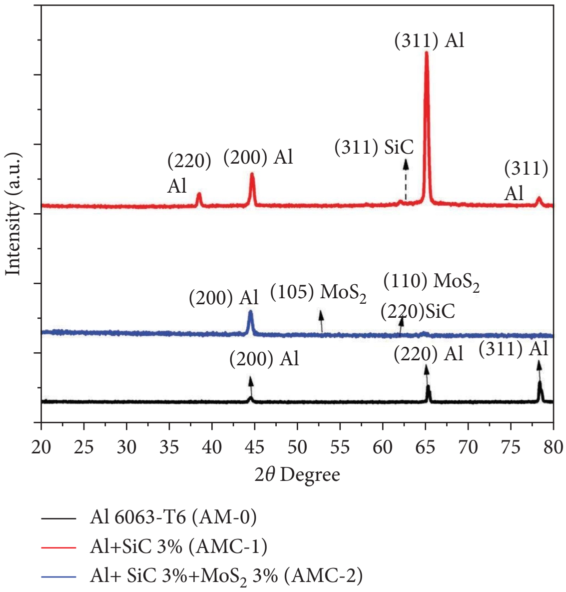
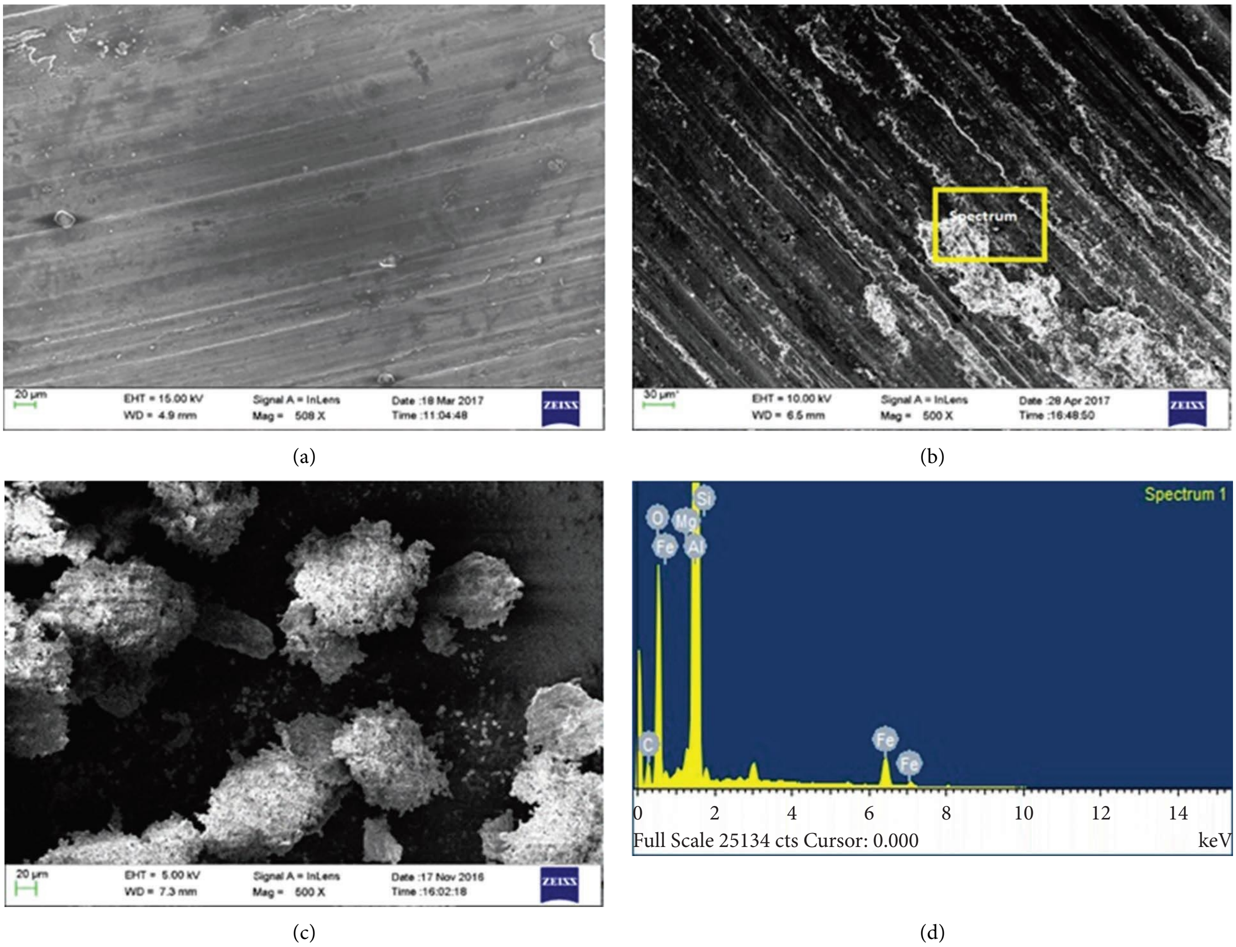


Figure 9: XRD patterns of AM-0 (Al 6063-T6), AMC-1 (Al6063 + 3%SiC), and AMC-2(Al6063 + 3%SiC+3%MoS_2) [76].

Candane, et al. [75] synthesized an aluminum matrix reinforced by nano-SiC and micro-graphite, and they studied the tribological behavior of these nanocomposites. By obstructing the migration of the dislocations, the hard SiC nanoparticles defend the soft matrix alloy. In comparison to the matrix alloy, the Al/0.4SiC/0.5Gr hybrid nanocomposite has better mechanical and tribological properties. At all applied loads, it has a lower coefficient of friction than the matrix alloy, and at 40 N of load, it reaches a minimum of 0.25. Compared to the matrix alloy, it had a much rougher wear surface. In comparison to unreinforced alloy, self-lubricating hybrid nanocomposites with hard SiC nanoparticles and soft graphite exhibit better friction and wear properties.

Figure 10(a) depicts the worn surface of an Al/0.4SiC/0.5Gr hybrid nanocomposite that was evaluated at a 10 N load. N. This surface has a parallel and shallow groove, which is a sign of abrasive wear. As seen in Figure 10(b), the existence of shallow craters shows that adhesive wear was less significant at the 40 N load applied. Al/0.4SiC/0.5Gr hybrid nanocomposite's worn surface showed extremely little alloy deformation when compared to the worn surface of Al6061 matrix alloy. Figure 10 displays the debris that was gathered following the Al/0.4SiC/0.5Gr hybrid nanocomposite's wear test at 40 N load under dry sliding contact (c). It denotes the morphologies of very fine, irregularly shaped particles and thin sheets. In comparison to the wear debris of the Al6061 matrix alloy, the wear debris of Al/



(a)

(b)

(c)

(d)

Figure 10: SEM image of the worn surface of Al/0.4SiC/0.5Gr: (a) 10 N, (b) 40 N, (c) wear debris particles of Al/0.4SiC/0.5Gr under a load of 40 N, and (d) EDS result of Al/0.4SiC/0.5Gr.

0.4SiC/0.5Gr hybrid nanocomposite samples is much lower in size. The Al6061 matrix alloy exhibits greater plastic deformation on worn surfaces than the hybrid Al/0.4SiC/0.5Gr nanocomposite. Al/0.4SiC/0.5Gr hybrid nanocomposite surface for the wear test under the applied load of 40 N is shown in Figure 10(d) together with the EDS analysis of the worn surface. It demonstrates that the sample's surface has far more iron, graphite, and oxygen than does the Al6061 matrix alloy.

Iacob G. et al. [78] investigated the effects of reinforcement wt% and milling time on the wear rate, coefficient of friction, and mechanical behavior of Al/Al_2O_3/Gr HAMCs manufactured through powder metallurgy, discovering that increasing Al_2O_3 and Gr particulate wt% and prolonging milling time have a potential impact on the structural advancement of the AMCs. The mechanically homogenized zone formed between the HAMC specimens and the steel ball's surface decreased the rate of wear under the best conditions (Figure 11). Gr particulates function as a solid lubricant and minimize the rate of wear. Vickers micro-hardness was increased by optimizing the reinforcing wt% and lengthening the mechanical milling duration. Higher microhardness was achieved by embedding hard Al_2O_3 particles in the Al matrix.

Ekinci et al. [79] studied Al_2O_3 (5, 10, 15 wt%) reinforced AMCs fabricated via powder metallurgy process at different milling times (1, 2, 3, and 4 h). Ball-milling in a vertical high-energy attritor produced block specimens, which were then compacted under 800 MPa using a uniaxially pressing machine with a standard die of 6.35 × 12.70 × 31.70 mm dimensions and sintered using a tubular furnace at a temperature of 650°C for 4 h with argon-controlled atmosphere. Milling was done with steel balls as milling medium in a vertical high-energy attritor. Zn-stearate was employed as a process control agent (PCA) to avoid aluminum particulates from welding together and adhering to the steel balls and cylinder inside. The results revealed that increasing the milling time leads to more homogenous distribution of Al_2O_3 in the matrix and enhanced hybrid mechanical assets. The hardness of all sintered samples improved as the milling duration was extended.

Sudindra and Kumar [80] synthesized 10 wt% Al_2O_3 and (3, 6, and 9 wt%) Gr particulates hybrid reinforced Al6061 matrix composite using the stir casting technique to study the tensile strength, hardness, and resistance to wearing. When compared to the base material Al6061, the addition of Al_2O_3 increased the tensile strength and hardness of composites. This increase in tensile strength and hardness of

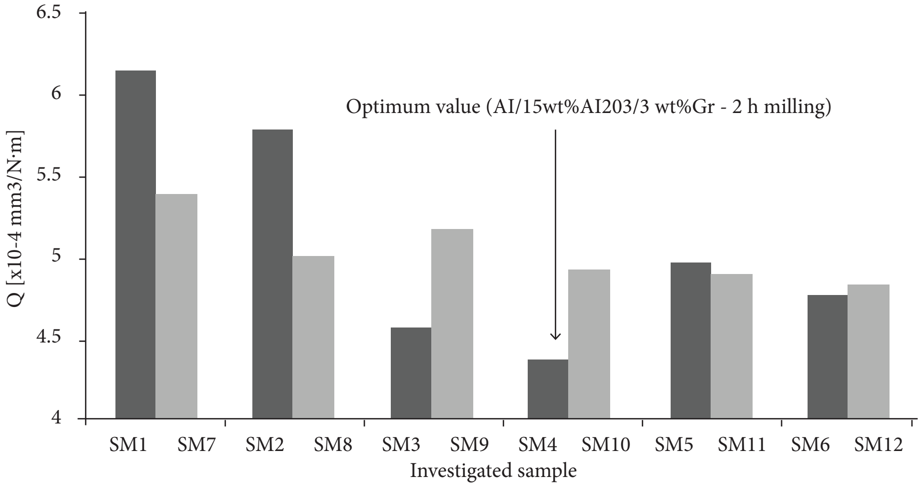


Figure 11: Wear rate of the hybrid composites, reproduced with permission from Ref. [78], copyright 2015, Elsevier.

composites could be ascribed to the stiffer and harder Al_2O_3, which resists deformation and has a higher-pressure survival ability. Despite the fact that the incorporation of Gr particulate makes the material ductile, the strength and hardness of the Al_2O_3 added composite and the basic material do not differ much (Figure 12). Moreover, the addition of Al_2O_3/Gr particulates decreases the wear rate, so these hybrid reinforced Al matrix composites could be used for automotive and antennas in aircraft.

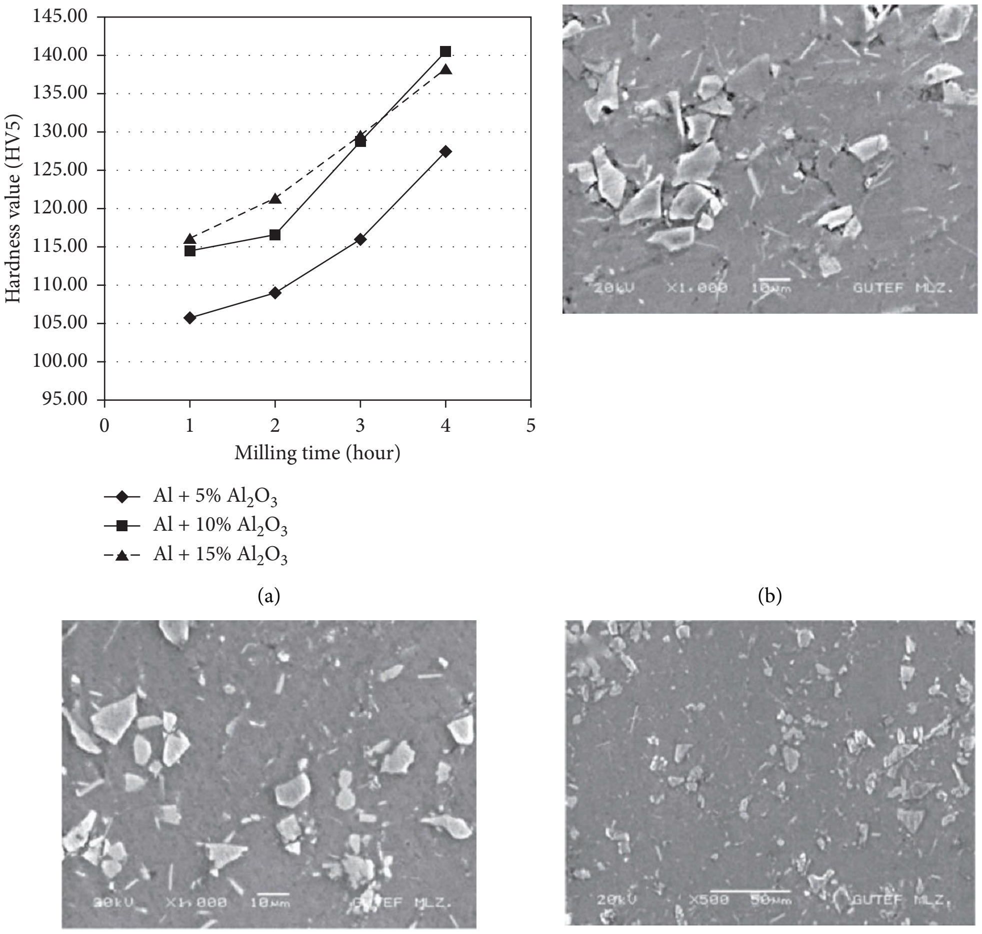
Vencl et al. [73] studied Al_2O_3, SiC, and graphite particle reinforced HAMCs using A356 aluminum alloy as the matrix material using a composting method and compared the structural, mechanical, and tribological characteristics of the produced HAMCs with the matrix alloy and among themselves. They discovered that adding reinforcing particles, particularly graphite, enhanced the wear resistance of the Al356 alloy at the price of raising the friction coefficient. The inclusion of the strong reinforcing particles in the composite C1 made it more resistant to wear than the A356 aluminum alloy (Figure 13). Due to the optimal arrangement of SiC reinforcing particles in the composite matrix and the higher hardness of the SiC particles, the wear resistance and coefficient of friction of the composites reinforced with SiC particles were higher and the coefficient of friction was lower than the wear resistance and coefficient of friction of the composites reinforced with Al_2O_3 particles. The addition of graphite particles (1 wt%) to the composite with SiC particles lowered the wear rate and coefficient of friction even more, although the effect of such a little amount of graphite was not evident enough and should only be treated as a trend of behavior.

2.3.3. Solid Waste Particulate as Reinforcements of AMCs and HAMCs.

Agro-industrial solid wastes are increasingly being employed in AMCs because their ashes may be used as reinforcing particles in metal matrices to increase their structural characteristics. Furthermore, using agro-industrial solid wastes as reinforcement of AMCs can reduce product manufacturing costs while also reducing pollution to the environment. Many solid waste materials can be used as reinforcement for MMCs and they are generally classified into three types: industrial solid wastes, agricultural solid wastes, and post-consumer solid wastes [81]. We only focused on agro-industrial solid wastes because they are excellent candidates for secondary reinforcement in AMCs. Recently, various studies have been conducted on AMCs that use meta-kaolin, filter cake, rice husk ash, coconut shell ash, corn cob ash, bagasse ash, palm oil fuel ash, bamboo leaf ash, red mud, cow dung ash, furnace steel slag, and copper slag [81–84]. Large amounts of sugar cane are processed in Ethiopia, resulting in a large amount of solid waste [85]. A portion of this solid waste is used to feed animals, while others are disposed of and burned in public landfills, both of which have a negative impact on the environment.

Sugar cane bagasse ash (SCBA): Bagasse is a remnant of sugar production. Because of its high calorific value, it is frequently burnt in millers to supply process power or steam energy to processing machinery, resulting in the formation of ash as solid waste with no industrial purpose. SCBA has a high concentration of Si components, ranging from 62 to 71 percent by weight, according to EDS data, while XRD analysis reveals that SCBA contains ceramic oxides such as Al_2O_3, SiO_2, and Fe_3O_4 [86]. SCBA had a specific gravity of 1.234 g/cm^3 according to a density test. Because these solid wastes, ashes, and gases pose environmental challenges, an innovative reuse method for these solid wastes must be established. SCBAB is an excellent reinforcing material for AMCs [87]. Aluminum metal reinforced with a solid waste bagasse ash (having high silica and alumina particulate content) produces a composite material having the combined physical and mechanical characteristics of metal matrix and reinforcement.

Gupta et al. [88] investigated Al 7075-based HAMCs fabricated via stir casting with sugarcane bagasse-ash reinforcing particulates differing in wt% (3, 6, and 9) and SiC 3 wt%. They conducted hardness, dry sliding wear, and tensile strength tests on single SiC-reinforced alloy 7075-based matrix composites and binary (SiC and SCBA)-reinforced HAMCs. The findings revealed that the HAMC



(a) (b)

(c) (d)

Figure 12: (a) VH of samples with various Al_2O_3 wt% and milling times. After sintering, SEM of Al + 10 wt% Al_2O_3 composite milled at different times: (b) 1 h (c) 2 h, and (d) 3 h, reproduced with permission from Ref. [79], copyright 2021, Wiley Online Library.

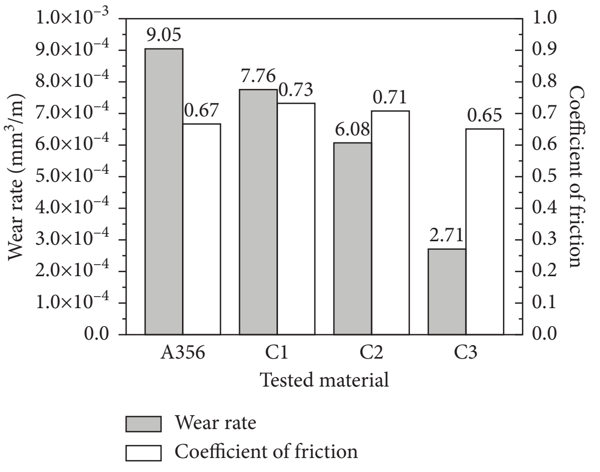


Figure 13: Wear rate and coefficient of friction values of heat treated (T6) A356 aluminum alloy, composite C1 (with 10 wt% Al_2O_3 particles), composite C2 (with 10 wt% SiC particles), and hybrid composite C3 (with 10 wt% SiC and 1 wt% Gr particles); coefficient of friction values is for the steady state period—after 300 m [73].

(Al7075 + 3 wt% SiC + 3 wt% SCBA) was more efficient, economical, and superior to single SiC-reinforced alloy 7075-based matrix composites and unreinforced matrix. Based on the findings, we can conclude that, rather than using single-reinforced Al-SiC composites, Al-SiC-SCBA binary hybrid composites could be an excellent advanced material in areas where lightweight and enhanced mechanical properties are important.

Naim Shaikh [89] employed powder metallurgy to statistically examine the wear performance of HAMCs strengthened with SiC and flay ash particulates. They examined the wearing characteristics of HAMCs strengthened with 10 wt% SiC and 0, 5, 10, and 15 wt% fly ash. Wear loss was lower for Al/SiC/FA HAMC than for Al/SiC composite. Figure 14 shows that the minimal wear loss was 10 wt% FA with a load of 20 N, a sliding speed of 2 m/s, and a sliding distance of 600 m. Al/SiC/FA HAMC has a reduced wear loss than Al/SiC composite. Figure 14 shows that with a load of 20 N, a sliding speed of 2 m/s, and a sliding distance of 600 m, the minimal wear loss was recorded at 10 wt% FA. The Al/SiC/FA HAMC outperformed the basic matrix in terms of physical mechanical

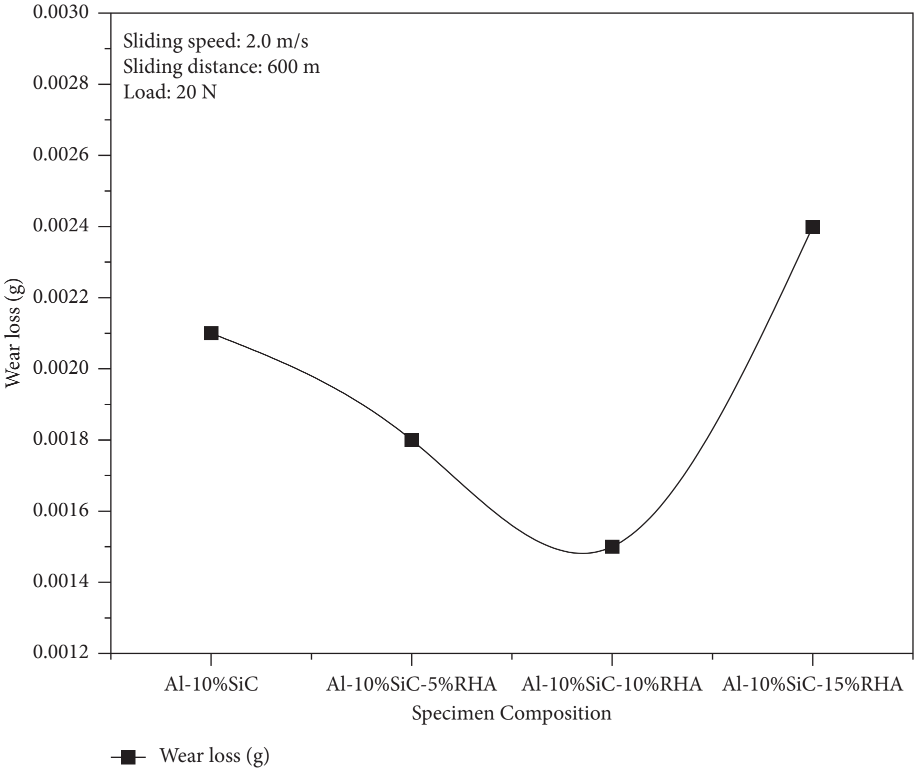


FIGURE 14: Wear loss of Al/SiC/FA HAMCs with varied FA wt% [89].

behavior and wear resistance [90, 91]. This increase in resistance to wear was caused by the following factors: the high hardness proclaimed by fly ash particulates, which inhibits plastic flow throughout the sliding condition and strong interfacial interaction between the reinforcing particulates and the matrix material. The inclusion of fly ash particulate concentration enhanced the resistance to wear of the composite materials. At 10 wt% FA-reinforced Al/SiC, the wear rate was reduced by 28% compared to the Al/SiC composite material. With increasing velocity, sliding distance, and load while sliding, the wear behavior becomes more severe.

Kulkarni et al. [92] carried out work on hybrid reinforcement of as-received fly ash and alumina in an aluminum matrix. The use of FA as reinforcement in AMCs reduces the density and cost and mechanical properties are also enhanced. Different mechanical characterizations of AMCs generated by the stir casting approach, including tensile, compressive, and hardness, were investigated in this study. The results showed that as the wt% of FA grew, the tensile, compressive, and hardness properties improved, while density and cost reduced. The hybrid reinforcement of fly ash and alumina maintains a compressive strength in the range of single-reinforced composites, keeping density low (Figure 15). Hybrid-reinforced fly ash composites have improved physical mechanical characteristics and wear resistance to single-reinforced fly ash composites [92]. The hybrid reinforced aluminum composites were found to have improved mechanical characteristics and lower densities.

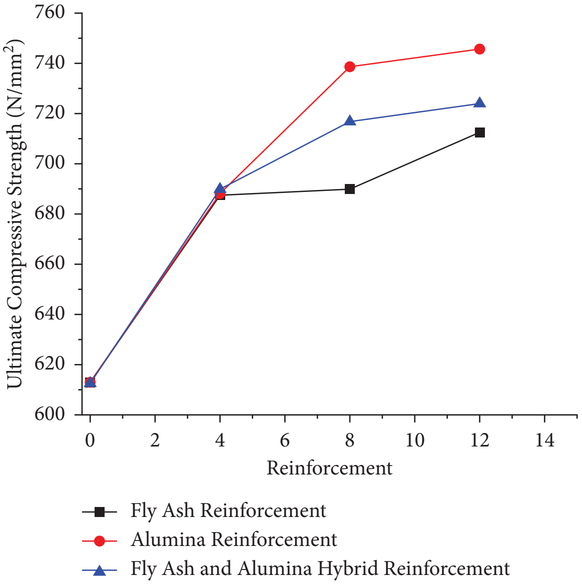


FIGURE 15: Compressive strength of various composites. Reproduced with permission from Ref. [92], copyright 2014, Elsevier.

2.3.4. Solid Lubricant Reinforcement Particulate AMCs and HAMCs. Graphite is a low-density, solid-lubricant 3D carbon material [1, 93]. According to investigations, hybrid reinforced metal matrix composites constructed from ceramic particles such as SiC and Al_2O_3 as well as solid waste materials such as rice husk ash and fly ash exhibit intriguing

Table 5: Solid lubricants (Gr, MoS$_2$, and soft metals such as Pb, Ag, Au, Cu) properties and application area [95, 96].

Requirements	Characteristics	Application area	Drawbacks
1. Avoid abrasion in dirt-filled conditions.	Low friction coefficient	1. Locations where liquid lubricants are prohibited.	Due to oxidation, the use of Gr in high-temperature applications is limited.
2. Do not contaminate the product or the environment.	Exceptional thermal stability	2. In spacecraft and rovers with limited weight	
3. Offer long-term storage or a fixed service.		3. Farm and mining equipment, as well as off-road trucks and equipment	
4. Fretting corrosion and wear	Shear strength is very low	4. In extreme freezing 5. Ineffectiveness of fluid lubricants in some areas 6. When the temperature is exceedingly high	

degrees of ductility and fracture toughness comparable to single SiC or Al$_2$O$_3$ reinforced composites [72, 84, 92]. However, potential enhancements in mechanical properties and wear and corrosion performance are yet uncertain and rewarding subjects for further research [81, 94]. Graphite is used as a solid lubricant among the composite material and the contacting surfaces within AMCs to significantly lower composite wear without the requirement of ordinary liquid or solid lubrication (Table 5) [97]. Furthermore, graphite has been employed in AMCs as a hybrid reinforcement with SiC and Al$_2$O$_3$, ensuing in significant improvements in hardness, strength, and wearing characteristics [81]. The influence of wt%, grain size, normal load, sliding velocity, followed by sliding, surface roughness, temperature, and environment on the wear rate and friction coefficients of metal and ceramic matrix composites was investigated by Menezes et al. [98]. They discovered that increasing the amount of graphite discharged on the worn surface resulted in a tiny transfer coating on the contacting surfaces, lowering the overall wear rate and friction coefficient. Material selection is crucial for (1) ensuring that the solid lubricant portions are not sheltered by worn waste and (2) facilitating the formation of lubricating transferring layers at the contact surfaces. Finally, the ability to have an endless source of solid lubricant, which has been preserved while the matrix material wears, is a benefit of self-lubricating composites over thin solid lubricating films deposition on ceramic surfaces [99]. When compared to the material deposited by solid lubricant films, which fail after the film has worn away, self-lubricating composite materials have a reduced failure probability [1]. Without the need for external lubricants, self-lubricating composite materials can sustain wear and friction. As compared with comparable monolithic material, the inclusion of graphite particulates decreases the wear and friction coefficient of graphite particulate-reinforced metal and ceramic matrix composites. With increasing graphite particle wt%, the matrix composite's friction and wear rate decrease. When utilized at high temperatures, graphite particulates were found to be preferable to many other lubricant particulates and provided effective lubrication [100].

Using a two-step stir casting technique, Alaneme et al. [94] investigated the microstructural properties, and physical mechanical, and tribological behaviors of trident (Al$_2$O$_3$, RHA, and Gr) reinforced HAMCs. Al$_2$O$_3$ with an average particle size of 30 mm, RHA, and graphite with particle sizes of 50 mm were combined in various wt% to form 10 wt% tridents reinforced AA 6063-based hybrid composites. To reduce humidity and promote wettability in the molten AA 6063, the Al$_2$O$_3$, RHA, and Gr particulates were separately warmed at 250°C. Then, at a temperature (600°C), charged to the semi solid melt and manually swirled for 10 min. After that, the semi solid hybrid reinforced composite was heated to 780 ± 30°C and swirled with an automated mechanical stirrer. The physical mechanical properties and wear behaviors of hybrid reinforced composites were examined, and the results revealed that hardness decreased as the wt% of RHA and Gr in the hybrid composites increased and that when wt% of RHA exceeds 50%, the impact of Gr on hardness becomes less significant. In comparison to the hybrid reinforced composites containing graphite, the hybrid reinforced composites without graphite demonstrated increased wear sensitivity. However, increasing the graphite concentration from 0.5 to 1.5 wt% reduced wear resistance. Table 5 discusses the solid lubricants, including Gr, Mos2, Au, and others, as well as their applications.

Ravindran et al. [71] used pin-on-disc equipment to investigate the tribological characteristics of Al 2024–5 wt% SiC–y wt% Gr ($y = 0$, 5, and 10) powder metallurgy-produced HAMCs. According to the findings, increasing the Gr content decreases wear loss and friction coefficients, with 5 wt% Gr having the lowest wear loss and coefficients of friction due to Gr's self-lubricating properties and the formation of a thin graphite layer on top of the worn surface. The density and hardness of the HAMCs were reduced as the Gr content rose, owing to the softening of the Gr particulates. Graphite acts as a solid lubricant and provides antifriction properties by reducing metal-to-metal interaction between sliding surfaces. In general, the employment of hybrid reinforcements such as dual, triplet, and tetra hybrid reinforcements increases hardness, strength, elastic modulus, and resistance to friction, wear, and corrosion while decreasing the overall weight and cost of the products, processing costs, and raw resources. The decrease in the coefficient of thermal expansion, in particular, implies that hybrid reinforcements can produce significant dimensional stability by inserting into the Al matrix [101]. Table 6 shows the prospective reinforcements and characterizations, methods of fabrication, enhanced characteristics owing to these reinforcements, and shortcomings of current research findings.

2.4. Tribological and Corrosion Behavior of AMCs and HAMCs.

Aluminum alloys are lightweight and simple to manufacture. Because of their low density, they are ideal for reducing weight in massive metal frameworks. Aluminum alloys, unfortunately, deteriorate quickly due to their weak

Table 6: Summary of properties, processing methods, outcomes, and research drawbacks in particulate-reinforced AMCs and HAMCs.

N	Matrix	Reinforcement (s)	Characterization of properties	Method	Outcomes	Drawbacks	Ref.
1.	A356 alloy	wt% SiC (0, 3, 6 and 9) and 3 wt% Gr	(i) SEM (ii) Hardness (iii) Tensile strength	Stir-cast	(i) Uniform dispersion of reinforcements (ii) Hardness improved by 9% and tensile strength by 5%	(i) Wear (ii) Corrosion (iii) Compressive (iv) Thermal stability	[74]
2.	A356 alloy	4, 8, and 12 wt% fly ash and 4, 8, and 12 wt % Al_2O_3	(i) Porosity (ii) Density (iii) Hardness (iv) Tensile (v) Compressive	Stir-cast	(i) Lower porosity and density (ii) Improved mechanical properties	(i) SEM (ii) Wear (iii) Corrosion (iv) Thermal stability	[92]
3.	Al	(SCBA) up to 4 wt%	(i) SEM, (ii) Composition and hardness	PM	(i) Hardness increased from 88.9 to 93.94 HV	(i) Compressive (ii) Tensile (iii) Wear corrosion	[87]
4.	Al6061 alloy	2.5, 5, 7.5 and 10 wt% SiC and 1, 2, 3 and 4 wt% Gr	(i) SEM (ii) XRD (iii) Hardness	Stir casting	(i) Hardness increased up to 6–8% (ii) Ultimate shear strength is shown 2–3% improvement	(i) Wear, (ii) Corrosion, (iii) Compressive (iv) Thermal stability	[102]
5.	Al6061	0 and 30 vol% of SiC and 0, 3, 5, 9, and 13 vol% of Gr	(i) Porosity, (ii) Hardness (iii) Microstructure analysis using SEM (iv) Wear rate and friction	In situ powder metallurgy (IPM)	(i) Increasing the Gr wt% lowered friction coefficient, hardness, and porosity (ii) The friction coefficient decreased by 40 and 20%	(i) Variations in the wt% of SiC are not performed (ii) Corrosion (iii) Physical and mechanical properties	[70]
6.	Al6061	0.4, 0.8, 1.2, 1.6 wt% of SiC_{np} and 0.5 wt% of Gr	(i) Microstructural analysis using SEM and XRD (ii) Hardness and wear surface analysis	Ultrasonic-assisted stir casting	(i) Increased resilience to wear (ii) Lower friction coefficient (iii) Surface roughness decreased by 66% at low load and 75%	(i) Compressive (ii) Tensile (iii) Corrosion (iv) Thermal stability	[58]
7.	Al	0, 2.5, 5, 7.5, 10, 12,5 and 15 wt% of SiC	(i) Tensile (ii) Hardness (iii) Fracture toughness (iv) Microstructure analysis	Mechanical alloying process	(i) Have higher stiffness and strength than unreinforced alloys of the same kind	(i) Wear (ii) Friction (iii) Corrosion (iv) Compressive	
8.	AA6082	(5, 10, and 15) mass% of SiC and Gr	(i) SEM (ii) Tensile, hardness (iii) Density and porosity	Stir casting	(i) Uniform distribution (ii) Density and porosity increased (iii) Hardness increased	(i) Wear (ii) Friction (iii) Corrosion (iv) Compressive (v) Thermal stability	[103]
9.	Al 7075 alloy	1, 3, and 5 wt% Gr and 2, 4, and 6 wt% SCBA	(i) Tensile, compression, and hardness tests	Stir casting	(i) High tensile, compression and hardness (ii) Ductility decreases	(i) SEM (ii) Tribological (iii) Corrosion (iv) Thermal stability	[104, 105]

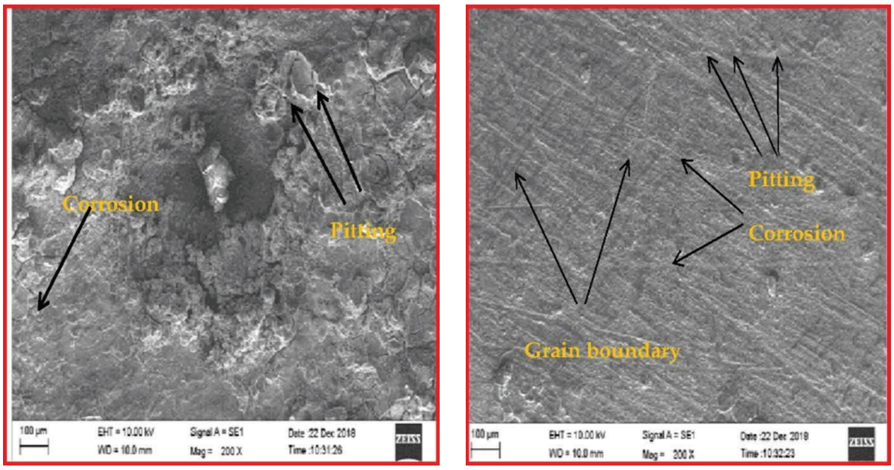
Table 6: Continued.

N	Matrix	Reinforcement (s)	Characterization of properties	Method	Outcomes	Drawbacks	Ref.
10.	Al 7075 alloy	2, 4, 6, and 8 wt% Al_2O_3 and 5 wt% Gr	(i) Hardness (ii) Tensile (iii) Flexural (iv) Compression (v) Morphology		(i) Higher hardness, tensile, flexural, and compression superior wear-resistance	(i) Corrosion (ii) Thermal stability	[106]
11.	AA6061 alloy	0, 2.5, 5, 7.5, 10, 12.5 and 15 wt% each of SiC and RHA	(i) SEM (ii) Tensile (iii) Hardness (iv) Ductility (v) Corrosion	Stir casting	(i) Enhanced tensile and hardness while reducing ductility and toughness	(i) Wear (ii) Creep (iii) Fatigue (iv) Compressive	[83]
12.	Cu	Al_2O_3 and B_4C	(i) Microstructural analysis using SEM and EDS	PM	(i) Uniform distribution (ii) Excellent interfacial bonding (iii) Hardness increased	(i) Wear (ii) Creep (iii) Compressive (iv) Fatigue (v) Corrosion	[107]
13.	Al	5 wt% Al_2O_3 + 5 and 10 wt% MoS_2	(i) SEM (ii) Wear, friction properties	PM	(i) Provides significant enhancements in tribological characteristics.	(i) Corrosion (ii) Hardness (iii) Tensile (iv) Compression	[108]
14.	Al	wt% of Al_2O_3 (3, 6, and 9) and 3 wt% of Gr	(i) SEM (ii) Brinell hardness	Stir casting	(i) Better particle dispersion in the matrix (ii) Improved hardness and tensile at 6 wt% Al2O3 and 3 wt% Gr	(i) Wear (ii) Creep (iii) Fatigue (iv) Corrosion (v) Tensile and compression	[109]

wear resistance, severely limiting their potential applications in the aerospace, automobile, defense, and marine industries [110, 111]. Furthermore, due to the greater lubricating action of graphite under dry sliding, Gr reinforced AMCs were utilized as self-lubricating materials [77].

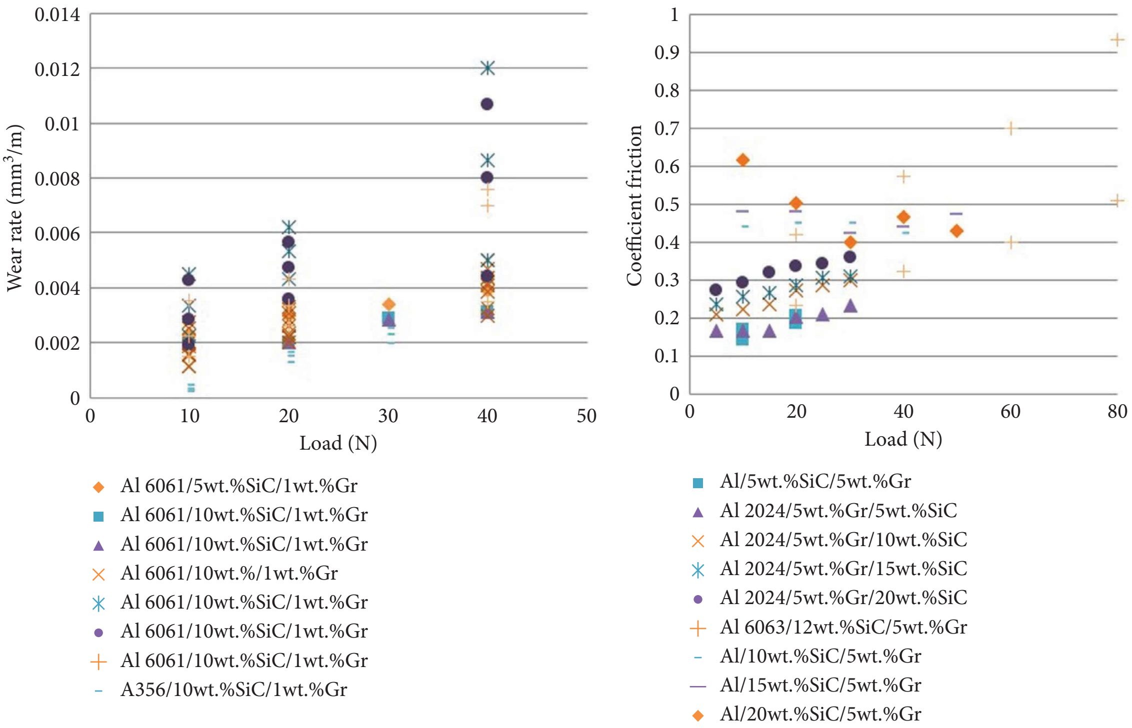
Ravikumar et al. [112] experimented with the fabrication of Al_2O_3 and SiC particulates reinforced HAMCs via stir casting method to examine the impact of reinforcement and processing conditions on corrosion behaviors of Al matrix and HAMCs investigated by polarization, impedance (EIS), and weight loss methods. They found that rising the contents of Al_2O_3 and SiC particulates in the HAMCs reduces the rate of corrosion. The SEM micrograph examination showed the minor formation of pits due to corrosion upon increasing Al_2O_3 content, which can utilize for future corrosive applications in various sectors. The unreinforced metal has a corroded surface compared to the Al/Al_2O_3/SiC composite because the material loss due to corrosion had decreased by the presence of Al_2O_3 (as shown in Figure 16). Additionally, pitting and grain boundary corrosion had been seen on the pure Al matrix and the Al/Al_2O_3/SiC composites. The combined impact of inclusions and defects generated at the time of AMC fabrication decrease the sensitivity of Al/Al_2O_3/SiC composites to pitting by decreasing the needed driving force.

Veličković Gajević et al. [113] utilized a pin-on-disc tribometer to investigate the impact of load, silicon carbide, and graphite wt% on the wear rate and coefficient of friction of Al/SiC/Gr HAMCs. The load varied between 10 and 80 N, the sliding speed between 1 and 3 m/s, and the sliding distance between 100 and 1000 m. The SiC reinforcement particulates were nm in size, whereas the Gr particles were mm in size. Because the HAMC material's hardness has increased with increasing the wt% of SiC reinforcing particulates in HAMCs, the wear rate increases as the load increases (Figure 17(a)). Increasing the sliding speed causes a drop-in wear rate under identical experimental conditions (same load and sliding distance). Figure 17(b) shows the effect of loading on the coefficient of friction of SiC and 5 wt % Gr reinforced hybrid composites with varied SiC particle wt%. The friction coefficient grows from 10 to 80 N as the wt % of SiC particulates increases and the sliding distance increases as well. With increasing sliding speed, the friction coefficient of the HAMC material drops. The kind of reinforcement, its stiffness, grain sizes, weight percentage, and dispersion homogeneity inside the matrix, as well as the process of HMMCs production, all have a role in enhancing the characteristics of Al/SiC/Gr HMMCs. The fabrication process can also improve the properties of HMMCs if the fabrication parameters are chosen correctly (the compaction pressure, sintering temperature, milling time, time at the sintering of reinforcement, etc.). In comparison to the identical qualities of the base aluminum matrix, the inclusion of the hard reinforcer-ceramic materials (SiC)-improves the physicomechanical and tribological capabilities of the HAMCs (hardness, compressive strength, toughness,



(a) (b)

Figure 16: SEM micrographs of (a) monolithic (pure Al) and (b) Al-6 wt% Al_2O_3-wt% SiC composites. Adapted with permission from Ref. [112], copyright 2018, JSR.



(a) (b)

Figure 17: The influence of load on the friction coefficient of Al/SiC/Gr HAMCs with various SiC particle wt% and fixed (a) 1 wt% Gr, (b) 5 wt% Gr. Adapted with permission from Ref. [113], copyright 2018, EDP Sciences.

corrosion resistance and wear resistance). As a consequence, it is possible to deduce that the right combination of processing techniques, reinforcing materials, quantity, and reinforcing grain size can result in HAMCs with excellent tribological characteristics that outperform traditional composites [72].

Radhika et al. [114] produced Al_2O_3 and Gr reinforced HAMCs using the stir casting process in order to increase dry sliding wear resistance and investigate the impact of sliding velocity, pressure, and reinforcing percentage on wear characteristics and interface friction. Al_2O_3 particulates with an average diameter of 15–20 m and wt% of 3, 6, and 9, as well as 3 wt% Gr particles with average sizes of 50–70 m, were used as reinforcements. HAMCs' mechanical characteristics, such as tensile strength and hardness, had increased dramatically. For the aluminum matrix and composite materials, the wear rate and friction coefficient reduced with rising sliding velocity and rose with reducing sliding speed

[115]. They investigated the worn surfaces of the HAMC samples using SEM and the deterioration was found to be larger in Al than in the HAMCs. The depths and number of notches grow as the sliding velocity and increase in weight. In Al/9 wt% Al_2O_3/3 wt% Gr, the layer of materials discarded as trash was smaller, as seen by the comparably smooth worn surface. When compared to the Al matrix, the wear and friction rate in HMMC is much lower due to the presence of graphite particles [114].

When compared to monolithic or unreinforced bath matrix materials, the tribological performance of TiC, TiB_2, B_4C, ZrB_2, WC, Si_3N_4, SiO_2, TiO_2, Al_2O_3, ZrO_2, and other ceramic particle reinforced aluminum matrix composites is much superior [116]. This is due to the fact that these ceramic materials have superior wear and mechanical characteristics (better hardness, compressive strength), stronger abrasiveness, and good friction resistance. Moreover, solid waste particulate used as secondary reinforcement also improves the wear and friction of AMCS and HAMCs in the form of lightweight, low density, low cost, and suitable properties with ease of processing [84]. When compared to single-reinforced AMCs and monolithic metal matrix materials, HAMCs have superior tribological characteristics. Simsek et al. [68] investigated the wear loss of Al-Gr and Al-Gr-Al_2O_3 composites with 2 vol% of Gr and varied (3–12) vol% of Al_2O_3. The hardness and density of Al-Gr-Al_2O_3 HAMCs were found to be superior compared to Al-Gr AMCs, owing to the increased hardness, strength, wear resistance, and abrasiveness behavior of Al_2O_3 particulates. The highest density, hardness, wear loss, and friction coefficient, as well as the lowest wear loss and friction coefficient, were recorded at 12 vol% Al_2O_3. Figures 18(a) and 18(b) illustrate how increasing the vol% of Al_2O_3 increased the density, hardness, and friction coefficient of the HAMCs, respectively.

Ramadoss, et al. [76] investigated the influence of SiC and MoS_2 particulate reinforcement on the wear and corrosive behavior of aluminum matrix nanocomposites (AMNCs). The addition of nano-SiC particles considerably enhanced the wear resistance of Al6063 + 3%SiC+3%MoS_2 and Al6063 + 3%SiC, whereas the inclusion of micro MoS_2 with nano-SiC reinforcements boosted the wear resistance of Al6063 + 3%SiC and Al 6063-T6. The corrosion behaviors of Al 6063-T6, Al 6063 + 3% SiC, and Al 6063 + 3% SiC +3%MoS_2 are revealed in Figure 19 by means of SEM photographs. The corrosion resistance of Al 6063 + 3% SiC + 3%MoS_2 (e, f) is considerably greater than that of Al 6063 + 3% SiC and Al 6063-T6. To resist corrosion, secondary reinforcement MoS_2 serves as a reaction barrier. The corrosion process is begun at localized places, preferably in both primary and secondary phases, as may be seen on the surface of the Al 6063-T6, and these characteristics are visible in the case of Al 6063 + 3% SiC and Al 6063 + 3% SiC +3%MoS_2 composites due to their tiny grain size.

2.5. Fabrication Process of MMCs and HMMCs. Mussatto et al. [15] investigated advanced manufacturing methods and MMC applications (Figure 20). For the fabrication of MMCs, powder metallurgy and casting techniques are still widely utilized [15].

Guttikonda et al. [117] investigated the influence of powder metallurgical processing in a proper dispersion of the reinforcing phase by milling or mechanically milling, as well as how the powder metallurgical route enhances the physicomechanical characteristics of composite materials. According to previous research, the main challenge faced by MMCs is wettability and the interfacial interaction bonding formed among the interface of the reinforcement particulates and the matrix materials as they are fabricated using traditional methods such as stir casting, friction stir processing, centrifugal casting, squeeze casting, and other methods that use liquid molten materials [7, 118, 119]. Tables 7 and 8 provide a comparison of liquid and solid-state manufacturing methods, respectively.

2.6. Powder Metallurgy Processing Route. The PM method for MMC manufacturing was developed to address difficulties such as wettability and interface interactions that are common in liquid processing, with the additional benefit of enhanced particle spatial distribution in dis-continuously reinforced MMCs [121].

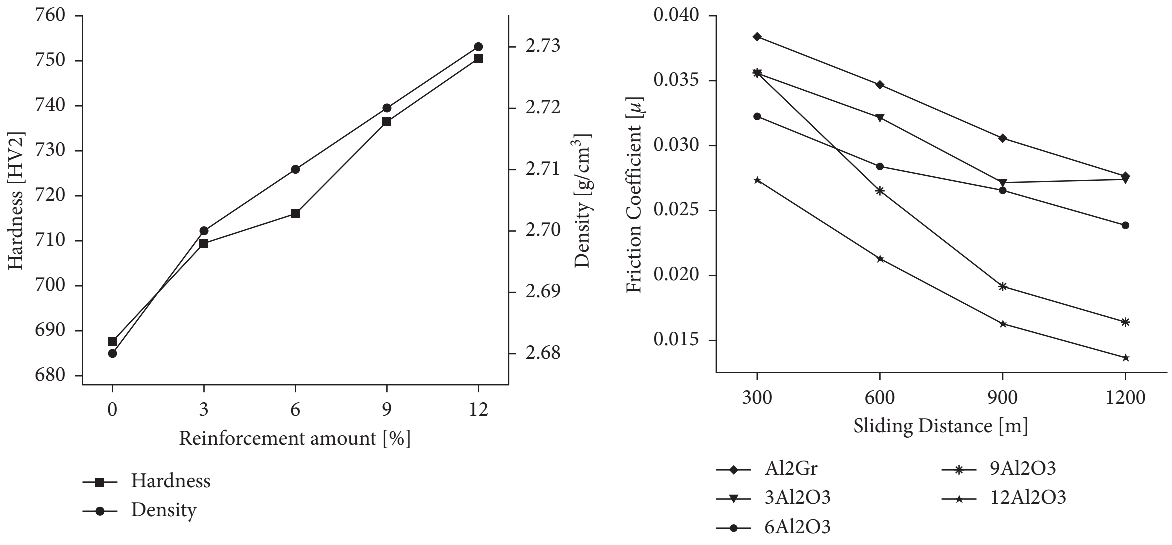
Advantages of powder metallurgy process in the production AMCs and HAMCs:

(i) Suitable for high-temperature matrix;
(ii) Prevents segregation and the production of brittle products;
(iii) Has the ability to manufacture complicated shapes with sufficient dimensional precision;
(iv) Produces the least amount of material loss;
(v) Fewer secondary machining processes are required;
(vi) The parts produced are usually defect-free;
(vii) Reinforcement can range from a low to a high weight percent.

The PM process also allows for the fabrication of net-shape or near-net-shape parts, which lowers machining and finishing costs [122].

Powder blending is one of the most important phases in PM, for which powders of various materials with a variation of physicomechanical and thermochemical behaviors are mixed in a single form using a ball mill. Particle size reduction (material breakdown), blending or mixing and particulate shape are the three main goals of the milling process [123]. Blending results in structural homogeneity and homogenous powder particle mixing, leading to different mechanical behavior with consistent features all across the composite. The particles are broking into fine particles by compressing operation in compression force type [124]. The fine powders are blended or mixed with a solid lubricant, and the lubricants service adequate fluidity to the particles.

Powder compaction is accomplished with the assistance of a die and punches assembly, which applies tremendous pressure to the particles in order to produce a cohesive link between them [125]. At ambient temperature, the



(a)

(b)

Figure 18: The influence of Al_2O_3 content (a) on hardness and density and (b) on friction coefficient of Al-2 vol% Gr-(3–12 vol%) Al_2O_3 [68].

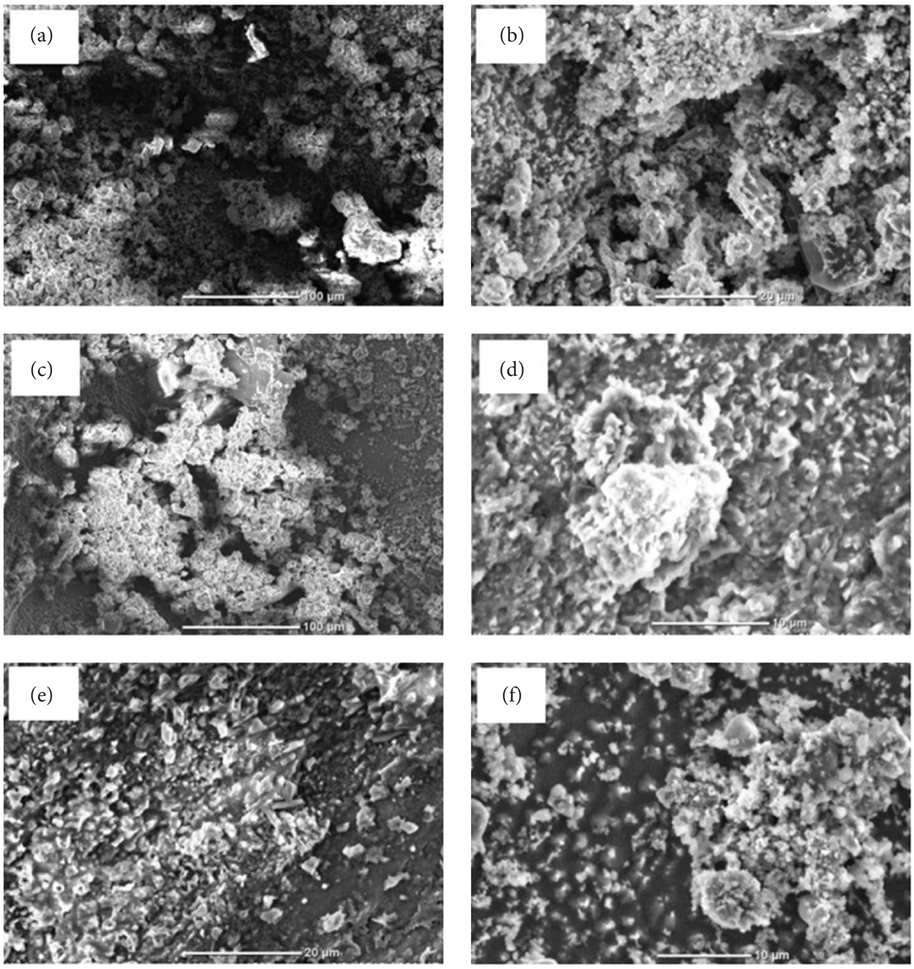


Figure 19: SEM study on corroded surface of Al 6063-T6 (a, b), Al6063 + 3%SiC (c, d) and Al6063 + 3%SiC+3%MoS_2 (e, f) [76].

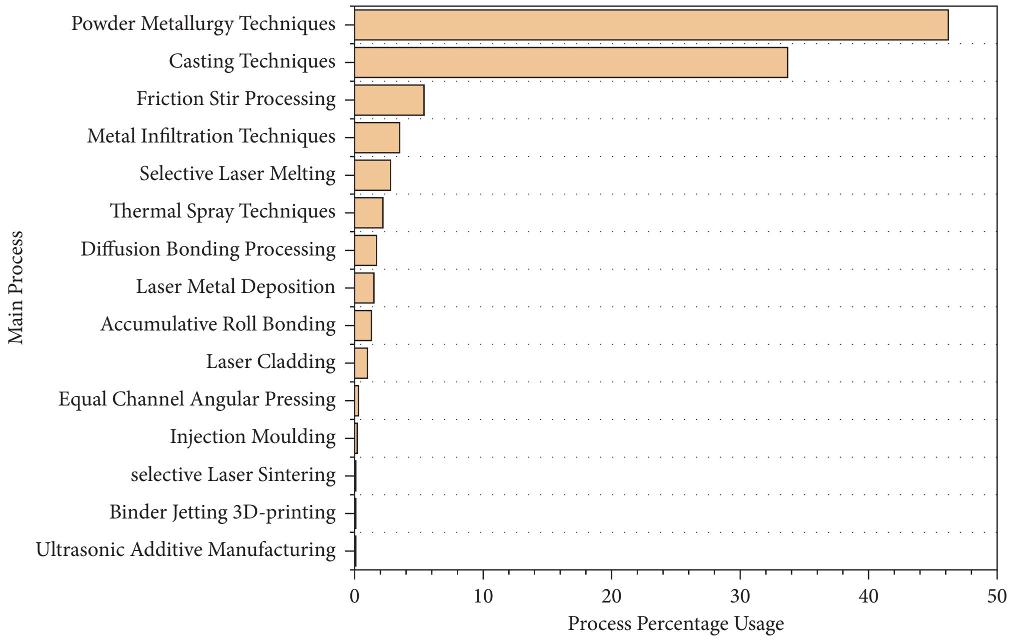


Figure 20: Comparison of MMCs Processing techniques [15].

Table 7: Comparison of MMC liquid state manufacturing methods [120].

Process	Cost	Application	Explanations
Stir casting	Least expensive	For large quantity fabrication. The commercial method of fabricating AMCs.	It is dependent on the material qualities as well as the process conditions. In AMC, it is suitable for particulate reinforcement.
Squeeze casting	Medium	Suitable for making complicated systems; widely used in the automobile industry for producing pistons, connecting rods, rocker arms, and cylinder heads.	It can be utilized for large-scale fabrication and is broadly applicable to any sort of reinforcement.
Spray casting	Medium	Abrasive components, electrical brushes, contacts, and cutting and grinding tools are all manufactured using this process.	Particulate strengthening is utilized and complete density composites are possible.
In-situ processing	Expensive	In the aerospace and automotive industries.	The reinforcement particulates are distributed uniformly.
Liquid-metal infiltration	Low/ medium	Produces structural forms having maximal characteristics in a uniaxial direction, such as rods, tubes, and beams.	Reinforcing filaments had been utilized.

Table 8: Comparison of MMC solid-state manufacturing methods [120].

Route	Cost	Application	Comment
Powder metallurgy	Medium	Fasteners, cylinders, valves, max hardness, and high-temperature- temperature materials are used to make tiny items (particularly circular ones).	Both the matrices and the reinforcements are all in powder form; this really is ideal for particle strengthening; since there is no melting, no problems encountered arise, resulting in a high-strength composite.
Ultrasonic assisted casting	Expensive	Utilized large-scale manufacturing and net form manufacturing of complicated structural parts.	Reinforcement particles are distributed rather evenly and dispersed well.
Diffusion bonding	High	Sheets, blades, vane shafts, and structural parts are all made from this technology.	Handling matrices foils or sheets, as well as strengthening component fibers

compaction process will be conducted which is called cold compaction. Green strength represents the strength that results in the development of compaction. The spaces between the powder particles decrease as a result of compaction. It also results in particulate attraction and interaction. Compacting can also encourage plastic deformation between the particles, resulting in a higher density of the consolidated particle. The green density of the specimen rises when the compaction pressure is increased. In general, cold compaction serves four purposes: (1) creating the required form, (2) controlling dimensions, (3) controlling the porosity, and (4) imparting sufficient strength for handling [126].

Sintering is commonly done at a high temperature and atmospheric pressure. The sintering temperature of the material must be lower than the basic material's melting temperature. However, the temperature of its components (with low Tm) would be up to (0.7 to 09) Tm, allowing diffusion between nearby particles [126]. To avoid oxidation, the heating procedure is done in a controlled environment with an inert atmosphere. The sintering process improves the mechanical properties of the final product, such as density, by reinforcing the impending holes and boosting the area of contact between the powder particulates. Table 9 depicts the three primary PM processing phases and their implications.

Hot isostatic pressing (HIP), high-energy, high-rate processes, and resistance sintering are some of the other commercially available methods.

Kumar et al. [128] studied the impacts of process factors on the densities, porous, strength, and hardness of powdered metallurgical MMCs once again. Compaction pressure, sintering temperature, and sintering time are all powder metallurgical processing factors that have a substantial influence on the physicochemical characteristics of AMCs generated by PM. Among the three PM process parameters, compaction pressure has the greatest influence on the physicomechanical characteristics of AMC materials (compaction pressure, sintering temperature, and sintering time). Sintering temperature and duration have an impact on the physicomechanical characteristics of AMCs materials. Sintering temperature and duration have a complicated effect on physicomechanical characteristics. The ideal compaction pressure, sintering temperature, and sintering time for AMCs made via powder metallurgy are 600–700 MPa, 520–600°C, and 3–4 hrs., respectively [123, 128]. The physicomechanical characteristics of AMCs and HAMCs generated by powder metallurgy are also altered by the type, grain size, and amount of reinforcing material. For instance, the density of fly ash [129], sugar cane bagasse ash [130, 131], and most other solid wastes [131] is lower than the density of aluminum, so the addition of such materials as reinforcement into AMCs and HAMCs decreases the overall density of the composite material (Figure 21). Ceramic reinforcing particulates such as SiC, Al_2O_3, TiB_2, and others increase AMC strength by preventing dislocation movement. Reinforcing components, such as CNTs and GNPs, improve the strength of AMCs and HAMCs by enhancing grain refinement in the composite material. There is always an ideal range of reinforcing weight percent. Density, porosity, hardness, and other AMC characteristics decrease above the optimal 7 wt% for nanoparticulate reinforcing materials, whereas wt% within the range of 5–10 wt% is optimal for microparticulate reinforcing materials [128].

The density of solid waste (such as agro-industrial and others) reinforced metal matrix composite decreases with increasing reinforcements. For instance, the density of rice husk ash aluminum matrix composite (CRHA) and bagasse ash reinforced aluminum matrix composite (CBA) decreases with increasing vol% of each solid waste as shown below in Figure 21. The addition of tough, durable, and low-density reinforcing materials with densities of 0.397 g/cm^3 and 0.238 g/cm^3 for RHA and BA, respectively, inevitably resulted in the substitution of a soft and high-density Al alloy matrix with a density of 2.840 g/cm^3 in the composites, resulting in an overall reduction in densities of up to 15% and 19% of the control composites, respectively. BA has a lower density than RHA, leading to a lower metal matrix composite [131].

Table 9: Basic powder metallurgy processing steps [123, 127].

P/M steps	Description
Blending	To make a homogenous mixture, the metal powder and reinforcing particulates are combined altogether.
Cold compaction	To make a "green" body, the particles are mashed together.
Sintering (hot consolidation)	The particles are heated until they are completely compacted.

Meignanamoorthy et al. [132] investigated the impact of powder metallurgical process variables on the density, hardness, and compressive strength of AA8079 matrix composite with different B_4C wt% (0, 5, 10, and 15). The green compacts were sintered at 375, 475, and 575°C for 1, 2, and 3 h at three pressures: 300, 400, and 500 MPa. Every sintered sample was also exposed to XRD, EDAX, and SEM investigations. The SEM analysis revealed that the B_4C particulates were spread equally throughout the AA8079 matrix and without any holes or grain boundaries. Various electrochemical methods such as polarization and EIS measurements were used to examine the corrosion behavior of produced composites. As the wt% of B_4C reinforcements in the AA8079 matrix rose, the corrosion resistance of AA8079-B_4C composites improved. Density, hardness, compressive strength, and corrosion resistance all improve as PM process variables (such as compaction pressure, sintering temperature, and sintering time) are increased [127].

2.7. Potential Application of AMCs and HAMCs. Composites are attractive for applications comprising high mechanical properties, low densities, tailorable properties, design and manufacturing flexibility, excellent corrosion resistance, and cost-effective product development [6, 7, 34, 63]. Figure 22 depicts the application of MMCs and HMMCs.

Before widespread usage, biomedical applications may need particular research and development operations and the resolution of technological issues. Mechanical and physical properties such as exceptional corrosion resistance and low temperature, as well as biocompatibility, are crucial in biomedical advances (Table 10). For instance, Al-Mg alloys reinforced with Gr, ZrO_2, and Al_2O_3 HAMC could be favorable materials for biomedical applications [135]. Table 11 describes the relevance of future engineering materials in the automotive industry and their requirements. The AMCs and HAMCs that excel in many application areas are

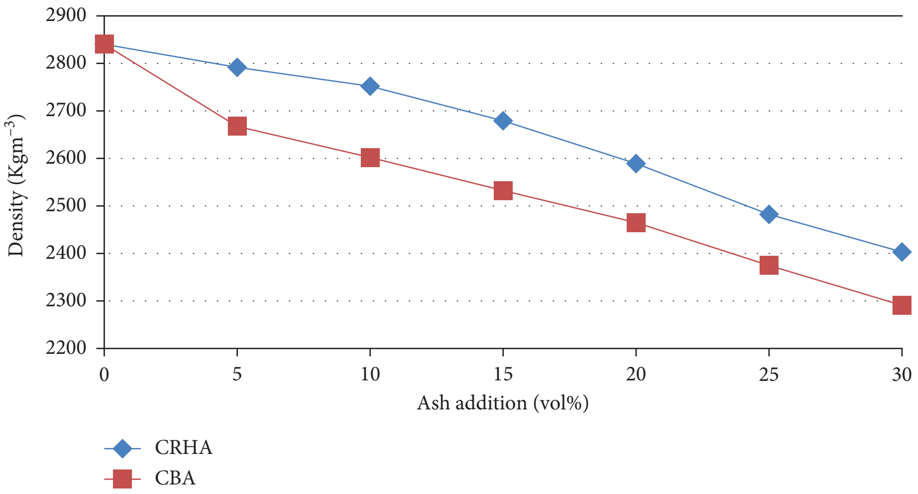


Figure 21: Effect of type and wt% of RHA and SCBA on density AMCs, adapted with permission from Ref. [131], copyright 2019, Elsevier.

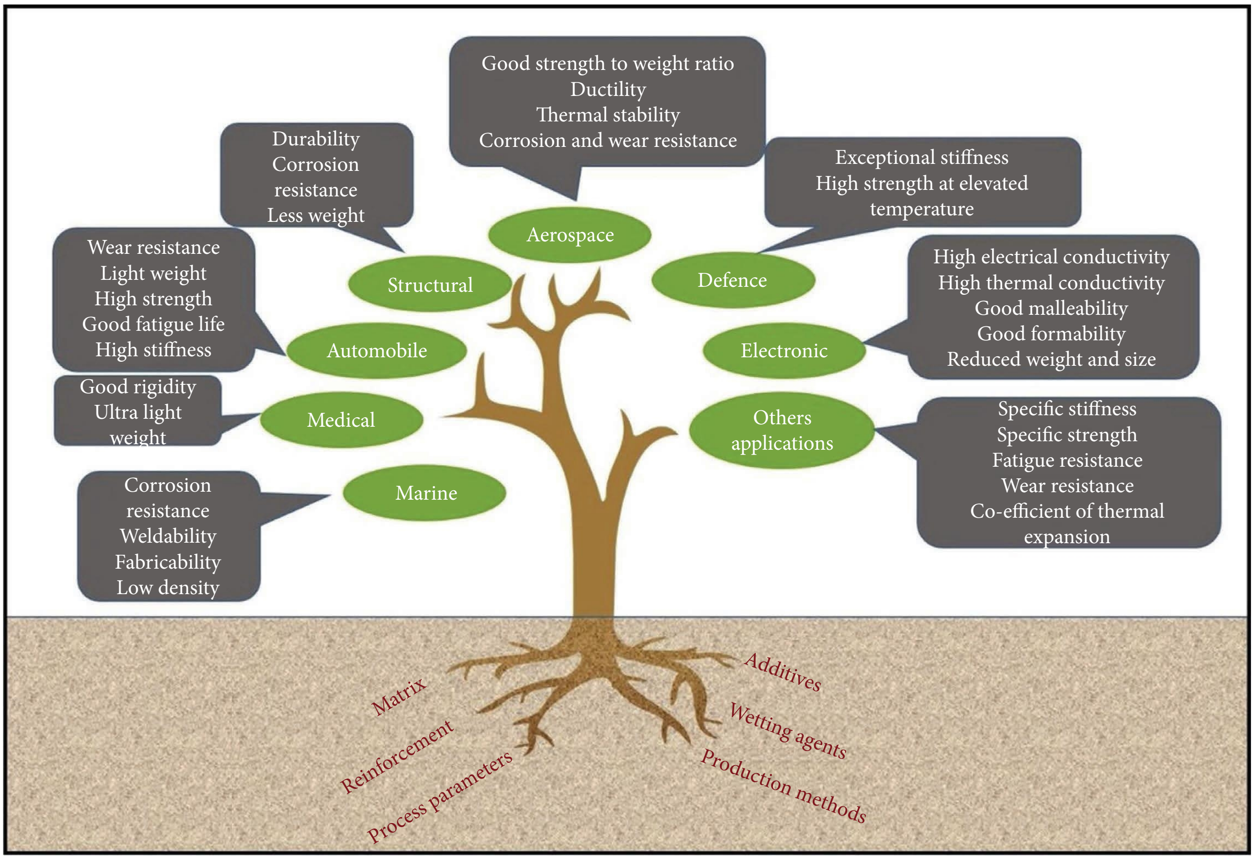


Figure 22: Applications of MMCs and HMMCs in various fields, reproduced with permission from Ref. [7], copyright 2019, Elsevier.

shown in Table 12 along with the unique qualities that make them stand out.

Composites have emerged as the preferred material for decreasing weight and fuel consumption while improving powertrain performance in vehicles. Hybrid composite materials are used in a wide range of engineering applications due to their diversified properties such as lightweight, strength-to-weight ratio, low cost, ease of structure ship building, and high strength. Examples of hybrid reinforcements that have been employed with metal matrix, including Al, Mg, Cu, Fe, Ti, Ni, and their alloys, to create various HAMCs for various applications are shown in Table 13 [15].

When each of the aforementioned hybrid reinforcements is sufficiently distributed within the appropriate range, the resulting HAMCs will outperform the AMCs and the majority of the alloys created thus far [15, 146]. One of the most current innovative materials,

Table 10: The important criteria that material should meet for the automobile and aerospace industries [133, 134].

No	Criteria	Definition/Description	Comments
1.	Lightweight (weight reduction)	(i) Lightweight is the most important factor in the automotive industry when it comes to reducing greenhouse gas emissions and improving fuel efficiency. (ii) As the mass decreases, so does the gas flow and the number of congenital emissions.	(i) Without losing stiffness or durability, lower density materials such as al, Mg, and their composites can be used to replace high-specific weight materials such as steel. (ii) Improving the architecture of load-carrying systems and exterior attachments to reduce weight while retaining stiffness and usefulness. (iii) Improving the manufacturing process
2.	Economic effectiveness	(i) Among the most important consumer-driven variables in the automobile industry is cost, which determines how well a novel technology or material has a chance of being picked for a car component.	(i) The most promising method of cost reduction is the use of solid waste materials as secondary reinforcement.
3.	Safety	(i) The ability to absorb impact energy through regulated failure modes and systems while remaining safe for passengers.	(i) Using solid lubricants with lightweight and low cost, such as MoS2, Gr, and others, could result in tailorable and superior properties in high temperature and harsh environments.
4.	Recyclability	(i) The automobile manufacturing industry's top concerns include raw material sustainability and recycling options, as well as research and development programs focused on recycling technologies and the creation of economically recyclable materials, as well as their integration into autos and their components.	(i) Recycling solid wastes such as fly ash sugar cane bagasse ash and others to use as secondary reinforcement in the automotive and other industries. (ii) Moreover, for composite production metal scraps in automotive components and other industries can be used as reinforcement.
5.	Corrosion and wear resistance	(i) Corrosion and wear are major concerns in both the automotive and aerospace industries, as most components are made of metals with a low resistance to wear and corrosion (such as steel, al, Mg, and their alloys).	(i) The use of HMMCs provides superior wear and corrosion resistance compared to single-reinforced and monolithic materials.

Table 11: Future material requirements in the automobile industry [133].

Requirements on automotive industry	The reaction of the automotive industry	Significance of materials engineering
Resource management	Intake and weight management	Characterization combinations for lightweight materials, materials having a high efficiency/weight ratio, and low-friction materials
Care of environment	Pollution reduction in cars and the manufacturing process	Low-emission process and nontoxic materials
	The closed system of materials cycles	Recyclable materials with tailorable properties Application of Al and its alloys
Price reduction	Manufacturing and development costs are being reduced.	Materials with a low cost of production, as well as procedures that are low in cost.

Table 12: Potential applications of AMCs and HAMCs.

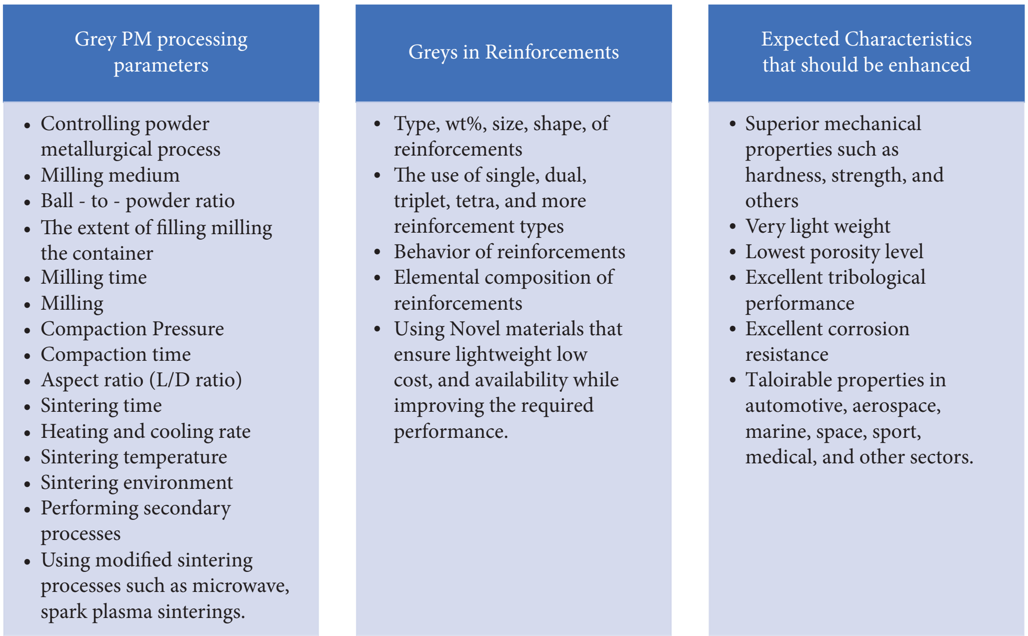
Application	Material system	Required property	Advantages	Fabrication	Ref.
Automotive Driveshaft, brake disk, piston, stiffeners,	Al-Al_2O_3, Al-SiC, Mg-SiC, and Mg-Al_2O_3 Al/ (discretized reinforcing) (SiC, Al_2O_3, and graphite)	High specific strength and stiffness, temperature resistance, resistance to wear and corrosion, Low CTE	Reduced weight leads to fuel efficiency, reduced tooling cost, wear and corrosion resistance, and lower part count	Powder metallurgy squeeze casting, extrusion, forging	[1, 134, 136–139]
Aircraft Supporting tubes, gearboxes, stiffeners, wings, blades, turbine blades,	Ti-SiC, Al- TiB_2 Al-Al_2O_3, Mg- Al_2O_3/SiC, and Al-B Al/(SiC, Al_2O_3, and graphite)	Weight reduction, reduced part count, reduced cycle time, manufacturing flexibility	Weight reduction leads to higher speeds, increased payloads, higher range and fuel economy, higher fatigue and corrosion resistance	Powder metallurgy, diffusion welding, and soldering, hot pressing, melt Infiltration	[1, 12, 50, 140–144]
Space Stiffeners, antennas, joins and payload adapters, and fairings	Al-SiC, Al-B, Al-C, Al-Al_2O_3, Mg- Al_2O_3 (continuous and discontinuous)	Weight reduction, reduced part count, reduced cycle time, manufacturing flexibility	Reduction in weight, cost, process, while improving high temperature and pressure and others	Melt infiltration, extrusion, diffusion bonding, and joining	[12]

Table 13: Examples of Hybrid reinforcements used with metal matrix (such as Al, Mg, Cu, Fe, Ti, Ni, and their alloys) to produce different HAMCs for different applications [15, 145].

Hybrid reinforcements		
TiB + TiC	Graphite + Al_2O_3	Al_2O_3 + rice husk ash
TiC + TiB	Nb + Zr + hydroxyapatite	Al_2O_3 + B_2O_3
SiC + Al_2O_3	Cr + TiN	Al_2O_3 + TiB_2
Al_2O_3 + graphite	SiO_2 + Mg	TiO_2 + fly ash
TiC + graphite	SiC + graphene	SiC + MWCNTs
ZrO_2 + Y_2O_3	Graphene + Ag	ZrO_2 + Al_2O_3 + SiO_2
Al_2O_3 + SiC	SiC + B_4C	Fly ash + Mg
SiC + fly ash	Al_2O_3 + Cu + glass bubbles	CNTs + B_4C
TiB_2 + TiC	WC + Cr	B_4C + MWCNTs
B_4C + MoS_2	SiC + $ZrSiO_4$	TiO_2 + B_4C
SiC + graphite	ZrB_2 + TiB_2	SiC + Mg
B_4C + graphite	Ti + C(f)	Diamond + Ti
Si_3N_4 + AlN + ZrB_2	Nb + Ti	Ni + WC
CNTs + Al_2O_3	SiC + NO	Cu + diamond
Graphite + MoS_2 + ZrO_2	SiC + rice husk ash	TiB_2 + B_4C
SiC + Ni	Ti_2 + Al + C	Mullite + ZrO_2
SiC + CNTs	WC + TiC + Cr + graphite	Al + SiC
CNTs + SiC	Al + Cu + Mg	Cu + Sn
Ni + Fe + Al_2O_3	B_4C + CNTs	Cu + Mn
TiC + Y_2O_3	AlN + Si_3N_4	TiN + Co
WC + TiC + Fe_3C + Mo_2C	MWCNTs + B_4C	WC + TiC + Co
Ag + BaF_2 + CaF_2	Mo + P + C + B	WC + CrC + Ni
MWCNT + Ti	Cr + SiC	Cr + diamond
SiC + Al	Al + Cu	W_{core} SiC + NiTi
Ni + ZrO_2	Ni + Cu	Mo + SiC
Sr + Ba + TiO_3	B_4C + rice husk ash	Nb + C
SiC + TiC	SiC + carbonized eggshells	Graphite + medium-carbon steel
TiB + TiN	Fly ash + S-glass	ZrO_2 + Al_2O_3
CNTs + TiC	SiC + Cu	Cr_2O_3 + Mo + Ag

Table 14: Examples of the current application areas and advantages of AMCs and HAMCs.

1. Automotive components [63, 139]	2. Aerospace components
(i) AMC piston connecting rod reinforced with SiC (ii) Light-weight (AMC's weight is 57% lighter than steel) (iii) Reduced fuel consumption and (iv) Improved motor power	AMCs for aircraft landing gear. Adapted from [147] (i) Minimize landings gear mass by up to 30%., fuel consumption, and noise (ii) Decreasing maintenance, repairs, and operational costs. (iii) Capability at higher temperatures (iv) Resistance to fire (vi) Transverse stiffness and strength are increased. (vi) Higher strength and stiffness
A cylinder liner fabricated from SiC and Al_2O_3 reinforced HAMCs. [63] (i) High-temperature quality, (ii) Great wear resistance	(a) Sentinel-1 aluminum-silicate-magnesium alloy antennas support, (b) high-value aerospace brackets constructed of Ti-6Al-4V, (c) flange, and (d) aircraft bracket. [148]
AMC pistons, particle reinforced AMC car brake disc [63] (i) Capability at higher temperatures (ii) Resistance to fire (iii) Transverse stiffness and strength are increased. (iv) Higher strength (v) Higher stiffness	Boeing 787 Dreamliner uses more than 50% composite materials [149] (i) Weight reduced by 20–50% (ii) Capability at higher temperatures (iii) High impact resistance (iv) Transverse stiffness and strength are increased. (v) A high level of damage tolerance enhances accident survival. (vi) Protection of lightning strikes with conductive composites
Automotive crankshaft made from Al/SiC-Gr HAMCS. Particle-reinforced AMC car brake disc. [63]	



Grey PM processing parameters

- Controlling powder metallurgical process
- Milling medium
- Ball - to - powder ratio
- The extent of filling milling the container
- Milling time
- Milling
- Compaction Pressure
- Compaction time
- Aspect ratio (L/D ratio)
- Sintering time
- Heating and cooling rate
- Sintering temperature
- Sintering environment
- Performing secondary processes
- Using modified sintering processes such as microwave, spark plasma sinterings.

Greys in Reinforcements

- Type, wt%, size, shape, of reinforcements
- The use of single, dual, triplet, tetra, and more reinforcement types
- Behavior of reinforcements
- Elemental composition of reinforcements
- Using Novel materials that ensure lightweight low cost, and availability while improving the required performance.

Expected Characteristics that should be enhanced

- Superior mechanical properties such as hardness, strength, and others
- Very light weight
- Lowest porosity level
- Excellent tribological performance
- Excellent corrosion resistance
- Taloirable properties in automotive, aerospace, marine, space, sport, medical, and other sectors.

Figure 23: Grey research areas in AMC and HAMCs and PM process parameters.

hybrid MMCs have the following qualities: low thermal expansion, high specific strength, strong wear resistance, and lightweight. In automotive engineering, hybrid composites play a significant role in the development of piston rods, piston pins, braking systems, pistons, frames, valve spring caps, disk brake calipers, brake disks, brake pads, shafts, and other components (Table 14) [15, 145, 146].

3. Conclusion and Future Perspectives

According to previous research, reinforcement materials such as ceramic particles, SiC, Al_2O_3, graphite, and agro-industrial solid wastes such as FA, RHA, SCBA, and others influence the physicomechanical and tribological properties of hybrid aluminum matrix materials. The literature cited above demonstrated that composite materials made of Al reinforced with SiC, Al_2O_3 particles, solid wastes (such as SCBA, RHA, FA, and so on) and solid lubricants (such as Gr, MoS_2) have the potential for excellent wear resistance and tailorable properties suitable for tribological applications. To date, no research has been conducted to investigate the behavior of SCBA, $Al_2O_{3,}$ and SiC fine particulates as tetra hybrid reinforcement or Gr, $Al_2O_{3,}$ and SiC fine particulates as tri hybrid reinforcement with the pure aluminum matrix material. Furthermore, Gr has never been used as part of a tri or tetra hybrid reinforcement to HAMCs in prior studies for self-lubricating purposes. This study will look at the effects of varying wt% of reinforcing components, including SiC, Al_2O_3, SCBA, and Gr on the microstructure, physicomechanical and wear and corrosion behavior of the Al matrix. There is also no research on the fabrication of either of the aforementioned hybrid reinforced aluminum composites using powder metallurgy. In composites characterization investigations, there seems to be limited research on the application of sophisticated characterization techniques.

3.1. The following Qualities of HMMCs Are Being Investigated. Corrosion and wear behavior of hybrid reinforced metal matrix composites in a variety of circumstances, including self-lubricating reinforcements, harsh corrosive environments, and wide temperature ranges. Hybrid reinforced metal matrix composites' physicomechanical, thermochemical and electrical properties for prospective and field-specific application sectors. There are enough research gaps concerning (1) self-lubricating combined with using solid wastes from various sources, such as bio-solid wastes or agro-solid wastes such as rice husk ash, sugar cane bagasse ash, palm kiln shell ash; industrial solid wastes such as fly ash; post consumer solid wastes, such as plastic wastes from home use to industrial scrap wastes as secondary reinforcements when looking at environmental issues, problems, difficulties or challenges. (2) The long-term viability of these solid wastes when using various approaches to reduce porosity, weight and cost necessitate extensive investigation into the modification of existing processing procedures as well as other processing factors. There are also grey areas in the use of MMCs and HMMCs in various applications, such as (1) biomedical applications, which require ultra lightweight, biocompatible, nontoxic, nonallergic, nonflammable, noncarcinogenic and nonpoisonous materials such as bio-fiber solid wastes for further composite material strengthening. The future grey areas for PM processing parameters, reinforcements, and characterizations are depicted in Figure 23.

Data Availability

All the dataset for supporting the results and conclusion is provided within the article.

Conflicts of Interest

The authors declare that they have no known conflicts of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Conceptualization was done by D.A.A.; investigation was performed by D.A.A.; formal analysis was performed by D.A.A.; supervision was done by G.A.M., and D.K.S.; validation was performed by G.A.M., and D.K.S.; original draft written by, D.A.A.; review and editing were done by D.A.A., G.A.M., and D.K.S. All authors have read and agreed to the published version of the manuscript.

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